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Amitava Rakshit
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Rahul Datta
Editors

Handbook of Energy Management in Agriculture

Springer

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Handbook of Energy Management in Agriculture

With 161 Figures and 92 Tables

Springer

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Dedicated to our parents who encouraged us to go on every adventure.

Preface

Agriculture is one of the most imperative sectors that contribute to the economy across different agro-ecologies of the universe. Energy inputs are found in each stage of production, from making and applying chemicals to fueling tractors that lay seeds and harvest crops to electricity for animal housing facilities. This noteworthy energy consumption has left farmers susceptible to elevated energy costs and impulsive energy market fluctuations that impact agrochemical costs as well. Efficient energy management practices, energy saving, and exploiting farm's existing energy resources are ways to reduce dependency on fossil fuel use and maintain a delicate balance. If executed effectively, judicious and effective energy efficiency measures can help the agricultural sector save energy without harming ecological integrity, productivity, and impairment of the environment ensuring maximum profit. Good agricultural practices, the use of renewable energy, and effective policies, including educational training and incentives for energy efficiency improvements, can help humanity to achieve everlasting sustainability.

The majority of agricultural research has focused on the use of input, production, and productivity, whereas rational energy budgeting and use remain an overlooked and likely underestimated segment, ignored so far while formulating an agro-ecosystem framework. Energy management study is a new frontier of agriculture and is challenging due to complex enterprises, spatial-temporal variability, exposure to pollution, and the predominant effect of the anthropogenic factor on the ecology and environment. But it is worth taking the challenge considering the important prerequisite role of energy for sustainable development which has been evidenced by increasing research in recent times. Of recent origin, there are critical, in-depth studies around the globe assessing the capture and flow of energy in the ecosystem, which will help to develop a conceptual framework to incorporate this vital resource in agriculture management template. However, there is a lack of consolidated effort in documenting these studies carried out elsewhere. Therefore, this handbook would provide an important document for the international funding agencies, universities, public energy institutions, farmers and farming industries, public health and other relevant institutions, and the broader public in order to understand and maximize the benefits.

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Last but not least, our deepest gratitude to our caring, loving, and supportive family members for their generous support and encouragement during the preparation of this manuscript.

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Rahul Datta an Assistant Professor of Soil Science at Mendel University in Brno, Czech Republic, is renowned for his research in sustainable agriculture, primarily aimed at boosting crop productivity. His work addresses critical agricultural challenges including drought stress, heavy metal toxicity in soil, and the reduction of greenhouse gas emissions linked to climate change. Dr. Datta's research has notably improved the quality and yield of staple crops like wheat, maize, barley, and rice, along with a variety of other crops such as mangoes, spinach, and cotton. His impactful work has been cited over 5000 times by researchers worldwide, attesting to its significance.

In addition to his research contributions, Dr. Datta actively participates in the academic community. He serves as an editorial board member for reputed journals, including *BMC Plant Biology*, the *Turkish Journal of Agriculture and Forestry*, and *Open Agriculture*, where he continues to influence and shape the academic landscape.

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Part I

Energy Requirement in the Agricultural Food Chain

Carbon Footprint in Rice Cultivation

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Abstract

Rice is one of the widespread crop in South-East, East, and South Asia with a predominance in the Indian subcontinent. China is the largest producer and consumer of rice, sharing for 30% of global production, and next to this, India (24%), Bangladesh (7%), Indonesia (7%), Vietnam (5%), and Thailand (4%) are some other major rice producers. Rice cultivation is often considered as an important sequester of atmospheric CO_2 while also an important source of GHG emission (e.g., CH_4 and N_2O). Under submerged soils of rice fields, the anaerobic condition is created (more negative redox potential), and thus CH_4 is produced by the number of biogeochemical cycles, which is second-most important next to CO_2 as a GHG. A large share of CH_4 escapes from the soil and is lost to atmosphere as plant-mediated CH_4 emission, while the rest of it comes up from the soil via ebullition and/or gradually diffuses into the soil. Carbon footprint of crop is calculated as the total amount of carbon produced during the various production practices in growing season of that particular crop. Being a major crop, the estimation of carbon footprint under different rice production systems is a matter of priority for researchers. This is very much relevant for the environmental point of view. Many laboratories are focusing on this particular aspect, both the estimation and management point of view, and some interesting findings showed the way out for positive C balance in soil by trapping more C in soil and less GHG emission. Here in this chapter, we review the status, measurement procedures, and management options of crop production practices related to carbon footprint, more specific to rice cultivation. This compilation would help researchers to assess the current scenario and possibility to find out new opportunities.

Keywords

Rice · Climate change · GHG emission · Soil C-sequestration · GHG estimation

1 Introduction

Carbon is an important element for crop (constituent of plant tissue) as well as for soil (soil carbon). Soil carbon is a central key attribute governing almost all the soil properties and is very important for sustainable agriculture. Carbon is present in the atmosphere as carbon dioxide and cycled through plants in soil via photosynthesis. Photosynthesis and respiration cover the natural process of global carbon cycle. But due to overexploitation of natural resources, agricultural system, mechanization, urbanization, industrialization etc. and other related activities, imbalance in the carbon cycle has been noticed which is increasing the level of CO_2 in the atmosphere resulting in increased atmospheric temperature (global warming). Global warming is not only due to the increasing concentration of CO_2 but also other GHGs like methane, nitrous oxide, etc. These gases are even more harmful than CO_2 in causing global warming, and its capacity is measured in terms of global warming potential (GWP). It is an index used to compare the effectiveness of GHGs to trap heat in the atmosphere (cause of global warming) relative to CO_2 whose GWP is considered as one (Pathak et al., 2005).

Agricultural system is one of the important contributors in the GHGs emission. Globally, a significant portion (13.5%) of greenhouse gas (GHGs) comes from agriculture (IPCC, 2007). In India, the agriculture sector contributes18% of the total GHG emission (INCCA, 2010). When measured against the total GHG emissions, the amount of CH_4 emitted from rice fields accounted 9.8% in India (in 2006) as compared to only 0.1% in the USA (in 2005) (Leip & Bocchi, 2007). Thus, to mitigate climate change, GHGs emission from agriculture sector must be reduced. Different management strategy has been implemented to reduce the GHGs emission and to increase the carbon content in soil through carbon sequestration, like conservation agriculture, incorporation of residue in soil, integrated nutrient management, etc. However, the exact amount of net carbon or GHGs emitted from the agricultural system was not calculated properly because this calculation needs consideration of different parameters (direct or indirect) together. To compare the system and to identify a more carbon-efficient system or agricultural management options, a new concept was introduced called carbon footprint.

Carbon footprint is simply understood as carbon emission minus carbon sequestration. But, carbon footprint for any system or product can be calculated by the total amount of GHGs produced directly or indirectly (electricity, fertilizers, agricultural implements, diesel, petrol, etc.) converted into CO_2 equivalent (Liu et al., 2021). Hence, a carbon footprint of crop is defined as the total amount of carbon produced during the production practices in the growing season of that particular crop (Zhang et al., 2017). It is an indicator or index to find out the contribution of each and every event to the GHGs emission. It is a sum of all the carbon sources and sinks which is converted to the CO_2 carbon equivalent during a life cycle of a particular activity or product (Wiedmann & Minx, 2008).

Rice is one of the staple food across the globe as well as an important GHGs source; hence, the increasing population will demand for more food which also increases GHGs emission. However, on the other hand, the agricultural production system also acts as an important component which helps in GHGs mitigation by sequestration of carbon in soil through carbon storage. Hence, carbon footprint of rice will include the net amount of carbon emission from different activities related to rice production (through one life cycle) directly or indirectly. Now-a-days, production technologies have been changed and include high use of fertilizers and pesticides to achieve more yield for the increasing population, but this increase in agricultural inputs leads to high carbon footprint too. Application of these inputs produce greenhouse gases, but production of these inputs also produced the GHGs (Zhang et al., 2017). Most of the rice is grown as transplanted crop during *kharif* season, and the chemical environment of these rice ecosystems has a large influence on carbon and nitrogen dynamics, which mainly governs the GHGs emission (Bhaduri et al., 2017). In India, puddled rice fields emit 3.37 Mt of CH_4 that accounts for 24% of total agricultural GHG emission (Bhatia et al., 2013).

As compared to other crops like wheat or maize, rice cultivation produces about four times more GHG emissions per ton (Linquist et al., 2012). Apart from the rice ecosystem, straw production is a major concern, and it was burned for quick disposal. However, it was recommended that these straw must be incorporated into soil to reduce the burning which also causes pollution and to improve the soil carbon content, but addition of straw again increases the GHGs during their decomposition in soil and causes global warming. As per the current estimate across the five agroclimatic zones and farm sizes in Punjab, the range in C-footprint per unit area of rice and per tonne of rice grain were 8.80 ± 5.71 t CO_2-eq/ha and 1.20 ± 0.70 t CO_2-eq/t, respectively, which was found to be double and 1.5 times of the similar reported values for wheat (Kashyap & Aggarwal, 2021).

In this chapter, we have emphasized the role of rice cultivation in making impact for carbon footprint, both globally and at national scale, and how important this is to be a researchable issue. Other important facets like monitoring of GHG emissions and the improved management practices reported from laboratories of all over the world to lessen the carbon footprint have been discussed. The problems of straw burning and its practicable management options to lower down the C-emission were also highlighted. The emerging technologies in the present aspect were also mentioned as Future Roadmap to be followed in the years to come.

2 Variation of C Footprint in Different Phenology of Rice Cultivation

Globally, about 530 million tons of CH_4 per annum (the value is converted in terms of carbon) is emitted (Ito, 2015). Contribution of rice-based agriculture to CH_4 emission is approximately 11% of total global anthropogenic emissions (IPCC, 2013), and as compared to the main food crops rice has the highest greenhouse gas intensity (Carlson et al., 2017). Methane production and oxidation equilibrium determine methane emission from rice paddies, and methanogenic bacteria under anaerobic condition trigger production of methane. A paddy field contributes 100 g of CH_4 to the atmosphere during production of 1 kg of rice grain. In continuous flooded rice cultivation, the default methane baseline emission factor is 1.3 kgCH_4/ha/day (IPCC, 2006; Balakrishnan et al., 2018). The greenhouse gases emitted due to production of rice crop are CH_4, N_2O, and CO_2 at 43, 0.2, and 75 g/kg, respectively, with a global warming potential (GWP) of 1221.3 CO_2 eq. (Pathak et al., 2010). The CH_4 produced in the rice soil is partially absorbed by the oxidized rhizosphere of rice roots or by the oxidized soil-flood water interface; in this phenomenon, the soil bacteria also play a major role. Most of the methane produced in flooded rice soil

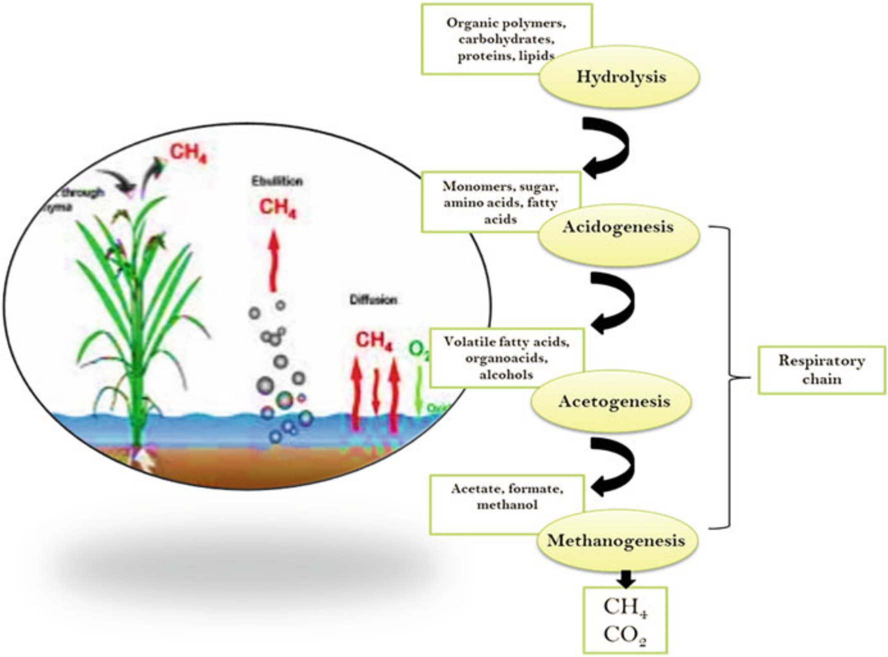

Fig. 1 Mechanisms of CH_4 production of paddy field and its cycling. (Modified from Dassonville & Renault, 2002)

escapes into the atmosphere with a small part leaching into the ground water (Fig. 1). Approximately 95% of the total CH_4 produced in flooded soil is oxidized to CO_2 before it is released into the atmosphere (Wassmann et al., 2000).

2.1 Methane Emission and Paddy Growth Stages

Methane emission through paddy is a function of changes in seasonal variations, soil conditions, and plant growth. The reproductive and ripening stages share the burden of highest emissions. This may be due to higher methanogenesis due to more availability of C in terms of fatty acids and sugars (Gaihre et al., 2011). A higher rate of CH_4 emission during flowering stage followed by ripening, tillering, postharvest, and preplantation was reported by Singh and Dubey (2012). This is attributed to the occurrence of acetotrophic methanogens together with the hydrogenotrophic group only at the flowering and ripening stages, and that could be correlated with high CH_4 production potential. During early stage of paddy growth, CH_4 emission is generally caused by soil OM and the added organic amendments. In this regard, Lu et al. (2000a) partitioned the active soil organic carbon (SOC) pool into two divisions, fast pool and slow pool. These two pools contribute to the CH_4 production at the initial and later phases of rice growth. The later phases of rice growth also supply carbon through root exudates and decaying tissue. The well-developed aerenchyma tissue during flowering stage serves as a medium for CH_4 transport and higher emission (Adhya et al., 1994). This conductance of aerenchyma tissue increases with plant growth and higher during reproductive stage when there is high root volume. Various studies reported that the rhizodeposition is the main source of CH_4 emission from rice fields (Kimura et al., 2004). The rhizodeposition is mainly root-secreted organic matter, dissolved organic carbon (DOC), etc. in the root zone that reaches the maximum value between flowering and maturity (Lu et al., 2000b) of paddy. The maturity stage reported a lower emission due to decreased DOC with reduced root exudates (Zhan et al., 2011) and also the decreased transport capacity of the aerenchyma tissues.

2.2 The Life Cycle of Rice Production and Carbon Footprint

Many studies have indicated that the whole life cycle of rice production has three stages, starting with mineral exploration and ending with products and GHGs emissions (Li, 2010; Xu et al., 2013). The same is depicted as a schematic diagram (Fig. 2).

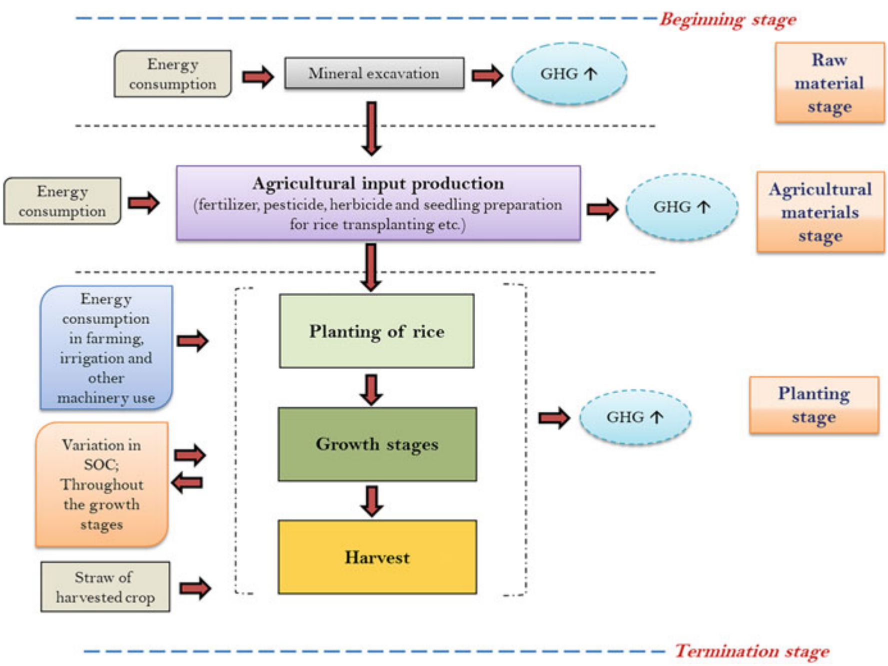

Fig. 2 Carbon footprint framework of rice production. (Modified from Xu et al., 2013)

2.3 Assessment of Carbon Footprint in Rice Cultivation

The carbon footprint during rice cultivation per unit area (in kg CO_2eq/ha) can be calculated as (Kashyap and Agrawal, 2021):

$$CF_{\text{per unit area}} = CF_A + CF_{N_2O} + CF_{CH_4} + CF_B$$

where

$$CF_A = \sum (A_i * EF_i)$$

CF_A: the sum of GHG emissions (per hectare) due to i^{th} activity/input in t CO_2-eq.
A_i: the activity data/amount of i^{th} activity/agricultural input like fertilizer (kg N/ha; kg P_2O_5/ha), pesticide (kg/ha), diesel (l/ha), and energy (kW.h/ha)
EF_i: the emission factor of the i^{th} process (in t CO_2-eq per unit volume or mass)

$$CF_{N_2O} = N_2O_{total} * 265$$

where CF is the GHG emission due to N_2O and 265 is the GWP of N_2O (IPCC, 2013).

Direct and indirect N_2O emissions were calculated as follows:

$$N_2O_{total} = N_2O_{direct} + N_2O_{indirect}$$

$$N_2O_{direct} = (F_{SN} + F_{ON} + F_{CR}) * EF_1 * \gamma\, N_2O$$

$$N_2O_{indirect} = N_2O_{(ATD)} + N_2O_{(L)}$$

$$N_2O_{(ATD)} = (F_{SN} * EF_4 * Fras_{GASF} + F_{ON} * EF4 * Fras_{GASM}) * \gamma\, N_2O$$

$$N_2O(L) = (F_{SN} + F_{ON} + F_{CR}) * EF_5 * Fras_{LEACHING} * \gamma\, N_2O$$

The F_{SN}, F_{ON}, and F_{CR}: the quantity of N in synthetic fertilizer, animal manure, and crop residues (both aboveground and belowground), respectively, that are added to the soil (in kg N/crop season)
N_2O(ATD) and N_2O(L): N_2O emissions through atmospheric deposition and leaching/runoff of N additions, respectively, from managed soils.
EF_1: the emission factor of N_2O emissions from N inputs (kg N/input); EF_4 and EF_5: the emission factors of N_2O emission due to volatalization and leaching/runoff of N from fertilizer and manure, respectively

$Fras_{GASF}$, $Fras_{GASM}$, and Fras $_{LEACHING}$ are the fraction factors of atmospheric deposition of volatilized N from mineral fertilizer, organic materials, and leaching from managed soil. The mass conversion factor for N_2 to N_2O is γN_2O (44/28) (IPCC, 2006).

$$CF_{CH4} = EF_d{}^* \, t^* \, A^* \, 28$$

CF_{CH4}: Direct methane emission due to submerged paddy cultivation (IPCC, 2006).
EF_d: the adjusted daily emission factor for a particular harvested area; it is practically the duration of crop growth (taken as 140 days for most commonly grown rice varieties in India).
A: the area harvested in hectares (ha); 28 is the GWP of CH_4 (IPCC, 2013).

$$EF_d = EF_c * SF_w * SF_p * SF_o$$

where EF_c: baseline emission factor for continuously flooded fields without organic amendments.
SF_w and SF_p: scaling factors to account for the differences in water regime during and precultivation period, respectively.
SF_o: the scaling factor to account for both type and amount of organic amendment applied. It can be calculated for individual farmer based on the following equation (IPCC, 2006):

$$SF_0 = \left(1 + \sum_i ROA_i * CFOA_i\right)^{0.59}$$

where ROA_i: the rate of application of organic amendment in t/ha
$CFOA_i$: the conversion factor for organic amendment (0.29 for straw incorporation; for straw incorporated for >30 days and 0.14 for farmyard manure incorporation (IPCC, 2006)

$$CF_B = Y^* R_f * DM_f{}^* \, B_f{}^* \, O_f{}^* EF$$

CF_B: GHG emission due to crop burning (IPCC, 2006)
Y: the crop yield based on survey data
R_f: residue to crop ratio
DM_f: dry matter fraction
B_f: fraction burnt
O_f: fraction oxidized
EF: the emission factors for CO_2, CH_4, and N_2O emitted while burning

3 Rice Straw Burning and C Footprint

Burning of rice straw has been a persistent problem because it cannot be recycled in soil due to limited time (20–25 days) left before sowing of succeeding crops, such as wheat. Open burning of rice straw residues has harmful environmental effects. It causes greenhouse gas (GHG) emissions, including 0.7–4.1 g of CH_4 and 0.019–0.057 g of N_2O per kg of dry rice straw, and emission of other gaseous pollutants such as CO_2, SO_2, NOx, HCl, and to some extent, volatile organic compounds (VOC), carcinogenic polycyclic aromatic hydrocarbons (PAH), dioxins, and furans (Oanh et al., 2011). Besides, rice straw burning is also an important source of aerosol particles such as coarse dust particles (PM_{10}) and fine particles ($PM_{2.5}$) (Chang et al., 2013), affecting quality, and reduces visibility as a result of gas and particle emissions. Open-field rice straw burning causes air pollution, GHGs emission (7300 kg CO_2-equivalent per hectare), soil nutrient and biodiversity losses, and human health hazards. Huge amount (731 million tons) of rice straw is produced globally in which India contributed around 126.6 MT, and 60% of it is burnt on the field.

A recent estimate showed that from November to December, 2017, around 70% of air pollution in the capital, New Delhi, was due to straw burning. Not only Punjab and Haryana, straw burning is also spreading over other states, very rapidly. Primarily, burning causes emission of CO_2, CO, SOx, NOx, particulate matter, and CH_4 which increases air pollution and GHGs/carbon footprint tremendously.

Asian countries contribute over 90% rice straw from the total global production (Worldwide annual production 731 million tons, with a distribution of Oceania 1.7 million tons, Europe 3.9 million tons, Africa 20.9 million tons, America 37.2 million tons, and Asia 667.6 million tons) (Karimi et al., 2006). In India, about 620 million tons of crop residue was generated every year. About 16% of it is burnt on farms. Out of this, 60% is paddy straw and wheat straw accounted for 22%.

Due to lack of economically viable options, farmers sometimes opt for open burning of rice straw residues that incurs both harmful environmental consequences as well as economic loss. In northern states like Punjab and Haryana, rice growers have already chosen to burn the straw after harvest which causes havoc air pollution and made a huge concern for common mass. As per the report of November–December, 2017, around 70% of air pollution in Delhi and NCR was solely due to straw burning. Moreover, the practice of open straw burning is also extending rapidly in major rice-growing states in eastern India, like West Bengal, Odisha, Bihar, and Jharkhand (Down to Earth November, 2017).

For second-generation biofuel production, utilization of renewable biomass resources (cheap, easily available, and nonfood materials) has gained global importance. In the cross-talk with global climate change scenario, "Bioconversion" of biomass to bioethanol process could help in reducing GHG emissions (mainly CO_2) by cutting down the sole dependence of fossil fuels. The second-generation biofuels include hydrogen, natural gas, bio-oils, producer gas, biogas, alcohols, and biodiesel, which are primarily dependent on lingocellulosic agricultural residues. Leftover crop residues often serve as feedstock for ethanol production owing to few benefits like output/input energy ratio, availability, low cost, and higher ethanol yields. Rice straw (including its stem, leaf blades, leaf sheaths, and remains of panicles after threshing) has been a potent candidate for feedstock for second-generation biofuel production with the same composition alike other agricultural residues (cellulose, hemicelluloses) with additionally having a significant amount of silica. By virtue of worldwide rice cultivation, it is accounted one of the most abundant lignocellulosic crop waste materials. The annual global production of rice straw is 731 million tons, and in Asia the average production is 667.6 million tons (Bhatia & Paliwal, 2011; Saini et al., 2015). Another recent study also found out the best possible industrial use suitable mainly for eastern India, by structural-morphological-biochemical characterization of straw of 18 popular rice varieties, that may curb down C footprint and

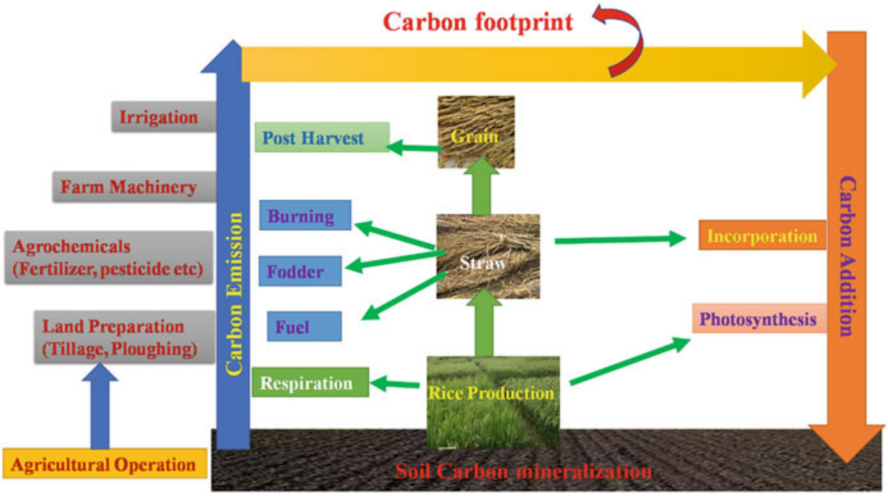

Fig. 3 Schematic diagram for showing components of carbon footprint in a rice production system. (Modified from Pandey & Agrawal, 2014)

channelize the rice straw for alternative purposes that may be economically exploited by farmers (Bhattachayya et al., 2019).

Bhattachayya et al. (2021) reported the possibility of using rice straw for producing bioethanol, biochar, compost, mushroom, fuel-briquette, fuel-pellets, pulp, animal-feed, eco-panel, erosion-control material, and in situ addition in conservation agriculture. Further, they analyzed the economic and environmental benefits of rice straw in lieu of straw burning, and technical, structural, institutional, and socioeconomic constraints forcing to opt for burning rice straw. The authors also estimated the net gain (both economic and environmental gain) of US$ 664 per hectare due to production of bioethanol from straw followed by biochar conversion (US$ 183/ha), and conservation agriculture (CA) practices (US$ 131/ha).

The schematic diagram depicts all input and output components of carbon footprint in a typical rice cultivation system (Fig. 3).

4 Monitoring of GHG Emission: Methodology and Calculation

The methodologies that are generally used for measurement of greenhouse gas emissions from soil have been described in this section in detail.

4.1 Measurement of Methane and Nitrous Oxide

The following are major methods employed for the measurement of CH_4 and N_2O emissions from soil:

Fig. 4 Collection of GHG from crop field using closed chamber technique. (Source: Daripa, 2009)

A. Closed chamber method: This is the most common technique for measuring GHG in air. In this technique, a sealed closed enclosed chamber is placed over the soil surface to determine the short-term buildup of gas emissions from soil (Fig. 4). Generally, the chamber material used is of plexiglass of dimension 50 cm length × 30 cm width × 100 cm height. The inside mixing of gas is ascertained with an internal fan in the chamber. A water seal is used at the basement of the chamber to make the chamber airtight while gas sampling. A thermometer is also inserted to monitor the temperature during collection. The chamber is thoroughly flushed several times with a syringe before sampling. Gas samples are drawn with the help of a hypodermic needle that are immediately air tightened with a three-way stopcock (Daripa et al., 2014). Over long-distance transfer of gas samples, evacuated vials fitted with rubber septa can be used. For each treatment, four replications are drawn from the field and the average is taken as a representative value for the treatment. Head space value is also recorded during sampling that is used for the final calculation of gas flux. Immediately after sealing the collection chamber,

the gas samples should be taken from the headspace at equal time intervals over a period not exceeding 2 h (Pathak & Kumar, 2008; Rosenstock et al., 2011; Bertora et al., 2018). After the final sample collection, the concentration chamber must be removed to minimize environmental interference of the ongoing experiment in the field. The gas samples containing CH_4 and N_2O are introduced into the gas chromatography (GC) by the syringe through a sampling valve. Methane is detected using flame ionization detector (FID) maintained at 250 °C. However, to detect N_2O through GC ^{63}Ni, electron capture detector (ECD) operational at 300–400 °C is used.

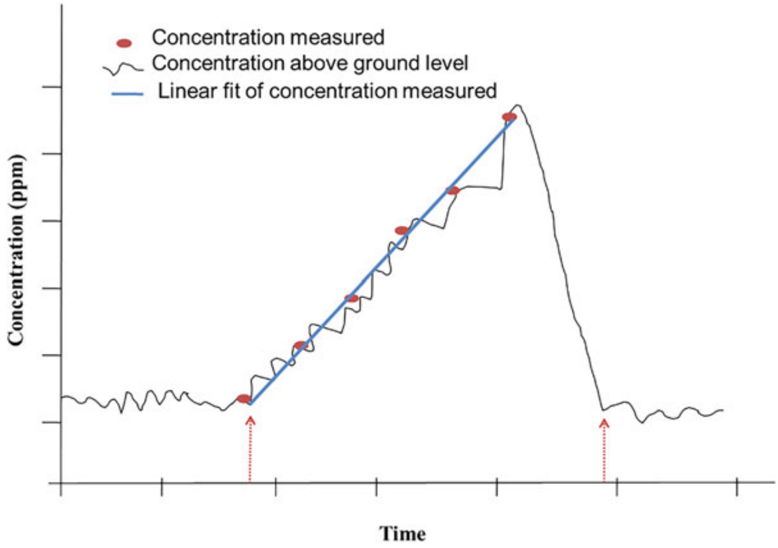

Fig. 5 The graphical representation of theoretical evolution of the gas from the soil upon use of a static closed chamber in a period of time

A GC-computer interface is used to plot and measure the peak area. Figure 5 showed the theory behind calculation of GHG concentration to be measured in a given period of time after the gas samples collected from the soil using the static closed chamber.

5 Calculation of CH_4 and N_2O Flux

Cross-sectional area of the chamber (m^2)	$= A$
Headspace (m)	$= H$
Volume of headspace (L)	$= 1000 \times AH$
CH_4/N_2O concentration at 0 time (μL/L)	$= C_o$
CH_4/N_2O concentration after time t (μL/L)	$= C_t$
Change in concentration in time t (μL/L)	$= (C_t–C_o)$
Volume of CH_4/N_2O evolved in time t (μL)	$= (C_t–C_o) \times 1000$ AH
When t is in hours, then flux (mL/m/h)	$= [(C_t–C_o) \times$ AH]/9A $\times t)$

Source: Pathak and Kumar (2008), Daripa et al. (2014)

Now 22.4 mL of CH_4 is 16 mg at STP
Hence, flux $= [(C_t–C_o)/t] \times H \times 16/22.4 \times 10{,}000 \times 24$ mg/ha/day
Again for N_2O, 22.4 mL of N_2O is 44 mg at STP
Hence, flux $= [(C_t–C_o)/t] \times H \times 44/22.4 \times 10{,}000 \times 24$ mg/ha/day

Fig. 6 Eddy covariance system installed at a lowland paddy field of ICAR-NRRI, Cuttack, with CO_2/H_2O analyzer (open-path infrared gas analyzer), covering a fetch area of 2.25 hectares, attached with sonic anemometer, temperature-humidity sensor, radiation sensor, and soil temperature probe, connected to a built-in data-logging facility. (Source: Authors' personal collection)

B. Micrometeorological measurements (Eddy covariance method):

Measurement of CH_4 emission from the real-life rice paddies is done using the eddy covariance method. This is a complex, expensive, and advanced method (Fig. 6). Classically, this technique of emission measurement is applied in flat terrain with large, homogeneous land use, such as pasture, grassland, monocrops, forests, or tree plantations. This method calculates fluxes of a scalar of interest (i.e., CH_4 and CO_2), at the same time measures turbulent fluctuations in vertical wind speed, and then computes the covariance between the two (Wang, 2013; Alberto et al., 2014). A sonic anemometer-thermometer (CSAT3) measures three-dimensional wind speed and temperature. This has to be fixed at certain meters above the ground level. An open-path CO_2/H_2O gas analyzer (LI-7500A) measures fluctuations in CO_2 and water vapor densities; simultaneously, an open-path CH_4 analyzer (LI-7700) measures CH_4 concentrations (Alberto et al., 2014). The data from CSAT3, LI-7500A, and LI-7700 is sampled at 10 Hz using a data logger (CR3000). To compute the fluxes of CH_4 and CO_2, the eddy covariance raw data need to be processed and quality control is done using EddyPro software.

5.1 Measurement of Carbon Dioxide (CO_2)

Generally, two techniques are used for quantitative CO_2 measurement from soil: (a) alkali trap method and (b) soil respirator.

5.1.1 Alkali Trap Method

CO_2 is trapped in an aqueous solution of alkali (usually KOH or NaOH), and this trapped CO_2 is precipitated to $BaCO_3$ by addition of $BaCl_2$. This $BaCO_3$ is titrated against HCl. The volume of acid needed to titrate the alkali is noted. In this method, 20 ml of 1 N NaOH in a glass jar is placed on a tripod stand and is covered with a metal cylinder immediately. The control samples of this experiment are incubated in the field using completely sealed metal cylinders without exposure to CO_2 (Pathak & Kumar, 2008). The following formula is used to calculate the amount of CO_2 evolved from the soil during exposure to alkali:

$$\text{Milligrams of C or } CO_2 = (\text{B} - \text{V})\ \text{NE}$$

where B is the volume of acid required to titrate NaOH in the control samples; V is the volume (mL) of acid required to titrate the samples exposed to soil atmosphere; N is the normality of acid; and E is the equivalent weight of CO_2 (i.e., 22). The final data is expressed in CO_2 m/h.

5.1.2 Soil Respirator

In this technique, a closed chamber is used to measure the soil respiration, i.e., flux of CO_2 per unit area per unit time. This consists of a soil respiration chamber (SRC) and an environmental gas monitor (EGM). Through the EGM, the air is continuously sampled in a closed circuit and the soil respiration rate is calculated. The flux of CO_2 per unit area per unit time is measured by the following equation:

$$R = \frac{(C_n - C_o)}{T_n} X \frac{V}{A}$$

where R: the soil respiration rate (flux of CO_2 per unit area per unit time); C_o: CO_2 concentration at $T = 0$ and C_n: CO_2 concentration at a time T_n; A: area of soil exposed; and V: total volume of the closed chamber.

5.1.3 Long-Term Measuring Chamber

To estimate soil respiration of CO_2, long-term CO_2 flux LICOR LI-8100 chambers are installed. The LI-8100 analyzer control unit estimates increase or decrease (flux) of gaseous CO_2 concentrations in the chamber headspace over time. To minimize chamber CO_2 concentration changes during analysis, the observation time for all measurements was 90 s and a 30 s dead band was programmed to allow for equilibration of the chamber pressure upon closure. Error from lateral diffusion of CO_2 in the soil column is reduced using PVC soil collars measuring 20.3 cm in diameter that are inserted to a depth of 3–5 cm and extended approximately 6–10 cm above the soil surface (Lee et al., 2018).

5.1.4 Temporary Portable Measuring Chamber

Infra-red-based continuous soil CO_2 flux analyzer: In this method, one portable infra-red-based continuous soil CO_2 flux analyzer (LI-8100) with a 20-cm short-term

Fig. 7 LI-8100 system along with short-term survey chamber to obtain soil CO_2 flux (Source: Daripa, 2009)

survey chamber is used to measure the CO_2 flux (Fig. 7). The closed-chamber was placed on the soil, and the rate of increase of the chamber CO_2 concentration was used to determine the soil flux. The desired value of the soil flux was determined when the chamber CO_2 concentration was the same as the ambient atmospheric concentration. The flux was estimated using the initial slope of a fitted exponential curve at the ambient CO_2 concentration (Daripa et al., 2014; Madalina et al., 2020).

6 Agronomic Intervention to Reduce GHG Emission Under Rice Cultivation

There are some improved agronomic management which can significantly reduce the load of C-emission as well as help to sequester C in soil thus can make an impact to lessen the C- footprint in the surrounding environment. These could be either alteration in existing irrigation management or an alternative nutrient management or using the new-age decision support tool for management of better nutrient recovery and reducing the GHG flux. A schematic representation gives the complete idea of this subsection (Fig. 8).

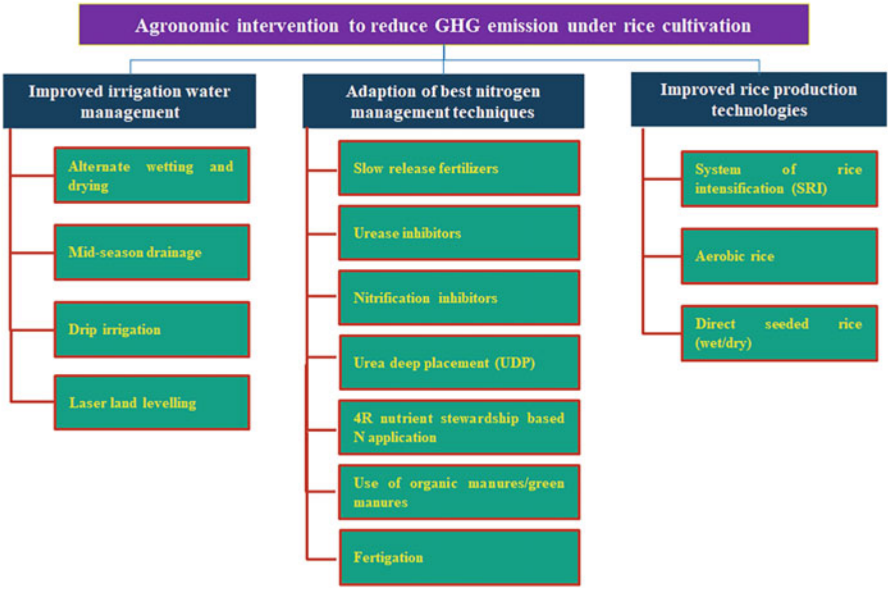

Fig. 8 Alteration in agronomic practices to reduce GHG emission

6.1 Improved Irrigation Water Management

The growing water scarcity especially in agricultural sector necessitated the need for rice production using improved irrigation methods. Besides consuming large portion of fresh water, the conventional rice production system also contributes emission of GHGs significantly. Many improved irrigation techniques such as alternate wetting and drying (AWD), midseason drainage, drip-irrigated rice, laser land leveling, and shallow flooding save irrigation water significantly besides reducing GHG emission in the rice production system. The irrigation method used in rice cultivation has profound effect on GHG flux. The fluxes of CO_2, CH_4, and N_2O is primarily controlled by soil microbial processes. The soil moisture regime is a major determinant of soil microbial diversity and its activity. Thus, through modifying irrigation method we can reduce the GHGs emission along with saving of precious irrigation water.

Appropriate irrigation water management is one of the most effective techniques to reduce CH_4 emissions from paddy fields. The demand for fresh water in most countries in Asia is also intensifying due to population growth, irrigated agriculture, and industrialization (Kumar et al., 2018; Vijayakumar et al., 2019). So judicious and efficient water use will not only help in curbing CH_4 emission from irrigated rice field but also conserve water for later use and use in different sectors. Kimura (1992) reported that a single midseason drainage might cut seasonal CH_4 flux from irrigated paddy fields by around 50%.

6.1.1 Alternate Wetting and Drying

The emission of CH_4 from rice field increases with increasing water level and duration of submergence. Thus, any method of irrigation which keeps rice field aerobic and reduces the depth of water logging subsequently reduces the methane emission besides saving irrigation water. Saturated soil provides favorable anaerobic conditions to methanogens which produce methane. When saturated soils were allowed to dry out and become aerobic, methane production practically ceased. The use of alternate wetting and drying (AWD) technology reduced CH_4 emissions on pump-irrigated farms by about 70%. Wassmann et al. (2000) reported that AWD of paddy fields reduced CH_4 flux by about 60% as compared to continuous flooding in Asia. When compared to IWD, continuously flooded rice fields produced more methane (Pathak et al., 2003). Average emission in saturated soil was 0.3 to 0.6 kg/ha/day while in intermittent wetting and drying (IWD) it was 0.1 to 0.4 kg/ha/day. However, under intermittent irrigation system, i.e., AWD, a significant increase in N_2O emissions is noticed over conventional rice production system. Denitrification is a biological process carried out by facultative microorganisms viz., *Pseudomonas, Bacillus, Thiobacillus,* and *Chromobacteria.* N loss due to denitrification is more under AWD. The 40% reduction in CH_4 emission is estimated by switching irrigation method from current practice to IWD in all irrigated paddy field of the country; nevertheless, the N_2O-N fluxes could rise by 6% under the intermittent wetting and drying scenario (Bhatia et al., 2012). Pathak et al. (2014) reported that intermittent flooding reduced GWP by 25–30% over continuous flooding.

6.1.2 Midseason Drainage

Midseason drainage (MD) is a technique that drains out water from the paddy fields for a short time (4–5 days) to aerate paddy soil during floods. It is generally carried out for 5–20 days before the maximum tiller stage to prevent ineffectual tillers production. Waterlogging during tillering stage of rice reduces the production of tillers and conversion tillers into effective tillers. Furthermore, in Japan, intermittent drainage after midseason is a frequently used water-management approach, which involves a series of free drainage and irrigation. Midseason and intermittent draining also avoid root rot by enhancing oxygen movement in the soil, as well as increasing soil hardness, which improves lodging resistance. For many years, Japanese rice farmers have been draining their paddy fields in the middle of the season, primarily to boost crop yields by increasing oxygen (O_2) in the rhizosphere and reducing the excessive growth of unproductive tillers (Leon et al., 2017). This method allows continued root development, eliminates root rotting, and minimizes the amount of irrigation water required for cultivation (Leon et al., 2017). Furthermore, the rate of CH_4 emission reduction is maximum at sites where CH_4 emission peaked early in the cropping season. This suggests that long-term MD is more successful at locations where CH_4 emissions peak early in the growing season.

The CH_4 flux reduced by 40% through adaption of midseason drainage and intermittent irrigation (Wassmann et al., 2009). According to Zou et al. (2005), midseason drainage is a good choice for reducing net GWP, albeit 15–20% of the benefit derived from lower methane emissions was countered by higher N_2O

emissions. A study conducted in Nanjing, China compared the methane flux from fields that were constantly flooded (W0) to those that were drained twice each season (W2). The W2 fields were drained once for 9 days at midseason and again for 2 weeks before harvest. The results showed that changing the irrigation plan led to a reduction of approximately 60% seasonal methane emissions. Specifically, the W0 plots emitted 390 kg of methane per hectare over the 469-day course of the season, while the W2 plots emitted only 156 kg per hectare. These findings suggest that managing irrigation can be an effective way to mitigate greenhouse gas emissions from rice cultivation (Wang et al., 2012).

6.1.3 Drip Irrigation

In drip-irrigated rice system, water and nutrients are applied in the vicinity of the rice crop. The methane and N_2O emission is drastically reduced under drip irrigation due to absence of anaerobic situation and conventional method of N application, respectively. Moreover, the fertigation system increases the nitrogen use efficiency through matching the N supply with rice crop N requirement (Subramanian et al., 2021). In fertigation system, the essential nutrients are supplied to rice crop through synchronized manner with more number of cycle. Unlike conventional method of fertilizer application, i.e., broadcasting in fertigation system, the requirement for human labor is very low even with more number of fertigation cycle. Results from previous studies show that the cumulative N_2O emission is lower in drip irrigation system (0.79 kg N_2O-N/ha/year)) compared to sprinkler irrigation (4.4 kg N_2O-N/ha/year) (Cayuela et al., 2017). Drip-irrigated systems emit 80% less N_2O than sprinkler systems, while drip irrigation paired with optimal N fertilizer administration resulted in a 50% reduction in direct N_2O flux (Sanz-Cobena et al., 2017). Similarly, the cumulative N_2O emission is lower in rain-fed compared to irrigated field (Cayuela et al., 2017).

6.1.4 Laser Land Leveling

The practice of laser land leveling saves 20% of irrigation water and improves nitrogen use efficiency significantly (Pathak et al., 2012). It prevents waterlogging for long time in several patches in the same field and thereby recesses N loss by leaching and denitrification. It also minimizes the runoff loss of N. It minimizes the GHG emission through minimizing the N losses and decreasing irrigation water pumping time which in turn reduce the electricity consumption. In rice and wheat, it saves 47–69 and 10–12 h per hectare per season, respectively. The use of laser land leveling saving 755 kWh electricity per hectare is reported in RWCS.

7 Adaption of Best Nitrogen Management Techniques

The use of N fertilizers in crop field as a source of plant nutrient is the major source of N_2O emission. Two key factors which control the flux of N_2O at the field level are the amount of N supplied and the efficiency at which it is absorbed by plants. So, to reduce the N_2O emissions, optimum N fertilizer application (in terms of input rate and time of application) and ideal fertilizer selection are crucial (Vijayakumar et al., 2021). MD and intermittent irrigation practices reduce the net GWP of paddy fields as long as N application matches with crop demand (Wassmann et al., 2009). Zou et al. (2005) reported surge in N_2O flux with midseason drainage in Chinese rice fields under application of higher rate of N fertilizer (277 kg N/ha). A study conducted in Japan found that, despite using lower levels of nitrogen fertilizer (ranging from 30 to 90 kg N/ha), there was a slight increase in N_2O emissions compared to conventional water-management strategies. This suggests that the impact of water management strategies on N_2O emissions may vary depending on the specific context and factors at play.

7.1 Slow-Release Fertilizers

Slow-release N fertilizers extend the period of N available to the crop plant by discharging the soluble N (NH_4 and NO_3) over several weeks/months and increase the amount of fertilizer uptake by the plant through synchronizing plant nutrient demand and soil N availability (Vijayakumar et al., 2021). These products have been found to improve the recovery of applied nitrogen by 33% in cereal grains all over the world and consequently decrease the external fertilizer application rate (Delgado & Follett, 2010). There are two types of slow-release N fertilizers available in the market viz. coated and uncoated products. Slow release is the inherent physical characteristics of uncoated products like isobutylidenedi urea (IBDU) (31% N), urea form (35% N), and methylene urea (39–40% N). In case of coated products, the release of N is primarily controlled by the external barrier that surrounded the N. Thus, it releases the N rapidly once the barrier is removed. Examples for coated products are neem-coated urea, sulfur-coated urea, and polymer-coated urea. Sulfur-coated urea was developed by the Tennessee Valley Authority, USA. In neem-coated urea, 0.5 kg neem oil is used per tonne of urea. In India, 100% urea manufactured is neem-coated urea.

7.2 Urease Inhibitors

When urea is added to a wet soil, it first undergoes hydrolysis by the enzyme urease to generate ammonium carbonate, which is then prone to ammonia volatilization loss. Urease is found both in soil and plant residues and is responsible for conversion of applied urea into ammonium. Urease inhibitors (UIs) impede the action of urea hydrolase enzyme known as urease and reduce the rate of hydrolysis of urea to ammonium and can reduce loss of N due to ammonia volatilization when urea is surface applied. The commonly known UIs are N-(n-butyl) thiophosphorictriamide (NBPT), N-(n-propyl) thiophosphorictriamide (NPPT), PPD/PPDA (phenyl phosphorodiamide), TPT (tiophosphoryltriamide), PT (phosphoric triamide), and HQ (hydrquinone). In the market, NBPT is available in the trade name of Agrotain and Limus is new UI that contains two active ingredients (NBPT & NPPT). Among the numerous forms of user interfaces, NBPT has seen the maximum commercial application (Abalos et al., 2014). The use of UIs enhances N use efficiency through improving N uptake by matching N availability with crop demand (Delgado & Follett, 2010). However, on the other hand, UIs can only be used in conjunction with urea or urea-containing fertilizers (including organic sources). UIs can only be used when urea or urea-containing fertilizers (including organic sources) are used. UIs can reduce N_2O emissions by up to 80% (Sanz-Cobena et al., 2017). Many factors like soil pH, texture of soil, and N application rate influence the efficiency of UIs. Among the soil type, in alkaline soils the efficiency of UIs is found highest. Similarly, in coarse-textured soils and at high N fertilization rates, the efficiency is higher (Abalos et al., 2014).

7.3 Nitrification Inhibitors

The microbial decomposition of nitrogen in soils, manures, and nitrogenous fertilizers produces nitrous oxide (N_2O), which is often exacerbated when available nitrogen exceeds plant requirements, especially in wet conditions. Urea is susceptible to gaseous losses (N_2O and N_2) when applied to puddled lowland rice fields, owing to ammonia volatilization and denitrification. There are evidences that NUE in lowland rice is increased by use of nitrate inhibitors (NIs). NIs viz*,* nitrapyrin (2-chloro-6-trichloromethyl pyridine) or N-Serve, AM (2-amino-4-chloro-6 methyl pyrimidine) (discovered in Japan), dicyandiamide (DCD), ammonium thiosulfate (ATS), thiosulphoryltriamide (ZPTA), terrazole (etridiazole), and CMP (1-carbamoyle-3-methylpyrazole), slow down the nitrification process in soil and lower N_2O emissions by 10–15% (Malla et al., 2005). However, few studies showed even 30 to 50% reduction in N_2O emission (Sanz-Cobena et al., 2017). The recommended dose of NI is 0.2–0.6 kg ai/ha. The use of NIs enhances N use efficiency (NUE) through extending the period of N available to the crop plants which leads to increased N uptake by crop plants due to matching of soil available N with crop N demand (Delgado & Follett, 2010; Vijayakumar et al., 2021). Prolonged periods of drought can lower soil fluxes greatly, and soils can therefore become a N_2O net sink. Under DSR conditions, the application of DCD could reduce N_2O emissions while also increasing grain yields and NUE. NIs also retard the N_2O emissions from upland soils). NIs are efficient with surface-applied urea and ammonium, or injected anhydrous ammonia. The NIs viz., nitrapyrin and dicyandiamide (DCD), are the most effective inhibitors of nitrification/denitrification for the period of 2–6 and 12–14 weeks, respectively (Delgado & Follett, 2010). Nitrapyrin and DCD are the most effective inhibitors of nitrification/denitrification for the period of 2–6 and 12–14 weeks, respectively (Delgado & Follett, 2010). Some plant-derived organics like neem oil, neem cake, and karanja seed extract have also been reported to work as NIs (*Malla et al.* 2005).

Ammonia volatilization (AV) is purely a chemical process and accounts up to 40% of the N loss in rice. AV loss is more with anhydrous ammonia. Nitrapyrin (discovered in USA) is a volatile compound and is difficult to use with solid fertilizers. Thus, its use is restricted to anhydrous ammonia which is injected in soil. DCD was discovered in Germany and is less effective if temperature is above 20 °C because of its rapid decomposition. The supply of NI with any NH_4^+-based N fertilizer will keep N in the soil in the form of NH_4^+ by suppressing nitrification process. Thus, the potential N loss through NO_3 leaching and NO flux is mitigated by the use of NIs. However, the probability of NH_3 volatilization is greater under ideal weather conditions and the fertilizer is delivered on soil surface due to increase of NH_4^+ in the upper soil. Nevertheless, the production and transport of inhibitors will increase CO_2 emissions. The effects of DCD on nitrous oxide and nitric oxide emission were examined using the automated closed chamber method, and the result revealed DCD is successful in reducing N_2O emissions by 73% when urea is applied through broad casting (Gaihre et al., 2020).

The most significant impediment to the deployment of NIs is the rise in fertilization costs by at least 9% (Timilsena et al., 2015). Second, only a few inhibitors have got approval for commercial marketing. The increase in cost of fertilization could be counterbalanced by an increment in crop productivity (Abalos et al., 2014). A potential improvement in crop NUE could minimize the rate of external N fertilizer application through reducing the losses, and thereby lowering fertilization costs (Abalos et al., 2014).

7.4 Urea Deep Placement

Under direct seeded rice (DSR), urea deep placement (UDP) reduced N_2O flux by 93% compared to broadcast urea and thereby increased NUE and grain yields (Gaihre et al., 2020). This is most plausible as UDP might have stored much of the nitrogen as NH_4^+ in an anaerobic zone for a long time, where nitrification is less likely due to the lack of O_2. As a result, both nitrification and denitrification emissions of N_2O and NO could be lowered. Furthermore, UDP minimizes N loss through other processes such NH_3 volatilization and surface runoff, leading to lower indirect N_2O emissions (Rochette et al., 2013).

7.5 More Use of Organic Manures/Green Manures

The use of organic manures reduces the N_2O emission; however, it depends on the type of manure used. Solid manure insertion reduced N_2O emissions (Webb et al., 2004) while application of organic sources such as FYM, green manure, and crop residues in rice and wheat increased the N_2O emission (Bhatia et al., 2005). In Mediterranean systems, use of solid manures significantly decreased N_2O emissions (23%) (Aguilera et al., 2013) and have the potential to exacerbate long-term C sequestration. Evidence from past experiments indicate that the technique of slurry application in agricultural soils is a crucial variable in regulating N_2O flux. According to Hou et al. (2015) a meta-analysis study indicated that slurry injection could dramatically increase direct emissions when compared to broadcasting.

Manure, such as farmyard manure (FYM), boosts CH_4 flux by providing organic carbon and nitrogen for microbial activities, as well as functioning as an electron source. In comparison to applying the total amount of N by urea, substituting 50% of inorganic N with FYM increased emission by 172% (Pathak et al., 2003). Crop residues incorporation/retention also influence the CH_4 flux by increasing the organic matter (OM) availability. The CH_4 flux increased from 100 to 500 kg CH_4/ha/year with the increase of rice straw incorporation from 0 to 7 t/ha (Sanchis et al., 2012). In another study, methane emissions were lowest in the unfertilized plot (28.4 kg ha^{-1}) and highest (41.3 kg/ha) when the total amount of N was applied by organic sources (Bhatia et al., 2005). However, when compared to FYM, biogas slurry lowered emissions by 2.3 times, indicating that biogas slurry should be favored over FYM for reducing CH_4 emissions (Debnath et al., 1996). On the contrary, incorporation of organic inputs, such as rice straw and green manure in rice soils, promotes CH_4 emission. Composting, incorporation of organic manures/crop residues during off-season, i.e., drained period and application of fermented manures like biogas slurry instead of unfermented farmyard manure, reduces methane emission (Pathak & Wassmann, 2007). Thus, promoting aerobic degradation of organic manure reduces methane emission.

7.6 4R Nutrient Stewardship Based N Application

The use of technology that enables more precise application of nitrogen fertilizer, based on factors such as soil conditions, plant characteristics, and field properties, can significantly increase nitrogen use efficiency (NUE) while reducing nitrogen loss. The 4R nutrient stewardship based N application involves applying right dose, right time, right source, and right place and enhances NUE. For example, demand-driven application of N by using a leaf color chart (LCC) reduced N_2O emission and GWP by about 11% (Bhatia et al., 2010), thereby synchronizing the timing of N application with plant N demand and reducing N losses, including N_2O emissions. It also helps in saving fertilizer cost due to saving of input N rate. An accurate estimation of the external nitrogen (N) requirements, taking into account factors such as indigenous supply and target yield, can significantly reduce nitrogen loss by avoiding excessive N application and the resulting direct and indirect N_2O emissions. This approach not only helps to minimize the environmental impact of nitrogen fertilizer use but also saves energy and reduces other greenhouse gas (GHG) emissions associated with the production of N fertilizers. The optimized N application might cut N_2O flux by up to 50% compared to nonoptimized practices in both irrigated and rain-fed Mediterranean agroecosystems (Sanz-Cobena et al., 2017). However, multiple studies have found that direct N_2O emission is nonlinear in response to N intake (Kim et al., 2013; Shcherbak et al., 2014), and other factors, such as cultural operations, method of fertilizer application, time of application, source of N fertilizer, and climate, play major role in direct N_2O emissions (Aguilera et al., 2013). For rice and wheat, three-split application of N was found more efficient than two-split applications. Several findings revealed that choosing the correct fertilizer could help reduce emissions (Dass et al., 2017). The use nitrate (NO_3)-based fertilizers significantly lowered N_2O emissions more than ammonium-based fertilizers. In India and many other Asian countries, nitrogen is typically applied through broadcasting, which involves spreading the fertilizer uniformly over the entire field. The broadcasting of urea and other ammonium containing fertilizers often associated with higher volatilization losses and it can be largely reduced by incorporating urea in to the soil. This is done in case of dry direct seeded rice and wheat in IGP regions. Use of seed cum fertilizer drills enable incorporation of urea into the soil, and this method is gaining importance in IGP for sowing zero till wheat in RWCS.

8 Adaption of Improved Rice Production Technologies

Irrigation has been proven to significantly affect N_2O and CH_4 losses. Advanced water-management practices modify soil redox conditions and thereby reduce CH_4 emissions. Under aerobic conditions, soils operate as CH_4 sinks whereas swamps and paddy fields are major CH_4 sources. Methane is produced due to microbial decomposition of OM present in the soil under anaerobic conditions. Rice cultivation under waterlogged condition is the potential source of CH_4 production. Use of organic manure and unceasing submergence in paddy soil increase CH_4 flux (Pathak 2015). By decreasing the flooding period and depth, both methanogenesis and CH_4 emission are limited. This leads to lower emissions and reduces water consumption, a crucial goal to improve the agriculture sustainability. The improved rice production technologies such as direct-seeding of rice (DSR), system of rice intensification (SRI), and aerobic rice cultivation were found most effective in mitigating methane emission from rice cultivation (Pathak & Wassmann, 2007).

When rice is grown as an aerobic crop such as DSR, SRI, and aerobic rice which do not require continuous submergence, methane emissions are substantially reduced. DSR and SRI have the ability to reduce the GWP by 35–75% in comparison to standard puddled transplanted rice (Pathak et al., 2014). SRI reduced methane flux by 22–64%, the GHG emission is converted to CO_2-equivalent using GWP, and the net GHG reductions vary from 20% to 40%, and even up to 73% (Choi et al., 2014; Jain et al., 2014).

During a rice-growing season, DSR had 47% lower CH_4 emissions than TPR. When compared to TPR, DSR lowered GWP by 46.4% (Susilawati et al., 2019). When compared to transplanted rice (TPR), DSR emits less CH_4 due to nonflooded aerobic situation (Pathak et al., 2010). Direct seeded rice (DSR) reduces CH_4 flux since it consumes less water during the early cropping process, but it can have unintended consequences, such as increased N_2O emissions. However, numerous studies have found that DSR can offer a more sustainable alternative to TPR due to the trade-off between N_2O and CH_4 production in rice soils, resulting in a lower GWP for DSR. In Indonesia, during rainy season, the total CH_4 flux in TPR was 352 kg per hectare per season, and it was 187 kg ha hectare per season in DSR.

During the growing season in TPR, the paddy field was flooded, creating an anaerobic environment. Methanogen metabolic processes create CH_4 in anaerobic conditions (Conrad, 2007). Standing water on the surface of the rice soil prevents O_2 reaching the rhizosphere from the atmosphere. The existence of decomposable organic matter (OM), absence of O_2, and the activity of anaerobic bacteria all contribute to the production of high amount of CH_4 (Pathak, 1999). Draining water from the soil surface, on the other hand, results in a higher redox potential (Eh) and a reduction in CH_4 flux. Because the DSR fields were not buried in water all the time, anaerobic conditions were not established. As a result, there is a reduction in the amount of CH_4 generated.

9 Decision Support Tool

Many decision support tools are now available for managing nutrient supply in different cropping systems. DSS is found to be an effective tool under both conservation and conventional production system (Kumar et al. 2015a, b). DSS provides SSNR even under absence of soil test values. It needs information which are easily given by farmer/user. Another example is nutrient expert decision support system (DSS) which is developed by International Plant Nutrition Institute (IPNI) and gives site-specific nutrient recommendation (SSNR) for hybrid maize genotypes. Similarly, rice RiceNxpert developed by ICAR-National Rice Research Institute (NRRI), Cuttack, gives N recommendation to standing crop by capturing the N status of the plant. Farmers need to take ten photos of standing rice crop randomly across the field using a smart phone. After uploading captured images, the output, i.e., N recommendation, is immediately delivered to the farmer in terms of urea. Similarly, unmanned aerial vehicle (UAV)-mounted sensors are capable of detecting N stress in rice plant even before it produces visible visual symptoms. The spectral signature of multispectral and hyperspectral sensors are highly correlated with N status of the plant. However, at present its application in field level is hindered by higher cost of the UAV system (Vijaya Kumar et al. 2020).

10 Soil and Nutrient Management to Reduce GHG Emission Under Rice Cultivation

Emissions of CH_4 and N_2O from soil are by-products of C and N transformation processes, hence linked to plant nutrition both directly and indirectly. Appropriate soil and nutrient management can help reduce CH_4 emissions from rice production and increase carbon sequestration in soil. Whereas improving N uptake, N use efficiency can minimize N_2O emission from rice.

10.1 Mitigating CH_4 Emission

The net emission of CH_4 from soil is the resultant of CH_4 production, its oxidation, and its diffusion in soil. The oxygen concentration in soil is a key parameter that regulates the production and consumption of CH_4 by influencing the soil redox conditions. Apart from soil moisture status and porosity of soil, the bioavailability of C and N compounds also regulate the O_2 concentration in soil and hence influence CH_4 emission. Significant negative correlation between sulfate concentrations in soil and CH_4 production and emission has been reported (Ro et al., 2011). Sulfates are the more preferred electron donor than the C compounds during reduction process; hence, higher level of sulfate ions could suppress the activity of methanogens and CH_4 production during rice cultivation. A study suggested that sulfate reducers were able to outcompete methanogens for the available acetate, a labile carbon substrate (Scheid et al., 2003). Many studies indicated application of ammonium sulfate and gypsum reduced CH_4 emission from Paddy field (Theint et al., 2016). Ali et al. (2007) observed decreasing trend of CH_4 emission from rice field with increasing application of phosphogypsum from 2 to 10 Mg/ha, and 24% reduction in CH_4 emission could be achieved with phosphogypsum applied at the rate of 10 Mg/ha. Gypsum amendment to rice paddy soil was observed to stimulate bacteria involved in sulfur cycling (Wörner et al., 2016). However, prolonged use of phosphogypsum may lead to development of soil acidity.

Silicate slag, which is a byproduct of steel industry, contains high amount of available silicate, active iron, free iron, and manganese oxides, which act as electron acceptors. Significant decrease in CH_4 emission by silicate amendment in paddy soils has been reported (Ali et al., 2009). In a comparative assessment among different amendments including coal ash, phosphogypsum, and silicate fertilizer, Ali et al. (2012) observed that silicate fertilization with urea and silicate in combination with ammonium sulfate reduced total CH_4 flux by 18–23% and 21–26%, respectively, which was higher than that recorded under other amendments.

Incubation study indicated fly ash application reduced flux by 33.0–37.5%, and this was attributed to retardation of CH_4 diffusion through soil pores by addition of fine-textured fly ash. Moreover, fly ash has a potential of C removal via formation of carbonate precipitates and decreases the substrate availability for reduction reaction (Lim et al., 2012). Ali et al. (2009) compared three industrial by-products, e.g., fly ash, phosphogypsum, and blast furnace slag, for their potential reuse as soil amendments to reduce methane emission from rice field. Applying 10 Mg/ha of fly ash, phosphogypsum, or basic slag has been found to reduce total seasonal CH_4 emissions significantly, by 20%, 27%, and 25%, respectively, as compared to non-amended soil. This could be due to the increased concentrations of active iron, free iron, manganese oxides, and sulfate in the amended soil, which acted as electron acceptors and controlled methanogens' activity by limiting substrate availability.

Biochar, produced by thermochemical combustion of lignocellulosic crop residues under oxygen-limited condition, is comprised of carbon resistant to microbial degradation; hence, it contributes to environmental sustainability through carbon sequestration. Biochar may also affect CH_4 emission from soil through its effect on soil aeration, substrate availability, and methanotrophic actions (Ji et al., 2020). Application of biochar at a lower rate (2.8 t/ha) on paddy fields has been reported to reduce CH_4 emissions by 41% (Nan et al., 2020). Feng et al. (2012) also observed significant decrease in CH_4 emissions from paddy field under biochar amendments. The qPCR revealed increased methanotrophicproteobacterial abundances and decreased the ratios of methanogenic to methanotrophic abundances with biochar amendment. Though biochar has short-term CH_4 mitigation potential, and its long-term impact is still uncertain.

10.2 Mitigating N_2O Emission

Emissions of N_2O are directly linked to application of N fertilizer, and hence the strategies that increase the efficiency of N fertilizer use also reduce N_2O emissions. Adopting 4 R principle (Right Source, Right Dose, Right Time, and Right Place/ Method of fertilizer application) based nutrient stewardship is key to ensure synchrony between N supply and crop N uptake and enhance N use efficiency and, hence, has potential to reduce N_2O emission.

Urea is one of the most widely used N fertilizers because of its high N content, low cost, and favorable physical properties. However, the major problem associated with urea is that upon broadcast in the rice field it is rapidly hydrolyzed producing NH_4^+ which is quickly transformed to NO_3^- by the process of nitrification. The NO_3^- ion is transported to underlying reduced zone where it becomes substrate for denitrification process, and nitrous oxide is a by-product of both denitrification and nitrification processes in soil. One of the important strategies to reduce N loss from urea is to slow down the process of conversion of urea to NH_4 and subsequently to NO_3. A number of urease and nitrification inhibitors have been developed and used for these purposes. The enhanced efficiency N fertilizers (EENFs) are the fertilizer products developed with the coatings of less permeable material and/or nitrification, and/or urease inhibitors incorporated as extra additive within the formulation or in the coating have been widely evaluated for their N_2O mitigation potential. Meta-analysis of effects of different EENFs on N_2O emission by Thapa et al., (2016), indicated that nitrification inhibitors (NIs), double inhibitors (DIs: urease plus nitrification inhibitors), and controlled-release N fertilizers (CRFs) consistently reduced N_2O emissions compared with conventional N fertilizers across soil and management conditions, and the mean decreases were of 38, 30, and 19%, respectively.

Neem (*Azadirachta indica*) seed oil contains active ingredients that inhibit nitrification activity in soil. The neem-coated urea prepared by mixing plain urea with neem oil emulsion contains active ingredients that inhibit nitrification activity and regulates the formation of NO_3^--N in soil (Upadhyay et al., 2011). Application of neem-coated urea could reduce N_2O emission by 21.4% as compared to plain urea in an aerobic rice production system (Mohanty et al., 2018).

Synchronization of N supply with the crop requirement by applying N in splits is an important strategy to improve N uptake, minimization of N loss, and regulation of

N_2O emission. Optical sensors, green seeker, SPAD meter, etc. are useful tools to decide the crop N demand on the basis of leaf reflectance; however, the associated cost prevents their large-scale use by farmers. The leaf color chart (LCC) is a low-cost easy-to-use alternative that can be used for monitoring the relative greenness of a rice leaf as an indicator of the leaf N status. It is a plastic, ruler-shaped strip containing four or more panels that range in color from yellowish green to dark green matching the color range of rice leaves that cover a continuum from leaf N deficiency to excessive leaf N content. The customized leaf color chart based N application could reduce N_2O emission from puddled transplanted rice by 13–21% as compared to conventional stage based N application schedule (Mohanty et al., 2017).

The rational combination of inorganic fertilizer and organic manure through integrated nutrient management (INM) approach has potential to reduce N_2O emission by regulating flow of inorganic N content in soil. Following substitutive approach of INM where 50% recommended dose of N (RDN) was replaced by different organic amendments (farm yard manure, poultry manure, rice straw, and blue green algae) could reduce N_2O emission by 5.3–24.6% than 100% RDN applied by urea alone (Mohanty et al., 2020), and the highest reduction was achieved with INM option comprising 50% RDN from urea, 25% RDN from blue green algae (BGA), and 25% N from FYM.

Recent studies on impact of biochar on soil N dynamics indicated its potential inhibitory effect on N_2O emission (Biederman & Harpole, 2013; Liu et al., 2014). This phenomenon has been attributed to various factors including enhanced soil aeration, increase in soil pH, altered enzymatic activities, and negative effect on nitrifier and denitrifier communities. Meta-analysis of data collected from 30 studies with 261 experimental treatments concluded that biochar reduced soil N_2O emissions by 54% in laboratory and field studies (Cayuela et al., 2014). However, pyrolysis conditions, C/N ratio, texture of biochar, and soil were also observed to influence soil N_2O emissions.

11 Future Roadmap for Carbon-Smart Rice Cultivation

- Climate-Smart Agriculture (CSA) is known to be an important opportunity for low-emission-based cultivation across the globe. A study was conducted in different parts of Africa to pinpoint suitable avenues to mitigate GHG emissions. It was observed that some CSA alternatives like organic nitrogen input, improved pastures and switching land-use practices, agroforestry, rotational farming, and advanced livestock breeding and feeding all showed GHG mitigation potential and paved the way for C-efficient cultivation (Anuga et al., 2020).
- Ground cover rice production system (GCRPS) can be an option in reducing the carbon footprint. Polythene replaced by biodegradable substances will further be more environment-friendly (Yao et al., 2017).
- Proper water management (alternate wetting and drying, intermittent drying), use of nitrification inhibitors, suitable cultivars (short growth period, low biomass, and less numbers of tiller), and cultivation method to avoid puddling and flooding may lead to C-footprint under rice cultivation (Susilawati & Setyanto, 2018).

- Switching to renewable energy sources (solar, wind, and water) and use of energy-efficient machine may cut down GHG emission significantly.
- Burning of rice straws has been one of the most talked-about environmental issues of recent times. Suitable in-situ and ex-situ management options should be explored by the farming community to reduce, reuse, and recycle the large amount of harvested straw for environmental and economic sustainability.
- "Food Miles" (the distance that food travels from the field to the grocery store) is another concept given by national and international trade experts. It was revealed that increasing "food miles" leads to inclined CO_2 emissions as well as the overall energy consumption associated with a given product. Mostly, post-production processes like food processing, distribution, wholesale, and retail can be energy expensive, accounting two-thirds of total energy expenditure (Pimentel and Pimentel, 2008). To solve this, environmentalists and organic associations are emphasizing to purchase locally produced food items, and this may prove to be an environment-friendly eating habit; however, this may restrict the export of organic products to distant places and international markets, and cut down farm incomes (Gomiero et al., 2011).
- Site-specific nutrient management (SSNM), integrated nutrient management (INM), use of leaf color chart (LCC) for nitrogen management, neem-coated urea application, midseason drainage in rice, use of nitrification inhibitor, use of humified organic materials which have a lower C:N ratio, etc. have been identified as major technology for mitigating GHG emission (Bhatia et al., 2011; Pathak and Aggarwal., 2012; Jain et al., 2014; Mohanty et al., 2021).
- Biochar application could potentially reduce the carbon footprint compared with conventional straw management in rice production by increasing the significant soil carbon sequestration and reducing the CO_2, N_2O, and CH_4 emissions (Yang et al., 2015; Purakayastha et al., 2015).
- Conservation agricultural practices involving minimum soil disturbance, zero tillage (ZT), laser leveling, and brown manuring which help in increasing input use efficiency and improving soil properties also help in mitigating GHG emissions and reducing the carbon footprint (Pathak and Aggrawal, 2012; Chakrabarti et al., 2014).
- Direct seeding of rice (DSR), where seeds are directly sown in soil and do not require any puddling, hence will reduce CH_4 emission and save inputs of labor and water (no need of continuous submergence). Presently, this is confined to a limited area, but it might be a potential technology for reducing the carbon footprint in the future years.

12 Conclusion

Lowland rice is both a sink and source of C; hence, estimation of carbon footprint of rice production is crucial to assess its environmental impact and devise means and ways to progress toward a low-carbon production system. This will also help in evaluating different management options with respect to their environmental cost-benefit. Apart from CH_4 and N_2O emission from rice soil during production process, recent practice of rice straw burning emits significant amount of C into the atmosphere. However quantitative information on GHG emissions and sink capacity from rice field under diversified ecologies is still insufficient. It is very much essential to improve the available estimates through emission-monitoring network covering diversified climate, soil, and crop management. Existing methodology to measure GHGs is highly time consuming and with a lot of uncertainties and biases; detailed research is needed to improve and standardize the methodology. The manual closed chamber method though simple is cost-effective; the modification in the environmental condition inside the chamber may influence the estimated value. Moreover, sensitivity of this method is very poor. However, they can be used for comparing the emissions among different management practices. Though automated chambers are capable of carrying out continuous measurement, their cost and maintenance prevent large-scale use. Flux towers are generally useful to monitor GHG emission for large farming areas under similar cultivation practices and cropping systems. Life Cycle Assessments (LCA) is another significant research methodology that quantifies all inputs and outputs, and includes all phases from raw materials to final disposal and recycling, to give insight in the full life cycle of a product. However, an LCA and a carbon footprint belong to different impact categories while carbon footprint emphasizes on environmental impact category, GHG emissions to be more specific, whereas an LCA adds other categories (land use, water use, and acidification) into account. Several advisable mitigation options, effective in reducing the carbon footprint from rice cultivation, were also reviewed. In agronomic management, diversified cropping system, crop rotation, enhancing soil C-sequestration by manures and straw incorporation, plantation of agroforestry, use of energy-efficient agricultural implements and other nonrenewable energy sources for machineries, and precise nutrient management are some of the methods which can help to reduce the GHG emissions and improve C-buildup in soil.

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Energy Requirements for Sustainable Sugarcane Cultivation

Rajesh U. Modi and A. K. Singh

Contents

Abstract

In pursuit of sustainable energy era, sugarcane is a major energy-consuming as well as energy-producing crop. It requires higher energy input for cultivation due to its bulky nature and lower mechanized farming as compared to other field crops in developing countries. Sugarcane harvesting, intercultural, and planting are the most energy-intensive farm operations in sugarcane production system. Despite higher energy involvement, it is a future green-energy production crop that produces ethanol and biofuel. The energy input is significantly linked to the

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farm mechanization in sugarcane crop. Farm mechanization is a fundamental need for timeliness of farm operations, quality of work, and enhanced production with optimum inputs in sugarcane production system. Findings revealed that sugarcane is the higher energy required crop certainly grown in Southeast Asia despite higher inputs and lesser farm mechanization. The introduction of energy-efficient technologies is needed to reduce energy input in sugarcane cultivation while adopting efficient and appropriate farm machinery and reducing inputs such as seed, chemicals, water, etc. This chapter represents the status of energy requirements in sugarcane cultivation and possible strategies to optimize energy input through the intervention of new areas such as artificial intelligence and precision farming.

Keywords

Energy · Energy requirement · Mechanization · Sugarcane farming

1 Introduction

Energy is an important input required in a sustainable sugarcane (*Saccharum* spp.) production system. Efficient and precise energy input is crucial for socioeconomic development and sustainable sugarcane production. Fruitful sugarcane production takes energy from different sources, such as plants, manure, fertilizer, plant protection, irrigation, and machinery. This energy supplied in the agriculture sector can be in the form of direct, indirect, or in combination. The former releases energy directly, whereas the latter releases energy through a conversion process. The classification of energy used in agricultural production systems is shown in Fig. 1. Direct energy facilitates to accomplish numerous farm operations starting from tillage to planting, intercultural and weeding, irrigation, crop protection, and harvesting, whereas indirect energy delivers energy including the energy required for packaging and transportation of the seed cane, fertilizer, pesticides, and machinery. Energy is nevertheless categorized as renewable or nonrenewable. Energy sources such as humans, animals, farmyard manures, and cane seeds are considered renewable energy supplies, whereas nonrenewable energy sources include fossil fuels, electricity, agricultural machinery with tractors, chemicals, and fertilizers. Cane production depends on both energy and demand. Energy is consumed and supplied in the form of bioenergy through farming (Alam et al., 2005). Farm inputs and output products through production stages involved in sugarcane farming are shown in Fig. 2.

Energy requirement in the sugarcane sector depends on farm size and soil type, level of farm mechanization, cropping pattern, climatic conditions, and available inputs such as seed, fertilizer, labor, etc. Average man-hours required in manual and mechanized farm operations are shown in Table 1. It is clear from Table 1 that about 99% of savings can be achieved in mechanized farming over conventional (manual) farming. This increases timeliness operation, which can reduce post-harvest losses, thus increasing output energy. Energy analysis improves energy productivity by

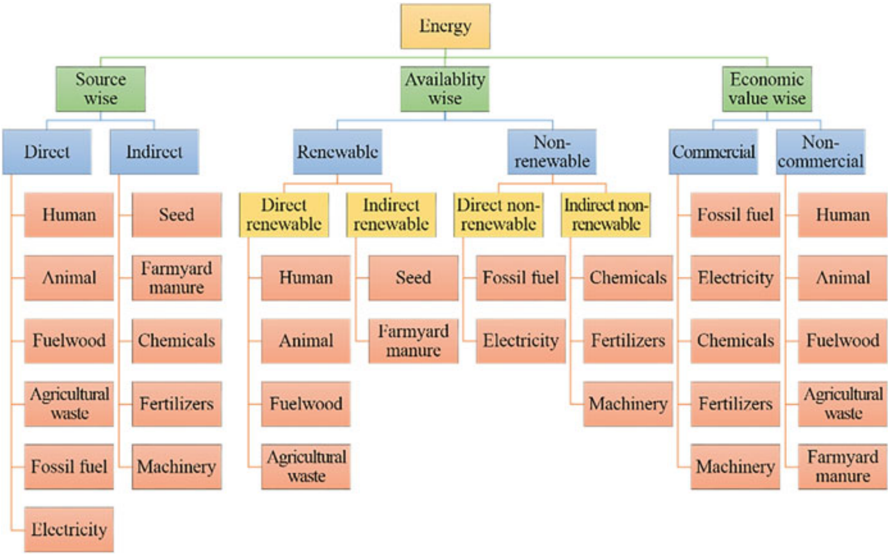

Fig. 1 Classification of energy used in agricultural production system

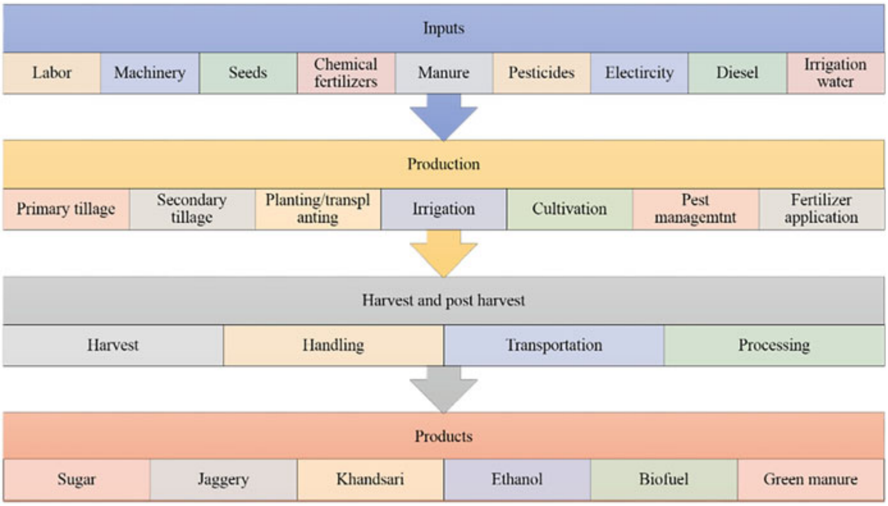

Fig. 2 An overview of sugarcane inputs and resulting products

efficiently reducing energy input in a crop production system. The efficiency of the system is determined by characteristics such as specific energy and energy ratio. Moreover, an assessment of energy input is increasing in demanding in agriculture as production is growing by the usage of different technological innovations day by day. Estimating energy inputs, particularly in agriculture, is more challenging than in the industrial sector since crop production is a biological conversion process

Table 1 Average man-hours required in conventional and mechanized farm operation (Murali & Balakrishnan, 2012)

	Labor requirement (man-h)	Saving (%)		
Operation	Conventional	Mechanized	Labor	Cost
Tillage	130.0	36.0	88.8	33.3
Manuring	40.0	0.0	100.0	100.0
Irrigation	130.0	40.0	87.5	87.5
Earthing up	25.0	5.0	80.0	50.0
Weeding	50.0	5.0	90.0	58.3
Harvesting	150.0	10.0	99.0	40.9

influenced by a variety of variables involved in crop production system. Increased agricultural output hence demands more sophisticated and efficient energy inputs. For different agricultural activities, however, the pattern of energy usage might be varied, resulting in a variation of energy use for a given activity. This chapter aims to discuss the energy footprints of farm operations, specifically in planted sugarcane cultivation, which can be helpful for different stakeholders such as farmers, researchers, and policymakers for future development needs in terms of farm inputs like machinery, fertilizers, and chemicals for its efficient use.

1.1 Method of Energy Calculation

Energy equivalents of various inputs for this study were obtained from the different literature as shown in Table 2. Energy output was calculated based on energy equivalents, which include production aspects such as human, tractor, machinery, diesel consumption, farmyard manure, chemical, fertilizer, seed cane, electricity, sugarcane yield, residue, etc. Different energy ratios and specific energies (MJ/kg) were obtained using the energy input, energy output (MJ/ha), and cane yield (kg/ha).

Following formulas were used for further energy calculation (Modi et al., 2018) from different sources of energy inputs for energy calculations.

$$E_H = E_{qh} \times L_h$$

$$E_A = E_{qa} \times A_h$$

$$E_T = \left(E_{qt} \times W_t \times W_{ht}\right) / \left(L_t \times W_{hyt}\right)$$

$$E_M = \left(E_{qm} \times W_m \times W_{hm}\right) / \left(L_m \times W_{hym}\right)$$

$$E_D = E_{qd} \times F_c$$

$$E_F = E_{qf} \times F_q$$

$$E_{C1} = E_{qc1} \times C_{q1}$$

Table 2 Energy equivalents of various inputs required for sugarcane cultivation

Input	Unit	Abbreviation	Energy equivalent (MJ/Unit)	Reference
Human	man-h	E_{qh}	1.96	Nassiri & Singh, 2009
Animal (large)	pair-h	E_{qa}	14.05	Nassiri & Singh, 2009
Diesel	l	E_{qd}	56.31	Singh & Mittal, 1992
Electricity	kWh	E_{qe}	11.93	Singh & Mittal, 1992
Sugarcane seed	kg	E_{qg}	5.3	Kumar et al., 2010
Water	m^3	W_i	1.02	Abbas et al., 2020
Farmyard manure	kg	E_{qf}	0.3	Singh & Mittal, 1992
Fertilizer	kg	E_{qc2}	60.60	Singh & Mittal, 1992
Chemical	kg	E_{qc1}	199	Helsel, 1992
Tractor	kg	E_{qt}	68.4	Singh & Mittal, 1992
Machinery	kg	E_{qm}	62.7	Nassiri & Singh, 2009
Residue	kg	E_{qs}	15.1	Smithers, 2014

$$E_{C2} = E_{qc2} \times C_{q2}$$

$$E_s = E_{qg} \times S$$

$$E_E = E_{qe} \times E_h$$

$$E_{op} = S_g \times E_{qg}$$

$$E_{ob} = Y_r \times E_{qs}$$

$$E_{total} = E_H + E_A + E_D + E_E + E_s + E_F + E_{C1} + E_{C2} + E_T + E_M$$

$$\text{Direct energy (MJ/ha)} = E_H + E_D + E_E$$

$$\text{Indirect energy (MJ/ha)} = E_s + E_F + E_{C1} + E_{C2} + E_T + E_M$$

$$\text{Renewable (MJ/ha)} = E_H + E_s + E_F$$

$$\text{Non-renewable}\left(\text{MJ ha}^{-1}\right) = E_D + E_E + E_{C1} + E_{C2} + E_T + E_M$$

$$\text{Commercial}\left(\text{MJ ha}^{-1}\right) = E_D + E_E + E_{C1} + E_{C2} + E_T + E_M + E_s$$

$$\text{Non-commercial}\left(\text{MJ ha}^{-1}\right) = E_H + E_F$$

$$\text{Energy ratio for produce} = E_{op}/E_i$$

$$\text{Energy ratio for by-product} = E_{ob}/E_i$$

$$\text{Specific energy}\left(\text{MJ kg}^{-1}\right) = S_g/E_{total}$$

where:

A_h = Animal hour (large size pair)
C_{q1} = Chemical required
C_{q2} = Fertilizer required
E_A = Energy from animal pair (large size)
E_{C1} = Energy from chemicals
E_{C2} = Energy from fertilizers
E_D = Energy from diesel
E_E = Energy from electricity
E_F = Energy from farmyard manure
E_h = Electricity hours
E_H = Energy from labor
E_i = Input energy
E_M = Energy from machinery
E_{ob} = Output energy for by-product (MJ/ha)
E_{op} = Output energy for produce (MJ/ha)
E_S = Energy from seed
E_T = Energy from tractor
E_{total} = Total energy (MJ/ha)
F_c = Diesel fuel used
F_q = Quantity of farmyard manure used
L_h = Labor hours
L_m = Life of machine
L_t = Life of tractor
S = Quantity of seed utilized
S_g = Sugarcane yield
W_{hm} = Machine working hours
W_{ht} = Tractor working hours
W_{hym} = Machine working h/year
W_{hyt} = Tractor working h/year
W_m = Weight of machinery
W_t = Weight of tractor
Y_r = Residue yield

2 Operation-Wise Energy Footprints

2.1 Seedbed Preparation

Sugarcane cultivation needs a well-prepared seedbed. In Asia, animal farming has been almost replaced with tractors not only in sugarcane but also in all other crops. Sugarcane agriculture has extensive demand for equipment such as disc plough, moldboard plough, duck foot cultivators, cultivators, disc harrows, culti-harrow, leveller, rotavator, ridger, bund cum channel former, etc. In India, tillage before planting required about 936 MJ/ha of the total operational energy (2795 MJ/ha), which could be saved without adversely compromising sugarcane yield (48.5 t/ha) in zero tillage as compared to conventional (49.4 t/ha) tillage treatments. Tillage levels did not affect the soil, irrigation, and crop characteristics significantly (Srivastava, 2003). Reducing the number of tillage operations did not significantly affect seedbed conditions (aggregate size distribution) or compromise crop performance. Reduced tillage maintained soil aggregate stability (MWD) and soil fauna compared with conventional tillage. Naseri et al. (2021) investigated energy indicators for sugarcane cultivation through conventional and conservation tillage methods in arid and heavy land in Iran. Energy calculations were carried out for four tillage methods: conventional method (two times subsoiler), Alpego tillage tool, Nardi tillage tool, and subsoiler for the first time + subsoiler five Sheng. Shares of energy sources in different tillage systems of sugarcane production are shown in Fig. 3. It is clear from Fig. 3 that electricity (60.57–64.10%) has a major share followed by nitrogen (16.79–22.25%). Conventional method had the lowest energy output (123,600 MJ/ha), whereas Alpego tillage tool had the highest energy output (139,200 MJ/ha) followed by the Nardi tillage tool. Alpego tillage tool and Nardi tillage tool gave high energy use efficiency ratio as 1.13 and 1.04, respectively, due to low energy input and higher energy output in a particular method. Alpego tillage tool was found to be more suitable than the others due to low production costs and higher productivity for Iran.

2.2 Planting/Transplanting

Sugarcane planting includes cutting seed setts; constructing furrows; placing seed setts, fertilizer, and chemicals; and covering setts with soil, which takes approximately 35 man-days per hectare. In Asian countries such as India and Pakistan, the majority of these tasks are performed manually with traditional tools and equipment. It takes a long time, is labor intensive, and requires a lot of drudgeries, which eventually increases energy intake. These facts opened a window of mechanization for various tractor-operated sugarcane planters to adopt at the farm level. Out of the various plating methods like trench planting, ring pit planting, staggered row planting, furrow irrigated raised bed (FIRB) planting, and spaced transplanting, flat planting is mostly adopted. Inputs required for planting of sugarcane were obtained from various literature (Singh & Singh, 2017; Sukhbir et al., 2017), and energy footprints were calculated using existing formulas (Modi et al., 2018). In India, three different popular planting machines such as PTO driven planter, ground wheel driven planter, and deep furrower planter are popular. Thus, energy analysis of these machines was carried out and compared with the conventional method of sugarcane planting. The percentage of share required in the planting operation has been shown in Fig. 4, which clearly shows that seed (38.63–41.30%) is the major input source due to its huge requirement (7.0–8.0 t/ha). It was found that the seed has highest energy input which varied from 27,560 to 31,800 MJ/ha due to higher requirement of seeding material (5.2–6.0 t/ha). Chemicals ranked second in energy input (25,472.0–39,800.0 MJ/ha) due to the necessity of its application to protect the planted cane against termite attacks in the

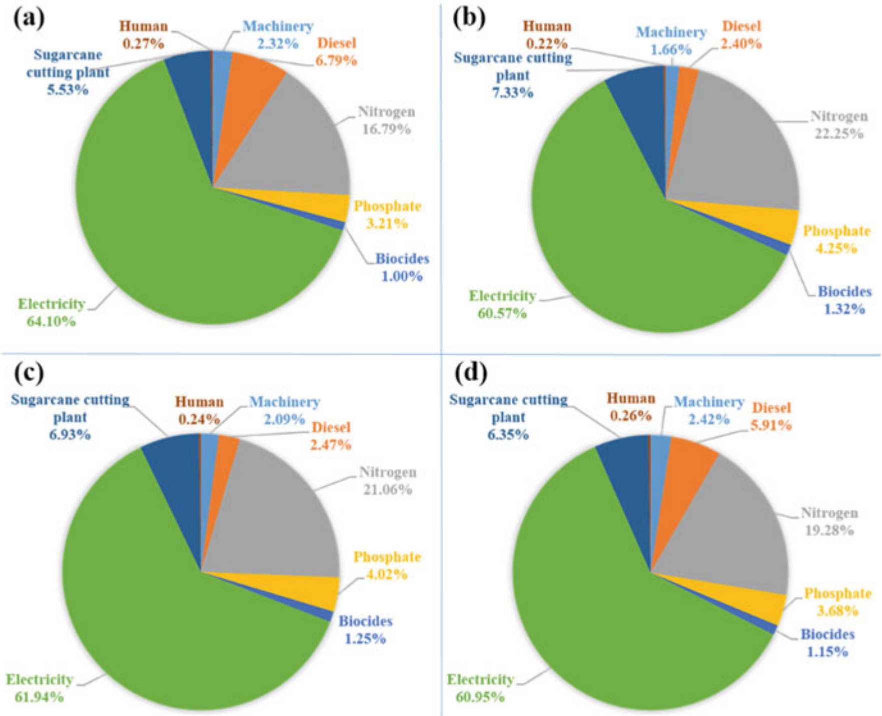

Fig. 3 Shares of energy sources in different tillage system of sugarcane production. (**a**) Conventional method (two times subsoiler), (**b**) Alpego tillage tool, (**c**) Nardi tillage tool, (**d**) subsoiler for the first time + subsoiler five Sheng

soil. Input energy from fertilizer was ranged from 14,665.2 to 39,800.0 MJ/ha. Sugarcane planting using PTO driven planter required highest energy input followed by conventional method, sugarcane deep furrower, and ground wheel driven sugarcane planter. On the other hand, sugarcane bud chip method is an emerging plating technique that reduces planting material to the tune of 79% as compared to conventional planting of 2–3 budded stalk pieces of sugarcane. About 85% of energy employed on humans can be saved using bud chip seedlings as mechanical sugarcane transplanting over manual transplanting (Naik et al., 2013).

2.3 Weeding and Intercultural Operations

Sugarcane crop is affected by weeds during its period of growth. This leads to the loss of cane yield ranging from 12 to 83% (Hossain et al., 2001; Pechiappen, 2001; Veeranna et al., 2001). Thus, it is necessary to control weed emergence during critical period starting from the early fourth week of its planting to the seventh week. In India, the average energy required for intercultural operation during the late

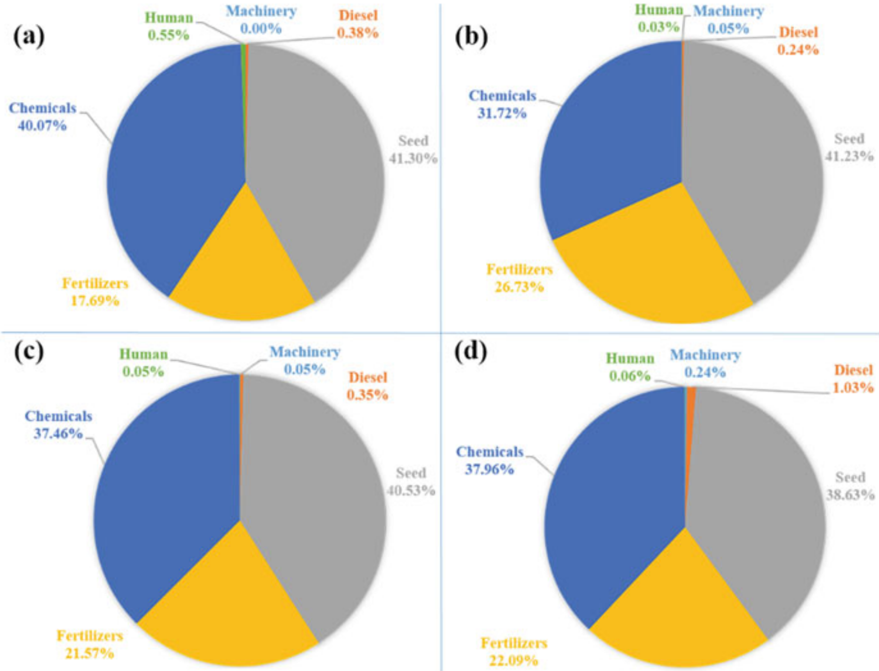

Fig. 4 Shares of energy sources in different planting machinery of sugarcane production. (**a**) Conventional method, (**b**) PTO driven planter, (**c**) ground wheel driven planter, (**d**) deep furrower planter

1990s was 1651.67 MJ/ha (Singh et al., 1997). This could be attributed to the fact that in the late 1990s, there was least mechanization in the intercultural operation for sugarcane farming. Now human energy demand for manual weeding is on verge of chemical weed control which may increase nonrenewable energy consumption. Presently, some of the machines such as power weeder, three-row rotary weeder, cultivator, and multipurpose tractor-operated equipment are now being adopted for intercultural operation. Mohan et al. (2020) evaluated a power weeder in sugarcane crops and found that energy consumption with power weeder was highest with 632.42 MJ/ha (60 DAS) followed by 620.74 (45 DAS) and 602.64 MJ/ha (30 DAS). Human energy consumption pattern for weeding in sugarcane at different stages is shown in Fig. 5. It is clear from these results that energy consumption has reduced about 2.5 times using recent efficient machinery for inter-row weeding.

2.4 Irrigation

Sugarcane is an extensively irrigated crop and requires 35–40 irrigations which can vary according to climatic conditions in South Asia (Murali & Balakrishnan, 2012). Surendran et al. (2016) studied water management in sugarcane cultivation using

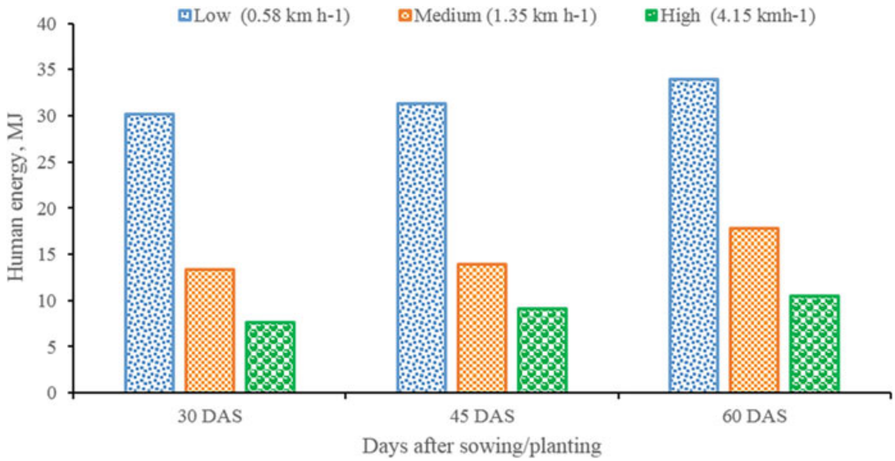

Fig. 5 Human energy consumption pattern for weeding in sugarcane at different stages

low-cost drip irrigation (LCDI) and flood irrigation in semiarid tropical agroecosystems in India. Average number of irrigation were 69.2 in LCDI as compared to 53.3 in flood irrigation method where respective actual water use reduced up to 515.7 and 3450 mm. Electricity saving using LCDI over flood irrigation was observed to be 2840.4–4471.2 MJ/ha, which led to average monetary benefit of 120 USD. Flood irrigation requires that the irrigation be restarted from the beginning after every power outage and that the same irrigated area be irrigated again, which is a waste of water. This is a loss of energy in terms of electricity and water in flood irrigated areas. Surface and subsurface drip irrigation methods can save energy consumption (in terms of water consumption) up to 40% and can enhance productivity by 20% (Shukla et al., 2019). Irrigation water required almost the same amount of energy in India (23,970 MJ/ha) and Pakistan (24,327 MJ/ha). Overall, sugarcane production in Iran has the highest value for irrigation water energy (41,739.5 MJ/ha) while Brazil has the lowest (11,551.5 MJ/ha).

2.5 Fertilizer/Nutrient Management

Sugarcane crops need healthy soil, large fertilizer dosages, and a high frequency of irrigation water and manure. By keeping this point in mind, farmers usually apply a high level of inputs such as fertilizer/nutrients to sugarcane plantations to maximize output and profit. The use of large amounts of fertilizer does not ensure an improvement in earnings (Mousavi Avval et al., 2012). An adequate amount of input energy at the appropriate time and in the right quantity boosts agricultural productivity (Karimi et al., 2008). In southwest Asia, the energy required for fertilizer and nutrient application ranged from 10,598.4 to 19,205.8 MJ/ha, whereas it was about 4120 MJ/ha in Brazil (Singh et al., 1997; Karimi et al., 2008; Khan, 2008; Veiga et al., 2015; Kumar et al., 2018; Powar et al., 2020). This difference reflects the fertilizer demand due to agroclimatic variation and soil health in Asia and Brazil.

2.6 Plant Protection

Sprayers are used for chemical spray to control insects, pests, and diseases at the beginning of their emergence based on the symptoms. Broad swath spray boom is recommended for successful and efficient spraying. Also, self-propelled high clearance sprayers and tractor-operated aero blast sprayers are useful in sugarcane production. On average, Indian sugarcane farms required 12.5 MJ/ha energy for spraying, while the energy requirement for plant protection in Iran was 1920 MJ/ha due to the higher application of chemicals for the eradication of insects, pests, and diseases.

2.7 Harvesting

Manual sugarcane harvesting includes base cutting, stripping and detrashing, detopping, bundling of 10–12 stalks, loading, and ultimately transporting sugarcane to sugar mills. On the other hand, mechanical harvesting does all these tasks except bundle making. It cuts sugarcane stalks into the billet form for easy transportation. Out of all the farm operations, harvesting and transportation are the most laborious. Asian countries are at a stage of replacing manual harvesting with mechanical harvesting, whereas developed countries such as the major sugarcane producer Brazil have prevalent large-sized mechanical harvesters. Manual harvesting of sugarcane demands energy of 295.5 MJ/ha against mechanical energy of about 20 MJ/ha (Murali & Balakrishnan, 2012). This indicates that mechanical intervention can save about 99% of human energy during harvesting. Energy demand for sugarcane harvesting in Indian farms was 2572.3 MJ/ha, whereas it was 1893.7–2504.3 MJ/ha in Iran. The energy required throughout the life cycle of a sugarcane harvester was investigated by Mantoam et al. (2014). In this study, it was found that the average energy demand for life cycle, mass, and power was 138.8 MJ/h, 202.6 MJ/kg, and 11,600 MJ/kW, respectively.

2.8 Residue Management and its Benefits

Average sugarcane straw availability on sugarcane harvested farm is about 14.1 Mg/ha (db) which depends on average straw to stalk ratio of 18.2% (Hassuani et al., 2005). Although sugarcane straw has a great energy potential, few efforts have so far been undertaken to build a suitable collection path to exploit this potential. In major sugarcane-growing countries such as Brazil and India, harvesting of cane stalks has been the main focus. Thus, the sugarcane industry is still unaware of collecting sugarcane residue for energy generation and utilization (Leal et al., 2013) as being done in the case of paddy residue. It may be due to utilization of residue as a mulch or incorporation under the flag of conservation agriculture for the subsequent ratoon crop to enhance soil properties. In studies, the total electrical surplus from sugarcane mills can reach 468–670 MJ/Mg of cane when 40–50% of the straw is available as extra fuel to the bagasse field (Seabra & Macedo, 2011; Dias & Sentelhas, 2019). However, there are problems since significant quantities of straw have to be handled and combusted in industrial bagasse boilers. According to Srivastava (2003), mulch-based treatments enhanced crop yields (49.4 t/ha without trash and 73.0 t/ha with trash), energy productivity (1.15–1.69 kg/MJ), and water use efficiency (762–1192 kg/hacm).

3 Source-Wise Energy

Overall energy footprint is discussed here for three Asian countries, namely, India (Singh et al., 1997; Surendran et al., 2016; Kumar et al., 2018; Powar et al., 2020), Iran (Shahamat et al., 2013; Elsoragaby et al., 2019), and Pakistan (Khan, 2008) against the major sugarcane producer country, i.e., Brazil (Fachinelli & Pereira, 2015; Veiga et al., 2015). Yields of sugarcane crop for various countries were obtained from (Anonymous, 2019). Shares of energy sources in four different sugarcane-producing countries are shown in Fig. 6.

In India, electricity, seed, irrigation, and fertilizer are the higher energy-demanding aspects of sugarcane production system. Short-duration-sugarcane (8 months)-based system offered a 14–27% more energy output as compared to conventional system (one plant + one ratoon). Short-duration sugarcane having multiple cropping systems (with 3–4 crops per cropping cycle of two years) demands nearly 40% more energy input than the conventional system (Sundara & Subramanian, 1987). Overall, share of electricity (37.01%), seed (23.28%), irrigation water (15.65%), and fertilizer (10.73%) are the highest among the different energy inputs (Fig. 6a). In Iran, production aspects such as irrigation water (32.87%), electricity (20.41%), diesel (18.21%), and fertilizers (15.13%) had the largest impact on the indices in planted farms (Fig. 6b). However, in ratoon farms, electricity, machinery, nitrogen fertilizers, and biocides have the largest share in increasing the indices. Similarly, energy requirement in mixed (animal and mechanical power) sugarcane farms of Pakistan had the highest share for seed (37.13%) and irrigation water (34.51%) as compared to fertilizers and chemicals (15.03%) as shown in Fig. 6c.

In Brazil, energy input in terms of irrigation water had the highest (50.53%) share followed by diesel (20.65%), fertilizer (18.02%), and machinery (4.02%). It is clear from Fig. 6d that water has the highest share due to sugarcane being an irrigation-intensive crop. Also, diesel and machinery totalled together required 24.67% of input energy due to heavy mechanical operations required in sugarcane cultivation.

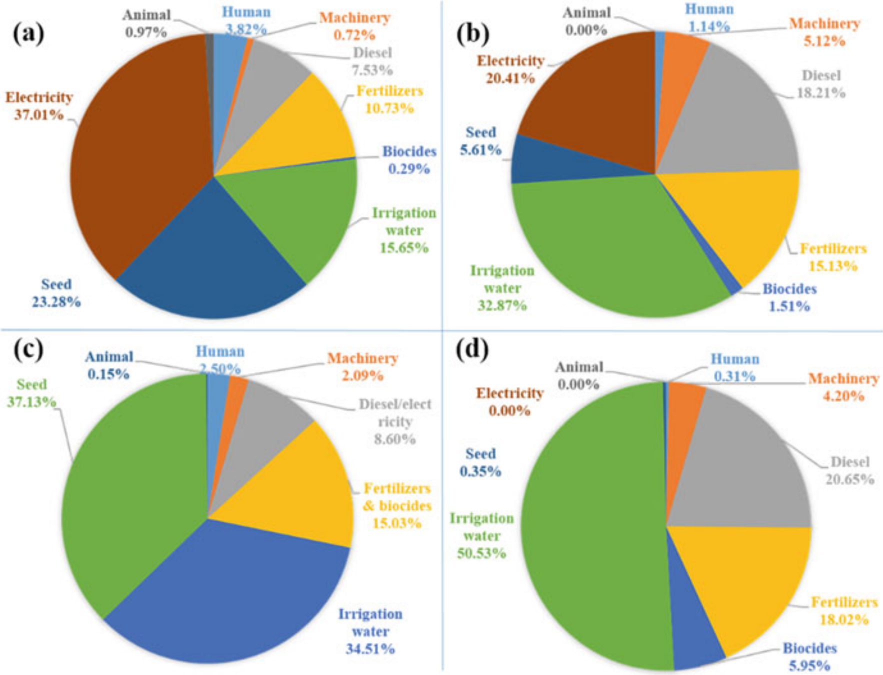

Fig. 6 Shares of input energy sources in four different sugarcane-producing countries. (**a**) India, (**b**) Iran, (**c**) Pakistan, (**d**) Brazil

3.1 Overall Energy Assessment Based on the Category of Energy

The source-wise category of energy consumption for sugarcane cultivation is shown in Table 3 and its percentage share in Fig. 7. It is clear from Fig. 7 that the consumption of indirect energy was found to be highest for Pakistan (88.8%) followed by Brazil (89.6%), Iran (60.2%), and India (50.7), while the rest was direct energy for the respective country. Share of renewable energy was higher for Pakistan (74.3%) and Brazil (51.5%), whereas share of nonrenewable energy was higher for Iran (60.4%) and India (56.3%). However, renewable energy had the higher share, and the rest was nonrenewable energy. However, commercial energy was higher for all countries like India, Iran, and Pakistan with 79.6, 66.0, and 62.9%, respectively, while the rest were of non-commercial energy. Brazil had almost an equal share of commercial (49.2%) and non-commercial (50.8%) energy in the sugarcane production system.

3.2 Energy Indices

Input vs output energy and energy indices for four different sugarcane-producing countries are shown in Figs. 7 and 8, respectively. It is evident from Fig. 7 that India

Table 3 Source-wise energy distribution in four different sugarcane-producing countries

Source of energy (MJ/ha)	India	Iran	Pakistan	Brazil
Direct	75,554.2	50,484.0	7925.2	4790.0
Indirect	77,606.3	76,493.1	62,575.0	18,071.5
Renewable	66,960.8	50,312.3	52,363.2	11,701.5
Nonrenewable	86,199.6	76,664.8	18,137.0	11,160.0
Commercial	121,852.6	83,789.8	44,310.8	11,240.0
Non-commercial	31,307.8	43,187.3	26,189.4	11,621.5

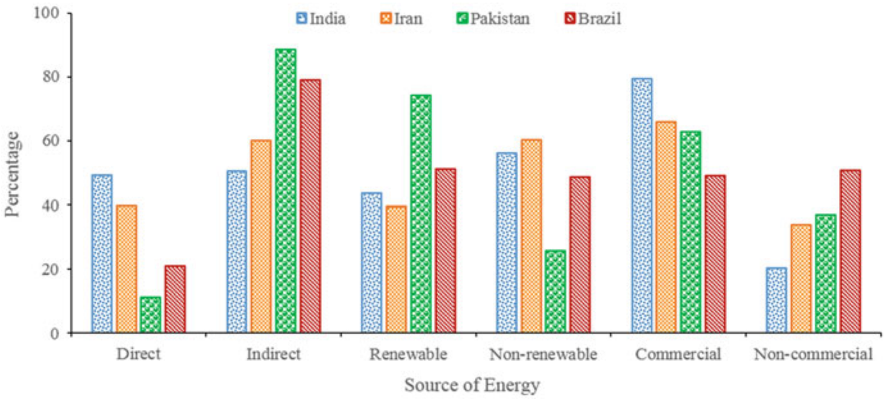

Fig. 7 Shares of source of energy for four different sugarcane-producing countries

has the highest (153,160.5 MJ/ha) energy input followed by Iran (126,977.1 MJ/ha), Pakistan (70,500.2 MJ/ha), and Brazil (22,861.5 MJ/ha) while highest energy output for Iran (462,690.0 MJ/ha) and Pakistan (306,758.7 MJ/ha). The net gain of energy was higher for Brazil (375,592.5 MJ/ha), Iran (335,712.9 MJ/ha), Pakistan (236,258.5 MJ/ha), and India (219,927.7 MJ/ha).

It can be seen from Fig. 9 that energy ratio was highest for sugarcane production in Brazil (17.43) followed by Pakistan (4.35), Iran (3.64), and India (2.44). A similar trend has been followed in terms of energy productivity, whereas a contrasting trend has been followed in specific energy. Minimum specific energy was observed in Brazil (0.30 MJ/kg), Pakistan (1.22 MJ/kg), Iran (1.45 MJ/kg), and India (2.18 MJ/kg). This indicates that Brazil requires the least energy to produce 1 kg of sugarcane, whereas India required the highest. Maximum energy productivity was observed for Brazil (3.29 kg/MJ), Pakistan (0.82 kg/MJ), Iran (0.69 kg/MJ), and India (0.46 kg/MJ).

4 Future Pathway

Sugarcane water requirement is the major aspect and most researchable component that has to be reduced in terms of application by at least up to 30%. Mechanization can be imparted in sugarcane cultivation for planting, weeding, and harvesting based

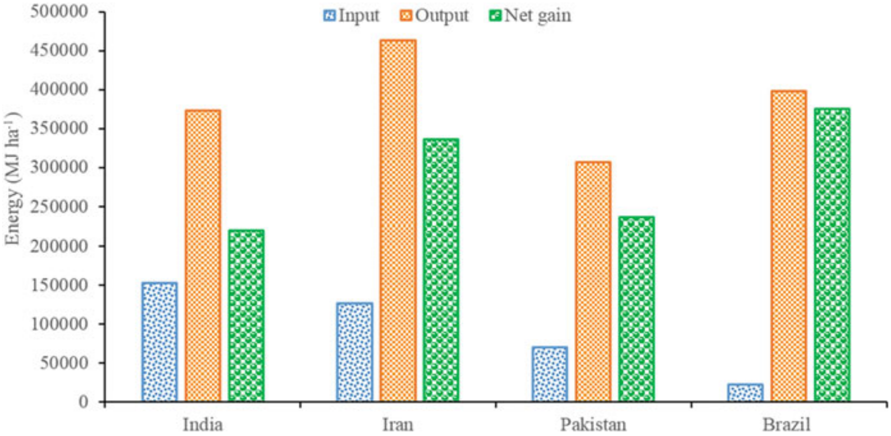

Fig. 8 Input vs output of energy for four different sugarcane-producing countries

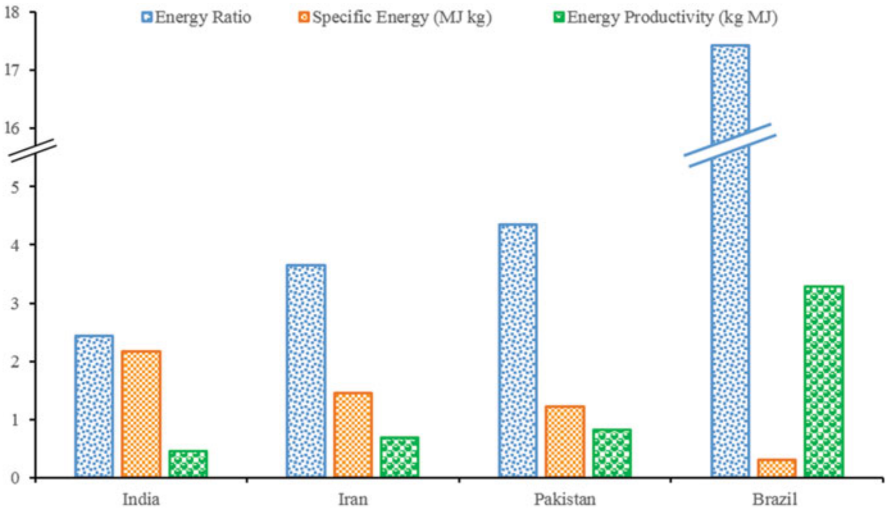

Fig. 9 Energy indices for four different sugarcane-producing countries

on precision farming (Modi et al., 2020). This can reduce the use of indirect as well as direct energy at a significant level. Adoption of controlled traffic farming in sugarcane production can reduce energy input during tillage operations followed by reduction in other operations such as weed control in terms of soil resistance offered to the weeders for easy movement. This will minimize energy input in seedbed preparation as well as minimize soil degradation in the long run and uphold productivity in a sustainable model. It was evidenced that CT will improve soil properties as compared to conventional tillage (Braunack & McGarry, 2006).

4.1 Strategies for Energy Optimization

Reducing as well as optimizing energy consumption can help improve input components of energy and also yield of sugarcane, ultimately attaining sustainability. Higher mechanization would contribute to higher productivity through reducing harvest and post-harvest losses but at the same time increase total diesel consumption. Some solutions for reducing nonrenewable inputs include replacing diesel with a renewable fuel (e.g., biofuel from vegetable oils and ethanol or their blending) and increasing the efficiency of machinery and transportation vehicles which will reduce associated GHG emissions. Minimum tillage can be adopted followed by sugarcane crop planting or transplanting in keeping view of controlled traffic farming. Reduced and minimum tillage has potential to reduce energy consumption as well as GHG emission. The energy input share of seed sugarcane is also greater, which may be reduced by using cane node and sugarcane transplanting techniques. Keeping view of water scarcity in water-deficit agroclimatic zones, drip/micro irrigation would help in saving energy in the form of water and electricity with timely irrigation of the crop. Adoption of nano-fertilizers such as nano-urea can reduce the application of urea through enhancing nitrogen use efficiency as compared to normal urea. A new era of artificial intelligence has the potential to reduce energy consumption through adopting models and decision support systems for implement selection and assistance, as well as timely identification of water stress and managing water scheduling and diseases with an appropriate advisory to gain sustainability in the sugarcane sector. Custom hiring centers can supply appropriate machinery at the optimum time, for instance, tillage has to be done at the upper plastic limit, which will require less energy vice versa. Some of the recent developments include weed detecting robots (Sujaritha et al., 2017), which will reduce human energy input during weeding and intercultural operation in sugarcane.

5 Conclusion

This chapter assesses the amount of energy required in sugarcane cultivation that is extremely beneficial to policymakers in strategizing energy-efficient and cost-effective sugarcane production systems. Energy has a significant role in the sugarcane sector. The total average energy input is highest in India and lowest in Brazil with 153,160.5 and 22,861.5 MJ/ha, while output energy was 373,088.2 and 398,454.0 MJ/ha, respectively. The net energy gain for Brazil was 375,592.5 MJ/ha and for India 219,927.7 MJ/ha. Moreover, energy ratio was highest for sugarcane production in Brazil (17.43) followed by Pakistan (4.35), Iran (3.64), and India (2.44). Study revealed that sugarcane cultivation is energy efficient in the world that would lead to sustainability. Furthermore, there is need to optimize the energy input for sustainable sugarcane production through reduction of irrigation water energy. Seed has a higher energy input share, which may be decreased by employing cane node and sugarcane transplantation techniques.

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Carbon Footprint of Different Energy-Intensive Systems

Debashish Dutta, Omkar Singh, and Shivangi

Contents

Abstract

Global warming, which is produced by an increase in greenhouse gas concentrations in the atmosphere, has become the most important environmental challenge

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worldwide. It is thought to have a significant impact on agriculture, especially crops, cattle, and fishing. Agricultural intensification is necessary to feed a population that is expanding and becoming more demanding. Intensification is linked to a rise in the GHG emissions from agricultural systems. The planet Earth is in decline, owing primarily to human activities; as a result, numerous planetary boundaries have been crossed, and the vulnerability of agricultural and food systems to disruption has increased. High-external-input, one of man's most destabilizing endeavors, agriculture contributes significantly to global dysfunction. Nonetheless, industrial agriculture is expected to continue to be a major source of food and GHG emission, which leads to frequent dry spells, heat waves, and variable monsoonal rains and results in climate change, thus threatening India's food security and also adding to farmers' hardships. Many agricultural practices, such as raising crops and cattle for human use, increase greenhouse gas emissions. Emissions from agricultural areas are influenced by the use of artificial and natural fertilizers, the growth of plants having the capacity to fix nitrogen, the draining of soil quality, and irrigation techniques. Methane (CH_4) is produced by livestock, particularly ruminants like cattle by the process called enteric fermentation as part of their natural digestive processes. It accounts for nearly a quarter of the emissions generated by the agricultural industry. The amount of greenhouse gases produced also depends on how the manure is treated and stored. Various measures, along with cropland and grassland management, can result in reduced carbon dioxide emissions or its sequestration (CO_2).

Keywords

GHG · High-external-input agriculture · Enteric fermentation

1 Introduction

We must cut global greenhouse gas emissions quickly if we are to avoid severe climate change. Almost 50 billion tons of GHG (calculated in the equivalent of carbon dioxide) is released into the atmosphere each year. To figure out how to reduce emissions most effectively and identify which emissions can and cannot be eliminated with the current technology, we must first understand where the emissions come from. Agricultural activities account for 10–14% of worldwide anthropogenic GHG emissions (Francesco et al., 2013), with enteric fermentation (methane), synthetic fertilizer application (nitrous oxide), and tillage accounting for the majority of these emissions (carbon dioxide) (Jantke et al., 2020). The average temperature of the earth has risen as the concentration of the CO_2 has increased. In the past century, the Earth's surface temperature has increased by 0.74 °C on average. If carbon emissions do not stop, temperatures are predicted to rise by an additional 3.4 °C by the end of the century. A shift in that size would undoubtedly be fatal for life as we know it on Earth. Some of the effects include water scarcity, forest fires, severe storms, floods, and cardiorespiratory illnesses. Pressure would be placed on agricultural systems, and in some parts of the world, they might even deteriorate.

Let us discuss various energy-intensive sectors and subsectors in the pie chart and their carbon footprint. The energy sector includes various subsectors like electricity, heat, and transport, which contribute 73.2% to the total GHG emission. Emissions from various sectors include (1) iron and steel manufacturing produces energy-related pollutants. (2) Chemicals and petrochemicals (3.6%): manufacturing of fertilizers, medicines, refrigerants, oil and gas extraction, and other energy-related emissions. (3) Food processing (1%): emissions from the manufacturing of tobacco products and processing of food (the conversion of agricultural raw materials into finished products, like the transformation of wheat into bread). (4) Transportation: includes all emissions directly produced while burning fossil fuels for the purpose of transportation as well as indirect emissions. (e) Waste also contributes in the manner as wastewater systems may gather organic materials and leftovers from animals, plants, people, and their waste products. Methane and nitrous oxide are produced as organic matter decomposes. Landfills are frequently low-oxygen areas. When organic matter decomposes in these conditions, it produces methane. Despite rising evidence of climate change's hazards, in most countries, there are few, ineffective, or no efforts made to limit carbon emissions.

2 Agriculture as an Energy-Intensive System

Because the world's population continues to grow, the worldwide demand for food to feed people and fuel will continue to rise for at least the next 40 years (Godfray, 2011). Agriculture requires modern energy, and the two are inseparably linked. Agriculture is the most important sector in the development of many developing countries' economies. An enormous increase in the amount of energy input is necessary for contemporary and sustainable agricultural cultivation and processing systems in order to move beyond subsistence farming and toward food and nutrition security, added value in rural areas, and expansion into modern agriculture markets. Energy services that properly support the production process, such as irrigation (pump), post-harvest treatment (cooling), and processing, can frequently be provided by renewable energy technologies and hybrid systems (drying, milling, pressing). Another essential component of agricultural output is the use of mechanical energy, which includes both human and animal labor as well as fuel for pumping, mechanization, and other processes. The universe is made up of several types of matter, all of which contain energy. The sun – the ultimate energy source – is the source of all forms of energy on Earth. Plants absorb solar energy and convert it into chemical energy through the process of photosynthesis. Energy is the currency of nature's economy. Because the human economy is based on the exchange of goods and services, it is a similar subsystem of the biosphere (Pelletier et al., 2011). The laws of thermodynamics entail all energy transformations to behave according to certain physical principles. These are universal principles, which means that they apply equally regardless of the situation. The first law of thermodynamics, known as the law of energy conservation, is as follows: energy can be transformed between its different states, but it can never be created or destroyed, hence the universe's energy level remains constant. As a result of this law, the energy inputs to a system any net storage inside it, and the energy output from the system is always in balance. The use of modern, energy-intensive technologies in the post-World War II era has resulted in a significant rise in food production. Food has changed much as a result of globalization and systems are becoming increasingly energy intensive. Agricultural production has turned out to be much more complex and thus an energy-intensive process.

3 Definition of Carbon Footprint

The phrase "carbon footprint" comes from a pioneering scholarly article that first established the notion of "ecological footprint" (Rees, 1992). The entire amount of greenhouse gases (such as carbon dioxide and methane) produced by human actions is known as a carbon footprint. There are two ways to describe a carbon footprint: (1) the total greenhouse gas emissions per unit of farmland, which quantifies the overall emissions in crop production that are more concerned with environmental health; and (2) the amount of greenhouse gas emissions related to each kilogram of grain produced, which emphasizes both emissions during the production of a crop as well as the products (i.e., grain yield) related to per unit of emission. There are times when the definition of carbon footprint did not include the release of GHGs other than carbon dioxide, but the truth is that nitrous oxide (N_2O) (Janzen et al., 2006), a gas with a global warming potential of 300 times (Forster et al., 2007), accounts for a major portion of GHG emissions connected with farming operations. Carbon dioxide equivalents could be used as a measure of carbon footprint, which is equivalent to the summation of all the warming impacts of various greenhouse gases together in order to give a single measure of total greenhouse gas emissions. We multiply the mass of non-CO_2 gases (such as kilograms of methane emitted) by their "global warming potential" in order to convert them into their carbon dioxide equivalents. GWP quantifies the warming consequences of a gas compared to CO_2; it basically assesses the "strength" of the greenhouse gas averaged over a selected time horizon.

4 Why Carbon Footprinting?

Agriculture in this era has become an energy-intensive task and thus requires huge energy input and in turn gives GHGs as output. This necessitates the involvement of carbon footprinting. To keep track of a financial budget, you must understand the revenue and spending balances. Carbon budget may be written as

Sources = amount in the atmosphere + amounts in the sinks (sinks represent removals from the atmosphere but inputs to the ocean or land).

Complex and intensive systems have resulted in heavy production and emission of greenhouse gases. In the post-World War II era, the deployment of new, energy-intensive technologies greatly expanded food production. Food has changed much as a result of globalization. By 2050, the economy is expected to grow significantly to fulfill the requirements of an ever-increasing and diverse population. By 2050, the average global carbon footprint per year must be under 2 tons to have the best chance of avoiding a 2 °C rise in global temperatures. At least 30% of the mitigation action required to avoid the most devastating effects of climate change can be found in nature. The world's trees currently store more carbon than the entire atmosphere. Deforestation, on the other hand, accounts for 11% of worldwide greenhouse gas emissions, which is more than all passenger cars combined. Soil respiration is the primary source of carbon between the atmosphere and the soil, and soil carbon loss may be measured using CO_2 and CH_4 emissions from the soil (Khan et al., 2017; Liu et al., 2019).

5 Agriculture and Climate Change

According to IPCC reports (2014), 76% of greenhouse gas (GHG) emissions is from heat, electricity, transport, or industrial processes, which accounts for the majority. According to data from the meta-analysis by Poore and Nemecek (2018), approximately 26% of global GHG emissions are attributed to food. Agriculture is presently one of the largest contributors to global carbon emissions. CO_2, CH_4, and N_2O are the most significant GHGs produced by agriculture. Microbial degradation or the combustion of plant litter and soil organic materials releases CO_2. Methane is created when organic materials breakdown in oxygen-depleted environments, such as paddy grown under flooded conditions and through ruminant livestock's fermentative digestion of stored manures. Microorganisms in the soil produce N_2O from manures and nitrogen fertilizers, which are often exacerbated under wet conditions when available N exceeds plant requirements.

Livestock, which includes animals farmed for meat, dairy, eggs, and seafood, contributes to emissions in a variety of ways. Ruminants, such as cattle, produce methane during digestion (known as "enteric fermentation"). Manure management, pasture management, and fishing vessel fuel usage are all examples of this. Crop cultivation for direct human consumption accounts for 21% of food emissions, while animal feed production accounts for 6%. They are the direct emissions from agricultural production, which include nitrous oxide emissions from fertilizer and manure application, methane emissions from rice cultivation, and carbon dioxide emissions from agricultural machinery. Food emissions are accounted for 24% of land usage. Agricultural expansion causes carbon dioxide emissions by converting forests, grasslands, and other carbon "sinks" into cropland or pasture.

Agriculture, on the other hand, also has the potential to be quite beneficial in adapting to and mitigating the effects of climate change by employing techniques that aid in soil improvement carbon sequestration and carbon protection sinks, resulting in a reduction in relative intensity carbon dioxide emissions.

6 Factors Contributing to Carbon Footprint of Different Systems in Agriculture

Energy conversion takes place in agriculture in and of itself, where conversion of solar energy into food energy for human and animal feed is done through a complex process known as photosynthesis. Primitive agriculture consisted primarily of dispersing seeds throughout the landscape and accepting the few harvests that emerged. The agricultural production steps, including the use of energy in farm machinery, are water management, irrigation, cultivation, and harvesting. All these require an energy input in modern agriculture. The steps involved in post-harvest energy use are food processing, storage, and transportation. In addition, mineral fertilizers, chemical pesticides, insecticides, and herbicides are all used in agriculture as indirect or sequestered energy inputs. These steps also contribute to the carbon footprint of the ecosystem. All these steps contribute to carbon footprint in some way or the other (Fig. 1).

Agriculture, forestry, and land use are responsible for 18.4% of total greenhouse gas emissions (Ritchie & Roser, 2020). This includes 0.1% from grassland; as grassland degrades, soils lose carbon, which is then converted into CO_2. Carbon may be sequestered by restoring grassland (e.g., from farming). The total balance of these carbon losses and gains from grassland biomass and soils is referred to as emissions. 1.4% from farmland carbon can be lost or sequestered into soils and biomass depending on cropland management techniques. CO_2 can be released when croplands are deteriorated or sequestered when they are recovered, affecting the carbon dioxide emissions balance. Carbon dioxide emissions are a reflection of the net change in carbon stocks. 2.2% of the net carbon dioxide emissions is from deforestation due to change in forestry cover. As a result, reforestation is classified as "negative emissions," whereas deforestation is classified as "positive emissions." The difference between forestry loss and gain is hence referred to as net forestry change. Emissions are calculated using the amount of carbon lost from forests and the amount of carbon stored in forest soils. Crop burning contributes 3.5% and releases carbon dioxide, nitrous oxide,

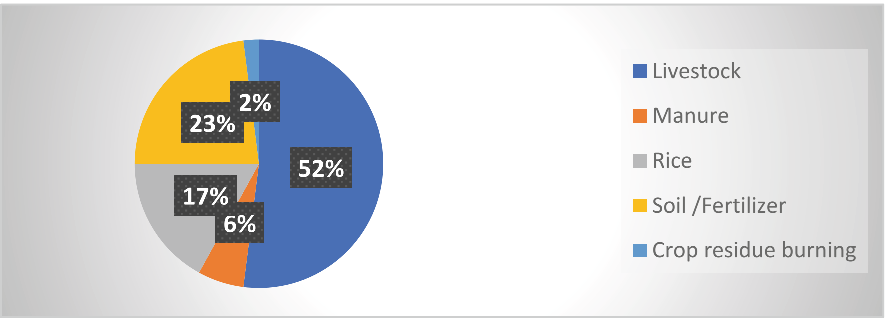

Fig. 1 Greenhouse gas production from different agriculture sectors. (Source: Pathak et al., 2010)

and methane when agricultural residues – remaining vegetation from crops such as rice, wheat, sugar cane, and other crops – are burned. Crop wastes are frequently burned after harvest to prepare land for resowing. Rice agriculture emits around 1.3% as flooded paddy fields create methane through an anaerobic digestion process. The low-oxygen environment of water-logged rice fields causes organic matter in the soil to be transformed into methane. The soils used in agriculture contribute to 4.1% since when synthetic nitrogen fertilizers are applied to soils, they generate nitrous oxide, a powerful greenhouse gas. This comprises emissions from all agricultural products, including food for direct consumption by humans, animal feed, biofuels, and other nonfood crops, as well as emissions from agricultural soils (such as tobacco and cotton).

Animals (mostly ruminants like sheep and cattle) create greenhouse gases through a process called “enteric fermentation,” in which bacteria of their digestive tracts fragment down food and methane is released as a by-product. As a result, lamb and beef have a large carbon footprint, and eating less lamb and beef is an efficient strategy to lower one’s diet’s emissions. Under low oxygen circumstances, the breakdown of animal manures can create nitrous oxide and methane. This is common on dairy farms, cattle feedlots, and swine and poultry farms, where manure is often held in enormous mounds or disposed of in lagoons and other forms of manure management systems. The term “livestock” refers to direct emissions from livestock exclusively; it excludes the effects of land-use change for pasture or animal feed.

Global greenhouse gas emissions are continuing to surge despite the fact that they should be progressively declining. To successfully cut emissions, we must first understand where they originate – which industries contribute the most?

7 Use of Inorganic N Fertilizer

Use of synthetic fertilizers has become an integral element of our global food chain supply and is required to retain our increasing population. Fertilizers, on the other hand, can contribute to GHG emissions as well as other possible nutrient losses in the ecosystem, such as by leaching emissions. The addition of nitrogen fertilizer to the soil enhanced the carbon (C) substrate and aided the expansion of methanogens, resulting in increased methanogenic activity and consequently increased CH_4 emissions. Furthermore, after utilizing ammonium nitrogen (NH_4 + -N), methane monooxygenase participates in the oxidation of ammonia (NH_3), impacting the catalytic oxidation of CH_4 (Willison et al., 1995; Lin et al., 2021). The carbon footprint of synthetic N fertilizers employed in the cultivation of the durum crop was the highest, accounting for 65% of total emissions. This includes direct and indirect emissions from NH_3 and NOx volatilization and nitrate leaching from the application of N fertilizers on farm fields (27% of total emissions), as well as emissions from the manufacturing, shipping, storing, and delivering of N fertilizers to farm gates, which are about 38% (Gan et al., 2011). The addition of nitrogen fertilizer to the soil enhanced the carbon (C) substrate and aided the expansion of methanogens,

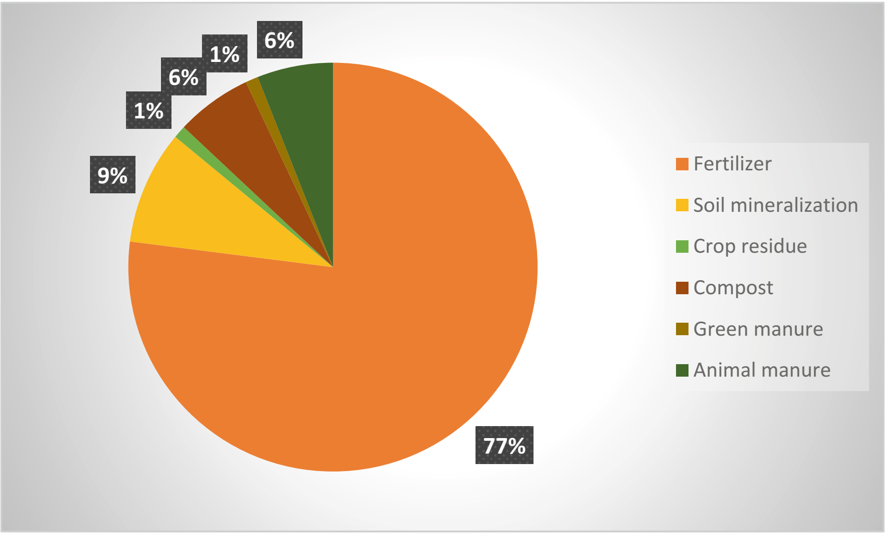

Fig. 2 Contribution of different sources to nitrous oxide emission from Indian agricultural soils in 2010. (Source: Pathak et al., 2010)

resulting in increased methanogenic activity and consequently increased CH_4 emissions. Furthermore, after utilizing ammonium nitrogen (NH_4 + -N), methane monooxygenase participates in the oxidation of ammonia (NH_3), impacting the catalytic oxidation of CH_4 (Wu et al., 2019) (Fig. 2).

8 Fossil Fuels

About 85% of the energy consumed in modern society comes from fossil fuels. Modern agriculture owes much of its success to a plentiful supply of fossil fuels, which are required for synthetic fertilizer production, transportation, storage, and delivery to the farm gate, as well as for a variety of farm operations such as seeding, fertilizer and pesticide application, and field crop harvesting. In general, emissions from industrial operations for synthesizing nitrogen fertilizers with fossil fuels prior to on-farm usage considerably outnumber emissions from pesticide manufacturing and application to field crops. Massive volumes of carbon dioxide, a greenhouse gas, are released into the atmosphere when fossil fuels are burnt. Greenhouse gases trap heat in our atmosphere and thus are a cause of global warming. The average global temperature has already risen by 1 °C. Warming exceeding 1.5 °C increases the danger of rising sea levels, harsh weather, biodiversity loss and extinction, food scarcity, and increasing health and poverty for millions of people throughout the world. Coal is the dirtiest of the fossil fuels, accounting for approximately 0.3 °C of the 1 °C rise in world average temperatures, making it the single most significant contributor to global warming. When oil is burnt, it emits a significant quantity of carbon, accounting for around a third of global carbon emissions. It takes energy to get energy, and fossil fuel extraction, processing, and delivery account for 8% of carbon emissions. Steel, cement, automobiles, and other manufactured products account for approximately 20% of global carbon emissions. Use of natural gas is commonly advertised as a more environmentally friendly energy source than coal and oil. However, fossil fuel is still accounting for a fifth of global carbon emissions.

9 Pesticide Use

Pesticides have an impact on climate change during their production, transportation, and application. Three major greenhouse gases are released during the production of pesticides: carbon dioxide, methane, and nitrous oxide (Heimpel et al., 2013). Many elements contribute to a crop's total footprint during its production cycle. Crop protection products, for example, represent just a small fraction of the overall carbon footprint of crop production (1–4%), but they can enhance productivity and safeguard harvests. According to research by the Intergovernmental Panel on Climate Change, agricultural activities, including pesticide usage, account for around 30% of global emissions that contribute to climate change. Each year, more than 200 million pounds of agricultural pesticide active ingredients are applied to California fields, with more than 40 million pounds of fumigants – among the most dangerous and greenhouse gas-producing pesticides – being used. It has been proven that the usage of fumigants contributes to the production of nitrous oxide, a greenhouse gas 300 times more powerful than carbon dioxide.

10 Fuels

Because direct emissions from the burning of fuels are dictated by the physical qualities of the fuel, they are consistent across the world. The indirect emissions from the rest of the fuel's life cycle depend on the technologies used to prepare and transport it, as well as the distances it must go. The indirect component is estimated from life cycle analysis literature to be roughly 10–20% of the overall life cycle.

When the direct and indirect variables are added together, an emissions factor for the whole life cycle of the fuel is obtained. Natural gas emits around 6.6 kg CO_2e/therm or 0.22 kg CO_2e/kWh, with combustion accounting for more than 85% of the total. The CO_2e content of heating oil is approximately 11.6 kg CO_2e/US gallon or 3.1 kg CO_2e/l. LPG has a CO_2e content of 6.8 kg per US gallon or 1.8 kg per liter.

11 Waste and Water

Methane generated at landfill sites, as well as transportation, is the primary source of emissions from waste disposal. You may calculate your annual waste generation by multiplying how much rubbish you create each week into 52. Your carbon footprint is calculated by multiplying this by a carbon intensity. Depending on how much garbage is disposed of in landfills, burnt, and recycled, the intensity will vary substantially from nation to country. Intensities that capture these differences can be calculated using life cycle literature or inferred using national greenhouse gas inventories. In some regions, water consumption may be unexpectedly carbon intensive. Emissions are mostly caused by two sources: power needed to pump water during its delivery and methane and nitrous oxide produced during wastewater and sewage treatment.

12 Carbon Footprint Calculation

The GHGs chosen are determined by the nature, requirements, and norms of the sector/activity. In the case of wastewater, for example, CO_2 is the major gas emitted as a result of bacterial activity, followed by CH_4 and N_2O emissions. In any sector, CO_2 from coal-fired power plants, for example, becomes the most significant GHG, surpassing CH_4 and other gases detected in trace amounts (Garg & Dornfeld, 2008; Peters, 2010).

This is done using emission factors for all GHG gas quantities/fluxes as CO_2-eq. (WRI/WBCSD, 2004; Wiedmann & Minx, 2007; BSI, 2008). For the quantification of C footprint, two approaches are used: (1) bottom-up, based on process analysis (PA), and (2) top-down, based on environment input–output analysis. From the source to the sink, the bottom-up method inherits a grasp of the environmental implications of specific products, regions, and categories. This method has a disadvantage in terms of determining an acceptable system boundary because it is focused solely on on-site impacts (Lenzen, 2001).

13 Carbon Footprint Calculations for Energy

The following calculations are used for direct energy emissions:

CO_2 = (Total Amount * (CO_2 Emission Factor * Heating Value) * Density)

CH_4 = ((Total Amount * (CH_4 Emission Factor * Heating Value) * Density) * GWP CH_4 Conversion)

N_2O = ((Total Amount * (N_2O Emission Factor * Heating Value) * Density) * GWP N_2O Conversion)

The following calculations are used for indirect energy emissions:

CO_2 = ((Total Amount Used Based on Occupancy * Emission Factor))

CH_4 = ((Total Amount Used Based on Occupancy * CH_4 Emission Factor) * GWP CH_4 Conversion)

N_2O = ((Total Amount Used Based on Occupancy * N_2O Emission Factor) * GWP N_2O Conversion)

14 Selection of Conversion Factors

It makes it easier to calculate conversion factors CO_2 emissions by multiplying activity data in their respective international units and converting them to kilos of CO_2 equivalent (kgCO_2e). CO_2e is a universal unit of measurement for GHGs' global warming potential (GWP), expressed in terms of the GWP of one unit of carbon dioxide (see Formula (1)). We used a variety of reference sources to choose the best conversion factors, taking into account variables like accessibility, consistency, and transparency in changes and updates. Conversion factors are evaluated and adjusted every year during the early months of the year.

$$\text{GHG (kg CO}_2\text{e)} = \text{aspect quantity data} \times \text{conversion factor} \tag{1}$$

15 Steps to Reduce Carbon Footprint

15.1 New Technologies to Reduce Enteric Fermentation

Ruminant animals (mostly cattle, sheep, and goats) account for around half of all agricultural emissions. The largest source of these emissions is "enteric methane," which is produced in ruminant stomachs due to action of microbes. Methane emissions will be reduced by the same strategies used to boost ruminant productivity and reduce land-use demands, owing to the fact that more milk and meat is produced per kilogram of feed. The biggest chances to cut emissions lie with poorer nations since the benefits are the greatest when going from the worst-quality feeds to even average-quality feeds. When very inefficient systems are improved, emissions per kilogram of meat or milk drop dramatically initially as productivity per animal rises. Other methods for reducing enteric methane emissions include utilizing vaccinations to manipulate microbial communities in the ruminant's stomach, selective breeding of animals that make fewer emissions naturally, and inserting special feeds, medications, or supplements into diets.

16 Cutting Emissions from Pasture Manure

According to the IPCC's benchmark emissions factors, nitrogen in feces and urine is converted into nitrous oxide at a rate about twice that of nitrogen in fertilizer. Our 2050 prediction currently accounts for productivity gains that reduce the intensity of emission from manure by 25%, but further progress in feed efficiency could result in minor emission reductions.

Other studies have found that there is little to no global potential to reduce emissions from this diffuse source. Given the continued growth of two emerging technologies, we are cautiously optimistic. Both work by preventing microbes from converting nitrogen from other molecular forms into nitrate, which can then be broken down to generate nitrous oxide.

Inhibitors of chemical nitrification have proven to be quite effective when applied two or three times per year to grasslands (Doole & Paragahawewa, 2011) and when swallowed by cows in a small number of studies.

17 Increase Nitrogen Use Efficiency to Reduce Fertilizer Emissions

In 2010, fertilizers applied to crops and pastures (mainly synthetic fertilizers, but also manure and other sources) were predicted to be responsible for 1.3 Gt CO_2e emissions. The manufacture, transportation, and application of nitrogen account for nearly all of these emissions. In our baseline scenario, we estimate that these emissions will climb to 1.7 Gt by 2050. Absorption of nitrogen applied to crops is less than half of the nitrogen applied to agricultural areas around the world. The left out either pollutes ground or surface waters or escapes into the atmosphere as gases, notably the powerful heat-trapping gas nitrous oxide. Nitrogen application rates per hectare and the amount of nitrogen absorbed by crops rather than lost to the environment (known as “nitrogen utilization efficiency” [NUE]) vary substantially between countries and particular farms.

Changes in agricultural practices are the focus of mitigation initiatives. Farmers who monitor nitrogen demands and frequently apply nitrogen in just the right amount over the growing season can achieve extraordinarily high rates of efficiency. The issue is that such rigorous management is costly, whereas nitrogen fertilizer is inexpensive. As a result, we believe that new ideas are required. Nitrification inhibitors and other “high-efficiency” fertilizers can boost NUE while lowering nitrous oxide emissions and increasing yields. However, they are only utilized with 2% of worldwide fertilizers (Byrnes et al., 2017), owing to considerable variations in performance and the fact that fertilizer makers currently devote little money to developing them. Another potential method is biological nitrification suppression. While the primary purpose of these restrictions is to prevent excessive nutrient leaks into the environment, particularly into bodies of water, they will also help in reducing agricultural GHG emissions.

18 Rice Management and Varieties That Reduce Emissions

The rice plant’s semiaquatic characteristic allows it to grow profitably in regions where no other crop could, but it also causes it to emit the principal greenhouse gas (GHG), methane, and other gases. Water regime and organic inputs control the majority of GHG emissions from rice fields, but soil type, weather, tillage management, residues, fertilizers, and rice cultivar also play a role. Flooding the soil is a requirement for long-term GHG emissions. In 2010, flooded or “paddy” rice cultivation accounted for at least 10% of all worldwide agricultural production GHG emissions, mostly in the form of methane. According to available research, rice emissions mitigation has a great technological potential, and most mitigation approaches offer some chance of economic rewards through increased yields and reduced water consumption. We will concentrate on four primary options: rice yields should be increased. Because methane emissions are proportional to paddy area rather than quantity, exceeding the FAO’s anticipated rate of yield growth would allow paddy area to remain steady or decline, lowering emissions. To limit methane production, remove rice straw from paddies before re-flooding. Straw can also be utilized for other useful purposes, such as mushroom cultivation or bioenergy production. Reduce the length of time that water is flooded to prevent methane-producing bacteria from growing.

19 Increasing Agricultural Energy Efficiency and Reducing Fossil Fuels

In our baseline, emissions from fossil energy use in agriculture will stay at 1.6 Gt CO_2e/year in 2050. Based on historical trends, we believe that a 25% increase in energy efficiency is counterbalanced by a 25% rise in energy demand. Mitigation options are similar to those used to reduce energy emissions in other industries, relying on increased efficiency and the use of renewable energy sources. Although there have been few studies of possible energy efficiency improvements in agriculture, there are a small number of country-level studies, for example, in alternate water pumps in India (Saini, 2013). Lamiaa and Tarek (2013) concluded that adding intelligence or smartness to every component of the power system, from generation to distribution, is a priority. The use of renewable energy sources to generate electricity rather than typical thermal power plants would save fossil fuels and enhance the environment by lowering greenhouse gas emissions (particularly) from thermal generating. Smart grid optimizes the utilization of existing lines and substations for optimum efficiency and minimal losses in the transmission network. In terms of consumption, implementing smart meters, as well as using smart housing amenities and expanding the usage of hybrid plug-in electric cars, will result in lower GHG emissions, energy saving, and environmental preservation.

While replacing on-farm coal will require unique, small-scale solar heating technologies, solar and wind energy may frequently provide heat and electricity. Tractors and other large pieces of equipment will need to consume less diesel fuel, making the switch to fuel cells that run on hydrogen produced by solar or wind energy more challenging. Battery-powered devices and artificial carbon-based fuels produced from renewable electricity are examples of alternative technologies.

20 Concentrate on Practical Options for Carbon Sequestration in Soils

Due to the difficulty in reducing agricultural production emissions, significant research and policy emphasis have been focused on techniques to trap carbon in agricultural soils to balance such emissions. To increase soil carbon, there are just two options: add more or lose less. However, new research and experience suggest that soil carbon sequestration is more difficult than originally anticipated (Powlson et al*.,* 2014, 2016; van Groenigen et al., 2017). When evaluated at deeper soil depths than previously observed, changes in plowing practices, such as no-till, once appeared to avoid soil carbon losses, now appear to yield only minor or no carbon gains. No-till solutions must also deal with negative effects on yields in particular areas, as well as the reality that many no-till farmers still plow up soils every few years, releasing much of any carbon gain (Powlson et al., 2014). Adding mulch or manure to soils is a proposed strategy for adding carbon to soils; however, it effectively double-counts carbon that would have been stored elsewhere. Allowing crop wastes that would otherwise be used for animal feed to decompose into soil carbon necessitates the animals getting their feed from somewhere else, which has a carbon cost because it frequently necessitates more agricultural land to cultivate that feed. Large amounts of nitrogen are needed by the microorganisms that convert decaying organic matter to soil organic carbon in order to build soil carbon. Low nitrogen inhibits soil carbon buildup in Africa, where nitrogen additions are insufficient even for crop demands, and it also limits soil carbon buildup in other parts of the world (Kirkby et al., 2014).

21 Reduction in Fertilizer Use and N_2-Fixing Pulses to Lower Carbon Footprint

Chemical fertilizers, herbicides, and manure must be used carefully to prevent the creation of nitrous oxide, a greenhouse gas with a 300-fold greater potential for global warming than carbon dioxide. In addition, low-cost nitrogen processing inhibitors in soils should be used. Countries all across the world are increasingly recognizing agriculture's particular role in carbon sequestration. Crop CFP can be reduced by 32 315% with agricultural diversification (Yang et al., 2014; Liu et al., 2016). Diversifying cropping systems with oilseed, pulse, and cereal crops organized in clearly defined cropping sequences significantly lowered the carbon footprint of durum wheat when compared to cereal-based monoculture systems. The carbon footprint of durum wheat was reduced by up to 34% compared to monoculture wheat systems when biological N-fixers were added to the systems. Due to the use of biological N fixation, N fertilization was reduced in diverse cropping systems, which significantly reduced the carbon footprint of durum grain (Gan et al., 2011).

22 Conclusion

The chapter emphasizes how agricultural operations, which account for 10% to 14% of all anthropogenic emissions, are a significant source of global greenhouse gas emissions. The usage of synthetic fertilizers, enteric fermentation from cattle, and burning of agricultural waste are some of the main sources that have been found. Agriculture systems have become more intensive and energy-dependent as a result of the expanding world population and increasing food demand, which has led to an increase in emissions. In order to effectively reduce climate change, the introduction highlights the urgent need for a thorough understanding of emissions from various agricultural practices and subsectors. It advises including emissions from all linked activities, such as the production of fertilizer, the use of fuel in farm equipment, and transportation, in addition to agricultural and livestock production. Given that the agricultural sector contributes 25% of all emissions and still has significant room for improvement in crop and manure management, adoption of renewable energy, and promotion of carbon sequestration in soils are all important strategies for reducing agricultural emissions. Overall, the chapter makes a compelling case for prioritizing climate change mitigation in agriculture by objectively analyzing emissions patterns across subsectors, identifying workable solutions, and putting in place targeted interventions to move toward low-carbon, sustainable food production.

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Carbon Footprint and Sustainability of Different Agricultural Production Systems in Climate Change Scenario

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Contents

Abstract

The increase of global warming risk is mainly due to increase in greenhouse gases (GHGs) concentrations in atmosphere. The contribution of agricultural systems to global climate change can be assessed through carbon footprint (CF). In this chapter, the CF of different agricultural systems with different crop systems in diverse soil types are highlighted. Although agricultural systems are a major source of GHGs, there are opportunities to reduce GHG emissions by adopting best management practices. Carbon footprint is the best indicator to measure GHG intensities related to human activity in different scenarios. Adopting less energy along with efficient use of resources can reduce the GHG emissions. There are various methods for evaluating the CF of different agricultural systems with various crop systems. Multiple functional units need to be used when assessing the CF of an agricultural system. One of the most important functions to be considered is the variation of SOC storage while

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evaluating CF in different agricultural systems. Carbon footprint estimates in context to agricultural systems help in increasing the understanding of factors behind differences in CF of different farms and systems. The accuracy of CF can be increased by using site-specific emission factors. This will provide an important information that helps to identify areas for decision-making for greenhouse gas mitigation.

Keywords

Agricultural systems · Carbon footprint · GHG emissions · Global warming and SOC

1 Introduction

Climate change is a serious threat with a negative impact on the global environment. The consequences of climate change are intense heat waves, glacier melting, water bodies swelling, rise in sea levels, etc. The CO_2 concentration level has reached 410 ppm as compared to 280 ppm in preindustrial era. Even, methane (CH_4) levels are raised from 715 to 1800 ppb, and nitrous oxide (N_2O) levels from 270 to 328 ppb (EPA, 2016). The rise in CO_2 as compared to preindustrial levels is attributed to various anthropogenic activities. It is well known that N_2O and CH_4 are having global warming potentials over 100 years of 298 and 34 times that of CO_2 and their increase is more than 50 and 250%, respectively, as compared to preindustrial levels. Further, over the next century, the Intergovernmental Panel on Climate Change (IPCC) predicts a temperature rise of 2.5–10 °F that can have detrimental effects on mankind. Hence, there is immediate need to curtail the greenhouse gas (GHG) emissions to the extent of 25% below the current level by 2050.

Agriculture plays a major role with 10–14% of global anthropogenic GHG emissions mainly due to enteric fermentation (CH_4), application of synthetic fertilizers (N_2O), and tillage (CO_2). Not only fertilizer application, but also its production and storage are associated with GHG emissions. Various implements used in the field for crop production and various other soil processes contribute to GHG emissions during arable crop production. Around 8% of the UK's annual net GHG emissions is contributed by agricultural N_2O. Further, it is considered as the single biggest contributor to UK agricultural GHG emissions (DECC, 2015). However, agriculture can also act as a sink by storing carbon in vegetation, and in soils. In order to meet the demand for agricultural crops for food and fuel has resulted in wide spread use of hybrids with the change in the management practices. Thus, there was increase in use of synthetic fertilizers and pesticides, irrigation, and mechanization as a consequence of the so-called "Green Revolution." This resulted in increased productivity at a high environmental cost. In India, the National Mission for Sustainable Agriculture under National Action Plan on Climate Change targets to reduce agricultural GHG emissions intensity by 33–35% by 2030. Emissions are not only related to the application of nitrogen fertilizers, soil management, use of agricultural machinery, crop residues burning, and land use change but are also related to livestock. Around 14.5% of global GHG emissions are from livestock sector (Gerber et al., 2013). However, the world's average per capita GHG emissions was 6.3 t CO_2e while in India it is only 2.4 t CO_2e. While the USA is 14 t CO_2e, Russian Federation is 13 t CO_2e, 9.7 t CO_2e in China, about 7.5 t CO_2e in Brazil and Indonesia, and 7.2 t CO_2e in the European Union (Climate watch, 2020).

There are eight missions under National Action Plan on Climate Change. One among them is National Mission for Sustainable Agriculture which was adopted by India in 2010. One of the objectives of the mission is to reduce agricultural greenhouse gas emissions. India also pledged to reduce the emission intensity by 33–35% by 2030 compared to 2005. According to the data compiled by *Potsdam Institute for Climate Impact Research, i*n India, GHG emissions were 3571 million tonnes of CO_2 equivalent (MtCO_2e) during 2015 which were reduced according to the IEA to 2307.78 MtCO_2e in 2018 which is still of 335.33% increase as compared to 1990 (www.climatescorecard.org). In this context, quantification of GHG in agriculture sector is possible through carbon footprint (CF). It is one of the best tools to determine the GHG emissions due to crop production at various levels. Presently, global GHG emissions are about 49 Gt CO_2e/year of which 74% is CO_2, 16% is CH_4, and 10% is N_2O (GHG protocol of World Resource Institute, IPCC 2006 guidelines, GHG accounting methods given by ISO 14064 (2006a, b), Publicly Available Specifications-2050 (BSI, 2008) of British Standard Institution (BSI), and ISO 14067 (ISO, 2 are several standards to estimate the GHG emissions)).

In the 1990s, the term carbon footprint evolved from the concept of "ecological footprint" (Ercin & Hoekstra, 2012). It gained importance from 2005 to account carbon emissions to mitigate climate change. It serves as an indicator to identify and mitigate the emissions. Accounting of indirect and direct GHG emissions during one crop production in a certain cropping system (kg CO_2-eq/ha) based on life cycle assessment is known as carbon footprint (CF) and expressed in CO_2 equivalent (CO_2-eq). There are numerous methodologies and models to calculate carbon footprint, both on individual level or a product/service, organization/institution level but also for communities, nations, and even at global level. However, there is no uniform or universally accepted method to calculate carbon footprint. It is a quantitative expression of GHG emissions during an activity/process. It gives an opportunity for cost reductions and to improve environmental performance. It has an important role in policy. It is a successful tool that helps in evaluating the extent of reduction in GHG emissions. It is now a worldwide concept for GHG management. Thus, many companies and organizations started accounting carbon footprints to estimate their own contribution to mitigate the GHG levels. Mostly, it is used as primary indicator to understand and mitigate the adverse effects of climate change. Also, it helps to accurately identify the sources of emissions. Another tool that helps in assessing the environmental impact is life cycle assessment (LCA). As per International organization for standardization (ISO), LCA is defined as a tool to analyze products in their entire life cycle. Products may be goods or services. In this tool, transport and energy are also tracked throughout the life cycle. In simple words "Cradle to Grave." Hence, CF and LCA are considered to be important tools while carrying environmental performance of crop studies. Holka and Bieńkowski (2020) stated that CF and LCC are important while carrying environmental performance of crop studies.

2 Emission from Mechanical Operations

Adopting zero emission machinery by shifting from traditional fossil-fuel equipment and machinery can create huge cost savings of $229 per t$CO_2$eq (Ahmed et al., 2020). Majorly agriculture machinery, fertilizer use, and cattle contribute to a huge volume of GHGs. Casolina et al. found that diesel (used in machinery) and fertilizer use typically determined 90% of the environmental load in Italy. It was reported that tillage produces 67% more CO_2 than the no tillage system. Soil management and weather conditions also influence the CO_2 emissions. Each kg produced in tillage (T) was on an average 42.2 kg more CO_2 emitted from wheat, 60.8 kg more CO_2 from legume, and 149.5 kg more CO_2 from sunflower than those emitted in no-tillage in southern Spain (Carbonell-Bojollo et al., 2019). In Canada, as compared to conventional tillage (baseline-1990), on farm GHG emissions were reduced by almost 3.6 Tg due to minimum tillage in all field crops. No till farming ensures reduced diesel consumption and also reduced soil disturbance, thereby less oxidation and subsequently less CO_2 emissions. However, the degree of emissions varies depending on soil types, rainfall, etc. In case of field crops, CO_2 emissions are closely related to soil moisture and temperature during the growing season. Thus, soil moisture and temperature are the most influential factors that are closely related to CO_2 emissions as the decomposition of organic matter is more intense when the temperature is moderate (about 25 °C) and soil moisture is in the range between 60% and 80% of the maximum retention capacity. Álvaro-Fuentes et al. (2008) reported that there was increment of about 0.10–0.15 g $CO_2/m^2/h$ in the three soil management systems with precipitation event of 22 mm in Thermic Xerollic Calciothird soil. In very wet and very dry soil, due to scarce and more moisture, the soil respiration ceases and consequently, emissions reduce. In no tillage, there is improvement in soil physical properties, and increase in soil carbon sequestration rate as reported in several studies. According to Zaheer et al., practicing no-till increased soil carbon sequestration by nearly 0.5, 0.3, and 0.2 Mg C/ha^{-1}/year (pooled for 30 years) in high, middle, and low rainfall zones, respectively.

Emissions also vary with the horse power of tractors used for tillage operations. Using a low-power tractor (55 kW) can lower the associated emissions per hectare as compared to high-power tractor (73 kW). In countries like India, there has been more demand for medium-sized tractor engines of 21–40 hp. in the markets. Moreover, the emissions also depend on tractor engine maintenance. Engine maintenance especially cleaning air filters reduces fuel consumption by 10–15%. Due to friction, heating, and wearing, there will be more emissions. However, correct use of lubricants can protect engine. The associated carbon emissions correspond to 1.97 t CO_2/

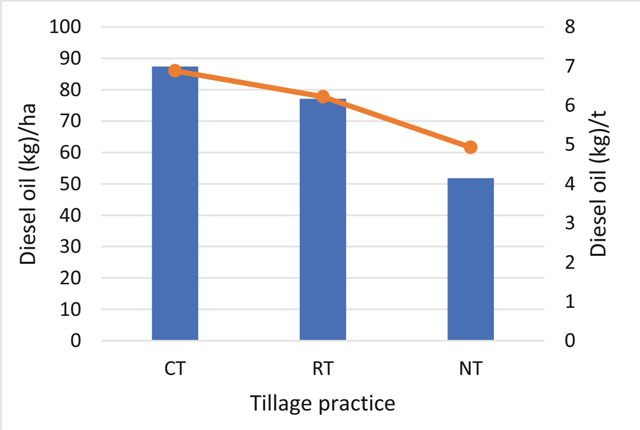

Fig. 1 The diesel oil consumption for different types of tillage based on area and maize yield. (Source: Holka & Bieńkowski, 2020)

year in 5.1 ha of cultivated area with an average three harvests/year (Ochoa et al., 2014). Again, the CO_2 emissions vary with the use of diesel and biodiesel. The associated CO_2 emission by using diesel is 74.3 gCO_2eq/MJ and is only 14 gCO_2eq/MJ by using biodiesel (Union, 2009). Nearly 18.84% emissions can be mitigated by opting biodiesel instead of diesel. In a study, ploughing, reduced tillage, and no tillage effect on soil CO_2 emissions were evaluated, and it was found that reduced tillage could produce 1.43 times more CO_2 as compared to no tillage while ploughing could produce 2.15 times more CO_2 as compared to no tillage (Krištof et al., 2014). Different tillage treatments including chisel plow, no tillage, and mouldboard plow were studied, and it was found that the highest proportion of energy input was nitrogen fertilizer, followed by diesel fuel. With an increase in the tillage intensity, the total energy input applied per hectare increased while the lowest energy input is observed for the no tillage and the highest with the use of mouldboard plow with the straw turning. The no tillage could record lowest average energy intensity followed by the chisel plow tillage in both cropping seasons (Lu et al., 2018). The tillage operation consumes 29–59% of diesel fuel (Fig. 1). Thus, reducing the tillage will obviously reduce the soil-based CO_2 emissions and reduced carbon footprints.

It is obvious that the use of different tillage implements has positive correlation with CO_2 emissions based on the intensity and volume of soil disturbed and depth of tillage. However, Antille et al. (2015) revealed that practicing controlled traffic farming (CTF) can mitigate N_2O emissions by 20–50% compared with non-CTF. This is because CTF practice could increase soil porosity in the range of 5–70% and water infiltration by a factor of 4. Pratibha et al. (2019) studied primary and secondary tillage implements like Cultivator (CV), Cultivator followed by Disc Harrow (CVH), Disc Plough (DP), Disc Plough followed by Disc Harrow (DH), Mould Board Plough (MP), Mould Board Plough followed by Disc Harrow (MPH), Rotovator (RO), Bullock Drawn Plough (BP), Bullock Drawn Harrow (BH), and No Tillage (NT) in single or in combination for seed bed preparation and found that there was 92, 81, 60, 60, and 40% lower fuel consumption-based CO_2 emissions due to use of BP, BH, tractor-drawn CV, DH, and RO, respectively, as compared to MPH, RO, and MPH. It is found that tractive and total efficiency varies with soil type and gears. In loamy sand, the highest values of tractive and total efficiency, as well as area productivity, were obtained in the third gear. The lowest value of fuel consumption, highest tractive efficiency, and the lowest fuel consumption were obtained in the second gear (Kolator, 2021). The GHG emission were to the extent of 3.07, 3.69, and 3.50 Mg CO_2-eq/ha/year for labor-intensive sugarcane cultivation, capital-intensive (Use of machinery) sugarcane cultivation, and combined labor-intensive and capital-intensive cultivation, respectively (Nakashima & Ishikawa, 2016). This clearly suggests that capital-intensive crop cultivation is associated with more CO_2 emissions than labor-intensive cultivation.

3 Emission from Irrigation

Irrigation is also emitter of GHG and contributes to global climate change. Globally, 23–48% of agricultural energy is used for pumping ground water. Moreover, the CO_2 emissions occur with the use of groundwater. Due to the association of high energy demand with use of groundwater, use of groundwater results in a high carbon footprint. Hence, improved irrigation management that involves lower groundwater extraction limits energy consumption; thus, it is a way to reduce CO_2 emissions. In developing countries like China, the biggest emission source is ground water pumping, accounting for 60.97% of total irrigation emissions (Zou et al., 2014). Pakistan's total energy use accounts for 4% for irrigation which contributes to CO_2 emissions by 9%, and about 99% of the irrigation-related CO_2 emissions are related to groundwater. The total carbon footprint of surface water in Pakistan is 36×10^6 kg/year, and for groundwater $16{,}000 \times 10^6$ kg/year (Siyal et al., 2021). Also, adopting improved irrigation schedules that result in increased water productivity and reduction in groundwater withdrawals for irrigation will result in a 62% decline in energy demand (diesel) and a 40% reduction in carbon emissions. Moreover, it was revealed that CO_2 emissions can be reduced by 31–82% by adopting gravity-fed canal systems instead of groundwater pumping. There exists a difference between diesel and electric pumps as diesel pumps are more energy-efficient than electric pumps. In China, the total carbon dioxide (CO_{2}-eq) emission from agricultural irrigation ranges between 36.72 and 54.16 Mt.

A study focused on estimating the changes in GHG emissions by converting a given area from dryland into irrigated acreage in Alberta and Saskatchewan. Due to the conversion, there was an additional emission of major GHG that ranged 1.68–2.61 t CO_2-eq/year with each hectare of land converted into irrigation (Kulshreshtha & Junkins, 2001). Moisture promotes microbial activities thereby results in SOM decomposition, and the extent of emissions will be less under limited irrigation. In this way, irrigation also adds CO_2 to the atmosphere. Zornoza et al.

(2016) reported that regulated deficit irrigation reduces soil CO_2 emissions and decreases microbial activity that in turn aids in soil C sequestration. They studied the effects of three irrigation strategies (100% irrigation (FI), regulated deficit irrigation (RDI)-RDI1, irrigated as FI except for the postharvest period where 50% of FI was applied and RDI2-severe) on soil CO_2 emissions, soil C pool dynamics, and aggregate content and stability and found that, in RDI2, there was significant decrease in CO_2 emission rates with an average of 35 mg CO_2-C/m^2/h lower than that of FI during the period when deficit was applied. The cumulative CO_2-C released followed the order: 410 g CO_2-C/m^2 in FI, 355 g CO_2-C/m^2 in RDI1, and 251 g CO_2-C/m^2 in RDI2. There were no significant differences for soil organic C, recalcitrant C, and organic functional groups among treatments. It was found that labile organic fractions increased under FI in summer. Arroita et al. (2013) studied the breakdown rates of alder and holm oak leaves, and of poplar sticks with and without irrigation, and the study revealed that in soil, stick breakdown rates were extremely low in nonirrigated sites (0.0001–0.0003/day), and increased with the intensity of agriculture (0.0018–0.0044/day). In water, stick breakdown rates ranged from 0.0005 to 0.001/day and increased with the area of the basin. This study clearly shows that irrigating soil will accelerate decomposition of organic matter and thereby results in CO_2 emissions.

Projections indicate that major source of soil methane emissions are from submerged rice fields due to microbial decomposition of organic matter under anaerobic conditions. Methane, due to rice cultivation, represents over 90% of the total GWP (Janz et al., 2019). Globally rice cultivation contributes to 1.5% of total anthropogenic GHG emissions (FAOSTAT, 2015). In rice, alternate wetting and drying irrigation increases water use efficiency and could reduce greenhouse gas (GHG) emissions compared to the farmers' practice of continuous flooding (Table 1). Thus, alternate wetting and drying (AWD) irrigation could reduce GHG emissions by up to 40%. Decreasing the emission of CH_4 from the soil is the most effective way to mitigate the GWP in rice cultivation. In India, of the total 3.37 million tons of methane emissions, irrigated rice fields account to 1.84 million tons (54.59%) (Bhatia et al., 2013). The strategies such as alternate wetting and drying (AWD), direct-dry seeding, aerobic rice, nonflooded mulch cultivation, and system of rice intensification (SRI) are known to mitigate GHG emissions from rice cultivation. However, studies report that there are considerable amounts of nitrous oxide emission due to alternate wetting and drying of rice fields. Sapkota et al. (2020) studied the effect of flood irrigation in paddy crop grown in different countries by collecting 32 articles and found that N_2O emissions ranged from 0.003 to 14.24 kg/ha while CH_4 emissions ranged 35 to 2328 kg/ha.

The field experiments were conducted at the Bangladesh Rice Research Institute (BRRI) farm, Gazipur, and at Bhaluka, Mymensingh, and found that the greenhouse gas emission intensity (GHGI) was high (1.56) for continuous flooding (CF) as compared to AWD (1.05) in Gazipur, while it was 0.47 for CF and 0.29 for AWD in Mymensingh (Islam et al., 2020). Higher N_2O emissions due to AWD are subjected to increased microbial nitrification and denitrification. Although AWD irrigation significantly increased the cumulative N_2O emissions compared to CF irrigation, it

Table 1 Effect of alternate wetting and drying in rice on methane and nitrous oxide emissions

Fertilizer rate	Location	Impact on emissions	Soil type	Reference
70 kg N/ha, 37.5 kg P_2O_5/ha, and 37.5 kg K_2O/ha	Thailand	The mean methane emission in AWD was 49% smaller than that in CF	Very-fine, mixed, active, acid, and isohyperthermic sulfic endoaquepts	Chidthaisong et al. (2018)
460 g N/kg, with 1.8 g/kg 3,4-dimethyl pyrazole phosphate as nitrification inhibitor	Central Italy	The CH_4 emissions decreased by 97%, while N_2O emissions increased more than fivefold under AWD	Fine-silty, mixed, nonacid, and mesic Thapto-Histic fluvaquent	Lagomarsino et al. (2016)
Urea split application (35/15/30/20) of 210 kg N/ha	Huaqiao, Hubei Province, China	Compared with CF, FWI and FDI irrigation strategies reduced CH_4 emissions by 60% and 83%, respectively	Silty clay loam	Xu et al. (2015)
150 kg N/ha, 50 kg P_2O_5/ha, 50 kg K_2O/ha, 25 kg $ZnSO_4$/ha, and 500 kg gypsum/ha. Gypsum and zinc sulfate, and diammonium phosphate (DAP) as a source of phosphorus, were applied as basal fertilizers	South India (Thanjavur District, Tamil Nadu)	Averaged CH_4 emissions over rice varieties decreased by 41% and 24%, compared with CF	Alluvial clay	Oo et al. (2018)

could offset the total GWP by only 1–3%. The reduction in CH_4 emissions was up to 37% due to AWD practice as reported by Li et al. However, methane emissions were reduced to the extent of 60–87% in California due to the practice of AWD. AWD influences nitrification and denitrification intensities, depending on oxygen availability. A meta-analysis study that included 43 studies conducted in Asia, 6 studies from America, and Europe reported that non-CF reduced CH_4 emissions by 53%; however, it increased the N_2O emissions by 105% (Jiang et al., 2019). Results from five intermittently flooded rice farms across three agroecological regions in India indicate that N_2O emissions per hectare can be three times higher (33 kg-N_2O·/ha/season) than the maximum previously reported (Kritee et al., 2018). Methane emissions reduction due to AWD is proven practice and is reported in various countries such as China, Philippines, Vietnam, and India. In China, the reported emissions ranged from 21 kg/ha to 335 kg/ha (Sun et al., 2020a, b). Similarly, emissions (monsoon rice) ranged from 113 kg/ha to 165 kg/ha in India (Oo et al., 2018). This variation in the emissions depends on the soil type, fertilizer rate and type, climatic conditions, etc. Residue incorporation also determines the extent of CH_4 emissions in rice fields due to the availability of additional substrate for methane production. The mustard biomass incorporation resulted in higher emissions in Gazipur, Bangladesh (Janz et al., 2019).

3.1 Emission from Fertilizer Use

The global warming potential (GWP) is an index and can be defined as the cumulative radiative forcing between the present and some chosen later time "horizon" caused by a unit mass of gas emitted now. It is being used to compare the extent of heat trapped by each GHG in the atmosphere relative to some standard gas, by convention CO_2. The methane (CH_4) and nitrous oxide (N_2O) are two major GHGs with a global warming potential (GWP) of 28 and 265 times that of CO_2 in a 100-year time horizon, respectively. Fertilizer application is one of the major sources of anthropogenic nitrous oxide (N_2O) emissions in croplands. Due to synthetic fertilizer use in South Africa, around 61%, 14%, and 25% GHG emissions from cereal crops are reported (Tongwane et al., 2016). Presently, N_2O emissions are increasing at a rate of 0.25% per year due to intensive agricultural activities.

Nitrogen is one of the major plant nutrients due to which the agricultural production is meeting the food demand. In India, nitrogen use was nearly 55,000 tons in 1950–1951 that further raised to 11.31 million tons in 2001–2002. However, it is observed that the nitrogen use efficiency (NUE) is decreasing across different cropping systems. Globally, India alone consumes 14% of total fertilizer use and the associated emissions due to fertilizer use were 558 and 775 kg CO_2e per ha, respectively, from rice and wheat (Sapkota et al., 2019). Further, it is estimated that the fertilizer consumption in India may get twofold by 2050, so there is immediate need to address N management strategies (Fig. 2). In China, GHG emissions were to the extent of 41.44 and 59.71 Mt. CO_2eq/year in wheat and maize with average application of synthetic N of 222 and 197 kg/ha respectively (Chai et al., 2019). The field experimental and laboratory data are the basis in

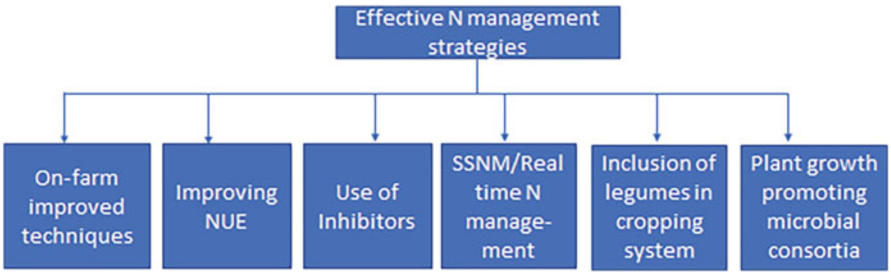

Fig. 2 Effective management strategies to mitigate N losses

developing semiempirical equations for developing an N_2O emission model. As per IPCC guidelines, nearly 1% of N_2O-N is emitted from the total N applied in agriculture soil. In Brazil, the urea and slurry in tilled soil increased cumulative N_2O emissions by 33% and 46%, respectively, compared to the control in maize-wheat cropping system. Thus, the EFs were 0.27% and 0.76% with the application of urea and slurry, respectively (Grave et al., 2018). There are process-oriented models like DNDC or Daycent which has high potential to correctly describe N_2O emissions of individual agricultural site. The global annual emissions were 3.3 Tg N_2O-N for fertilized croplands and 0.8 Tg N_2O-N for grasslands (Stehfest & Bouwman, 2006). The GWP and GHGI take soil C sequestration rate, N_2O and CH_4 emissions, and crop yields into account. Besides the direct effect of N fertilization on N_2O emissions, indirect effects, such as NH_4 volatilization, N leaching, and urea hydrolysis in the soil, can also counteract the mitigation potential. All of these factors should be considered while calculating net GWP and GHGI, regardless of management practices.

The fertilizer demand is growing continuously with the increase in human population to meet the food demand. Hence, within 10 years (2001–2011), N_2O emissions from agricultural soils in Asia, Americas, Europe, and Africa increased by 63%, 20%, 13%, and 3%, respectively, with highest from Asia (Tubiello et al., 2014). There are direct and indirect N_2O emissions due to N fertilizer application. Direct N_2O emission occurs from application of N-fertilizer on the soil whereas processes such as N-deposition from the atmosphere, N-fixation by legumes, and decomposition of biomass residues result in indirect N_2O emissions. Nearly 69–96% of the total GHG emissions are due to input use in different agricultural production systems (Huang et al., 2019). Mainly microbial transformation of compounds that contain nitrogen (fertilizer and animal dung and urine) results in N_2O emissions in agricultural soils. Similarly, CH_4 is produced by methanogenic bacteria in anaerobic soil and is consumed by methanotrophic bacteria in aerobic soil. Factors that influence the N_2O emissions include environmental, climatic, and N requirement. Considering the variations in rainfall, tillage, crop rotation, fertilizer production, and use of machinery in winter wheat-based cropping systems in USA, it was found that the N_2O emissions varied with rainfall. In high and middle rainfall scenarios, the N_2O emissions were up to 60–70% of the total CO_2-eq while in low rainfall scenarios, it was only 30–40% of the total CO_2-eq (Zaher et al., 2013). On average, about 22.3 kg N_2O-N/ha (1270.5 kg CO_2-eq/ha) is released from oil palm cultivation, and further it was observed that there is no significant difference in the yearly variation of emissions from 1986 to 2009 (Kusin et al., 2015). There is direct relationship between nitrogen fertilization typically and N_2O emissions, but there can be a variable effect on CO_2 and CH_4 emissions. However, N fertilization rates should not negatively influence crop yields. Several researchers found that N rates increased to certain levels (as per crop demand) can decrease GWP and GHGI. Application of N rates as per crop N demand allows crops to use the soil available N, thereby leaving little residual N in the soil. So, only excessive application of N fertilizers can induce net GHG emissions. Therefore, GWP and GHGI can be reduced if N fertilization rate is based on crop demand. Another important point is

Table 2 GHG emissions due to fertilizer management in climate-vulnerable villages of Gujurat and Rajasthan

Gujurat		**Fertilizer management**		**% Change**
District	***Village***	**Without**	**With**	
Valsad	Khuntil	11,273	15,037	+33.4%
Rajkot	Magharvada	34,063	27,417	−19.52%
Kutch	Bhalot	23,203	21,426	−7.66%
Rajasthan		**Fertilizer management**		**% Change**
District	***Village***	**Without**	**With**	
Jhunjhunu	Bharu	2863	2182	−23.79%
Jodhpur	Purkhawas	7578	6337	−16.38%
Kota	Chomakot	5343	5084	−4.85%
Bharatpur	Sitara	12,162	11,592	−4.69%

Note: Without denotes before the implementation of project, and with denotes after the implementation of project
Source: Srinivasarao et al.

that considering CO_2 equivalents associated with farm operations, N fertilization and other chemical inputs in addition to those from GHG emissions and SOC change can result in accurate estimation of net GWP and GHGI. In a study, it was revealed that Nutrient Expert (NE) tool-based fertilizer management lowered global warming potential (GWP) by about 2.5% in rice, and 12–20% in wheat, as compared to farmers' fertilization practices. Hence, strict country-specific polices can only cut down the N_2O emissions. One of the best examples is Europe due to both European and country-specific policies on agriculture, and the environment has resulted in a decrease in N_2O emissions by 37% in 2016 as compared to 1990 levels (Petrescu et al., 2021). In Gujurat and Rajasthan, India, with the adoption nutrient management practices with the implementation of NICRA project, there was decrease in GHG emissions that ranged from 4.69 to 23.79% (Table 2).

The usage of urease inhibitors in neem-coated urea, and better management of manure, urine, and crop residues, could result in a 20–25% improvement in NUE of India by 2030. Also, use of pilled urea reduced N_2O emissions by 1.47 times as compared to urea briquettes in rice (Islam et al., 2018). Application of urease-coated urea and polymer-coated urea lowers GHG emissions as compared to urea application. Eory and Moran reported considerable GHG abatement potential with "Improved timing of mineral N application" reaching 0.3 t CO_2-eq/ha. Also, precision agriculture mitigation measures such as improved timing of mineral nitrogen (N) application, improved timing of organic N application, full allowance of manure N supply, and avoiding N excess can help in GHG mitigation in croplands. Incorporation of root residue can increase soil C sequestration, but root respiration and mineralization of crop residue and SOC can result in GHG emissions. Legumes aid in biological N fixation (BNF). BNF accounts for 100–290 Tg/year in natural terrestrial ecosystem of which 40 Tg/year (1/3rd) is due to cultivation of legume crops. Pigeon pea with an acreage of 3.9 million ha in drylands of India contributed to 0.22 Tg/year N through biological N fixation process (Rao & Balachandar, 2017). Use of N efficient crop genotypes can potentially reduce N losses. One such study was carried at Indian Agricultural Research Institute (IARI), New Delhi, and found that Nagina-22, Himdhan, and Taipe-309 were found most efficient N users in rice among the ten rice genotypes that were screened for NUE. Another cost-effective tool is leaf color chart (LCC). It helps in identifying the N demand as per crop. It actually helps in knowing the N application timing in rice. Punjab Agricultural University (PAU) has linked LCC to smart phone where farmers can access the PAU-LCC recommendation for free of cost. LCC gave good results in optimizing N dose with higher yields not only in rice, but also in crops like maize, wheat, and cotton. In South Africa, grazing vetch fixed approximately 111.5 kg N/ha was adopted, which is equivalent to a savings worth US$220 (Murungu, 2012), and it also benefits the subsequent crop (maize) through soil N improvement and weed suppression. In this way, it resulted in highest benefit to cost ratio of 1.9 in maize. Cheng et al. (2015) found potential reduction in GHG emissions to the extent of 60 megatonne (Mt) CO_2-eq due to reduction in N fertilization up to 30% in China. Integrated Nutrient Management (INM) increases C sequestration rate by increasing organic C levels. In a study, it was found that total organic C increased significantly with the integrated use of fertilizers and organic sources (from 13% to 39.4%) compared with unfertilized control treatment at 0–7.5 cm soil depth (Das et al., 2016). SSNM reduces N_2O emissions due to need-based N application at proper timing to meet crop needs, thus avoiding N losses to volatilization, leaching, and runoff.

The mitigation strategies for N_2O emissions are shown in Fig. 2.

A household survey in Vietnam revealed that use of biogas instead of kerosene in house and use of biogas slurry in farm resulted in 50% reduction in fertilizer use, and it is estimated that it resulted in reduction of GHG emissions by approximately 0.08 tons of CO_2-eq per year (Campbell-Copp, 2011). In this way, if biogas slurry can be replaced with urea, it can result in 3.14 megatons of CO_2-eq emission reductions at national level. In addition to fertilizers, crop protection products (herbicides & pesticides) represent up to 35% of emissions per hectare in crops like wheat (Notarnicola et al., 2015). At China's national scale, it was estimated that 421.44 and 59.71 Mt CO_2-eq/year was the associated GHG emissions with the manufacture of synthetic N fertilizer and the associated N_2O emissions (direct) were 35.82 and 69.44 Gg N_2O/year for wheat and maize, respectively, due to N fertilizer application (Chai et al., 2019). Around 13.5 t CO_2-eq is emitted for every ton of N fertilizer manufactured in China while only 9.7 t CO_2-eq is emitted for every ton of N fertilizer manufactured in Europe (Zhang et al., 2013). Also, it is reported that the associated GHG emission due to urea production is 8.1 kg CO_2-eq kg urea-/N in China. In China for fruit crops viz., orange, pear, apple, banana, and peach, estimated farm CF ranged from 2.9 to 12.8 t CO_2-eq/ha and the product CF ranged from 0.07 to 0.7 kg CO_2-eq/kg fruit (Yan et al., 2016). In UK, 478 kg CO_2-eq is emitted to produce 1 tonne of wheat which can be reduced to 319 kg CO_2-eq due to reduced use of N application rate (Kindred et al., 2013) (Fig. 3).

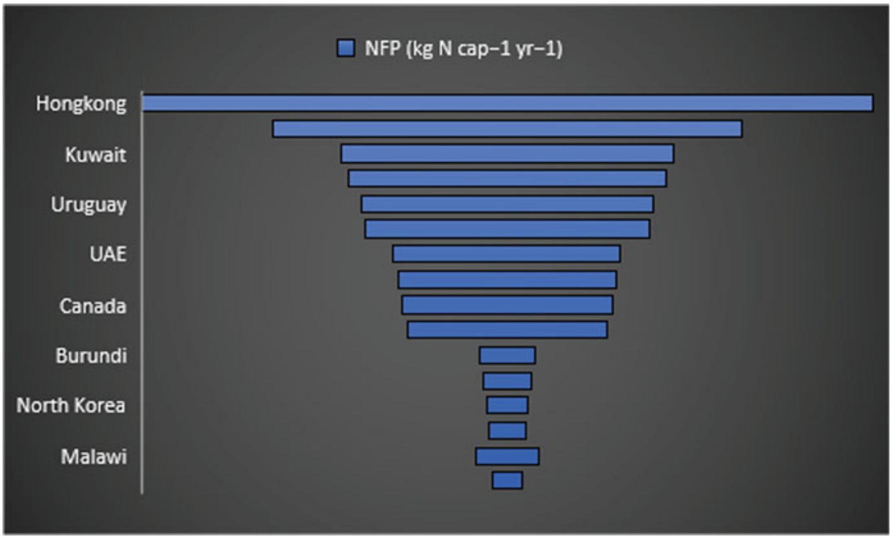

Fig. 3 Nitrogen footprint of different countries. (Source: Mahmud et al., 2021)

4 Emission from Livestock

Livestock are the richest source of protein, essential amino acids, and micronutrients. There is GHG emissions to larger extent in developed countries due to huge demand for animal products. Yet, GHG emissions are rising due to poor feed conversion ratio in developing countries. Moreover, population growth, urbanization, and income rise led to increased demand for livestock products in developing countries. This rise in demand for livestock products has resulted in increased GHG emissions and is responsible for about 14.5% of total anthropogenic greenhouse gas emissions (Gerber et al., 2013). According to the global livestock environmental assessment model (GLEAM) developed by FAO (FAO, 2017), the total emissions in terms of Gg t CO_2-eq were 1.8, 1, 0.5, 0.3, 0.2, 0.2, and 0.1 for beef cattle, dairy cattle, buffalo, pigs, sheep, goats, and chicken, respectively. India emitted 2299 million tonnes of carbon dioxide (CO_2) in 2018, according to a report by the International Energy Agency. This accounts for 7% of global GHG emissions. Agriculture and livestock account for 18% of gross national emissions (www.downtoearth.org.in). In developed countries like the USA, cattle accounted for over 95% of the methane emissions due to enteric fermentation which account for almost 20% of the total anthropogenic methane emissions (Mangino et al., 2003). Hence, in developed countries like the USA, Australia, European countries, and Canada steps are initiated to reduce the carbon footprints of livestock. Almost 60% of the global biomass harvested worldwide enters the livestock subsystem as feed or bedding material, and GHG emissions from feed production represent 60–80% of the emission coming from eggs, chicken, and pork, while 35–45% of the emissions are from milk and beef

Table 3 The livestock's share of GHG emissions

Sl.no		Percent emissions
1.	Feed production and processing	45
2.	Enteric fermentation	39
3.	Manure management	10
4.	Processing and transport of animal products	6

sector (Sonesson et al., 2009). The application of manure as fertilizer for feed crops and the deposition of manure on pastures also generate a substantial amount of nitrous oxide emissions representing about half of these emissions (Gerber et al., 2013). Again, production of feed to cattle is related to soil CO_2 and N_2O emissions. Feed production and processing contributes to about 45% emissions in livestock sector. Although livestock feed production often involves large applications of nitrogen to agricultural soils, good manure management can reduce the need for manufactured fertilizers. On a whole-farm view, major percent (45%) of emissions are processes associated with animal feed, such as production and transport and another 40% is caused by ruminant fermentation, while a small percent (10% and 5%) is from manure-processing activities and energy usage. With best management practice, there is a scope to reduce the GHG emissions from livestock up to 30%. More advanced technology is adopting precision livestock farming which uses IOT devices and data-modeling techniques. The GHG emissions from livestock can be cut down by following practices, that is, improved feeding and breeding practices, proper manure management, and improving on farm energy generation as well as efficiency. Life cycle assessments are widely used to study the environmental impacts of across the livestock industry. Life cycle assessment (LCA) accounts the greenhouse gasses (GHG) emitted from all stages of agricultural and food production. It includes mainly four steps: (i) mapping the process, (ii) setting scope and boundaries, (iii) collecting inventory data, and (iv) interpreting the results based on ISO 14040:2006 standard (ISO, 2006). Due to change in lifestyle, animal protein is being given more preference and is consumed largely. So, animal products alone account to 18% of global GHGs emission. However, reducing animal protein consumption mitigates GHG emission which is impossible due to several reasons (Table 3).

4.1 Methane-Reducing Feed Additives and Supplements

Feed additives are used in livestock diets to improve feed-use efficiency, quality of animal-source foods, and animal performance and health. These additives include vitamins, amino acids, fatty acids, minerals, pharmaceutical compounds, fungal products, and steroidal compounds. Recent advances in understanding methanogenesis have led to the development and discovery of feed additives that can reduce CH_4 emissions to varying degrees. A study was carried by Sun et al. (2020a, b) on sheep to study the effect of Na_2CO_3 as additive to forage rape

(*Brassica napus*) on ruminant pH and associated CH_4 emissions. For this study, they have divided the sheep into seven groups: The first two groups (P01 and P02) were supplemented with forage rape (without Na_2CO_3); two groups (P03 and P04) with forage rape + Na_2CO_3 @ 5%; two groups (P05 and P06) with forage rape + Na_2CO_3 @ 8%; and another one group (P07) where it was stopped. In this study, the methane emissions increased in sheep supplemented with Na_2CO_3 as compared to P01 and P02 (control) and emissions reverted back to normal range when supplementation was ceased in P07 group. Thus, Na_2CO_3 supplementation with forage rape increased emissions in sheep with the change in rumen pH. Dalby et al. (2020) discovered a microbial inhibitor combo that contains tannic acid and Na-F (TA-NAF), which was tested in pig manure, and found that it could efficiently reduce >95% ammonia emission and 99% methane emission. Hence, they stated that TA-NAF can be a better generic microbial inhibitor to reduce emissions. A study was carried in Australia on 180 dairy cattle located in Brymaroo, Queensland. In this study, powdered activated carbon (PAC) was added @ 0.5% to dry matter, and it was found that PAC could significantly reduce CH_4 and CO_2 emissions by 30–40% and 10%, respectively. The addition resulted in improved daily milk production, milk protein, and milk fat by 3.43%, 2.63%, and 6.32%, on average for the herd ($p < 0.001$ in all cases) (Al-Azzawi et al., 2021). A study revealed that application of manure obtained from cows fed with biochar along with feed could reduce the chemical fertilizer requirement and enhanced the soil properties (Joseph et al., 2015). Winders et al. revealed that inclusion of biochar in the feed of pigs and steers improved the digestibility and improved the manurial quality. Seaweeds are full of proteins, carbohydrates, and to smaller extent lipids, saponins, alkaloids, and peptides. Including seaweeds in the livestock dietary resulted in reduction of CH_4 emissions and improvement in overall health of livestock. The seaweeds that are found to be effective in mitigating CH_4 emissions include *Asparagopsis taxiformis*, *Alaria esculenta*, *Ascophyllum nodosum*, and *Chondrus crispus*. The extent of CH_4 emissions reductions were up to 98% due to seaweed supplementation to cattle (Abbott et al., 2020) and up to 80% due to the supplementation of red seaweed (*Asparagus taxiformis*) in beef steers (Roque et al., 2021).

5 Carbon Efficiency and Carbon Intensity

Carbon efficiency is defined as the production of a given level of output with minimum feasible carbon emissions. Global warming has been a serious concern, and many international organizations are working toward resolving this issue. For example, the Intergovernmental Panel on Climate Change (IPCC) has been publishing annual reports and the United Nations Framework Convention on Climate Change (UNFCCC) has been holding annual conferences to assess the impact of global warming and options for its mitigation. Even though Paris agreement was successful, there still exist concerns such as the temperature target.

The main aim is to reduce carbon intensity. According to Babylon's dictionary, carbon intensity is expressed as "the amount of carbon by weight that is emitted

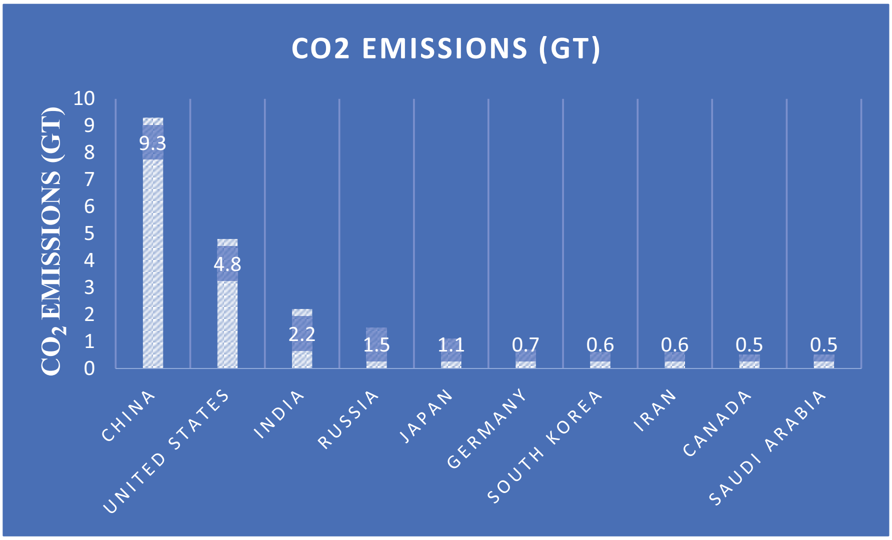

Fig. 4 CO_2 emissions of some of the major contributors of GHGs

per unit of energy consumed." It is also expressed as ratio of GHG emissions and gross domestic product (GDP). Most frequently, emission factor (EF) and carbon intensity (CI) are used interchangeably. Presently, carbon intensity reduction is the most important task that is being worked out in all countries across the world. There are different methodologies to assess the carbon intensity of any process.

1. Life cycle assessment (LCA) analyzes the cumulative environment impacts of a process or product in all the stages of its life.
2. Carbon footprint accounts the GHG emissions during manufacture of a product or any given activity that contributes to global warming.

Total global CO_2 emissions have increased to 36.2 gigatons (in 2017) and are expected to further increase, and the countries leading in emissions are shown in the Fig. 4.

6 Efficient Farming Practices That Reduce Emissions from Crop Production

Management practices play an important role in mitigating GHG emissions while enhancing crop productivity. Efficient management practices, such as tillage, manure, and fertilizer application, can mitigate GHG emissions to a larger extent. These practices result in increased SOC content in soil. Mainly the time and dose of manure and fertilizer application influences both crop productivity and GHG emissions. Another important practice that is adding GHG emissions includes poor crop residue management and burning. In India, in 2017, 488 million tons of crop residues was generated and 24% of it got burnt, emitting 211 Tg CO_2-e GHGs, along with other gaseous air pollutants (Ravindra et al., 2019). There are 25 improved climate-resilient management technologies that can reduce the GHG emissions by 20% by 2050 (Ahmed et al., 2020). These include (1) Zero-emissions on farm machinery and equipment, (2) Variable rate of fertilization, (3) Reduced N application (in places where it is used in excess), (4) Dry direct seeding, (5) Low or no-tillage, (6) Improved equipment maintenance, (7) Improved fuel efficiency of fishing vehicles, (8) Improved water management in paddy, (9) Improved rice straw management, (10) Improved animal health monitoring and illness prevention, (11) Improved feed grain processing for livestock, (12) Improved breeding and selection process, (13) Livestock nutrient use efficiency, (14) Optimal rice varietal selection, (15) N fixing rotations, (16) Improved fertilization in rice, (17) N-inhibitors in pastures, (18) Improved fertilization timing, (19) Controlled release and stabilized fertilizers use, (20) Animal feed additives, (21) Anaerobic manure digestion, (22) Improvement in livestock production efficiency, (23) Animal feed mix optimization, (24) Conversion from flood to drip/sprinkler irrigation, and (25) Speciality crop nutrition amendments. Adoption of improved management practices in selected villages of Gujarat and Rajasthan revealed that there was increase in sink capacity (GHG mitigation) across the villages ranging from 16.4 (Chomakot) to 96.9% (Khuntil) in annual crops, and 4.8 (Bhalot) to 63.8% (Khuntil) in perennials. The fertilizer management alone could increase the sink capacity in the study villages that ranged from 3.1 (Chomakot) to 39% (Magharvada) (Srinivasa Rao et al., 2017). To mitigate anthropogenic GHGs by 25%, it is estimated that a 0.4% increase in SOC to a depth of 30 cm is required as per the emissions in 2014 (Lal, 2015). Increase in SOC can improve water infiltration and storage, and nutrient cycling, increase land productivity, and increase below and potentially above ground biodiversity. Implementation of improved farming practices, that is, soil test-based fertilizer application, reducing frequencies of summer fallow, and crop rotation of cereals with grain legumes, resulted in -256 kg CO_2 eq/ha per year and lowered CF for wheat. Thereby, a net 0.027–0.377 kg CO_2 eq is sequestered into the soil for each kg of wheat grain produced (Gan et al., 2014).

7 Scenario of Carbon Footprints in Major Food Crops

According to a study in UK, high-yielding and low-input crop commodities, such as apple, potato, animal feed crops, wheat, and onion, are reported with low emissions (less than 1 kg CO_2 eq/kg); livestock or manufactured products such as milk are food commodities with medium emissions (between 1 and 5 kg CO_2 eq/kg) whereas livestock products and highly manufactured foods such as pig meat and beef are associated with high emissions (over 5 kg CO_2 eq/kg) (DEFRA, 2009).

The most important factors governing carbon emissions in agriculture were the application of nitrogen fertilizer (8–49%), straw burning (0–70%), energy consumption by machinery (6–40%), energy consumption for irrigation (0–44%), and CH_4 emissions from rice paddies (15–73%). The most important carbon sequestration factors included returning of crop straw (41–90%), balanced use of chemical nitrogen fertilizer application (10–59%), and no-till farming practices (0–10%) (Zhang et al., 2017). The annual amount and long-term changes of crop production have been well documented at national and global scales through inventory and census (e.g., FAOSTAT-Food and Agriculture Organization of the United Nations and the United States Department of Agriculture, National Agricultural Statistics Service (USDA NASS)). As a dominant GHG source, agriculture is challenged to reduce its carbon footprint (i.e., the carbon loss per unit of agricultural product produced) with increasing food production to feed the ever increasing population. However, intensively altered landscapes such as deforested tropical rainforests and drained peatland are suggested to have largest GHG mitigation potentials.

In Africa, total of 5.2 million tonnes of CO_2-eq emissions are reported due to field crops production. In this study, it was revealed that the crop residues contributed to 22% of CO_2 emissions. However, crop rotations with fodder crops can have both environmental and socioeconomic benefits, if properly managed. In Europe, cropland area covers significant source of both carbon dioxide (78 Mt C/year) and nitrous oxide (~60 Mt C-eq/year). In Poland, crop production is a source of approximately 33% of total GHG emission from agriculture (Pawlak, 2017). The most important drivers of the N_2O emission from agricultural soils include climate, soil fertility (C content), and fertilizer. Hence, in croplands, both crop type and soil wetness status determine the extent of N_2O emission. Also, the different practices adopted result in a different mix and intensity of GHG fluxes. Only mineral fertilizer application can result in 2–10 kg/ha/year of soil N_2O emission from a ley, while it was up to 28 kg/ha/year in Wales (Dobbie & Smith, 2003). Practices such as sewage sludge application can emit up to 23 kg/ha N_2O (Scottet al., 2000). There exists large uncertainty in revealing the GHG emissions. For example, few studies state that no-tillage can give N_2O fluxes up to four times greater than conventional tillage whereas other studies report smaller differences between tillage treatment. So, uncertainties can mislead in understanding the dominant drives and consequent GHG balance across agricultural lands.

Among food crops such as cereals, pulses, oil seed crops, etc., pulses have a lower carbon footprint in production than most animal sources of protein. In fact, one study showed that 1 kg of legume emits only 0.5 kg CO_2-eq, whereas 1 kg of beef produces 9.5 kg CO_2-eq (https://iyp2016.org/). In terms of carbon farming and carbon trading, bamboo is known for its tremendous capacity with a potential of 30–121 t/ha of carbon storage and 6–13 t/ha/year of carbon sequestration rate in Asia-pacific region. In Gujurat, India, three crops, namely, sorghum, pearl millet, and bamboo, were grown in saline- and drone-prone marginal land for biofuel, and the GHG emissions in terms of CO_2 equivalent were studied. It was found that among sorghum, pearl millet, and bamboo, the GHG emissions were

Table 4 Carbon intensity for important field crops across different countries

Country	Crop	CF	References
Northern Italy	Durum wheat	2462 kg CO_2/ha	Casolani et al. (2016)
Central Italy		2283 kg CO_2/ha	
Southern Italy		1880 kg CO_2/ha	
China	Maize	1192 kg ce/ha to 9282 kg ce/ha	Zhang et al. (2017)
	Wheat	502 kg ce/ha to 7513 kg ce/ha	
	Rice	5502 kg ce/ha to 17,568 kg ce/ha	
Southern Brazil	Tobacco	1398.5 kg CO_2-eq per ton of dry tobacco for Virginia variety and 1829.75 kg CO_2-eq per ton of dry tobacco for burley variety	Boettcher et al. (2020)
Southeastern Spain	Vegetables	6.05 to 12.01 t CO_2-eq/ha	Martin-Gorriz et al. (2021)
	Woody crops	7.12 to 9.60 t CO_2-eq/ha	

found lowest with 42.55 kg CO_2eq/MT in bamboo as compared to sorghum (48.97 kg CO_2eq/MT) and pearl millet (74.53 kg CO_2eq/MT). It was also revealed that income generated was highest for bamboo (124.66 USD) as compared to sorghum and pearl millet which is only 52.02 USD and 20.37 USD, respectively. As compared to sorghum and pearl millet, the income generated is 2.39 and 6.12 times higher due to bamboo cultivation. The average carbon footprint (CF) values for maize grain cultivated following conventional tillage (CT), reduced tillage (RT), and no-tillage (NT) were 2347.4, 2353.4, and 1868.7 kg CO2 eq, per ha, respectively (Holka & Bieńkowski, 2020). Hence, CO_2 emissions vary within crop varieties, crop management practices, nutrient management practices, etc. (Table 4). It was recently reported that 48.97 kg CO_2eq/MT is the emissions for biomass sorghum as compared to native sorghum variety which accounted for 92.42 kg CO_2eq/MT emissions. Emissions were nearly twofold for native sorghum compared to biomass sorghum (Patel et al., 2020). Also, Casolani et al., 2016, reported that intensification of durum wheat production in Italy led to an increase of water footprint (WF) and carbon footprint (CF) and found a marked distinction between the North and South Italy with respect to WF for durum wheat production. In the study, it was found that it is important to study CF along with WF to measure the GHG emissions (Fig. 5).

Abatement practices play a major role in enhancing SOC due to their unique potential to sequester atmospheric GHGs. These practices have the potential to mitigate climate change. The SOC sequestration maximizes with the inclusion of pastures in agricultural systems due to high carbon inputs from pasture. However, the SOC sequestered in the pastures was offset by emissions from livestock, as pastures support livestock. Greenhouse gas intensity (GHGI) is used to predict the effect of management practice toward increasing productivity without increasing GHG emissions. It is obtained by dividing GWP by the crop yield.

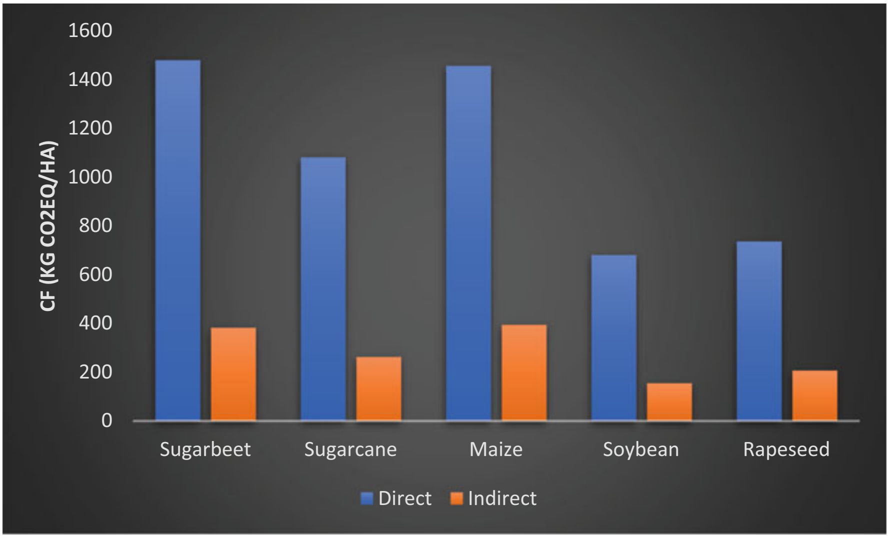

Fig. 5 Contribution of different crops' total CF due to soil management. (Source: Holmatov et al., 2019)

8 Conclusion

Fuel combustion activities are the main sources of CO_2 emission, whereas animal husbandry and rice cultivation are the main sources of CH_4 emission, and the emission of N_2O is mainly from turnover of nitrogen in soil, application of N fertilizer, and industry. Carbon footprint is the total set of GHGs emission caused by a product. It is often expressed in terms of carbon dioxide equivalent of all GHGs emitted. Emission of GHG occurs in various stages of the life cycle, i.e., production, transport, processing, and preparation of food products. Food chains around the world are responsible for a large share of total emission of GHGs. These GHG emissions should be actively addressed to limit climate change to 1.5 °C.

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Energy Budgeting of Crops Under Rainfed Conditions

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Abstract

The Indian economy is mainly dependent on agriculture, which contributes 21% of the country's GDP and 60% of the employment. Rainfed agriculture occupies 67% of the net sown area, contributing 44% of food grains and supporting 40% of the population. In view of the growing demand for food grains in the country, there is a need to increase the productivity of rainfed areas from the current 1 t/ha to 2 t/ha in the next two decades. The quality of natural resources in the rainfed ecosystem is gradually declining owing to over-exploitation. Rainfed areas suffer from bio-physical and socio economic constraints affecting the productivity of crops and livestock. In this context, a number of economically viable rainfed technologies have been discussed. These include soil and rainwater conservation measures, efficient crops and cropping systems matched to the growing season, suitable implements for timely sowing and saving of labor, and integrated nutrient and pest management (INM and IPM). To provide stability to farm income during drought and to utilize the marginal lands, different alternative land use systems such as silvi-pasture, rainfed horticulture, and tree farming systems were evolved and demonstrated on watershed basis. Integration of livestock with arable farming systems and the incorporation of indigenous knowledge into farming systems are also discussed. Formation of self-help groups, use of innovative extension tools such as portable rainfall simulators and focus group discussions to help the quick spread of rainfed technologies into farmers' fields are highlighted. The farming system's approach to rainfed agriculture not only helps to address income and employment problems but also ensures food security. The energy consumption pattern and greenhouse gas (GHG) emission of any rice production system is important to know the sustainability of varied cultivation and establishment techniques. This study was conducted to determine the energy use pattern, GHG emission, and efficiency of rice farms in puddled transplanted (PTR, rainfed) and direct-seeded rice (DSR, irrigated) production systems in Karnataka, India. The energy indices and GHG emission of different input and output in a rice production system were assessed by using energy and carbon equivalence. The efficiency of PTR and DSR farms was identified using data envelopment analysis and energy optimization was ascertained.

Keywords

Energy budget · Rainfed agriculture · Sustainable agriculture · Conservation agriculture

Abbreviations

CA	Conservation agriculture
DEA	Data envelopment analysis
DSR	Direct-seeded rice
GHG	Greenhouse gas
GLM	Green leaf manuring
HYV	High yielding variety
INM	Integrated nutrient management
IPM	Integrated pest management
PTR	Puddled transplanted
SOC	Soil organic carbon

1 Introduction

Rainfed ecology refers to the study and understanding of ecosystems that rely primarily on rainfall as their main source of water. Unlike irrigated ecosystems that receive water through artificial means, rainfed ecosystems depend on the natural precipitation patterns of a particular region. Rainfed areas are typically characterized by seasonal variations in rainfall, with dry periods and wet seasons influencing the overall dynamics of these ecosystems (Lal et al., 2015).

Rainfed ecology plays a crucial role in sustaining biodiversity and supporting the livelihoods of millions of people around the world. These ecosystems are found in various landscapes, including forests, grasslands, savannas, and agricultural lands. They contribute significantly to food production, water resources, carbon sequestration, and the provision of various ecosystem services (Wani et al., 2017).

The unique climatic conditions and water availability in rainfed areas create diverse ecological niches and habitats, fostering the development of specialized plant and animal species. The interplay between rainfall patterns, soil characteristics, and vegetation dynamics shapes the ecological processes and interactions within these ecosystems. Due to their reliance on rainfall, rainfed ecosystems are highly vulnerable to climate change and variations in precipitation patterns. Changes in rainfall intensity, distribution, and timing can have profound impacts on the functioning and resilience of these ecosystems. The understanding of rainfed ecology is therefore essential for developing sustainable land management practices, conserving biodiversity, and adapting to the challenges posed by climate change (Siebert et al., 2010).

2 Rainfed Ecology: A Fragile Ecology

2.1 Global Scenario

Agriculture and allied sciences, being the global mainstay, in the twenty-first century faces challenges worldwide on food, fodder, fuel, flowers, fishery, fiber, livestock, dairy, nutrition, ecological and health, as the global population will surpass 9 billion and agricultural production will need to increase around 70% by 2050. Global agriculture is now facing tremendous problems of population increase, per capita land decrease, proper utilization of water and other resources, along with climate change effects. Globally, rainfed agriculture is practiced on 83% of cultivated land, supplies more than 60% of the world's food, and plays a critical role in achieving global food security. In water-scarce tropical regions such as the Sahelian countries, rainfed agriculture is practiced on more than 95% of cropland.

2.2 Rainfed Ecology in the Indian Context

India is home to 18% of world's population, 15% of the world livestock, 4.2% of freshwater resources, 1% of forests, and 0.5% of pastureland, but only has 2.3% of the geographical area. Based on distribution of rainfall (at weekly intervals) during *kharif* season, ground water recharge prospects are being assessed on a district basis for advising possible *Rabi* cropping patterns across India. About 267 districts had low to extremely low prospects for groundwater recharge, 273 districts seem to have medium prospects, and 112 districts were normal across the country. Hence, tremendous efforts, on both the development and the research fronts are essential to achieve this target (ICAR Vision 2030).

2.3 Challenges Faced in Rainfed Ecology

India ranks first in rainfed agriculture globally in both area (86 m ha) and the value of produce. The estimate shows that by 2050 we need 345 million tonnes food grain, 50 million tonnes oilseeds, and 350 million tonnes horticulture production, in addition to 15 million tonnes fish, 200 million tonnes meat, and 100 billion eggs, and the rise must combat weather variability and climate vulnerabilities. Present-day livelihood options from agriculture and allied enterprises witness trade-off not only in ethics but also sustainability, making the biosphere vulnerable. The productivity of major crops was shown to be 30–50% lower in India than in developed countries because of the problems of fragmented lands, marginal farmers (more than 80%), lack of modernization, mechanized and organic agriculture, precision, cooperative and integrated farming, poor watershed development, and proper utilization of available resources. The agricultural development also showed a change of low external input agriculture to high external input agriculture and now to low external input sustainable agriculture, which was supposed to be needed from the beginning of the planning period. So, there is a need for increased productivity in a sustainable manner and pricing, along with a better utilization of natural resources and energy. This should be achieved only by wisely harnessing the available resources related to science, technology, and innovation while ensuring sustainability of the system as far as is possible in an eco-friendly environment.

About 70% of the rural population lives in dry farming areas and their livelihood depends on the success or failure of the crops. Rainfed and dry-land agriculture play a distinct role in India, occupying 60% of cultivated area and supporting 40% of the human population and 60% of the livestock population. They are critical to food security, equity, and sustainability. The rainfed regions of India contribute substantially (40%) to total food grain production, including rice (44%), maize and nutri-cereals (87%), food legumes (85%), oilseeds (72%), pulses (90%), and cotton (about 65%).

India is home to 25% of the world's hungry population of one billion along with an estimated 43% of children malnourished under the age of five. The net sown area in India has remained constant for several years at 143 mha, but the human and livestock populations have been steadily increasing. Although the Indian population increased from 36.1 billion in 1951 to 114.0 billion in 2011, tripling over 60 years (now 134 billion), the food-grain production has more than quadrupled, but the yield gains are largely from the irrigated agroecosystems. The increase in average productivity from 0.6 t/ha in the 1980s to 1.1 t/ha at the present time notwithstanding, large yield gaps exist for rainfed crops in the semiarid regions. Even after realizing the full irrigation potential, nearly 40% of the net sown area of 143 mha will remain totally rainfed. The per capita availability of land has fallen drastically from 2.4 ha in 1951 to about 0.32 ha in 2001; and it is projected to decline further to 0.09 ha by 2050 (ICAR Vision 2050).

2.4 Emerging Paradigm to Mitigate the Fragile Ecology

Increasing productivity of rainfed cropping systems is of critical importance to meet the food demands of an ever-increasing population in India. In the Navadhanya concept, particularly in dry land rainfed areas, the intercropping of millets with pulses and oilseeds (short duration + long duration) is followed using an organic farming concept, and has shown promising results.

Organic farming is a method of growing crops using an integrated farming system on irrigated, rainfed, or dryland farms (crops, livestock, fishery, duckery, apiculture, etc.) and using organic resources such as crop residues (CRs), green manure, composting, neem cake, organic manures such as corn gluten, cotton seed meal, vermicompost, parthenium compost, biofertilizers, rock phosphate, etc., mechanical cultivation, sustainable crop rotation where crops and flowers attack biological predators, and the use of the concept of integrated pest management (IPM) avoiding synthetic toxic pesticides and feed additives. Major attention is given to developing a soil heath with more and more carbon content that will increase in a sustainable manner by using biological resources. It will protect the long-term fertility of the soil by using biological N-fixation (using legume crops as sole, mixed, border, inter crops, etc.), recycling of CRs and weed plants by using conservation agriculture (CA), livestock residues through extensive management on the farm, and conservation of natural agri-friends or wildlife (earthworm, butterfly, honeybee, etc.) by using nontoxic chemicals in pest management (using natural biopesticides).

Rainfed agricultural research stations such as the Coordinated Research Project on Dryland Agriculture and the Indian Council of Agricultural Research highlighted the fact that rainwater management through an integrated farming system module implemented in farmers' fields under the farm pond, with cotton as a main crop on 2.5 acres, vegetables on 0.5 acre, and ten small ruminants yielded a net income of INR 78,690 with drought in the area compared with rainfed farming (farmer's practice), which yielded a net loss of INR 35,000/ha during 2018–2019. It was due to the management of dry spells by providing supplemental irrigations from farm ponds of a capacity of 600 m^3. The farm pond with solar powered sprinkler or drip irrigation system for cultivating vegetables was standardized for small farm holders in rainfed areas. A floating-type submersible pump set was designed based on the buoyancy principle to minimize the filtration requirement of the surface runoff collected in the farm pond and was implemented successfully for pumping water into the micro-irrigation system. The Agricultural Production Systems simulator model for sorghum is well calibrated for use in climate change impact assessment. Training and awareness programs on agricultural technologies and allied sectors are needed for farmers, with emphasis on livelihood activities.

In rainfed agriculture the intercropping of maize or nutria-cereals with legumes in *kharif* and CA for short-duration *rabi* crops that have a low water requirement has immense importance. In India, out of the total average rainfall of 130 cm during *kharif* season an average of 100 cm rainfall is available. In rainfed farming proper planning is necessary to utilize this rainwater not only to grow *kharif* crops but at the same time to store water through watershed management to grow another crop in *rabi* season using CA.

The *rabi* crops grown with CA technologies have the potential to contribute to increased productivity in a sustainable way. The term CA refers to a set of agricultural practices and is based on three fundamental principles: namely, following no-tillage, permanent soil cover, and diversified crop rotations. The government of India developed several programs on CA, its impact on climate change, its impact on agriculture, zero-tillage, carbon credits, to reduce global warming and to educate different individuals on carbon trading in agriculture in order to advise strategies to combat climate change. CA systems are aimed at enhancing soil health and function as a precursor to sustainable production intensification. Nutrient management in CA must be formulated within this framework of soil health. Thus, nutrient management strategies in CA systems would need to involve the following four general aspects, namely:

1. The biological processes of the soil are enhanced and protected so that all the soil biota microorganisms are privileged and that soil organic matter and soil porosity are built up and maintained;
2. There is adequate biomass production and biological nitrogen fixation for keeping soil energy and nutrient stocks sufficient to support higher levels of biological activity, and for covering the soil;
3. There is adequate access to all nutrients by plant roots in the soil, from natural and synthetic sources, to meet crop needs; and
4. The soil acidity is kept within an acceptable range for all key soil chemical and biological processes to function effectively.

As such, soil organic matter and soil biota are essential components in the complex system of interactions related to soil health and crop productivity. They provide a basis for optimizing the use of inorganic soil amendments and plant nutrients so that there is a positive sum effect on agricultural productivity and the environment.

Water scarcity is a reality in the world today and is a major threat to our food production systems, which must provide enough food for a growing and wealthier population. Rainfed agriculture includes both permanent crops (such as rubber, tea, and coffee) as well as annual crops (such as wheat, maize, and rice). For example, tubers, a staple crop for sub-Saharan Africa, have been all but uninfluenced by the technological developments of the green revolution. Rainfed farming constitutes 80% of the world's cropland and produces more than 60% of the world's cereal grains, generating livelihoods in rural areas while producing food for cities. In temperate regions with relatively reliable rainfall and good soils, rainfed agriculture generates high yields. Supplemental irrigation practices boost yields even higher (Molden et al., 2011).

Wheat, being a major cereal crop around the world, has a share of about 21% of the global food production. Based on the average data from 2007–2009, the global wheat area is 221.7 million ha, with an average yield of 2977 kg ha^{-1}, and production of 660 million tonnes. It is a major source of energy in the human diet, owing to its protein content, which is higher than almost all other cereals. It is the most widespread cereal in terms of planting area. Bread wheat (*Triticum aestivum*) accounts for more than 90% of global production and it is grown on a substantial scale (over 100,000 ha) in more than 70 countries on five continents. It is mainly used to make bread, including steamed bread, noodles, cookies, cakes, and breakfast cereals, and this crop is best fitted into CA after *kharif* crops (He et al., 2013).

Water-use efficiency is an important subject in agriculture in semi-arid regions, because of the increasing areas under irrigation and the high-water requirements of crops. The scarcity of water resources is leading to increasing controversy regarding the use of water resources by agriculture and industry, for direct human consumption, and for other purposes. Such controversy could be alleviated by increasing the crop water-use efficiency, so that improving the water-use efficiency of crops is becoming a main agriculture and food security goal. Moreover, climate change predictions show clear increases in temperatures (and a concomitant increase in potential evapotranspiration) and more frequent episodes of climatic anomalies, such as droughts and heat waves. In general terms, the efficiency of one process is the ratio between the obtained product (the numerator) and the energy or resource invested in the process (denominator). In the context of water-use efficiency the "product" is the assimilated carbon and the "inversion" is the used water (the resource). The numerator and denominator of this ratio may be considered at several levels, and consequently, different definitions of water-use efficiency can be made. The water issue is crucial for the environmental sustainability of agriculture, because 60% of agriculture is located in semi-arid areas and regular water applications are necessary to complete the growth cycle of crops. Crops in semi-arid regions grow and mature during the driest months, making irrigation scheduling and timing critical. Consequently, scientific interest in research on crop water-use efficiency has focused on the evaluation of new irrigation techniques and on genetic variation in water-use efficiency in rootstocks or cultivars, and reflects the social interest and necessity of optimizing water use in viticulture. Evapotranspiration, grain yield, biomass, water-use efficiency, and the harvest index of post-rainy season crops were all affected by controlled ranges of soil water content during growing seasons. Grain yield response to irrigation varied considerably owing to differences in soil moisture content and irrigation scheduling between seasons. Evapotranspiration was highest under continuous high soil moisture conditions, as was aboveground biomass. However, grain yield was not the highest under these conditions (Bhattacharya, 2019).

Studies by the All India Coordinated Research Project on Dryland Agriculture revealed that soil organic carbon (SOC) is a strong determinant of soil quality and crop productivity, especially in the arid and semi-arid environments of the tropics. Productivity levels of rainfed and dryland crops are far below those of the global average. Yields of significant rainfed production systems in long-term manurial experiments under different climate and soil types show declining trends, even with the adoption of some recommended management practices (RMPs). Some RMPs include diverse crop rotations with legumes, and integrated nutrient management (INM) involving the addition of farmyard manure (FYM), the use of groundnut shells (GNS) and other CRs, green leaf manure (GLM), etc. These RMPs have been tested in seven long-term experiments of 13–27 years' duration established in diverse soils and agro-ecoregions.

These studies were conducted under diverse soil and climatic conditions, viz., Anantapur and Bengaluru (Alfisol), Solapur and Indore (Vertisol), Sardar Krushinagar (Entisol), and Varanasi (Inceptisol). Seven rainfed cropping system experiments involved major crops of the region including groundnut (*Arachis hypogaea*), finger millet (*Eleusine coracana*), winter sorghum (*Sorghum bicolor*), pearl millet (*Pennisetum glaucum*), cluster bean (*Cyamopsis tetragonoloba*), castor (*Ricinus communis*), soybean (*Glycine max*), safflower (*Carthamus tinctorius*), lentil (*Lens esculenta*), and upland rice (*Oryza sativa*). Diverse nutrient management treatments assessed included cattle manure, GLM, CRs, and chemical fertilizers. Common soil fertility management treatments across seven experiments consisted of controls (no fertilizer or organics), 100% recommended dose of fertilizers (RDFs), 50% RDF + 50% organics, and 100% organics.

Maintaining or improving SOC concentration in rainfed and dry-land agro-ecosystems is a major agronomic challenge. Yet, the data from long-term experiments show that increasing SOC concentration by C sequestration and stabilization positively affects the yields of several crops. Agronomic efficiency of added nutrients and partial factor productivity of crops are maintained or enhanced with INM practices, including the application of organics in conjunction with chemical fertilizers, but decline with the application of only chemical fertilizers because of declining SOC concentration and soil quality with continuous cropping. In comparison with the control, the grain yield of all crops is significantly increased with the adoption of INM practices using locally available organic resources.

The magnitude of increase in yield (Mg/ha) in respect of controls is from:

(i) 0.78 to 1.03 in groundnut with 50% RDF + FYM 4 Mg/ha,
(ii) 0.40 to 1.34 and 0.82 to 3.96 in groundnut and finger millet respectively, through FYM 10 Mg/ha + 100% nitrogen, phosphorus, potassium (NPK) in groundnut–finger millet rotation,
(iii) 0.84 to 3.28 in finger millet through FYM 10 Mg/ha + 100% NPK,
(iv) 0.61 to 1.19 in winter sorghum through 25 kg N/ha (*Leucaena* clippings) + 25 kg N/ha (urea),
(v) 0.43 to 0.81, 0.32 to 0.58 and 0.44 to 0.83 in pear millet, cluster bean, and castor respectively, through 50% RDN (fertilizer) + 50% RDN (FYM),
(vi) 1.04 to 2.10 and 0.63 to 1.49 in soybean and safflower respectively, through FYM 6 Mg/ha + 20 kg N + 13 kg P/ha, and
(vii) 1.08 to 1.95 and 0.48 to 1.04 in rice and lentils respectively, through 50% N (FYM) + 50% RDF treatment.

Treatments receiving INM practices also exhibited a higher sustainable yield index (SYI) over unfertilized control and the sole application of either chemical fertilizers or organic manures. For every Mg/ha increase in SOC stock in the root zone, there was an increase in grain yield (kg/ha) of 13 for groundnut, 101 for finger millet, 90 for sorghum, 170 for pearl millet, 145 for soybean, 18 for lentil, and 160 for rice.

Improved nutrient management practices were identified on the basis of the mean rate of SOC sequestration. The average SOC sequestration rate (kg C/ha/year) measured with different management treatments was:

(i) 570 for 50% RDF + 4 Mg/ha GNS,
(ii) 570–720 for FYM 10 Mg/ha + 100% NPK,
(iii) 650 for 25 kg N/ha (sorghum residue) + 25 kg N (*Leucaena* clippings),
(iv) 240 for 50% RDN (fertilizer) + 50% RDN (FYM),
(v) 790 for FYM 6 Mg/ha + 20 kg N + 13 kg P, and
(vi) 320 for 100% organic (FYM).

The critical level of C input requirements for maintaining SOC at the antecedent level ranged from 1 to 3.5 Mg C/ha/year and differed among soil type and production systems. The critical level of C input was higher in soybean systems, lower in winter sorghum systems, and increased with an increase in mean annual temperature from humid to semi-arid to arid ecosystems. Thus, RMPs based on locally available organic resources are a win–win situation for improving productivity and SOC sequestration, thus advancing food security and improving the environment (Srinivasarao et al., 2013).

Work conducted by Yadav et al. (2017) at Tripura on energy budgeting in rice-based cropping systems revealed that efficient utilization of rice-fallow systems can accelerate the growth of Indian agriculture; the introduction of lentil into rice-fallows requires lower energy inputs than other crops, while chemical fertilizer application resulted highest energy input (44–54%) followed by the land preparation (13–17%) and diesel use (12–15%) and the rice–lentil system had low global warming potential (GWP; 7.97 CO_2e Mg/ha/year) and greenhouse gas intensity (0.93 kg CO_2e/kg).

Efficient utilization of rice (*Oryza sativa* L.) fallow (11.6 m ha) systems can accelerate the growth of Indian agriculture. But bringing a larger area under cultivation is an energy-demanding process and a source of gaseous emissions in the era of climate change. Hence, development of environmentally sustainable cropping systems requires the efficient use of rice-fallow lands for sustainable productivity. Therefore, the present study was conducted with the objective of identifying sustainable and environmentally safer cropping systems with low GWP and low energy requirements for the rice-fallow land of India. Seven diverse crops (e.g., tori (*Brassica campestris* var. *toria*), lentil (*Lens culinaris*), field pea (*Pisum arvense*), garden pea (*Pisum sativum L.*), green gram (*Vigna radiata*), black gram (*Vigna mungo*), and maize (*Zea mays*)) were introduced into rice-fallow systems by adopting no-tillage production technology to develop sustainable and environmentally cleaner production systems in the subtropical climate of Tripura, India. All these rice-based cropping systems were evaluated on the basis of the energy requirements and system productivity. Results indicated that rice had the highest energy input followed by maize, and the least for lentil. System productivity regarding equivalent rice yield was the highest in the rice–garden pea system. The relative amount of energy input in all cropping systems involved 44–54% for chemical fertilizers, 13–17% for land preparation, 12–15% for diesel, and 11–14% for labor. Total energy input of 28,656 MJ per hectare (MJ/ha) was the highest for rice–maize and the lowest of 22,486 MJ/ha for rice–lentil systems. The highest system productivity and the highest energy productivity were obtained for the rice–garden pea system. The GWP was lower for legume-based than for cereal- and oilseed-based cropping systems. The lowest GWP of 7.97 Mg CO_2e/ha per year was observed for the rice–lentil cropping system and the highest GWP of 8.39 Mg CO_2e/ha per year for the rice–maize cropping system. The rice–vegetable pea and rice–lentil cropping systems also had low GHG emission intensity. The rice–pea and rice–lentil cropping systems are recommended for the region because of their low energy requirement, high energy and system productivity, and low GWP. These systems are suited to the efficient utilization of the rice=fallow lands of eastern India to sustain productivity while adapting to and mitigating the climate change.

Choudhary et al. (2017) also revealed higher yield and economic returns in CA practices; CR in CA shares the highest total energy and carbon input and higher energy and carbon use efficiency in no-residue plots.

Modern agricultural systems are energy and carbon intensive. Reducing the carbon footprint and increasing energy use efficiency are two important sustainability issues of modern agriculture. Realizing the implications of energy and carbon use, the present study was conducted to compare pearl millet–mustard production systems in conventional and CA practices. The results showed that zero tillage with 4 t/ha CR increased the grain yield of pearl millet and mustard by 22.3 and 24.5% respectively in comparison with conventional tillage without residue, which ultimately helped to maintain higher net returns (US$ 1270 ha). Mulching of CR consumed considerable energy and carbon. It comprised 72.3–87.1% of the total energy consumption. Thick residue cover (4 t/ha) noticed significantly higher energy output and energy intensiveness in both conventional and zero tillage whereas energy-use efficiency (11.5), net energy return (201,977 MJ/ha) and energy productivity (0.32 kg/MJ) was highest under no-residue cover. Carbon footprint value was increased with the intensity of residue cover and was found to be least under no-residue treatment. Therefore, CR should be judiciously used in arid and semi-arid regions where livestock mainly depends on it for fodder requirements.

Therefore, in rainfed agriculture two types of farming can be beneficial for long-term sustainable productivity and increasing farmers livelihood status by using the available resources in a judicious way. Using perennial plantation crops like tea as intercropping and key cereals or nutricereals in *kharif* season with low-energy crops like pulses as an intercrop in *kharif* and follow-up crop in *rabiseason* using CA may be viable alternatives.

Besides the advantages of the huge amount of CRs in making compost from maize we can achieve carbohydrate, baby corn, maize flour, corn flakes, corn oil, medicines against cancer, etc.; from nutria-cereals, carbohydrate and protein, nutria-flour, cattle food, etc.; from pulses protein, edible dal, vitamins and micronutrients, salads, breads, and desserts, and also the most important additional atmospheric nitrogen 50–500 kg/ha through the root nodules with the association of *Rhizobium* bacteria and the enzyme nitrogenase; and from oilseeds, fat, edible and non-edible oil, cake, medicinal impacts, etc. The benefits of perennial crops such as tea as the main crop or areca nut as the border crop help the farmers immensely to receive a permanent income. Areca is used for the treatment of the mental disorder schizophrenia and the eye disorder glaucoma; as a mild stimulant; and as a digestive aid. Some people use areca as a recreational drug because it speeds up the central nervous system. The benefits of tea include reducing the impact of stress, protecting from chronic diseases, such as Alzheimer's, Parkinson's, and its ability to strengthen the immune system, to fight cholesterol, and the naturally stimulating function of L-theanine – are essential for a twenty-first century lifestyle.

The Ministry of Agriculture and allied sectors, of the Government of India, should develop more watersheds, reform the marketing structures, and develop the processing units in rural areas in rainfed ecosystems, along with creating awareness about the benefits of CA and sustainable green agriculture for increasing the livelihood status of small and marginal farmers.

3 Energy Issue under Rainfed Agroecology

The future of agriculture is at stake as the world's population rises and food demand increases. This fear is not new; it has been around for decades. Agricultural productivity has attracted much scholarly attention recently. Since Thomas Malthus (Malthus, 1965) wrote his book, land usage has changed and the population has grown. Almost 200 years prior, the prestigious paper on the "Principle of Population" was composed. However, the intricacy of the issue has shifted substantially during the last two centuries. The increased cycle has prompted significant additions in worldwide horticultural yield and harvested yields. Food production has increased by around two and a half times what is was in 1950 (FAO, 1962, 1992; Grigg, 1993). On a global level, agricultural production has outstripped population expansion. Despite the uptick in grain harvests in several Sub-Saharan African countries, the per capita production has remained static (Plucknett, 1994; Byerlee, 1994).

3.1 Intensification Processes

Horticulture usefulness has fundamentally expanded in both created and agricultural nations. During the course of the most recent 50 years, developing nations have made huge headway. This has been shown in three ways: i) expanded yields each day; ii) expanded yields per hectare for a particular yield; and iii) completely by Gains benefits each year with a shorter development period, just as low-yielding harvests are replaced by high-yielding or big-time remunerative crops. Yield development, rather than yield decrease, is something to be thankful for. Area growth has been the main driver of the increase in agricultural output over the last three decades. In the case of grain yield, it has been estimated that the increase in output has contributed to the overall growth of manufacturing (Plucknett, 1994). Rice, maize, and wheat have been at the center of agricultural intensification research. Rice, for instance, is being selected for production under warm tropical conditions whereas maize is being selected in areas with poor water management (Evans, 1993). In some nations of the South Asia these new crops are displacing large pulses, which are a vital source of protein. Rice, wheat, and corn as food have become more prevalent globally (Plucknett, 1994). Over the last 50 years, yield growth in staple agricultural crops has not been driven by a single technological breakthrough; rather, it has been driven by a steady stream of technological advancements and new, synergistic inputs. Various inputs are necessary to successfully produce high-yield, nutrient-responsive seeds (Evans, 1993; Oram & Hojjati, 1995; Loomis & Connor, 1992; Cochrane, 1993; Khush, 1995). Climate change, soil erosion, and anthropogenic changes are just some of the factors that can affect the conditions of rainfed areas. Rashid and colleagues (2004) stated that most rainfed areas are now being cultivated using traditional and primitive crop management techniques. Moisture-related stress monetary shortage, soil disintegration, and supplement/nutritional deficiency are the key limitations. Agriculture in the rainfed area remains a high-risk, low-input sector owing to rain uncertainty. Indeed, even in serious contexts, sun dominate the energy balance in food production, accounting for 90% or more of the absolute energy inputs (Pimentel et al., 1973; Pimentel & Hall, 1984). Crops use solar energy inefficiently, whereas solar inputs are still the main energy source in intensive systems (Loomis & Connor, 1992). In a growing season, photosynthesis collects only about 1% of the solar energy that reaches most crops (Heichel, 1974; Pimentel, 1980). The maximum CO_2 exchange rate has not been linked to an increase in potential crop yield during field tests. The relationship between the high carbon equivalent of some food crops and yield has a negative effect on the whole operation.

Furthermore, selecting for highest Certified Emission Reductions has tended to lower yields rather than increase them.

3.2 Soil Water/Moisture Stress

There is a solid connection between a country's capacity to deliver food and the accessibility of inexhaustible water assets. The "water footprint" idea was set up to have a utilization-based marker of water that might provide significant data. The total volume of freshwater expected to create labor and products devoured by the country's populace is known as the water footprint (Hoekstra & Hung, 2002). As indicated by Mekonnen and Hoekstra (2011), the worldwide normal water footprint from 1996 to 2005 was 1385 m^3 each year for every occupant, with rural products representing 92% of this. Soil dampness has consistently been a basic factor restricting yield execution in rainfed agricultural practices. Natural precipitation is rarely sufficient and evenly distributed over the growing season across most rainfall areas to support economic crop production (Baig et al., 1999; Adnan et al., 2009). According to Alam (2000), roughly 50–60% of water is lost annually through spillover, bringing about a lack of dampness and disintegration in rainfed regions that receive moderate to high measures of precipitation. In this manner, water gathering, dampness preservation, and the development of minuscule dams are needed to increase plant water (Papendick, 1989; Zia et al., 1997). In many areas of the planet, expanding agrarian water security through a water system to make up for soil dampness shortfalls has brought about expanded horticultural creation. The Green Revolution in the post-World War II era had intentions of boosting food production, but it turned out to be impractical. Unseen side-effects included diminished streams, free water flow hindrance and congestion, groundwater consumption, and critical water defilement. The seriousness of the detrimental impacts has provoked the subject of how much more the worldwide water flow framework can take without causing a major long-term water shortage. Despite the Green Revolution, significant swathes of the world's driest climates remained impoverished and hungry.

More global consideration was engaged in the absence of water in specific regions, such as dry spells and desertification, as opposed to the wealth of water (Nhantumbo & Salomao, 2010). During the 1990s, it was proposed to zero in closer on green water in the soil as a fundamental part of the hydrological cycle (FAO, 2003). Subsequently, a more far-reaching appraisal of the measure of water needed for food creation and human prosperity became conceivable. In many nations with a dry environment, the predominant type of water is precipitation, and expanding crop creation involves green water security, which must be accomplished by overcoming the problems of precipitation changeability and creating imaginative approaches to depend on nearby water by water gathering for an advantageous water system. Blue water, then again, is an important part of mechanical assembly. Today, people are becoming more aware that blue water scarcity can lead to water supply disruptions and, under some circumstances, the closure of businesses (Falkenmark, 1986). Water is now widely recognized as the biosphere's bloodstream (Falkenmark & Rockstrom, 2006). As a result, it is at the heart of human living situations and serves as a foundation for socioeconomic progress.

According to Kummu and Varis (2011), the most inhabited latitudes are also the ones with the scarcest water. Agricultural water consumption is more prevalent in these areas than in other parts of the world. This geographical domination of water shortage is of major importance for water security assessments, given the many parallel activities of water in nature and civilization.

Water deficiency has numerous countenances of pertinence for water security, as numerous social exercises and cycles are water subordinate: food security, human water supply, mechanical yield, hydel-power creation, nuclear power plant cooling, etc. Water security can be analyzed on different scales depending on the concentration: neighborhood and territorial scales for crop creation, food security, and different sorts of monetary creation; public and mainland scales for a nation's hydro climate, and remote connections between regions that feed the climate with moisture deficiency and those where that moisture stress is accordingly hastened (Meyer & Turner, 1992).

3.3 Genetic Resource Constraints

The absence of any hereditary upgrade in photosynthetic effectiveness has not yet hampered yields of significant food crops. This void has been filled by effective yield rearing that better disperses energy to collected organs (such as grain) and higher nitrogen manure inputs (Evans, 1993). The extension of nitrogen fertilizer extends the viability of solar radiation use in photosynthesis from commonly ranging between 0.25% and 2% in different principle cereal crops, according to Loomis and Connor (1992). Low-input cultivating frameworks that do not utilize nitrogen compost are less productive light converters, and they do not use water or soil supplements as proficiently as in the present day, high-input rural frameworks. In India during the 1990s, the innovation that introduced the green transformation during the 1970s and 1980s started to show signs of receding. Farming creation development was fairly delayed during the 1970s, with a normal annual rate of 1.95%. It increased at a rate of 3.82% every year during the 1980s. Creation development has declined since 1990, averaging just 2.09% every year (Fan, 2002). The commitment of a specialized alteration to the improvement of farming utility was identified using the intriligator method of dealing with giving priority into mechanical halts (Binswanger, 1978). In 1996–1997, around 40% of the country's collective land was under high yielding varieties (HYVs), up from 21% in 1970. The areas under HYVs of harvests ranged somewhere between 2% and 69% through all the states, and this divergence in gathering rates builds neighborhood pay contrasts. A Gini coefficient of 0.60 shows that there is huge heterogeneity in the gathering of HYV crops between states (Ramasamy & Selvaraj, 2001). Rice production technologies and expansion have also been painfully sluggish. India continues to have one of the most insignificant rice yields on earth. Over two thirds of the 414 rice-developing areas report yields below the public normal, demonstrating that even after the presentation of high-yielding innovations, a huge piece of the nation is still low-yielding. Bihar, Orissa, Assam, West Bengal, and Uttar Pradesh represent 60% of the low-efficiency rice regions. Shockingly, low yields are created in 32% of watered rice districts. Concentrated yield differences additionally show that with the current high-yielding cultivars cultivated on profoundly useful watered soils, 30–40% of the potential yield still cannot seem to be reached. After a significant period of innovative leaps forwards and reception, a yield hole actually exists in a large number of the states. The decrease in factor efficiency and yield input proportions obviously show that the speculative profits of farming have been decreasing. Ranchers might have had the option to support the current assorted yields by utilizing greater measures of nonland inputs, bringing about a descending pattern in total factor productivity and agrarian productivity. Because of a lack of benefit, ranchers are pushed to extend development on minor terrains, fueling the difficulty of keeping up with the normal asset base. Therefore, because of worrying yield input costs, the potential for further developing harvest creation through the receipt of a wide range of new innovations has remained undiscovered in many areas of the country.

3.4 Soil/ Water Erosion

Various groups have analyzed the land space of debased/wastelands in various ways. For different settings, these assessments have been normalized by coordinating spatial information with geographic data frameworks (Maji, 2007). Disintegration eliminates soil from land surfaces, diminishing the efficiency of every single regular biological system, including rural, woodland, and field environments (Lal 1990; Pimentel et al., 1995; Troeh et al., 2004). Soil deterioration, water availability, ecological change due to petrol subordinate usage, eutrophication of inland and ocean side marine streams, and biodiversity setbacks are among the world's most pressing issues. Approximately 66% of the world's population suffers from malnutrition (improper nutrition caused by insufficient or unbalanced nutrient intake, or poor digestion or utilization of nutrients) (WHO, 2000; Pimentel & Satkiewicz, 2013), the highest proportion of malnourished individuals ever. Erosion affects plant nutrient utilization efficiency, harms seedlings, reduces plant rooting depth, reduces soil water-holding capacity, reduces plant permeability, increases runoff, and reduces the infiltration rate. The cost of losing nutrients owing to soil erosion alone is estimated to be up to $20 billion per year in the USA (Hudson, 1992). Silt from water erosion as it slows can bury seedlings and cause superficial crusts that impede seedling emergence, reducing annual crop yields. The combined impacts of soil deterioration and poor plant growth frequently lead to even more erosion in the future. Soil formation rates in generally tropical and mild environments are viewed to be within the range of 0.3–2.0 t/ha/year (Pimentel, 1993); however, these figures are still challenged. Oldeman (1994) and Dregne and Chou (1992) announced that around 2 billion ha of cropland, pastureland, and range land all around the world

(17% of vegetated land on Earth) have been spoiled, basically as a result of water and wind breaking down. Of this corrupted land, 38% is assessed to be slightly debased (prompting a deficit in rural usefulness of up to 10%, yet with full recuperation potential), 46% moderately debased (prompting a 10–25% decrease in agrarian efficiency and ideal for being reestablished distinctly through huge monetary and specialized ventures), and 15% seriously debased (prompting a deficit in horticultural usefulness of up to 25%; however, with full recuperation potential). The degree of corruption changes extraordinarily by locale, with almost three quarters of Central America's farming area base and 66% of Africa's agrarian land base being moderately debased. Soil disintegration rates in modern nations are assessed to be more than 10 tonnes for every hectare each year by and large, and in excess of 100 tonnes for each hectare each year in certain parts of India, Central America, and Africa (Lal, 1990). Disintegration is most severe in locations where crops are grown on steep slopes, vegetative cover is lost, massive amounts of heavy material are used to lay the ground, and possible windbreak trees, bushes, and fences are destroyed.

3.5 Nonjudicious/Rampant Use of Inorganic Fertilizers

Because of the extension of land use for farming creation without successful utilization of outside inputs, soil supplement exhaustion is a significant concern directly connected to food weakness in developing and least developed countries (Henao & Baanante, 1999). Proceeding with consumption of supplement drained soils, i.e. supplement misfortunes because of wind and water disintegration, is demolishing soil decay and undermining horticultural sustainability there (Ayoub, 1999; Sheldrick et al., 2002). This might be found in the prolonged reduction in crop yields in numerous nations of Africa, Asia, and Latin America because of inadequate information (FAO/UNDP/UNEP/World Bank, 1997). Many examinations have endeavored to assess soil supplement spending plans for agroecosystems utilizing the general mass equilibrium idea; however, few have zeroed in on the usefulness of individual yield. Subsequently, deciphering how the soil supplement financial plan identifies with either regular supplement misfortunes or supplement shortages because of lacking remuneration for crop gathering is difficult, and assessing the ramifications of human-instigated supplement deficiencies for explicit yields is comparably hazardous. Following the oil crises of the 1970s, a huge number of research projects saw energy use in agribusiness in industrialized countries (Stanhill, 1984). They would in general disregard the energy typified in labor and other normal assets such as water, zeroing in rather on direct petroleum derivative data sources (FAO, 1992). Nitrogen manures, which were previously utilized in the developed environment, were by far the most elevated energy input in our assessments. On different occasions, nitrogen fertilizers utilize more energy per tonne than phosphorous and potassium manures, and they constitute 55–65% of on-farm energy use for exceptional yield crops.

3.6 Low Soil Organic Carbon Content

Soil Organic Matter (SOM) adjustment or upgrade is vital for decreasing the risk of soil disintegration and guaranteeing the sustained suitability of tropical agribusiness. SOM exhaustion causes the actual quality of soil to crumble, just like the deficiency of valuable biodiversity and the beginning of various health deficiencies. Climate, soil type, and land use (Dalal & Mayer, 1986) all affect SOC content, as does biomass input. The low SOC fixation in tropical soils is an essential factor, adding to low soil maturity and usefulness. On account of a high pace of oxidation and accelerated disintegration, dryland soils are broadly decayed and have low SOC focuses (Fig. 1). Low biomass data and fast surface soil deterioration after substantial storms are two additional fundamental considerations that add to low SOC centers (Srinivasarao et al., 2011). Low SOM content, together with low information sources, is one of the crucial drivers of low yield and a wide yield contrast. SOC exhaustion has impacted soil quality, crop efficiency, and maintainability in India's rainfed agro-ecosystems. SOC stocks at the best 30-cm depth are dominated by Vertisols, Inceptisols, and Alfisols. For sure, SOC stocks in soil profiles differ significantly throughout the country, with Vertisols>Inceptisols>Alfisols>Aridisols being the most well-known.

3.7 Low External Inputs

Rainfed crops utilize less creation inputs than inundated yields (e.g., manures, additional water system, great quality seeds, bug sprays, and herbicides). Thus, rainfed agrarian yields are low. Proof that rainfed soils are inclined to multi-nutrient shortfall notwithstanding, rainfed crops infrequently accomplish adjusted use of fundamental sources of information. Owing to the numerous vulnerabilities in crop yield in rainfed agribusiness, there are huge variations in the measurement of sources of information used in watered versus rainfed locations. About 30% of rainfed ranchers in numerous distant spaces of the nation do not utilize any composts

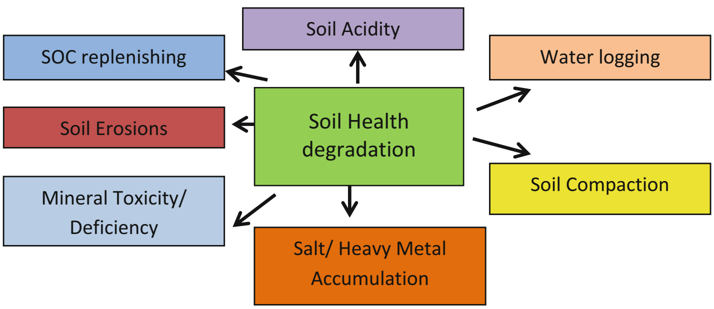

Fig. 1 Factors affecting soil quality

or pesticides (Venkateswarlu, 2008). Along these lines, there is a fast decrease in proportion of yield reaction to applied compost supplements (NPK).

4 Energy Use, Dynamics, and Efficiency Under Different Crops

The global energy calamity compelled researchers to think in the area of competent energy use and conservation for agricultural production. Therefore, energy study is necessary for proficient management of rare resources for better agricultural production (Babu et al., 2014). Energy is a crucial factor in agriculture, and energy use has risen over the years to satisfy the expanding populace under the pressing factor of decreased arable land and the labor supportability of farming and natural securities (Bergtold et al., 2017; Wiser et al., 2016). Proficient utilization of energy is an essential need to decrease ecological adversity, secure the natural assets, and improve the sustainability of farming (De Jonge, 2004; Ghorbani et al., 2011; Yuan & Peng, 2017). It has been accounted for that roughly 60% of the total populace is poorly taken care of (Pimentel et al., 2005). Accordingly, limiting energy use and strengthening the viability of energy use are life-supporting for food security.

4.1 Farm Power Use Patterns

The expanding interest for food grains with an expansion in the populace, the changing propensities for energy use for individuals, the new oil crisis, and the proportion of contamination created by the fuel utilized in different agricultural operations have stressed the requirement for energy-related research. Farm power for field tasks has a significant influence in expanding use efficiency of different inputs for crop production with direct effects on energy use dynamics. The increment in power consumption has been mostly through the introduction of tractors, whose involvement with farming has expanded day by day. In various places in the country, the populace of farm animals has decreased by 70–80% and animal farms have transformed to either mixed or tractor farms (De et al., 2000). The mixed farms, which still maintain draft animals, have usually relied on hired tractors to complete vital operations such as seedbed preparation. Among the different states of India the density of tractors varies extensively (0.9–71.4 work vehicles/thousand ha) (De et al., 2000).

4.2 Energy Use Pattern

Agriculture itself is an energy provider and energy consumer as bio-energy (Alam et al., 2005). Energy necessity and its production potential largely depends upon the type of crop and establishment methods used. Energy usefulness is declining with

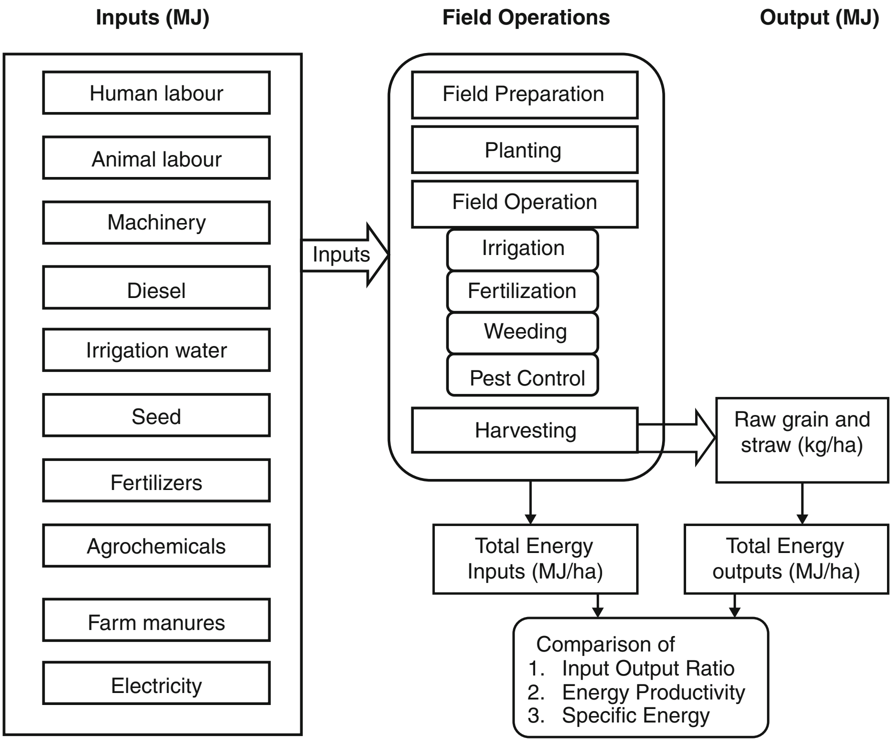

Fig. 2 Energy flow from factors to product

the rising input costs, without proportionate improvement in the yield of specific crops (Singh et al., 2016). Various energy-intensive operations such as tillage, seedbed preparation, sowing, fertilization, irrigation, etc., are involved in crop cultivation (Mohanty et al., 2014). In order to sustain agricultural production, efficient energy utilization is necessary, as it provides ultimate economic savings, safeguarding of fossil resources, and reduction of environmental distortion (Demircan et al., 2006) (Fig. 2).

4.2.1 Crop Establishment Methods

Various crop establishment techniques can be compared with regard to gross energy output on the basis of solar energy transformed into biochemical energy. Research studies found similar energy in conventional transplanting, drum seeding, and mechanical transplanting in respect of the pattern of energy use in different crop establishment methods in rice. According to Bhardwaj et al. (2016) the energy requirement varies from 11.208 × 103 MJ/ha to 11.255 × 103 MJ/ha for crop establishment in rice by broadcasting and drum seeding through dry or sprouted seeds. Crop establishment through drum seeding can be a better option in comparison with conventional transplanting as it needs less energy for the production of grains, it is easy to use, and is an energy-efficient technology (Table 1).

Table 1 Yield and energy as influenced by different rice establishment methods (Bhardwaj et al., 2016)

Treatments	Yield (q/ha)		Energy Input (MJ/ha × 10^3)	Gross energy output (MJ/ha × 10^3)		Net energy output efficiency		Energy use efficiency (MJ/t)		Specific energy
	Grain	Straw		Grain	Biomass	Grain	Biomass	Grain	Straw	
T1	44.18	68.43	11.520	64.64	150.48	53.42	139.0	5.64	13.06	2628.16
T2	39.80	63.76	11.558	58.51	138.21	46.95	126.7	5.06	11.96	2925.21
T3	43.70	67.90	11.255	64.24	149.12	52.98	137.9	5.71	13.25	2590.59
T4	37.13	60.21	11.208	54.57	129.83	43.37	118.6	4.87	11.58	3024.75
T5	36.50	59.32	11.208	53.66	127.82	42.45	116.6	4.79	11.40	3081.90
CD ($P = 0.05$)	5.82	8.05	–	8.56	17.85	8.56	17.85	0.75	1.57	399.84

T1 conventional transplanting, *T2* mechanical transplanting, *T3* drum seeding of sprouted seeds, *T4* broadcasting of sprouted seeds, *T5* broadcasting of dry seeds

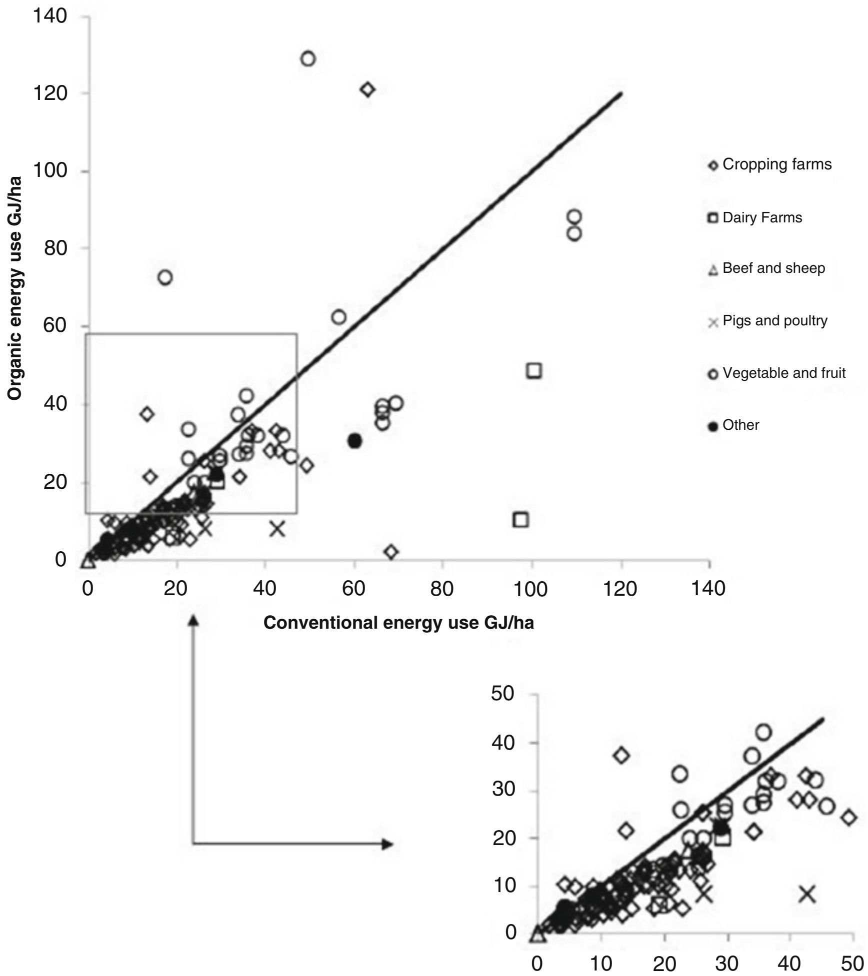

Fig. 3 Organic versus conventional energy use per hectare with expanded selection. Organic performs better below the line, and worse above the line. Please note that the 'trend-line' is x = y for the purposes of illustrating the relative performance for each product type and is not a line of best fit. (Source: Rahmann & Aksoy, 2014)

4.2.2 Organic Farming

Any kind of organic system continuously utilizes less fossil-fuel energy per unit of area in almost all types of livestock and crops (Fig. 3). In some research findings, organic cropping systems have a worse performance, as they provide a lower yield for pest attack and higher energy use for weed management. Williams et al. (2006) reported that potatoes produced through organic systems provide a lower harvest for insect pests, disease attacks, and higher weed growth. Some of the organic poultry systems were found to be less efficient owing to mortality rates and a higher feed conversion ratio (Leinonen et al., 2012). Similarly, organically produced dairy systems tends to result in lower energy use per liter of milk produced, owing to greater energy efficiency in the production of forage and reduced reliance on imported concentrates (Cederberg & Mattsson, 2000; Haas et al., 2001). Increasing the need for mechanical weeding under organic farming makes it energy intensive owing to involvement of more human energy (Nguyen & Haynes, 1995). Organic farming systems have the potential to contribute toward more efficient agriculture, but with lower yields. Organic methods could still be applied to increase the efficiency of the agriculture sector as a whole, although energy use is only one aspect of sustainability.

4.2.3 Conservation Agriculture

From the crop production point of view, energy input is one of the prime indicators. The monetary return and net energy of a cropping system can be quantified by sound planning of sustainable systems (Chaudhary et al., 2006). With the increase in fertility level a linear increase in yield and yield attributes is found, but the opposite trend is observed in the case of energy use efficiency, energy intensity, and productivity (Bilore et al., 2005). According to Sindhu et al. (2004) and Chaudhary et al. (2006) an increase of up to 30% in the yield of different crops is found with the use of optimal energy inputs. Nowadays, CA has gained importance owing to the need of farmers to reduce variable costs of cultivation, as a major portion of energy (25–30%) is utilized for crop establishment and field preparation. This can be minimized by reducing the intensity of tillage operations. The zero tillage method of sowing is cost effective, energy efficient, and beneficial to the environment compared with conventional sowing practices (Tripathi et al., 1999; Filipovic et al., 2006).

4.2.4 Energy Dynamics for Different Farm Operations

Energy used in farming is important for crop production, processing, value addition, and transportation. In crop production, human, livestock, and mechanical sources of energy are widely utilized. Energy necessities in agriculture are broadly divided into two groups, i.e., direct and indirect. Direct energy is needed to perform different farm operations such as land preparation, irrigation, interculture, threshing, harvesting, and transportation of agricultural inputs and farm produce. On the other hand, indirect energy consists of the energy used in the manufacture, packaging and transport of fertilizers, pesticides, and farm machinery.

Seedbed Preparation and Sowing

Seedbed preparation is one of the most energy-consuming activities, which involves a major cost share for crop planting (Perfect et al., 1997; Patil et al., 2009). Various influential factors such as physical characteristics of soil, type and intensity of the primary tillage, CRs present, and crop type to be sowed are important for the selection of suitable ploughing machineries and methods. These factors determine the type of seed drill (pneumatic or in-line) to be used and, therefore, the necessity of preparing a seedbed that is more or less pulverized. The depth of tillage affects the agricultural environment and plays a significant role in crop yields and quality (Kim et al., 2020).

Fertilizer Application

Samootsakorn (1982) estimated the energy necessary for the production and transport of fertilizers and found that 80 MJ/kg, 14 MJ/kg, and 9 MJ/kg energy is consumed for the production of nitrogen (anhydrous ammonia), phosphorus (normal super phosphate), and potash (muriate of potash) respectively. In India, the fertilizer energy coefficient used is 60.6 MJ/kg for nitrogen, 11.10 MJ/kg for phosphorus, and 6.70 MJ/kg for potassium (Table 2). The energy input of nitrogen, phosphorus, and potassium fertilizer was calculated using the formula given by Chaudhary et al. (2014).

$$\text{Efr} = \text{NEC} \times \text{ANA},$$

where:

Efr = fertilizer input energy, MJ/ha
NEC = fertilizer energy coefficient
ANA = amount of nutrient applied, kg/ha

Pesticide Application

The application of pesticides, insecticides, and herbicides is mostly used in all crops to prevent the yield loss caused by insects, disease and various kinds of weeds. Doering (1980) found that approximately 238 MJ/kh and 101.2 MJ/kg of energy are consumed for the manufacture of herbicides and insecticides respectively. The energy input of pesticides is computed using the following formula given by Chaudhary et al. 2014 (Table 3).

Table 2 Energy utilized for the manufacture of fertilizers

Group	Energy (MJ/kg)	Reference
Ammonium nitrate	49.1	Patyk and Reinhardt (1997)
P_2O_5 (acid)	17.7	Patyk and Reinhardt (1997)
K_2O	10.5	Patyk and Reinhardt (1997)
Lime	2.39	Patyk and Reinhardt (1997)

Table 3 Energy utilized for the manufacture of pesticides

Pesticide	Typical energy in manufacture and delivery (MJ/kg)	Reference
Herbicide	238	Helsel (1992)
Pesticide	199	Helsel (1992)
Fungicide	92	Helsel (1992)
Pesticides (General)	315	Meir-Ploeger et al. (1996)

$$Ep = PEC \times APA,$$

where:

Ep = pesticide input energy, MJ/ha
PEC = pesticide energy coefficient
APA = amount of pesticide applied, kg/ha

Irrigation

After the green revolution in India with the introduction of yielding varieties and the increase in cropping intensity, the demand for the most precious input (water) is increasing day by day. In the present era of agriculture rain and canal water will not be able to satisfy the crop water requirement, resulting in intensive use of groundwater for crop production. Lifting of groundwater through electrical or fuel-operated pumps consumes a higher amount of energy. This may result in farming becoming more dependent on commercial energy sources. On the other hand, the productivity of irrigated land is more than double that of rainfed land. In sub-Saharan Africa, only 4% of the area in production is under irrigation, compared with 39% in South Asia and 29% in East Asia (World Bank, 2007). The increasing demand for energy for irrigation purposes is the energy needed to lift water by pumping from surface sources such as ponds, streams, or canals; or from below-ground sources using open wells or boreholes. The energy demand for water lifting is calculated by multiplying the head (the vertical distance from the water source to the field in meters) by the volume of water to be lifted in cubic meters (m^3).

Road Transport

Like machinery, road transport uses fuel directly and also involves energy costs in manufacture and maintenance.

4.2.5 Energy Dynamics Under Different Crops

Energy use dynamics of various crops differ mainly with the input use pattern, ongoing farm operations, and type of farm power use. Based on the national scenario of major crops (presented in Table 4) in India it can be concluded that these crops cover 71.3% of gross cropped areas. This indicates that rice and wheat are high energy-consuming crops among the food grains owing to the high level of fertilization and irrigation provided. Maize crop (22.4% irrigated area) requires 76% more energy than rice, whereas sorghum (92% of rainfed areas) consumes 50% less energy than rice and wheat. According to Dipankar De (2006) oilseed crops also consumed less energy within the range 6382–8051 MJ/ha. Among the cash crops, sugarcane and potato are the most energy-consuming crops in terms of high fertilizer and irrigation energy use. High crop productivity in sugarcane and potato resulted in high energy productivity of 1.039 kg/MJ and 0.495 kg/MJ respectively (Dipankar De, 2006). The food grains have higher energy productivities than oilseeds and pulses. Among them, rice and wheat, which receive higher inputs, had significantly higher crop productivities than coarse cereals, resulting in better energy-use

Table 4 Energy use and energy productivity of some of the major crops in India

Crops		Total energy (MJ/ha)	Energy productivity (kg/MJ)
Food grains	Rice	13,076	0.239
	Wheat	14,657	0.196
	Maize	9956	0.215
	Sorghum	4745	0.200
Pulses	Green gram	4315	0.118
	Black gram	3870	0.105
	Bengal gram	5464	0.190
Oilseeds	Mustard	8051	0.119
	Soyabean	6382	0.171
Cash crop	Sugarcane	59,192	1.039
	Cotton	9972	0.094
	Potato	31,352	0.495

efficiencies. Most of the pulses and oilseeds have low energy productivities owing to insufficient cultivation inputs and low yield returns. The crop productivities of the major crops in India are still lower than in some of the other Asian countries. Increases in crop productivities in India, driven by future food demands, would require higher energy investments with present cultivation practices.

4.2.6 Energy Analysis Parameters

To determine the energy budget of any crop production, the amount of each input (tractor, disc harrow, diesel, human labor, bullock, potato seed, fertilizer [NP K], water for irrigation, insecticide, and sprayer) will be considered for common energy input. Cultivar and fertilizer have to be considered for treatment energy input, whereas calculation of output energy by must consider the economic produce, i.e., seed. To estimate the energy value, the quantity of different inputs and output has to be converted to energy by multiplying the respective energy equivalents (Table 5). The energy indices equations are given below (Singh et al., 2003; Dessane, 2003; Risoud, 2000).

1. $\text{Nutrient energy ratio} = \text{Energy Output (MJ/ha)}/\text{Nutrient Energy Input (MJ/ha)}$
2. $\text{Energy use efficiency} = \text{Energy Output (MJ/ha)}/\text{Energy Input (MJ/ha)}$
3. $\text{Energy productivity} = \text{Economic Output (kg/ha)}/\text{Energy Input (MJ/ha)}$
4. $\text{Human Energy profitability} = \text{Economic Output (kg/ha)}/\text{Labor Energy (MJ/ha)}$
5. $\text{Direct energy} = \text{Labor} + \text{Fuel}$
6. $\text{Indirect energy} = \text{Seed} + \text{Fertilizers} + \text{Pesticides} + \text{Machineries} + \text{irrigation}$
7. $\text{Renewable energy} = \text{Labor} + \text{FYM}$

8. Nonrenewable energy = Fuel + Seed + Fertilizers + Pesticides + Machineries

9. Specific Energy = (Energy Input (MJ/ha)/Crops output (MJ/ha))

10. Energy Intensiveness (MJ/Rs) = Total Input Energy (MJ/ha)/
Cost of Cultivation (MJ/Rs)

Table 5 Energy conversion factors used

Sl. No.	Component	Unit	Energy equivalent coefficient (MJ/U)	Remarks
A.	Inputs			
a.	Human labor (h)			
1.	Adult man	Man hour	1.96	
2.	Women	Women hour	1.57	1 adult man = 0.8 adult woman
b.	Bullock (medium)	Pair-hour	10.10	Body weight 352–450 kg
c.	Diesel	Liter	56.31	
d.	Farm machinery	Hour	62.7	
e.	Chemical fertilizer			
1.	Nitrogen (kg)	kg	66.1	
2.	Phosphorus (kg)	kg	12.4	
3.	Potassium (kg)	kg	11.1	
4.	Zinc sulfate	kg	20.9	
f.	Organic manure			
1.	Vermicompost/ farmyard manure/ neem cake	kg (dry mass)	0.3	
g.	Agrochemicals			Chemical requiring dilution at the time of application
1.	Herbicides	kg	254.45	
2.	Fungicides	kg	97	
3.	Pesticides	kg	184.63	
h.	Irrigation water	m^3	1.02	
i.	Seeds	kg	3.6	
B.	Outputs	kg		
1.	Rice grain (kg)	kg	14.7	
2.	Wheat (kg)	kg	15.70	
3.	Vegetable pea (kg)	kg	3.91	
4.	Green gram (kg)	kg	14.03	
5.	Maize (kg)	kg	15.10	
6.	Mustard (kg)	kg	22.72	
7.	Pigeon Pea (kg)	kg	14.07	
8.	Soyabean (kg)	Kg	18.14	

Source: Mittal et al. (1985), Mittal and Dhawan (1988), Singh et al. (1997), and Parihar et al. (2013)

5 Designing a Sustainable Solution for Energy Management

Ensuring food security for an expanding global population with limited resources is one of the major global challenges faced by humanity. To meet this increasing demand, growers have started using higher quantities of inputs vis-à-vis energy to get maximum returns/output. As a result, agriculture has become energy intensive (Yuan et al., 2018). This intensive use of energy has many tradeoffs. The food–energy nexus in present-day agriculture poses many global challenges, such as water scarcity, global warming, and pollution, that threaten the sustainability of agricultural production systems in many regions across the globe (Xu et al., 2017, 2020), especially in the fragile ecologies of rainfed farming situations. With relatively lower productivity levels under rainfed agriculture, return on the energy investment is not acceptable, and thus intensive use of inputs for higher returns cannot be sustained for long without major changes. Thus, identification of energy-efficient and low-emission (low global warming potential) technologies is the need of the hour to make agriculture more productive and sustainable.

Management of energy in agricultural production systems is directly proportional to the management of inputs such as tillage/sowing, seed, fertilizers, pesticides, irrigation, etc. Optimization of different energy inputs not only provides sustainable solutions to the energy crisis that persists in rainfed ecologies, but is expected to boost crop production too. Crop cultivation requires application of both animate (bullock, human power) and inanimate (tractors, tillers, etc.) forms of energy at different stages (Devasenapathy et al., 2009). Therefore, a better understanding of energetics may provide useful information for identifying better and efficient crop management practice (Tzanakakis et al., 2012). Agricultural production systems are heavily dependent on the use of fossil fuels, which include indirect energy inputs such as fertilizers and pesticides, as well as direct inputs such as diesel for tractors and machinery for tillage operation. Sustainable energy management can be carried out through appropriate technology changes and improved management practices/operations, thereby improving energy use efficiency or reducing energy demand for all energy-intensive agricultural processes.

A three-way strategy can be adopted/explored for sustainable energy management. These are:

(i) Implementing farming practices that reduce energy consumption, thus improving energy efficiency and conserving natural resources,
(ii) Adoption of state-of-the-art technologies in agriculture, and
(iii) Production and use of renewable energy for farming operations.

5.1 Farming Practices that Improve Energy Efficiency

Improving the efficiency of energy use is the cheapest, quickest, and cleanest way to cut farm operation costs and the consumption of nonrenewable energy. Energy-conserving strategies usually focus on the processes, actions, or materials that demand a major energy input to the system (Mikkola & Ahokas, 2010). Identification of major energy consumers in various farming situations is crucial to be able to conserve energy. Tillage, irrigation, and fertilization are the principal consumers of energy and contributors of GHG emissions in agriculture as these operations are based on fossil fuel and electricity (Pratibha et al., 2015). Under the rainfed system, irrigation does not consume much energy as it depends on seasonal rainfall for growing crops. Thus, tillage and fertilization are the potential options for saving and optimizing energy consumption, thereby improving energy efficiency and reducing energy costs easily under rainfed systems.

5.1.1 Improved Fertilizer and Pesticide Use

Indirect energy inputs such as fertilizer or pesticides may provide substantial energy-saving potential in agriculture, as more than half of the total energy used in agriculture goes on fertilizer and pesticide usage. Under a rainfed farming situation, farmers can reduce the energy input significantly by reducing the usage of commercial fertilizers and pesticides by adopting cover crops and manures, composting, nitrogen-fixing crops in rotations, and integrated nutrient/pest management. Precision farming also reduces the excessive use of fertilizer applications.

5.1.2 Zero Tillage and Conservation Agriculture

The energy intensiveness of agriculture can be substantially reduced by adopting reduced or zero tillage-based cropping systems. Zero tillage perhaps provides the biggest opportunity for energy conservation in a farming situation. CA based on three principles of minimum or zero tillage, CR retention, and diversified crop rotations can reduce energy use, while improving crop, energy, and water productivity. CA-based zero tillage has energy-conserving potential owing to no or drastically reduced tillage operation. However, in a tillage-intensive conventional system, where 4–5 primary and secondary tillage operations are performed, tillage and crop establishment operations contribute largely to the total energy use (Erenstein & Laxmi, 2008; Jat et al., 2014). Drastic reduction of preparatory tillage operations in CA-based management practices could potentially save 50–60% fuel (diesel) ha^{-1} and thereby a saving of 3000 MJ energy/ha (Sangar et al., 2005). Under a zero tillage system land preparation and sowing operations are carried out in a single pass of the tractor leading to a saving of 6–7 tractor hours per hectare, which is equivalent to 35–36 l of diesel (Erenstein et al., 2008). Use of minimum or zero tillage reduces energy input and maximizes the energy output–input ratio in rainfed cropping systems (Singh et al., 2008). Pratibha et al. (2015) observed that omitting the tillage operation through CA-based zero tillage could save 58% and 81% fuel respectively in rainfed pigeon pea–castor cropping systems. CA-based management practices involving zero-tillage and raised bed planting could save 91% energy in land preparation with 8% lower total energy use compared with a tillage-based conventional system in a diversified cropping sequence (Saad et al., 2016). CA-based zero tillage systems also offer the benefits of improved crop productivity, soil health, carbon sequestration, soil moisture conservation, and timely sowing of crops.

5.1.3 Cultural or Ecological Practices

Being ecologically sound, appropriate use of cultural or ecological practices is key to the sustainable use of energy in agriculture. Adoption of best management practices (BMPs) can help to reduce energy consumption with subsequent lower GHG emissions and GWP. Besides zero/reduced tillage, diversified crop rotation, short-duration high-yielding varieties, lower rates of fertilization, especially N fertilizer, etc., are among the important BMPs (Mosier et al., 2005).

(i) The principal factor responsible for lower energy efficiency under rainfed agriculture is the low crop productivity. Highly vulnerable soil and climatic conditions with frequent droughts occurring and higher dependency on seasonal rainfall limit the active growing season for farmers to only a few months per year. Under these scenarios, sustainable transformation of rainfed farming systems to irrigated systems through water harvesting (capturing runoff rainwater in reservoirs for subsequent use) and smart crop management practices can be a profitable and energy-efficient alternative for small-scale farmers with an assured irrigation water supply for the dry season (Jaramillo et al., 2020). Jaramillo et al. (2020) observed that the highly vulnerable rainfed farming systems could be transformed into sustainable and profitable irrigated systems through a combination of rainwater harvesting and smart crop management practices with 2–4 times higher crop yields than under rainfed situations for small and medium-scale farmers in Nicaragua and Mexico.

(ii) Diversified crop rotations improve the resilience of the systems against abiotic and biotic stresses that help better recovery of the system and avoid use of external and artificial inputs, thus improving energy conservation and energy efficiency. Inclusion of legumes in the cereal-based cropping systems can be a sustainable option for improving energy efficiency. Rice–garden pea, rice–field pea, and rice–lentil systems are more suitable cropping sequences for higher energy efficiency, especially in the rainfed tracts of India, where rainfed rice–fallow systems is in vogue (Yadav et al., 2017).

(iii) In rainfed farming, moisture losses from the water-starved soils is one of the major factors responsible for crop stress, as the rainy season lasts for a limited period. The potential yield losses can be minimized only when supplemental irrigation is provided, which is a costly and energy-intensive input in rainfed agriculture. Practices that minimize water losses, which in turn reduce water consumption are needed to be employed to cut the amount of energy use for irrigation. For example, weeds transpire heavily, leading to moisture losses from the soils; appropriate control of weeds thus conserves a considerable amount of water.

(iv) On-farm use of by-products for recycling and returning of harvested nutrients to the soil from which they come. Also, increased use of organic manures maintains soil health and quality, and reduces the extensive use of synthetic fertilizers, reducing the energy inputs.

(v) The fact that fertilizer and pesticide usage contributes more than half of the total energy used in agriculture, provides an opportunity for substantial energy saving in agriculture through the reduction of commercial fertilizer and pesticide usage. For this, ecological/agronomic approaches such as the choice of appropriate high yielding short-duration cultivars adapted to the local environmental conditions, nitrogen-fixing crops and green manuring, mycorrhizal inoculants (arbuscular mycorrhizal fungi), seed treatment for better crop establishment, biological pest control and IPM through beneficial organisms, intercropping, cover-cropping, trap and decoy cropping, agro-forestry for improving the regeneration capacity of the agro-ecosystem, providing a favorable micro-climate to crops (microclimate management) through wind breaks, shelterbelts, and hedgerows, etc., lower the levels of external energy inputs.

(vi) Designing and the development of model farming systems or agro-ecosystems by using local and natural ecosystems that lessen energy inputs. Integrated farming systems suited to the local resources, environmental conditions, and market demands can be energy efficient, productive, and profitable farming strategies for marginal/small and medium farmers under rainfed situations.

5.1.4 Tractors and Machinery Maintenance

Tillage systems and tractor fuel efficiency offer the biggest opportunities for energy savings. Tractor fuel efficiency can be improved through proper tire inflation, regular vehicle maintenance, and reduced idling of the machine. These measures help to save a considerable amount of fuels vis-à-vis reducing CO_2 emissions, and also prolong the working life of the tractor (Table 6).

Table 6 Summary of technological interventions for improving energy efficiency. (Source: Sims, 2014)

Direct energy	Indirect energy
Fuel-efficient tractor engines/better maintenance	Less input-demanding crop varieties
Precision farming for accurate fertilizer application	Agro-ecological farming practices and nutrient recycling
Adopting minimum or no-tillage practices	Reducing water demand and losses
Better control of building environments	Improved fertilizer and machinery manufacture
Improved heat management of greenhouses	

5.2 Adoption of State-of-the-Art Technologies in Agriculture

5.2.1 Precision Agriculture

Precision agriculture emerged in the 1980s as a sustainable solution for input/management optimization, preferably for large zones. Variable rate technology can be used to optimize spraying, seeding, and fertilizing operations. Over the past few decades, there have been significant improvements in satellite imagery, development of cost-effective unmanned aerial vehicles for guidance and surveillance, and ground vehicle-mounted remote sensing units, which have enabled the growers/resource managers to detect spatial differences in crop (or pest) activity at different growth stages, pest abundance, soil nutrient variability, etc. If combined with "ground truthing" (human observation), this offers a tremendous opportunity of input optimization and avoids the unnecessary process of wasteful "whole-field" treatments (Tullberg, 2014), thereby reducing heavy energy use.

Precision agriculture provides the multiple benefits of:

(i) Precise band application of chemicals to crop row or inter-row zones instead of blanket spraying,
(ii) Precise in-crop fertilizer application that synchronizes with the nutrient demands of crops,
(iii) Timely pest management, which provides an opportunity for reduction in application frequency and use rates of chemicals.

5.2.2 Use of Robotics

Small and cost-effective robots can be used in place of large and expensive field machines for seeding, fertilizer application, weed/pest control, harvesting, etc. (Blackmore et al., 2005). Based on convenience and degrees of difficulty, the use of robotics in weed management has been the most significant. These small autonomous machines with spatial capability can follow rows, differentiate between crops and weeds/pests, and precisely target control measures. Robotic weeding machines manage weeds mechanically or chemically or through fire flame. These artificial intelligence-enabled automated robotic weed control systems may reduce the dependency on herbicides, thus improving sustainability and reducing the environmental impact (Slaughter et al., 2008), particularly in vegetable crops and organic agriculture (Korres et al., 2019). These machines identify weeds through a real-time machine vision system followed by precise weed control and mapping. Further, these automated machines target weeds in patches rather than entire fields and may reduce usage of herbicides and the cost of control. This could potentially eliminate herbicide use in fields or the extent of reduction could be as high as 90%.

5.3 Production and Use of Renewable Energy for Farming Operations

Renewable energy is generated from natural resources such as sunlight, wind, rain, geothermals, and biomass. The term "renewable" denotes that it is replenished at the same rate as it is used. Use of renewable and sustainable energy sources is becoming increasingly necessary to counter the dual challenges of the energy crisis and global warming. The United Nations' "Sustainable Energy for All" agenda focuses on doubling global renewable energy use by 2030 (Griggs et al., 2013). With agriculture consuming a significant amount energy, renewable energy in agriculture is expected to play a significant role in achieving sustainable energy goals. Development of on-farm energy sources is crucial. Installation of small-scale solar or wind systems can enable the farmers to generate renewable energy for their on-farm and household use (Babatunde et al., 2019). On-farm biodiesel and ethanol production (from feedstock) and development of cellulosic biofuel (from energy-related crops) technologies are being suggested to improve the sustainable farm energy availability, reduce the dependency on fossil fuels and curb GHG emissions (Chel & Kaushik, 2011). These are expected not only to conserve energy but also to cut fossil fuel consumption, thereby saving farmers money and helping them to achieve self-sufficiency. Self-sufficiency through the use of renewable energy protects the farms from fluctuating fossil-fuel prices. Farmers can also generate additional income by selling extra energy to other enterprises (Table 7).

The complexity of the food–energy–water nexus should be understood and managed through conjunctive approaches (Hogeboom et al., 2021). Energy conservation and improving efficiency in agriculture can be achieved through several approaches, including direct savings through technology improvements and behavioral changes or indirect savings through the adoption of improved farming practices or full/partial replacement of conventional energy sources by renewable energy. Avoiding food wastage also improves energy-use efficiency in agriculture, as it reduces the loss of the energy embedded in the food production system. For this to happen quickly, developing a viable demand–supply ecosystem for improved technologies through capacity building and raising awareness, and firm government policies for institutional support and capital investments, would be required.

6 Conclusions

The importance of rainfed agriculture varies by region, although rainfed lands produce the majority of the food for disadvantaged communities in developing countries. Rainfed farmers are becoming increasingly vulnerable as the frequency of droughts, midseason droughts, decrease in the number of rainy days, intense and untimely rainfall, and natural disasters such as hail storms has increased in recent years. The consumption pattern of both direct and indirect energy inputs has shown that energy consumption per hectare of net and gross cultivated area has grown over time, resulting in a drop in the production per unit of energy use. Soil and water management are crucial for increasing productivity and closing production disparities. The main focus is on constructing the SOM in order to restore soil health. Water is a precious natural resource, and rainfall management in situ or runoff water gathering and recycling are essential for rainfed agriculture to thrive. The optimal use of water, soil, and farm management practices in an integrated strategy is both

Table 7 Potential use of renewable energy sources on farms

Renewable sources	Potential uses	Remarks
Solar energy	Photovoltaic for electricity generation	Electricity generation for household use
		Water pumping for irrigation with photovoltaic-powered pumping systems
	Solar thermal applications	Drying crops and grains by simply exposing them to the heat of the sun
		Modern solar crop driers
		Solar water heaters
		Lighting, space heating, and water heating, particularly in livestock operations
		Greenhouse heating
Wind energy	Wind turbine and windmill applications	Water pumping using wind turbines
		Electricity generation from wind turbines
		Grinding grains and legumes using windmills
Geothermal energy	Indirect use	Electricity generation
	Direct use	Production of hot fluids for varied uses such as dehydration of alliums, heating buildings, milk pasteurization, growing plants in greenhouses, etc.
Biomass energy	Conversion and use of biomass energy: on-farm energy generation from cattle dung and manure (bio-gas plant)	Cow dung for cooking gas and electricity generation
	a) Biodiesel: low-polluting diesel alternative to fossil fuel made from vegetable oils, animal fats, and even recycled cooking oils b) Bio-ethanol: alcohol-based fuel derived from crops, usually corn, barley, and wheat. It can be blended with gasoline in varying concentrations	Renewable fuels for transportation and farm machines
	Perennial energy crops	Development of cellulosic biofuel for use in farm operations

vital and a necessity for making rainfed farming more inexpensive and sustainable. Our decision-makers' primary worries are how to manage the growing demand for energy in agriculture in order to meet the target growth and match domestic supplies to the demand. On two fronts, action will be required. First, more efficient use of available energy resources to partially alleviate supply limits, with technological solutions clearly having an edge in this task. The second strategy should focus on boosting alternative renewable energy sources through technologies, institutions, and regulatory initiatives.

Farm research centers and Agricultural Technology Management Agencies, which are located in every district of the country, as well as various national/state government programs, are required to scale these technologies in order to realize productivity gains and large-scale impacts. We hope that publishing this chapter will encourage and reinforce efforts to close yield gaps and unlock the potential of rainfed agriculture, both of which are vital to India's food security.

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Energy Use and Economic Evaluation Under Conservation and Organic Farming

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Abstract

Organic farming is one of the approaches that can contribute to food and nutritional safety in sustainable agriculture. Organic farming has been reported to be more efficient and effective in lessening of greenhouse gases emissions, soil and water pollution, and also threat of human health as compared to conventional farming production system. Hence the farm level analysis of conventional and organic farming is most required to prompt the farmers and policymakers to prefer the most economical viable farming practices. This chapter aims at upgrading the current state of knowledge on organic-conventional debate and identifying the most efficient system in energy consumption and economic aspect. It is reasonable to assume that organic agriculture uses less energy than conventional methods because it is more comprehensive and thus more sustainable. However, a growing body of literature has been presenting some differences in this regard, providing some illumination of debates. Also, it's not a new phenomenon to have discussions about the financial implications of buying organic food. Therefore, this chapter compares and contrasts conventional and organic systems in terms of energy use and cost. The purpose of this chapter is to improve our understanding of the organic vs. conventional argument and to determine which system is more cost-effective and energy-efficient.

1 Introduction

Agriculture is the vital source of economic sustainability across major developed countries in the world. So far, with the development of global agriculture, the increase in food production has been accompanied by a multitude of challenges and problems. To better address these challenges, more comprehensive system-oriented approaches are gaining momentum with the complexity of farming systems which is the need of the hour. Organic farming is one of the approaches that can contribute to food and nutritional safety in sustainable agriculture. According to FAOSTAT, at the end of 2017, more than 69.8 million hectares of land were organically cultivated which comprises 1.4% of total global land. Environmentally oriented approaches encourage the farming systems to reliably produce adequate yields of high-quality food, enhance the environment, be profitable, and promote social wellbeing. On the other hand, conventional farming delivers tremendous gain in productivity and efficiency. It includes rapid technological intervention, high capital investment, high-yielding hybrid crops, and high intensive use of pesticide. However, with the advancement of technology and increased demand of productivity, various operational farming practices are adopted. As agriculture is the backbone for socioeconomic enhancement, the differentiation of farming practice preference should be done by taking the farmer's mind into concern. Hence, the farm-level analysis of conventional and organic farming is most required to prompt the farmers and policymakers to prefer the most economical viable farming practices.

1.1 Why Should Energy and Economic Budgeting Be Done for Farming System?

- This technique gives a summary of the present situation of energy and economics which are useful to evaluate several farming systems and decide the best management approach (Kaltsas et al., 2007).
- It helps to improve the farming system in order to reduce the excess inputs compared to output energy, ultimately reducing emission of excess CO_2 from agriculture (Dalgaard et al., 2001).
- The major and minor energy inputs and their relative contribution can be assessed, and energy efficiency can be improved on each input component basis (Mrini et al., 2002).
- The economics can be improved with optimization of input-output energy and cost components (Kaltsas et al., 2007).
- It also helps to attain sustainability in agriculture by best utilization of input-output energy without negatively affecting the finance of farmer and quality of environment (Pervanchon et al., 2002; Gündoğmuş, 2006).

2 Farm-Level Economics of Conventional and Organic Farming

The farm-level economic analysis can be conducted through two methods:

1. Direct comparisons between organic and conventional farms based on farm input and output data.
2. Modelling comparisons of organic and conventional farms.

2.1 Direct Comparison Between Organic and Conventional Farms Based on Farm Input and Output Data

According to MacRae et al. (2007), organic farming is characterized by lower yields (10%), lower input use, as well as higher output prices as compared to conventional systems. Due to the diversification of crops, organic farms are less vulnerable to the same pest or unfavorable weather events despite reduced pesticide and fertilizer use (Cacek & Langner, 1986). The efficient seasonal input and output distribution in organic farming is better than conventional which leads to a balanced income. Organic farming includes shorter food supply chains, such as farmers' markets, roadside stands, and community-supported agriculture, which help farmers to achieve higher income compared to conventional farming. But the higher yield

Table 1 Farm-level economic characteristics of conventional and organic farming (Durham & Mizik, 2021)

Characteristics	Conventional	Organic
Yield	Normal	At least 10% lower
Pesticide cost	Normal	Much lower
Fertilizer cost	Normal	Much lower
Labor cost	Normal	Higher (+15%)

variability is the major economical constraint in organic farming compared to conventional counterparts. However, several studies have been done on farm-level economical evaluation of organic and conventional farming. Eberle and Holland (1979) compared three organic and three conventional farms and concluded that net returns per unit area were 38% higher on the conventional farms than the organics. Kraten (1979) compared six organic farms with representative conventional farms and found 22% higher net income in organic farms. Berardi (1978) reported that when cash operating costs are included, the returns are higher on the organic farms. Positive economical indicators for organic production are lower operating costs, higher weather resilience, price premium, and shorter supply chain. According to Reganold and Wachter (2016), organic farms are more reliant on ecosystem services for the production of high crop yields, whereas conventional farms rely more on external inputs. With an average price premium of 111–138% and lower production costs and yields, organic systems achieve 2.4 times greater net returns at lower risk (Cavigelli et al., 2009). Aslam et al. (2020) revealed that higher mean expenses exist on irrigation and labor force with 12% and 7% difference, respectively, while fertilizers and pesticides possess higher mean expenses in the case of conventional farming. Durham & Mizik (2021) provided a summary of the major characteristics of the farm-level economic analysis of conventional and organic farming which is given below in Table 1.

Considering the cost of manure in organic farming, Helmers et al. (1984) suggested that it is approximately equal to the application costs and the returns can be comparable to conventional farming. Taking livestock component into consideration, which is the vital component of organic farming, Brusko et al. (1985) reported that the economic returns of the organic farming without livestock followed up by a crop rotation system, such as clover and oats mix, can be compared favorably with conventional farming. Apart from this, Forster et al. (2013) suggested that organic soybean production is a viable option for smallholder farmers under the prevailing semi-arid conditions in India.

2.2 Modelling Comparisons of Organic and Conventional Farms

Modelling approach can be inculcated as a simulation tool in economical evaluation of both organic and conventional farming to gain a better understanding and interpretation of different economical aspects of these farming systems. The Farm Accountancy Data Network (FADN) is a farm-level economical model which includes economic variables (production, costs, and revenues) and the most widely used structural, economic, and balance sheet indices. It compares organic and conventional farming and identifies the major differences (Cisilino et al., 2011). The model outputs show that organic farmers can (partially) overcome the productivity gap with respect to conventional ones by more efficient use of their inputs. James (1983) modelled six different scenarios including livestock enterprises and found that conventional farming is more profitable than organic farming. The study concluded that organic practices are most feasible for small-scale farming and the interference of livestock operation is most vital to maximize returns. However, most of the modelling studies have revealed that the net returns from organic farming are consistently lower than the returns of conventional one. Apart from this, a linear programming model can be applicable for the economical evaluation of different farming systems. It is a mathematical model in which different economical indicators are taken as variables and the net return is represented as the objective function. Acs et al. (2007) applied a linear programming model to compare the economical analysis of a conventional arable farm and an organic arable farm. The model includes environmental externalities such as losses of nutrients and pesticide use. It has been reported that the expenditure on hired labor is much higher in organic farming which also leads to higher variable costs. Prices for organic products are higher than for similar conventional products.

However, the diversity of crops on organic farms can have other economic benefits and provides some protection from the volatile market price. The relative economic performance of organic farming and conventional farming is sensitive to the benefit-cost ratio which must be greater than 1 to be economical viable. The fluctuations in both input and output prices impact on the economic benefits of the two farming systems. Hence, a future research must be needed to increase the benefit-cost ratio of both the farming systems by developing different economical indices, and it should be extended for different cropping systems under organic and conventional farming practices.

3 Comparison of Energy Budgets of Different Conventional and Organic Farming Production Systems

While discussing on different farming system approaches, it is a necessary step to know more about the budgets as well as the economic view of the farming system which is going to be implemented. Organic agriculture has been reported to be more efficient and effective in the lessening of greenhouse gas emissions, soil and water pollution, and also threat of human health as compared to conventional farming production system. As compared to conventional farming system, organic farming system reportedly used less non-renewable sources (like fossil fuels) which brought reduction in harming the environment (Dazhong & Pimentel, 1984; Jorgensen et al., 2005; Moreno et al., 2011). By energy budget, it means how much is the income generated as per the use of energy input in a production process. Energy inputs can be divided into direct (energy which are directly used in agricultural farms, viz., fuel, machines, fertilizers, seeds, seedlings, herbicides, human labor, etc.) and indirect

Table 2 Energy equivalents of different input and output values used

Equipment/input	Energy coefficients (MJ/unit)	Equipment/input	Energy coefficients (MJ/unit)
Human labor (h)	1.96	**Pesticides (kg)**	
Machinery (h)	62.70	Insecticides	199.00
Chemical fertilizers (kg)		Fungicides	92.00
Nitrogenous	60.60	Herbicides	238.00
Phosphorus	11.10	**Diesel oil (l)**	56.31
Potassium	6.70	**Electricity (kWh)**	11.93
Farm manure (kg)	0.30	**Irrigation water**	0.63

Source: Singh and Singh (1992), Hessel (1992), and Yaldiz et al. (1993)

(energy which are not consumed in the agricultural farm but in the development, manufacturing, or handling of inputs). Energy outputs are considered as the calorific value of the harvested biomass, which is calculated from the total production (kg/ha) and its corresponding energy (Table 2).

Many studies have been conducted so far by many researchers on the energy consumption of organic and conventional farming systems around the globe. According to Fess and Benedito (2018), organic farming systems require 15–35% more labor than the conventional farming systems depending on the crops cultivated (Table 3).

Mansoori et al. (2012) followed the random sampling method, and the sample size was calculated using the formula:

$$\mathrm{n} = \frac{NS^2}{(N-1)S_x^2 + S^2}$$

where n is the required sample size; N, population volume; S, standard deviation; S_x, standard deviation of the sample mean ($S_x = d/z$); d, permissible error in the sample size; and z, reliability coefficient.

The energy efficiency of a system will be calculated by using the ratio of output energy and input energy (Alam et al., 2005):

$$\text{Energy efficiency} = \frac{\text{Energy output}}{\text{Energy input}}$$

So, in order to compare the energy efficiency or budget of both the farming systems, it is required to know the share of direct and indirect energy from total energy input. For example, in the study conducted by Mansoori et al., 2012, on the energy budget and economic analysis on rice production, it has been reported that the organic rice production system shows higher output-to-input ratio as compared to

Table 3 Distribution of "direct" and "indirect" energy use from eight studies with comparison of organic and conventional productions (Smith et al., 2015)

Production system	Unit	Fuel and electricity	Purchased feed (indirect)	Fertilizer, compost, and pesticides (indirect)	Machinery and buildings (indirect)	Other	References
Chickens-broilers-organic	GJ/ton	7.5	32.8	−0.5	0.5	0.0	Leinonen et al. (2012a)
Chickens-broilers-conventional, free range	GJ/ton	7.6	18.2	−0.4	0.3	0.0	
Chickens-broilers-conventional, standard	GJ/ton	9.1	16.4	−0.4	0.2	0.0	
Chickens-layers-organic	GJ/ton of eggs	6.6	19.9	−0.4	0.3	0.0	Leinonen et al. (2012b)
Chickens-layers-conventional, free range	GJ/ton of eggs	6.1	12.9	−0.5	0.3	0.0	
Chickens-layers-conventional, barn	GJ/ton of eggs	10.3	12.1	−0.4	0.2	0.0	
Chickens-layers-conventional, caged	GJ/ton of eggs	5.5	11.6	−0.4	0.3	0.0	
Pigs-organic	GJ/ton of pigs	0.0	21.3	0.0	0.5	0.5	Basset-Mens and van der Werf (2005)
Pigs-conventional	GJ/ton of pigs	0.0	11.8	0.0	0.4	3.7	
Pigs-organic	GJ/ha	0.0	21.6	0.0.0	0.4	0.3	
Pigs-conventional	GJ/ha	0.0	21.7	0.0	0.8	6.7	
Beef suckler cow farms-organic	GJ/ha	8.0	1.5	0.1	6.4	0.2	Schader (2009)
Beef suckler cow farms-conventional	GJ/ha	11.2	3.9	2.2	7.8	0.4	
Broccoli-organic	GJ/acre	18.3	0.0	2.6	0.0	11.5	Venkat (2012)
Broccoli-conventional	GJ/acre	16.0	0.0	5.5	0.0	5.4	

(continued)

Table 3 (continued)

Production system	Unit	Fuel and electricity	Purchased feed (indirect)	Fertilizer, compost, and pesticides (indirect)	Machinery and buildings (indirect)	Other	References
Soybean, corn, oat, hay rotation, with manure charges, organic	GJ/field	0.7	0.0	9.5	0.0	0.0	Karlen et al. (1995)
Soybean, corn, oat, hay rotation, without manure charges, organic	GJ/field	0.7	0.0	1.4	0.0	0.0	
Conventional corn and soybean	GJ/field	0.8	0.0	1.4	0.0	0.0	
Potatoes-organic	GJ/ton	1.0	0.0	0.2	0.2	0.0	Williams et al. (2006)
Potatoes-conventional	GJ/ton	0.8	0.0	0.4	0.1	0.0	
Bread wheat-organic	GJ/ton	1.4	0.0	0.2	0.0	0.1	
Bread wheat-conventional	GJ/ton	0.8	0.0	1.5	0.0	0.1	
Greenhouse tomatoes-organic	GJ/ton	222.4	0.0	1.2	2.0	3.6	
Greenhouse tomatoes-conventional	GJ/ton	118.5	0.0	0.7	1.0	1.9	
Lettuce-greenhouse crop, organic	GJ/ha	7.5	0.0	31.4	3.1	128.7	Alonso and Guzmán (2010)
Lettuce-greenhouse crop, conventional	GJ/ha	4.7	0.0	3.5	3.1	140.1	

conventional system and also conserves energy resources with the reduction of non-renewable resources input.

4 Farm-Level Energy Budgets of Conventional Farming and Organic Farming

Energy budgeting is now a concern as a consequence of the international focus on climate change. Organic farming is considered as an environmentally friendly and sustainable farming for combating climate change. Practice of organic farming minimizes the negative impact on the environment; hence, there is a need to assess the energy balance of the farming system. It has been suggested that a range of methods can be employed to describe the energy flows of agricultural systems. At the highest level, it would be possible to include all energy flows within a system; such analyses could be described as thermodynamic or ecosystem-based. Hence, it is important to consider all sources of renewable and non-renewable energy including solar energy. We tried to compare farm-level energy budget from few important literatures; for ease of comparison, we considered only major energy input processes, viz., machinery, diesel, fertilizers (N, P, K), manures, pesticides, biocides, seeds, and labor. Net energy is calculated from the difference between total input and output energy, while the energy efficiency is calculated from the ratio between input and output energy (Table 4).

Comparison of farm-level energy inputs and outputs is presented in Table 4. Figures 1 and 2 represent the energy inputs from different sources and energy efficiency of organic and conventional farms of different crops across various countries. In most cases, energy inputs were higher in conventional farming compared to organic farming except in few instances where energy inputs of organic farming were higher, viz., sugar beet (Czech), soya bean (South Korea), rice (Spain), and pear (China). The major input energy in the organic farms were manures, diesel, and machineries. The type and application of manures are mostly the reason for such high energy input in organic farms of Spain (Alonso & Guzmán, 2010). Seed materials also had higher energy in organic farms over conventional farms. In conventional farms, inputs, viz., fertilizers, machine, diesel, and pesticides, contributed a major portion (>60%) of the total energy input in all the cases. Among the fertilizers, nitrogen (N) fertilizers had the highest energy input. Even though there is no fertilizer input in organic farms, an equal amount of energy was contributed from manures. The energy output in terms of yield varied with respect to crops within conventional and organic farming. In cereal crops, conventional farming showed higher yield in all the cases over organic farming except in paddy (India), while in pulses and horticultural crops, organic farms outyielded conventional farms. Even though conventional farms had yield advantage, the energy efficiency was always higher in organic farms with respect to cereals except rice (Spain). The opposite was true in the case of pulse and horticultural crops. However, we cannot come to a conclusion that organic farms are energy-efficient while considering all the

Table 4 Farm-level energy input and output budget of different crops across different countries

Energy/crops (MJ/ha)	Paddy		Sugar beet		Ley grass		Paddy		Wheat-pea		Rice		Wheat	
Location	India		Czech		UK		Iran		Canada		Spain			
Farm type	Org	Con	Org	Con	Org	Con	Org	Con	Org	Con	Org	Con	Org	Con
Machine	1322	4553	6556	5097	2570	2570	1442	3642	2102	2367	8773	8246	3755	4037
Diesel	–	–	6253	6054	3530	3530	31,533	68,360	14,229	16,133	–	–	–	–
Fertilizers	–	15,352	–	–	–	–	–	–	–	34,980	–	5940	–	6732
N fertilizers	–	–	–	4471	–	7692	–	11,514	–	–	–	–	–	–
P fertilizers	–	–	–	1217	–	469	–	1014	–	–	–	–	–	–
K fertilizers	–	–	–	1118	–	452	–	376	–	–	–	–	–	–
Manures	8823	–	13,645	–	223	–	900	–	–	–	100,614	2734	2454	2208
Seed	1089	1046	1471	–	–	–	1165	2186	7902	7902	–	–	–	–
Pesticides	–	–	–	1930	–	418	–	1116	–	7116	–	1701	–	231
Biocides	940	–	–	–	–	–	–	–	–	–	152.9	–	–	–
Labor	1333	1778	–	–	–	–	1407	947	–	–	136.8	155.3	10	12
Total inputs	13,507	22,729	27,925	19,887	6323	15,131	36,447	89,155	24,233	68,498	109,676.7	18,776.3	6219	13,220
Total output	75,797	64,772	212,205	172,608	33,705	27,720	71,101	86,260	252,054	465,841	61,515	95,690	32,318	41,454
Net energy	62,290	42,043	184,280	152,721	27,382	12,589	34,654	−2895	227,821	397,343	−48161.7	76913.7	26,099	28,234
Energy efficiency	5.61	2.85	7.60	8.68	5.33	1.83	1.95	0.97	10.40	6.80	0.56	5.10	5.20	3.14
Reference	Shrine and Umadevi (2020)		Šarauskis et al. (2018)		Jawad et al. (2013)		Mansoori et al. (2012)		Hoeppner et al. (2006)		Alonso and Guzmán (2010)			

Inputs/energy	Pear		Apricot		Wheat		Maize		Wheat		Corn		Soya bean	
Location	China		Turkey		Italy		Italy		USA		USA		South Korea	
Farm type	[a]Org	Con	Org	Con	Org	Con	Org	Con	Org	Con	Org	Con	Org	Con
Machine	24,200	150	921	1022	4080	2440	7880	3780	1427	1427	4125	4125	904	556
Diesel	3500	2800	6200	7449	–	–	–	–	2204	2204	1269	1269	6948	4190
Fertilizers	–	15,000	–	–	–	19,300	–	33,750	–	–	–	–	–	
N fertilizers	–	–	–	8405	–	–	–	–	–	3364	–	7009	–	5696
P fertilizers	–	–	–	498	–	–	–	–	–	322	–	911	–	–
K fertilizers	–	–	–	–	–	–	–	–	–	46	–	561	–	–
Manures	32,200	–	721	223	1040	–	3230	–	792	–	1838	–	6391	–
Seed	–	–	–	–	5750	5870	10,140	2930	1304	1304	1927	1927	891	331
Pesticides	–	6100	–	3261	–	–	–	2990	–	724	–	3301	–	1145
Biocides	1900	–	3524	–	–	–	–	–	–	–	–	–	23	–
Labor	5000	9100	1265	1165	–	–	–	–	196	196	194	194	619	376
Total inputs	66,800	33,150	12,631	22,023	10,870	27,610	21,250	43,450	5923	9587	9353	19,297	15,776	12,294
Total output	35,000	31,000	30,555	33,166	48,510	77,620	87,120	161,980	25,118	26,165	115,026	116,187	16,501	23,641
Net energy	−31,800	−2150	17,924	11,143	37,640	50,010	65,870	118,530	19,195	16,578	105,673	96,890	725	11,347
Energy efficiency	0.52	0.94	2.42	1.51	4.46	2.81	4.10	3.73	4.24	2.73	12.30	6.02	1.05	1.92
Reference	Liu et al. (2010)		Gündoğmuş et al. (2006)		Sartori et al. (2005)				Pimentel et al. (1984)				Lee and Choe (2019)	

[a]Org, organic farming; Con, conventional farming; MJ/ha, energy at megajoules per hectare

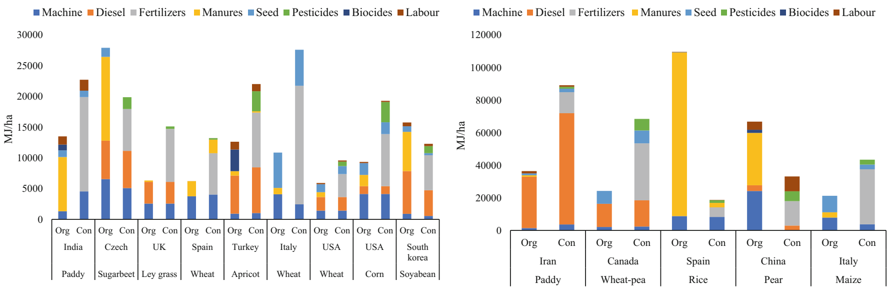

Fig. 1 Energy inputs in conventional and organic farms of different crops across different countries

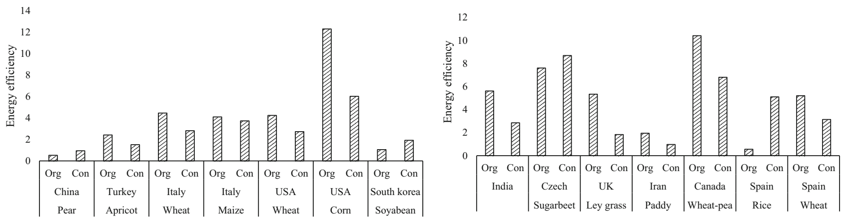

Fig. 2 Energy efficiency (output/input) in conventional and organic farms of different crops across different countries

renewable and non-renewable energy inputs into consideration, viz., solar, irrigation, electricity, post-harvest processing, transport, etc.

5 Energy Budgeting of Conventional and Organic Farming

Agriculture with conventional practice mainly deals with use of fossil energy (directly for farm machineries, electricity, and/or indirectly in other plant protection and interculture operations). Agriculture claims 5% of global fossil fuel consumption (Pinstrup Andersen, 1999). Fossil fuels, being the limited resources, must be conserved and judiciously used in agriculture activities; moreover, the climate change perspective must be considered to reduce CO_2 emission. Hence, adoption of low input use mechanisms has been encouraged (Dalgaard et al., 2001; Payraudeau & van der Werf, 2005).

Energy budget deals with the calculation of energy in relation to the input to and the output from a process. There are several forms of energy requirement in agriculture commodity production such as machinery (including manufacturing, marketing, and repairing of equipment), fossil fuel used, as well as the manual labor required to perform the operation and other indirect forms of energy (Bridges & Smith, 1979). Hence, in general, the methodology which is being used for energy budgeting has logical components of input and output energy sources in commodity

Table 5 Energy equivalent/coefficient for energy budgeting

Item (unit)	Av energy equivalent	References
Farm machinery		
Tractor (hr)	23.8–57.8	Fluck (1992), Biondi et al. (1987), Bonnie (1987), Tsatsarelis (1991)
Plow (hr)	22.3–37.5	
Cultivator/ harrow (hr)	17.1–42.8	Fluck (1992), Biondi et al. (1987), Bonnie (1987), Pimentel et al. (1973)
Seed planter (hr)	70.6	Fluck (1992), Biondi et al. (1987), Bonnie (1987)
Sprayer (hr)	0.38–4	Fluck (1992), Biondi et al. (1987), Bonnie (1987), Genitsariotis et al. (1996)
Ridger (hr)	42.3–44.2	Fluck (1992), Biondi et al. (1987), Bonnie (1987), Tsatsarelis (1993)
Fuel		
Diesel (liter)	47.3–47.7	Cervinka (1980), Fluck (1992)
Electricity (kWh)	12.1–12.7	Fluck (1992), Bonnie (1987), Jarach (1985)
Fertilizer		
Nitrogen (kg)	74.2–75.4	Spugnoli et al. (1993), Bonnie (1987), Lockeretz (1980), Tsatsarelis (1993)
Phosphorus (kg)	10.9–13.7	
Potassium (kg)	9.7–9.9	
Manure (kg)	8.4–23.5	Makhijani and Poole (1975), White and Taiganides (1971)
Chemicals		
Insecticides (kg)	363.6	Pimentel (1980), Fluck (1992)
Fungicides (kg)	99–310.6	Pimentel (1980), Fluck (1992), Tsatsarelis (1993)
Labor (hr)	2.2	Pimentel and Hall (1984), Fluck (1992), Pimentel and Pimentel (1996)

production process. All inputs and outputs are transformed in energy terms by considering the energy equivalent (conversion factor) to corresponding input/output. This energy equivalent is nothing but the energy embodied to an item per unit of that item (Mrini et al., 2002) as shown in Table 5.

In energy budgeting, different field operations (right from seedbed preparation (tillage), sowing, irrigation, fertilizing, plant protection and weed management, harvesting and baling, till loading transport/handling storage, etc.) are to be observed and recorded in relation to each direct and indirect energy input. In long-term evaluation, these observations are recorded each year and averaged for the final energy budgeting of that system. Energy budgeting depends on many factors such as farm size, commodity type, machinery used, sources and types of inputs (fertilizer, manure, irrigation, etc.), number of interculture operations, climatic and geographical condition of the farm/area, etc. The farming system (conventional and organic) also has a huge effect on energy budget. Hence, the required units of that item are subjected to the above factors creating the variation in energy budget place to place even for the same commodity. Nevertheless, the minimum useful energy is essentially the same for a particular operation everywhere (Bridges & Smith, 1979).

Conventional and organic farming systems differ in terms of the input types and output capacity. Similarly, the energy applied as input in these systems depends on the operations involved, their schedule and time taken to complete them, manpower and their capacity, machinery being used, and other inputs in field operations. Hence, energy budgeting is a suitable technique to assess these two farming systems in relation to energy efficiency, productive energy yield, and utilization. On the basis of energy budget sheet energy use efficiency, energy productivity is calculated as Eqs. (1) and (2), respectively, to make quantitative comparison of farming systems (Demircan et al., 2006):

$$\text{Energy use efficiency} = \frac{\text{Energy output (MJ/ha)}}{\text{Energy input (MJ/ha)}} \tag{1}$$

$$\text{Energy productivity} = \frac{\text{Crop Yield (kg/ha)}}{\text{Energy input (MJ/ha)}} \tag{2}$$

Gündoğmuş (2006) studied a comparative evaluation of apricot production under organic and conventional farming systems in Malatya Province, Turkey. The analysis was performed for ten pairs of farms (one organic and one conventional). In both the farming systems, the allowable practices were adopted with required unit. The energy equivalent in this study was adopted from Singh et al. (2002) and Helsel (1992). The study found that the input energy consumption was 13,779.35 and 22,811.68 MJ/ha in organic and conventional systems of farming, whereas the total energy output was calculated to be 30,555.20 and 33,166.10 MJ/ha, respectively. The energy efficiencies for organic and conventional systems were found to be 2.22 and 1.45, respectively. The input energy for organic system was assessed to be lower than conventional because organic system does not require high energy chemical fertilizer, whereas the output energy was found to be more in conventional system because the output produced was more in conventional farming as a result of chemical fertilizer and pesticide use; however, the efficiency of energy use was measured more in the case of organic farming system. Similarly, the higher energy efficiency (ratio of output to input energy) was found in organic system over conventional for wheat (Berardi, 1978), raisins (Erdemir & Bayramoğlu, 2006), rice (Mansoori et al., 2012), and maize (Bilalis et al., 2013).

6 Economic Budgeting of Conventional and Organic Farming

Farming economics deals with the money involved in relation to the various inputs to crop production and monetary gains from such outputs. The cost of inputs and prize of outputs decide the profitability of farming. Profitability between organic and conventional farming may be of the range of ±20%. Organic system of farming consumes lower input energy and provides lower yield of product than intense conventional farming (MacRae et al., 2007). Economics of farming involves the

Table 6 Economics of organic (Org.) and conventional (Conv.) farming system

Crop	Gross return (INR/ha)		Net return (INR/ha)		Total cost of production (INR/ha)		B:C ratio	
	Org.	Conv.	Org.	Conv.	Org.	Conv.	Org.	Conv.
Redgram	27,984	42,000	11,654	16,550	2817	2923	1.72	1.68
Foxtail millet	30,510	28,440	19,899	17,151	631	693	1.87	1.60
Bajra	36,240	37,080	21,940	20,330	949	1092	2.54	2.22
Onion	59,280	75,000	18,880	22,250	412	424	1.46	1.42

Source: Babalad & Navali, 2021

calculation of the total cost of production, total value of production, net return, and benefit-cost ratio (for unit area) as given by Eqs. 3, 4, 5, and 6 (Mansoori et al., 2012). The total cost of production is the cost involved with the machinery operations, fuel, seed inputs, interculture operation, interculture material, labor, etc., whereas the gross value of production is the total output produced multiplied by its unit price.

$$\text{Gross value of production} = \text{Crop Yield} \tag{3}$$

$$\text{Total cost of production} = \text{Variable cost of production} + \text{Fixed cost o production} \tag{4}$$

$$\text{Net return} = \text{Gross value of production} - \text{Total cost of production} \tag{5}$$

$$\text{Benefit cost ratio} = \frac{\text{Gross value of production}}{\text{Total cost of production}} \tag{6}$$

Babalad and Navali (2021) studied the economics of organic and conventional farming for major crops. The study revealed the lower yields for most of the crops; also, lower input cost was reported from organic farming than conventional. Table 6 shows the economics of these two farming systems from study during 2019–2020.

7 Conclusions

Modern intensive agriculture is structured by a heavy use of fossil fuels that further elevates the production and input costs in farming. Such large dependence on fossil fuels raises a big concern on its environmental effects creating pollution, and thus most of this intensive agriculture is called out to shift from conventional to organic agriculture. Since organic agriculture is a holistic approach and regarded as more sustainable than conventional, it is also expected that energy consumption must be relatively lesser in organics. However, an increasing body of literature has been depicting few discrepancies in this aspect, shedding some light of controversies. Moreover, debating on the economic aspects of organic food is not a new trend. Therefore, this chapter discusses the in-depth energy use and economic comparison between conventional and organic systems. This chapter aims at upgrading the current state of knowledge on organic-conventional debate and identifying the most efficient system in energy consumption and economic aspect.

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Part II

Different Aspects/Concepts of Energy Efficiency and Management

Agricultural Residue Management Using Forced Draft Gasifier Cookstove

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Abstract

Nearly 3 billion people around the world use biomass fuels for cooking, water heating, and space heating purposes. Indoor air pollution and emission from biomass cookstove remain an issue for a long time. Clean burning and high fuel efficiency are two focal areas to consider when designing improved biomass cookstoves. A forced draft wood gasifier with a separate gas generator and gas burner was considered to overcome pollution issues associated with biomass combustion. This study focuses on separating biomass combustion gasification chamber located outside the kitchen. Cooking is done by having a producer gas burner in the kitchen. The impact of operating the gasifier stove in both top-lit updraft (TLUD) was studied. This concept permits the gasifier to be located away from the kitchen, avoiding indoor smoke during the ignition stage. The kitchen remains clean and comfortable. Operating the gasification chamber in TLUD mode provides a stable flame with higher heat content. The developed gasifier had higher efficiency and clean burning with tar removal facility, with the guarantee for clean kitchen and less indoor air pollution.

Keywords

Agriculture residue · TLUD gasifier · Cookstove · Thermal efficiency · Emission

1 Introduction

Biomass meets the basic energy requirements for cooking and heating for rural families and provides energy to a range of traditional industries. Biomass fuels are easily converted into gaseous, solid, and liquid fuels (Zhou et al., 2016). Over 40% of the world's population relies on solid fuels for space heating and cooking (Yip et al., 2017). Around the world, more than 160 programs distributing improved biomass burning cookstoves were running in 2011 (Mercado et al., 2011). "Improved" means the stoves use less fuel and emit less pollutant. Over the last 40 years, improved cookstoves have been an important topic of research. Some 2.6 billion people around the world still use traditional cookstoves, and it is assumed the number will remain constant until at least 2030 (Kshirsagar & Kalamkar, 2014; IEA, International Energy Agency, 2012).

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In the 1980s and 1990s, design efforts tried to maximize efficiency and minimize heat losses in developing countries (Gallagher et al., 2016). In the last few decades, many improved stoves have been introduced, but they are often difficult to control, use, or manufacture and all too often rejected by cooks (Raman et al., 2013a; Kaupp, 1984). The benefits of improved cookstoves have to be agreed upon within a specialized social and financial setting, since individuals, markets, and territories differ (Peša, 2017). In addition, goals of improved cookstove programs have evolved and diversified, with more focus on indoor air quality. Women and kids are extremely affected by indoor air contaminants produced because of deprived biomass cooking practices (WHO, 2005). Globally, over four million deaths happen every year from illnesses linked to the smoke delivered by indoor burning, which generally influences ladies and kids (Lim & Vos, 2012).

Inefficient cooking practices consume huge quantities of fuel and deliver indoor air contamination, with bad health effects mainly among ladies and kids. Advanced cooking stoves can possibly use less fuel and decline health problems related to smoke in kitchens (Ahmad et al., 2021a). Forced draft stoves are deliberated as a possible choice to overcome these complications (Mukunda et al., 2010a). Gas is preferred for cooking wherever it is available. Gas can be made from wood and biomass in gasifiers (Reed & Larson, 1996). The process by which biomass can be converted to a producer gas by supplying less oxygen than actually required for complete combustion of the fuel is known as gasification. It is a thermo-chemical process, and it is performed by a device known as a gasifier (Kalbandhe et al., 2015). Biomass gasifiers offer great promise in this regard. Numerous researches have revealed that gasification-based stoves have better performance and fewer contaminants than other designs like traditional and natural draft stove (Ahmad et al., 2019a, 2021b; James et al., 2016).

In the absence of proper flame regulators in most of the natural draft improved cook stoves (ICS), controlling the flame is not possible. Cooking with wood gas stoves has advantages over other types of the biomass-fueled stove because of cleaner and easier operation (Kaupp, 1984). Low efficient cookstoves (irrespective of their technologies) result in high consumption of fuel (Ahmad et al., 2019b). In order to fulfill their cooking energy requirements, rural individuals utilize a wide range of biomass, for example, fuelwood, charcoal, agricultural residues, etc., in conventional cookstoves of different designs. The majority of these stoves are inefficient and lead to increase in health problems. Implementation of improved biomass stoves can result in significant decrease of indoor air pollution and greenhouse gas emissions with simultaneous health co-benefits (Masera et al., 2007). Evaluations of various improved stove designs demonstrate 20%–50% decrease in exposure to particulate matter (PM) and carbon monoxide (CO) through use related to conventional cookstoves (Kathleen et al., 2011). As an alternative means of cooking, a gasifier stove is used that uses high-density pellets from crop waste as a solid fuel. Gasification plays an important role in thermal processing (Pomykała & Mazurkiewicz, 2015). The high utilization efficiency and low emissions are an effect of the production of near-constant measure of gaseous fuel because of gasification and an exact air-to-fuel ratio used for burning of gases (Mukunda et al., 2010b). The gasifier-based cooking stoves are gas burners that make their own particular gases from dry solid biomass. Biomass gasification process creates the combustible gas at temperatures in the range of 700 and 1000 °C. Gasifiers change biomass into energy in four phases, namely, drying, pyrolysis (carbonization), gasification, and gas ignition. There are several advantages to gasifying and burning gaseous fuels over open-air combustion of biomass, such as cleaner, safer, and easier operation (Raman et al., 2013b).

The updraft gasifier is one of the oldest kinds of gasifiers because of its simple design and controllability. Biomass is loaded from the top of the chamber or reactor of the gasifier and moves downward during combustion, while the gasifying agents (air) are supplied from the bottom side of the gasifier and move upward. Most compound reactions occur at the base of the bed, where the temperature is maximum in the gasifier. The producer gas leaves from the upper side of the reactor at a fairly low temperature (420 K–570 K) (Mandl et al., 2011). This kind of gasifiers can gasify biomass with high moisture content because of high heat conversion rate between the burning zone and the drying zone. Because of the long residence time of the fuel, it could accomplish high carbon transformation rate (Puig-Arnavat & Bruno, 2010). In 2000, the fluidized bed gasifier stove that uses peanut shells as fuel-based centralized cooking system was installed in Henan Province of China to supply producer gas for 100 families (Lin & Robert, 2001). Another updraft gasifier that uses agricultural residue as fuel with a high energy output of 1400 MJ/h is used to supply energy to 90 rural families daily in China (Zhenhong et al., 2002). About 400 such units are in operation in China (Yongzhi, 2005). Although various designers have created improved biomass stoves guaranteed to be more fuel efficient, thermal performance is still much lower compared with fossil fuel-based stoves (Barnes et al., 1994). This is due to the variation in the combustion properties of biomass fuels and fossil fuels.

The principal objective of this study was to test the performance of a gasifier producing cooking gas supplied to a separate burner and compare it with the TLUD (top-lit updraft) method. The current study was aimed at providing an easy-to-use, biomass-fueled cooking system, which is capable of placing the gasification device outside the kitchen and the burner inside the kitchen.

2 Methodology

Development of the gasifier cookstove involved three major accomplishments:

(i) To exceed the performance of a conventional biomass cooking stove with an appropriate design of a separate gas generator and gas burner.
(ii) To compare the performance of the gasifier and conventional cookstove for quantifying the improvement.
(iii) To incorporate user-friendliness into the design of the stove.

2.1 Designing Parameters: Stove

The overall performance of the stove is affected by various conditions such as ambient temperature, wind speed, air pressure, shape, weight, specific heat capacity and the size of the vessel, fuel type, and preparation.

Cookstoves should be designed according to user requirement and to save fuel, effort, and time (Raman et al., 2014a). Conventional biomass stoves work at lower efficiency and produce higher emissions and higher amount of fuel consumption (Raman et al., 2014b). The efficiency of a stove can be increased by optimizing the primary and secondary air into the burning chamber using a blower with the controller (Odesola & Kazeem, 2014). Gasifier cookstoves can be distinguished by the direction of the gasification air (Thomas et al., 2016).

Easy operation and convenient fuel feeding are the basic requirements of gasifier stoves. In order to overcome those issues, a forced draft gasifier stove was selected to provide higher thermal performance, convenient fuel feeding, safety, and cleaner gas in the kitchen. Several types of gasifier cookstoves exist in the world. Some of the gasifier stoves work on natural draft mode, and the rest work on forced draft mode. The forced draft cookstove has several advantages over the natural draft cookstoves. Forced draft cookstoves work with higher efficiency due to adequate air supply by using a small blower fan. Due to clean combustion requirements, forced draft gasifier works with a considerable reduction in emission rate. As part of the present study, an improved forced draft gasifier cookstove was designed with reference to the biomass gasification reactor design parameters (Table 1). In addition to the key design parameters, several other factors influenced the operation of cook stove to meet the user's requirements.

2.1.1 Amount of Air and Energy Needed for Gasification (AFR)

AFR refers to the amount of flow of air required to gasify biomass. This is imperative in deciding the size of the fan or of the blower required for the reactor in gasifying the biomass and calculated using Eq. 1 (Odesola & Kazeem, 2014):

$$AFR = \frac{\{\Phi \times B \times SA\}}{\rho a} \tag{1}$$

Table 1 Key parameters considered for designing the improved gasifier cookstove

Parameter	Unit	Value
Cooking power	kW	20
Fuel consumption rate (FCR)	g/min	12–16
Hearth load (HL)	$kg/m^2/h$	200
Fuel holding capacity	Kg	12
Ash storage	Kg	2
Continuous operation	H	1

Energy needed refers to the quantity of heat provided by the stove for cooking. The amount of energy expected to cook the meal for six family persons is assessed to be 15.8 MJ (Panwar, 2009).

2.1.2 Cooking Power and Fuel Burning Rate

The forced draft stove designed for the present study can handle 3–5 kW. Cooking power of a cookstove was estimated by Eq. 2 (Belonio & Anderson, 2005). Fuel burning rate is a key parameter that influences the design of the fuel storage space in the cookstove. Fuel burning rate of the cookstove can be derived from Eq. 3 (The Water Boiling Test Version 4.2.3, 2014).

$$C_{ps} = \frac{\{B \times C_v \times \eta\}}{3.6} \tag{2}$$

$$B = \left\{ \frac{C_p}{(C_v \times \eta)} \right\} \times 3.6 \tag{3}$$

2.1.3 Hearth Load and Fuel Storage Capacity

Gasifier cookstove is a type of updraft gasifier. In an updraft gasifier, the fuel consumption rate with reference to the grate area is in the range of 50–210 $kg/h/m^2$. Hearth load of the gasifier cookstove can be estimated by using Eq. 4. Fuel storage capacity of the TLUD cookstove is proportional to the biomass fuel burning rate (B), the bulk density of the fuel (ρ in kg/m^3), and the duration (d) in number hours (for which the cookstove needs to be operated). Fuel storage capacity by volume can be estimated using Eq. 5.

$$H_l = \left\{ \frac{G_f}{A_t} \right\} \tag{4}$$

$$S_v = \left\{ \frac{B \times d}{\rho} \right\} \tag{5}$$

A set of factors that need to be considered in designing cookstoves are listed in Table 2. These factors are essential for the adoption of cookstove in a large scale.

Table 2 Factors and components to be considered in designing a gasifier cookstove

No.	Factors	Components
1	Convenient fuel feeding	Hopper lid
2	Convenient ash removal	Ash removal grate and ash port
3	Clean combustion and fuel saving	Efficient burner
4	Improved efficiency	Air column and preheated air supply
5	Fire power and control	Blower
6	Low temperature walls	Insulation layers
7	Clean environment	Condensate removals

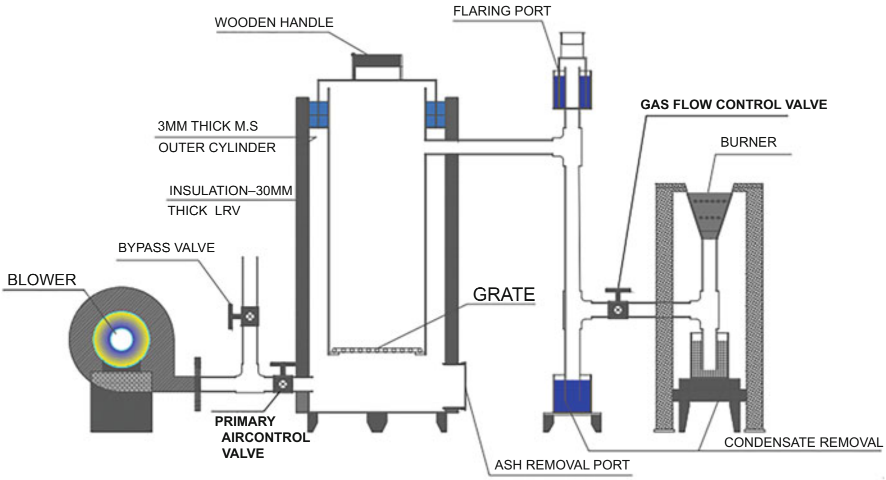

Fig. 1 A sectional view of the gasifier cookstove with details of its components

2.2 Description of the Gasifier Stove

Considering the design procedure discussed in the above chapters, a forced draft gasifier-based cookstove was designed. A sectional view of the gasifier stove is shown in Fig. 1. It should be noted that the reactor is fitted with a small blower (of 0.5 hp. capacity) to provide necessary air for gasification. An air control valve is provided to control fuel burning and gasification rate. A fuel feeding port is provided at the top of the gasifier, and an ash removal port is located at the base. The producer gas outlet of the gas generator/reactor is equipped with two burners. One is for flaring the poor-quality gas created during the initial startup of the TLUD stove. The second is the burner for cooking with the provision of secondary air supply for a clean combustion.

The main burner is provided with a cooking vessel support structure. The flare burner is provided with a water-sealed cap. Condensate removal ports are shown in the drawing. Note that the combustion chamber is provided with an air gap and layer of insulation to avoid heat loss and maintain a high sidewall temperature. This apparatus has the key advantage of keeping the reactor outside the kitchen and the burner inside. The reactor is provided with gas sampling ports for analyzing the gas composition and properties.

2.3 Principle of Operation

The gasifier stove is comprised of two main parts: the gas reactor and the gas burner. The reactor generates flammable gases, primarily CO and H_2, by oxidizing biomass with partial combustion of biomass. The fuels are oxidized just sufficiently to

Table 3 Features of the proposed forced draft-gasifier cookstove

No.	TLUD forced draft	Conventional cookstove
1	Clean combustion due to adequate air supply	Combustion with natural draft with pollutants
2	Combustion of gaseous fuel	Solid biomass fuel combustion
3	The gasification unit is out of kitchen	Gasification unit is in the kitchen
4	Higher safety aspect due to the gasifier is out of kitchen	Entire combustion system is in kitchen
5	High efficiency	Low efficiency

pyrolyze the fuel into char, which can form molecular carbonaceous gases such as carbon monoxide (CO), methane (CH_4), and hydrogen (H_2). Additional incombustible gases formed during gasification include CO_2 and water vapor (H_2O). The amount of air necessary to gasify fuels was provided by a small blower fitted with an air flow regulator. The fuel was gasified inside the reactor in a batch mode. When operating in TLUD mode, the ignition of the fuel was done from the top of the reactor, and the oxidation zone propagates downward. As the air was supplied from the bottom, the oxidation zone moved down at a rate of 1.0 to 2.0 cm/min, depending on the quantity of air supplied. As the oxidation zone moved downward, fully pyrolyzed fuels in the form of char or carbon were left inside the reactor.

The ignitable gases leaving the reactor were conducted by pipe to the cooking station. Air was supplied into the gas stream from the same blower, creating a premixed air-gas supply. At the burner, this premixed gas burns with additional air drawn through the secondary holes. This created a luminous blue flame. The key features of the system are presented in Table 3.

2.4 Observations and Findings: TLUD Cookstove

The system was operated as described above, and the gas supplied was burned to conduct a water boiling test. It was observed that a stable flame was found because of the good gas quality. It was observed that the flame was more stable if tapped from the top of the reactor, rather like a conventional micro-gasifier with a close-coupled flame. When diverting the gas to another room via a pipe, the flame intensity and quality of the flame deteriorated with distance and the gas temperature.

The gas quality was analyzed using gas chromatography (GC), and water boiling test was conducted to establish cooking efficiency. The air supply rate to the reactor was measured to optimize the efficiency of gasification process and to establish the primary air requirement for the burner. The gas produced when operating in TLUD mode was analyzed using GC. Air supply rate needed to obtain good-quality gas was established using a hot wire anemometer. Similarly, the air volume supplied to the burner for premixing was also determined. A three-phase water boiling test was conducted to analyze the performance of the cooking station – essentially a single-burner gas cooker. Cooking efficiency was established at three different times. The different phases of the water boiling test were as follows:

Phase i. Cold start at full power, and raise the water temperature till boiling point (without lid).
Phase ii. Hot start water at full power, and raise the water temperature till boiling point (without lid).
Phase iii. Simmering phase at low power, maintaining water temperature close to 97 °C.

Input energy, output energy, fire power, turndown ratio, and efficiency of the stove were estimated during the water boiling test.

The useful and input energy during the cold start can be estimated by Eqs. 6 and 7.

$$U_{CS} = \left[\{(T_2 - T_1) \times Cp_a \times m_1 + (m_2 - m_1) \times 2257\} + \left\{\left((T_2 - T_1) \times Cp_{pot}\right) \times Mass\ of\ pot\right\}\right] [J] \tag{6}$$

$$I_{CS} = (w_2 - w_1) \times C_v \times M_c \tag{7}$$

The useful and input energy obtained during the simmering phase was estimated by Eqs. 8 and 9.

$$U_{SP} = \left[\{(T_4 - T_3) \times Cp_a \times m_3 + (m_4 - m_3) \times 2257\} + \left\{\left((T_{24} - T_{13}) \times Cp_{pot}\right) \times Mass\ of\ pot\right\}\right] \tag{8}$$

$$I_{SP} = (w_4 - w_3) \times C_v \times M_c \tag{9}$$

The useful and input energy obtained during the hot start phase was estimated by Eqs. 10 and 11.

$$U_{HS} = \left[\{(T_6 - T_5) \times Cp_a \times m_5 + (m_6 - m_5) \times 2257\} + \left\{\left((T_6 - T_5) \times Cp_{pot}\right) \times Mass\ of\ pot\right\}\right] [J] \tag{10}$$

$$I_{HS} = (w_6 - w_5) \times C_v \times M_c \tag{11}$$

The average efficiency of the stove is calculated by dividing the total useful energy obtained during the two water boiling phases by the total energy consumption during those phases.

The efficiency of the stove during the WBT can be estimated by following Eq. 12.

$$\eta_{Boil} = \frac{(U_{CS}) + (U_{HS})}{(I_{CS} + I_{HS})} \times 100 \tag{12}$$

Energy used during the simmering test is estimated using Eq. 13 (Belonio & Anderson, 2005).

$$U_{sp} = \{w_{mw} \times MC \times 4.186(\Delta T + 2257)\}/C_v \qquad [\text{MJ}] \tag{13}$$

Total energy in the gas consumed during the test can be estimated following Eq. 14.

$$U_{All} = U_{CS} + U_{Hs} + U_{SP} \tag{14}$$

Total energy input during the two boiling phases can be estimated using Eq. 15.

$$I_{Boil} = U_{HP-CS} + U_{HP-Hs} \tag{15}$$

3 Results and Discussion

3.1 Air Supply and Gas Concentrations

The average concentrations of CH_4, H_2, CO, CO_2, and N_2 were found to be 1.4 ± 0.5%, 7.74 ± 01.44%, 19.9 ± 1.9%, 27.4 ± 2.1%, and 60.08 ± 2.5%, respectively. The error bars showing the variations of the three replications were taken for the gas samples as shown in Fig. 2. The details of fuel-air supply to the TLUD gasifier and burner are mentioned in Table 4.

To obtain good-quality gas, the air supply rate to the fuel was controlled; equivalence ratio of air supplied for gasification was found to be 0.31 (kg of air per kg of fuel) as shown in Table 4. It was observed that 1.08 m^3 of air was supplied per m^3 of producer gas. With these combinations of the flammable gas existing in the producer gas, the higher heating value (HHV) of the gas was calculated to be 6.95 MJ/Nm^3, when the equivalence ratio of air supply was 0.33. With an equivalence ratio of 0.4, the CV of the gas was 4.3 MJ/Nm^3. The scope of air-to-fuel proportion varied from 1.37 to 1.64 Nm^3/kg, and that of equivalence ratio differed from 0.262 to 0.314.

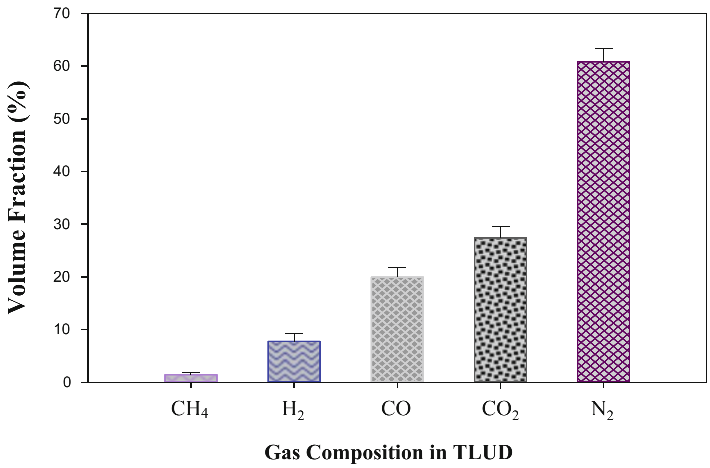

Fig. 2 Comparison of the gas components operated in TLUD mode

Table 4 Details of fuel-air supply to the TLUD gasifier and burner

Parameter	Value	Unit
Fuel consumption rate	10.2	Kg/h
Air supplied for gasification	18.99	Kg/kg
Equivalence ratio of air supply to unit mass of biomass	0.31	Kg/kg
Air supply to the burner	42.83	Kg/h
Gas flow rate	28.56	m^3/h
Air supply ratio of producer gas	1.13	Kg/kg

It is no doubt that primary air fundamentally influences temperature profile of the gasifier, nature of producer gas, hearth load, etc. (Martinez et al., 2012). Feed kind with a HHV (i.e., low moisture, low ash, and high carbon content) will yield producer gas with more flammable components, which implies higher gas quality (Jia & Joseph, 2018). The results are varied with a comparison between the earlier studies reported by Jaojaruek et al. (2011): 4.65 MJ/Nm^3 with lower gas composition CO 20.15%, H_2 11.96%, CH_4 1.05%, and higher CO_2 14.62%. In another previous study reported in (Kramreiter et al., 2008; Martinez et al., 2011), the concentration of H_2 (17%) is almost similar with our finding, but LHV 5.8 MJ/Nm^3 and composition of CO 20%, CH_4 2.4%, and CO_2 12.5% slightly varied. This result proved with Barnes et al. (1994) who found that the CV rises when the equivalence ratio gets a greatest value of 0.388, for which the CV is stated to be 5.62 MJ/Nm^3. Stoichiometric air fuel ratio of 1.2 and 1.3 was stated for producer gas, ensuring a heating value of 5.6 and 6.0 MJ/Nm^3 (Ahrenfeldt, 2007). With an equivalence ratio of 0.27, a hazelnut fired gasifier generates the gas with 5 MJ/Nm^3 that is still lower than our finding (Ma et al., 2012). Hence, the TLUD stove produces high calorific value gas, when compared to Saravanakumar et al. (2007).

The gas stove supplied with a biomass gasifying reactor has several advantages like clear separation between the gas production unit and the gas burner unit. There are various studies of cookstove performance in a standard water boiling test sorted by consideration, for example, time to boil, fuel burning rate, and efficiency (Varunkumar et al., 2012; Chen et al., 2016). Efficiency is generally estimated as the ratio of the heat consumed by the water to the heat content of the fuel. However, comparatively few measure the impacts of the heat supplied by the syngas and the charcoal. By estimating the heat supplied by the syngas, the gasification efficiency may be observed.

Water was boiled to determine the thermal efficiency, fire power, and turndown ratio of the stove while the reactor was in TLUD mode. The three-phase water boiling test was conducted using an aluminum vessel weighing 2.78 kg used to hold 10 liters of water. The efficiency of the stove burning gas during the cold start phase was 25.8%. The efficiency of the stove during the second phase was 29.2% (Tables 5 and 6).

The water temperature profile along with time is shown in Fig. 3. It may be noted that the thermal efficiency of the stove during the cold start and hot start differed by 3.4%. Unlike typical biomass cookstoves, where the biomass combustion chamber is

Table 5 Results of the three-phase water boiling test

Phase I (Cold start water boiling)				
Components	**Unit**	**Exp. 1**	**Exp. 2**	**Exp. 3**
Weight of the vessel	kg	2.78	2.78	2.78
Weight of water	kg	10.0	10.0	10.0
Initial temperature of water	°C	34.1	34.5	34.2
Final temperature of water	°C	100	100	100
Temperature rise	°C	65.9	65.5	65.8
Fuel wood consumed	kg	0.68	0.65	0.69
Efficiency	%	25.1	26.1	25.8
Phase II (Hot start water boiling)				
Weight of the vessel	kg	2780	2780	2780
Weight of water	kg	10	10	10
Initial temperature of water	kg	34.2	34.3	34.5
Final temperature of water	°C	100	100	100
Temperature rise	°C	65.8	65.7	65.6
Fuel wood consumed	kg	0.59	0.61	0.58
Efficiency	%	28.9	27.9	29.2
Phase III (Simmering phase)				
Water evaporated	kg	2.89	2.95	2.98
Fuel wood consumed	kg	0.88	0.87	0.92
Efficiency	%	42.8	44.2	42.2

Table 6 Key performance results for boiling water and simmering

Phase of WBT	Energy input (kJ)	Energy output (kJ)	Duration (min)	Efficiency (%)	Fire power (kW)
PH-I	11,319	2918	9	25.8	20.96
PH-II	9947	2906	8	29.2	20.72
Total	21,266	5824	17	27.4	20.85
PH-III	15,778	–	45	–	5.8

just below the cooking vessel, this stove is physically separated from the biomass reactor. Hence, radiation from the reactor does not contribute any useful heat to the cooking process, while the thermal mass of the hot reactor chamber also does not contribute any energy to the vessel.

The comparison of the thermal efficiency of the gasifier stove obtained from both phases was still higher as reported by Ahmad et al. (2016), 17.8%.

Similar findings with some variations have been obtained by previous researchers (Caballero et al., 2000; Kirubakaran et al., 2009; Ryu et al., 2006). Biomass cook stove has a thermal efficiency of 33% obtained by Lupesh et al. (2015). According to Khadija and Munir (2015), the gasifier wood stove has a maximum thermal efficiency of 30%, which is similar with some variations.

The thermal performance of the Oorja-Plus stove which was recorded as 32% during cold start and 33% during the hot start phase was similar with small variation

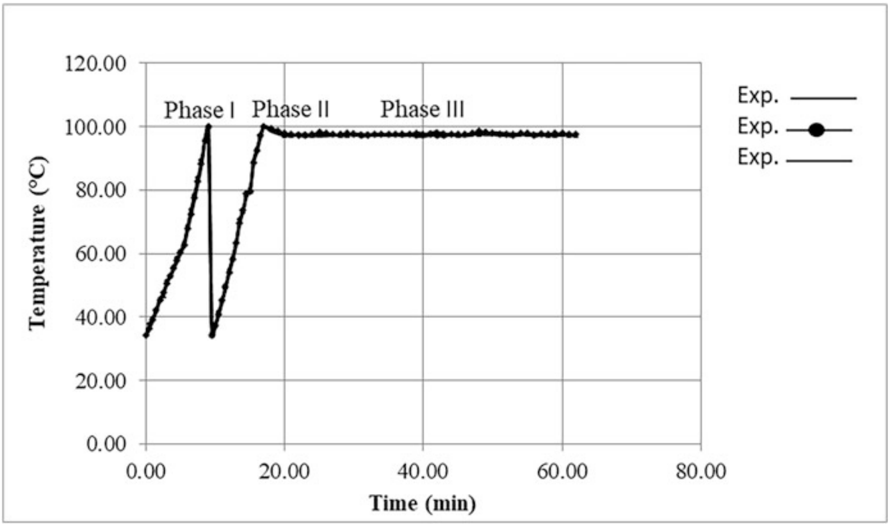

Fig. 3 Water temperature profile along with time

reported by Raman et al. (2013). The thermoelectric generator cookstove efficiency was recorded around 42.3% and 46.9% during the cold-start high-power phase and hot-start high-power phase, respectively, that are not similar with our results (Jang & Tsai, 2013). The thermal efficiency of fixed bed micro-gasifier is achieved to be about 36.7 ± 1% for coconut shell, 36 ± 1% for *Prosopis juliflora*, and for wood pellets about 38.5 ± 1% that are different from our findings (Sakthivadivel & Iniyan, 2017). However, the efficiency of the stove is higher than some forced draft, improved, and traditional stoves.

4 Conclusions

A biomass gasification system with a gas cookstove was designed and tested. Adding an air injection nozzle just above the grate was found to enhance performance when the fuel was ignited from the bottom. The gas produced during TLUD operating mode provided gas with a sustainable and clean flame, irrespective of the vertical position of the oxidation zone. The stove cooked with an average efficiency of 27.4% at high power. The maximum fire power is estimated to be 21 kW. The minimum power during the simmering phase was determined to be 5.8 kW. The turndown ratio was 3.6:1. Air supply ratio for the gasification of biomass was found to be 0.31:1. To conclude, when operated in TLUD mode, the stove is user-friendly; it provides clean combustion and safely separates the gas burner from the gas reactor. Separation of these provides flexibility in the usage of space and delivers a cleaner environment in the kitchen.

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Nomenclature

C_{ps}	Cooking power of the stove, kW
B	Biomass burning rate, kg/h
C_v	Calorific value of the biomass (moisture free), MJ/kg
H_l	Hearth load, g/cm^2/h
G_f	Gas flow rate, Nm^3/h
A_t	Area of the grate, cm^2
S_v	Fuel storage capacity, L
d	Duration of operation in one stretch, h
Cp_a	Specific heat of the producer gas, kJ/kg/K
M_c	Moisture content of the fuel wood, %
SA	Stoichiometric air
AFR	Amount of the air needed for gasification, kg
ICS	Improved cookstove
WBT	Water boiling test
η	Efficiency of the stove during the water boiling test, %
U	Useful energy obtained during the water boiling test, MJ
T_1, T_3, T_5	Initial temperature of the water, ˚C
T_2, T_4, T_6	Final temperature of the water, ˚C
w_2, w_4, w_6	Remaining weight of the biomass, kg
m_1, m_3, m_5	Initial mass of the water, kg
m_2, m_4, m_6	Final mass of the water after boiling, kg

Subscript

sp	Simmering phase
HP	High power
CS	Cold start
HS	Hot start

Greek Symbols

Φ	Equivalence ratio
ρa	Air density

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Biomass Energy from Agriculture

Conversion Techniques and Use

Santosh Kumar, Shiv Kumar Lohan, and Dilwar Singh Parihar

Contents

Abstract

Environmental alarms like climate change, acid rain, and air pollution from the use of fossil fuels and developments in biomass technology have rejuvenated the attention in biomass energy as a renewable and sustainable energy source. Worldwide, biomass energy contributes to 10–14% of total energy demand. In rural areas, 90% of energy is obtained by biomass, and in urban areas it is 40%. The share of biomass is more than one-third of primary energy requirements. After forest, agriculture sector provides the largest contribution for total biomass energy production. Totally, 140 billion metric tons of biomass is produced by agriculture every year. Improper management of such massive amount of agricultural biomass is becoming a growing problem as rotten agricultural biomass emits methane and leachate, and open burning by farmers to clear the fields release CO_2 and other harmful particulates in local environment assisting for climate change, water and soil impurity, and local air pollution. This volume of

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biomass can be converted to a vast amount of energy, and raw materials for energy production can greatly displace fossil fuel, reduce emissions of greenhouse gases, and provide renewable energy to farmers in developing countries like India, which still lack access to electricity. Using agricultural biomass as energy source will decrease the agricultural waste management cost and would make revenues from the sale of the mended energy. To manage agricultural biomass and to convert it into a beneficial resource, extensive efforts are being taken by many governments and other institutions, and there are stagnant gaps to be filled.

1 Introduction

Biomass is organic matter that is derived from recently living organisms. This organic matter can come from plants, animals, and their byproducts and can be used to generate electricity, heat, or other forms of energy. Biomass can also be used to produce biofuels such as ethanol and biodiesel (Demirbaş, 2001). A biomass is defined as the mass of living organisms, such as plants, animals, and microorganisms, or, from a biochemical perspective, cellulose, lignin, sugars, fats, and proteins. In addition to leaves, twigs, branches, boles, tree roots, and grass rhizomes, plant biomass consists of aboveground and belowground tissues. There are two ways of expressing biomass: mass per unit area and dry weight (water removed by drying) (Houghton, 2008). A biomass can be classified chemically into five primary components: cellulose, hemicellulose, lignin, extractives/volatiles, and ash. For centuries, people have used wood for cooking food and creating heat; therefore, fire wood is still the leading biomass energy source for rural areas. Biomass may also be derived from food crops, grasses, woody plants, agricultural or forestry residues, oil-rich algae, municipal wastewater (crop wastes, forest residues, purpose-grown grasses, woody energy crops, algae, industrial wastes, sorted municipal solid waste, urban wood waste, and food waste), and industrial wastes (Balaman, 2018). There is also the possibility of using landfill fumes for biomass energy. Landfill fumes contain methane, the main component of natural gas. Biofuels can be in solid form (fuelwood, charcoal, wood pellets, briquettes, etc.) or liquid (bioethanol, biodiesel).

Bioenergy, derived from plants that use sunlight and CO_2 to assimilate carbon into biomass, has emerged as a potentially sustainable energy source with low climate impact (Rahman et al., 2017). Energy derived from biological and renewable sources (biomass) can be classified as bioenergy; it can be converted into heat or electricity. Biomass can be used for fuels, power production, and products that would otherwise be made from fossil fuels.

We have relied on biomass in all its forms for every essential need throughout history, often concluded as the six “Fs”: food, fuel, fiber, feed, feedstock, and fertilizer (Rosillo-Calle et al., 2015). In the early nineteenth century, biomass was a primary source of energy for industrial countries, and it is still the main source of energy in most developing countries today. The use of biomass fuels for cooking is widespread throughout households, institutions, and cottage industries, ranging from brick and tile manufacturing, bakery operations, food processing, weaving, and restaurants. In recent years, many new biomass-based plants have been built to provide energy directly through combustion, for electricity generation, or to generate ethanol directly (Balat & Ayar, 2005). Three quarters of the world's population gets approximately 35% of its energy needs from biomass energy, particularly in its traditional forms. In the poorest developing countries, this number can reach between 60 and 90%. It is estimated that in developed and developing countries, 20–25% of total biomass energy is now used for modern applications biomass energy (Surendra et al., 2014).

The primary energy consumption in India grew by 2.3% in 2019 and is the third biggest after China and the USA with 5.8% global share. More than 70% of India's population is dependent upon biomass for its energy needs, which provides 32% of our total primary energy in the country (IEA, 2021). In the near future, many people are expected to rely on the energy sector as their primary source of energy. Biomass is used for multiple purposes throughout the universe, so it is critical to understand how these uses interact. A new form of biomass energy will most likely be successful only if it uses modern technology (Thomas et al., 2018). To have a long-term future, bioenergy would have to be able to deliver what people want: cost effective, clean, and sustainable power forms such as electricity, as well as liquid and gaseous fuels.

Biomass is used since many years for meeting numerous human demands including energy. Among all the biomass energy sources, wood fuels are the most prominent (Keoleian & Volk, 2005). In 2017, the renewable energy share was 17.7% in the globally energy consumption which was a drop of 0.2% from the earlier year. Among all renewable energy sources, bioenergy is the largest energy source accounting 70% of all renewable sources (Statistics WGB, 2019). In the nineteenth century, biomass' share in total energy declined steadily with a steady increase in the use of fossil fuels. However, the share of fire wood consumption is decreasing from the past few years, but the consumption is rapidly growing.

In the Asia, biomass is used as a primary source of energy particularly in developing countries like India, Pakistan, and Bangladesh. Due to their agricultural economies and extensive forest cover, most Southeast Asian countries have turned to biomass for their primary and additional energy needs (Hall et al., 1994). Biomass energy potential from agriculture and forest residues in this region is estimated to be more than 8000 million gigajoules per year, or more than 500 million tons per year (Twidell & Weir, 2006). A decline in biomass energy has occurred in most Asian developing nations as a result of rapid industrialization and marketization over the past two decades. Over the past two decades, biomass energy consumption has grown at an annual rate of over 2 % (FAO, 1997; The Outlook for Energy, 2013). The sector-wise energy contribution and consumption of the world is given in Table 1.

The use of biomass has been sustained by various factors, such as a growing population and the shortage or unavailability of commercial fuels in rural and traditional sectors (Kaygusuz, 2011). A substantial amount of forest has already been destroyed as a result of population pressure on existing forests. Deforestation

Table 1 Global energy scenario of energy consumption 2001–2040 (estimated)

S. No.	Sectors	2001	2010	2020	2030	2040
1.	World energy consumption (M tonne)	10,038	11,752	13,553	15,547	17,690
2.	Biomass	1080	1291	1653	2221	2843
3.	Hydra (large)	223	255	281	296	308
4.	Hydro (small)	9.5	16	34	62	91
5.	Wind	4.7	35	167	395	584
6.	PV	0.2	1	15	110	445
7.	Solar (thermal)	4.1	11	41	127	278
8.	Solar (thermal power)	0.1	0.4	2	9	29
9.	Geothermal	43	73	131	194	261
10.	Marine	0.05	0.1	0.4	2	9
11.	Total renewable energy (RE)	1364	1683	2324	3416	4844
	Percent RE	13.6	14.3	17.1	22	27.4

Source: Rosillo-Calle et al. (2015)

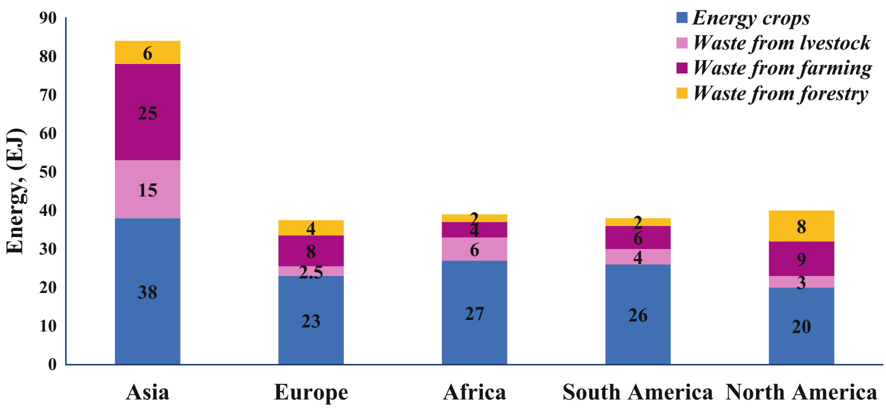

Fig. 1 Global biomass energy production from various sources in different countries

was more than eight times greater than afforestation in tropics during the 1980s despite various policy interventions by Asian countries. As a result of deforestation and land degradation, tropical Asian forests contribute more carbon dioxide (Dixon et al., 1994). To achieve sustainable biomass energy growth in Asia, modern plantations and energy crops need to be introduced along with technology that can efficiently convert biomass into energy. Recently, many Asian countries have initiated such programs. The global energy contributions of various sources are shown in Fig. 1.

At present, Indian coal production accounts for 51%, natural gas for 9%, and imported crude oil for 35% of the country's commercial energy demands. Hydropower and nuclear energy account for the remainder (Muneer et al., 2005). India has experienced economic growth of 7% annually since 2000, but the growth has been unbalanced between urban and rural areas. Despite a fast rate of economic growth, India is still energy poor in many parts of the country due to a lack of access to energy (Balachandra, 2012). There is no grid electricity accessible to nearly one-fourth of the country's population, and 44% of rural people (FAO, 2005). Around 30% of India's primary energy supply comes from biomass, which remains the dominant source of energy. Biomass is mostly used for cooking and space heating in rural areas where nearly 70% of the Indian population lives.

In the Indian context, biomass energy contributes one-third of the total primary energy resource. The majority of biomass fuels are used by rural households for cooking and water heating, as well as by traditional and artisanal industries. India's domestic energy needs are met by biomass to the tune of 90% in rural areas and 40% in urban areas in which 56% of contribution is from fire wood (NCAER, 1992; Sinha et al., 1994). Over the past two decades, fire wood consumption has grown by 2% annually (FAO, 1981, 1986, 1996). Since most biomass is not traded on the market, estimates of biomass consumption are highly variable. According to supply-side estimates, biomass energy can be obtained from domestic fuelwood (dry), crop residue (96 million tons), and cattle dung cake (37 million tons) (Ravindranath & Hall, 1995). India's fuelwood demand is estimated to be 201 million tons per year (Rai & Chakrabarti, 1996). Households typically collect biofuels for their own needs or grow their own. Approximately 40 million tons of fuel-wood have been added to the supply of fuel annually by the government's social forestry program (Ravindranath & Hall, 1995).

A total of 140 million hectares of arable and permanent crop land make up 43% of India's total area. The main crops are wheat, rice, oil seeds, pulses, and other commercial crops including cotton, sugarcane, mulberry, jute, coconut, etc. Cereals dominate the agricultural crops followed by pulses, cotton, and sugarcane. Bioenergy generation from agricultural crop residues in India is a promising source of renewable energy (Ravindranath et al., 2005; TERI, 2009). According to an estimate, crop residues' potential was about 317 million tons during 2005–2006 (MSSRF, 2011). The biomass availability from various crops, i.e., rice, wheat, jowar, bajra, maize, gram, pulses, cotton, and sugarcane residue, is shown in Table 2. The maximum crop reside is produced form rice crop followed by sugarcane.

A wide variety of biomass resources can be used to produce energy, including silviculture (forests), agriculture (fields), aquaculture (fresh and sea water), and industrial and social activities which produce organic waste residues (food processing, urban refuse, etc.

There are nearly 20 million hectares of barren and uncultivated lands in the country, representing more than 55 million hectares of wastelands. Due to their high investment costs and low economic returns, barren and uncultivated lands are rarely suitable for agricultural practice. By afforestation/reforestation and forest enrichment, it is possible to exploit part of these lands for energy wood plantation (Directorate of Economics and Statistics, 2012). A survey was conducted in which respondents were asked for suggestions on which tree species could be a promising candidate for energy wood plantation on various types of uncultivated lands, such as lands on roadsides, railway tracks, and embankments; forest lands; fallow lands; and

Table 2 Biomass availability from agri-residue in India

Crop	Economic produce	Gross cropped area	Total economic production	Total residue production	Type of residue
		Mha	MT	MT (air dry)	
Rice	Food grain	42.6	85.7	154.3	Straw + husk
Wheat	Food grain	26.5	70.3	112.5	Straw
Jowar	Food grain	9.0	7.2	14.3	Straw
Bajra	Food grain	9.3	8.2	16.3	Straw + cobs
Maize	Food grain	7.4	14.0	35.1	Straw
Other cereals	Food grain	3.2	3.7	7.4	Stalk
Red gram	Food grain	3.5	2.4	12.0	Waste
Gram	Food grain	6.8	5.5	8.8	Waste
Other pulses	Food grain	12.1	5.5	15.9	Shell + waste
Ground nut,	Oil seed	6.2	6.4	14.7	Waste
rapeseed, and mustard	Oil seed	6.3	6.7	13.3	Waste
Other oil seeds	Oil seed	16.1	14.9	29.8	Waste
Cotton	Fiber	8.4	16.0	55.9	Seed + waste
Jute	Fiber	1.0	11.0	17.6	Waste
Sugarcane	Sugar	4.3	279.0	111.6	Bagasse + leaves
Total		162.7		619.4	

Source: TERI (2009)

local government lands. Wood, charcoal, and gas can be produced from forests, whether natural or cultivated. Woods waste and byproducts from the forest-processing industries can be used at the mil (Pervin, 2017). Forest lands are used for more than just firewood; they are also used for sawn timber, papermaking, and other industrial purposes. Several rapidly energy-intensive plants, such as eucalyptus, poplar, and pine, are specifically grown for energy production. Numerous plants produce seeds or nuts that may be used for oil production with the help of crushing machinery. This vegetative oil can be used as biodiesel (Atabani et al., 2013). Oil-producing plants can be categorized as wild plants such as *Jojoba* and *Karanj* which do not require maintenance and agricultural crops, e.g., *Jatropha curcas* (*Ratanjyot*, produces seeds), which require common agricultural techniques. There are more than 300 different kinds of oil-producing trees; the majority of them are wild and therefore do not need any maintenance or effort. Those plants are quite resilient, requiring little water, can fight severe drought and pest, can live in hot and cold climes, and can thrive on most soil types (Thornton, 2012). In India, the experience with a wild, oil-bearing tree, *Karanj* (Pongamia pinnata), has been encouraging. Total 30 million hectares of Jatropha could be planted to produce equivalent biofuel that would replace the country's current fossil fuel use.

2 Biomass Conversion Techniques

Modern biomass technologies are considered over a decade for thermal, motive, and electricity power generation. Biomass conversion techniques refer to the processes used to convert organic matter, such as agricultural waste, wood, and other biological materials, into useful energy sources, such as electricity, heat, and biofuels (Naik et al., 2010). Common methods of biomass conversion include direct combustion, gasification, pyrolysis, anaerobic digestion, and fermentation (Dahlquist, 2013). Each process has its own advantages and disadvantages and can be used to create different types of fuels, such as ethanol, biodiesel, and biogas. Table 3 shows the sources of biomass with its conversion technology and how efficient these technologies are for energy generation.

Variability in mass, density, size, moisture content, and intermittent supply of feedstock has greater effect on biomass to energy conversion technologies. In modern industrial technologies (known as hybrid fossil-fuel/biomass technology), fossil fuel is used for drying, preheating, and maintaining the fuel supply during biomass interruption (Sharma et al., 2014). The following processes are used to convert the biomass into energy:

1. Direct combustion
2. Thermochemical conversion
3. Chemical conversion
4. Biological conversion

2.1 Direct Combustion

Direct combustion of biomass is a method of generating energy by burning biomass directly. Direct combustion of biomass is the most common method of generating heat from biomass, and it is also used to generate electricity from biomass in some cases (Demirbaş, 2001). Direct combustion involves burning the biomass material in a furnace, boiler, or other device that is designed to convert the chemical energy in the biomass into thermal energy. In this process, 800 and 1000 °C temperatures are achieved by the furnace. The thermal energy is then used to generate electricity or used directly for heating and cooking. The combustion process produces byproducts such as ash and gases, which must be managed and disposed of properly. The efficiency of direct combustion method depends upon the type of fuel burnt and varies from 60 to 70% (Sharma et al., 2000). Direct combustion is a mature and cost-effective technology, but it has significant environmental impacts due to emissions of air pollutants and greenhouse gases.

Table 3 Various types of energy sources conversion technology and energy output

Source		Biomass source	Technology	Conversion efficiency (percent)	Energy required for conversation	Energy from biofuel (MJ)
Grain crops		Straw	Combustion	70	Drying	14–16/kg dry straw
Sugar-cane	Juice	Ethanol	Fermentation	80	Heat	3–6/kg fresh cane
	Residue	Bagasse	Combustion	65	Drying	5–8/kg fresh cane
	Total	–	–	–	–	8–14/kg fresh cane
Animal waste	Tropical	Biogas	Anaerobic digestion	50	–	4–8/kg dry input
	Temperate	Biogas	Anaerobic digestion	50	Heat	12–4/kg dry input
Forest		Heat	Combustion	70	Drying	16–20/kg wood
Urban waste		Heat	Combustion	50	–	5–16/kg dry input
Sewage gas		Biogas	Anaerobic digestion	50	–	2–4/kg dry input

Source: Twidell and Weir (2006)

2.2 Thermochemical Conversion

Thermochemical conversion refers to the decomposition of algal biomass for the production of biofuels including liquid, gaseous, and solid fuels. Thermochemical conversion is considered as the simplest method for the conversion of microalgae into biofuel compared to chemical and biochemical process (Singh et al., 2016). For thermochemical conversion of biomass in partial controlled environment, high tempreature is applied which intiates chemical reaction to produce charcoal and producer gas. The produced producer gas is a mixture of carbon monoxide (CO), hydrogen (H_2), carbon dioxide (CO_2), and nitrogen (N_2). Advanced uses of this process include production of diesel, biofuel, and electricity generation. Thermochemical conversion can be classified as pyrolysis, gasification, and carbonization based on their temperature, pressure, and duration of heating.

2.2.1 Pyrolysis

Pyrolysis is heating of the feedstock in the absence of oxygen so as to interrupt the lengthy chain molecules into short chain molecules. In this process, biomass is generally used as a feedstock to produce syngas. The produced syngas is an aggregate of hydrogen, unstable natural compounds, and carbon monoxide (Carrasco et al., 2017). Change in the conditions results in the production of fluids just like diesel and many other different products (Fig. 2). Further work is done for the use of excess pressure reactor for the production of hydrogen and use of low-pressure catalytic systems (requiring zeolites) to produce alcohol from pyrolytic oil. The main benefit of pyrolysis is that it changes biomass into gases and vapor fuel which is easy for transport, shipping, and accumulation. The produced gases will burn in boilers, gas turbines, and reciprocating engines and increased the flexibility and security of gasoline. Combustion of methane and carbon monoxide present in syngas produce carbon dioxide which is a less effective greenhouse gas than

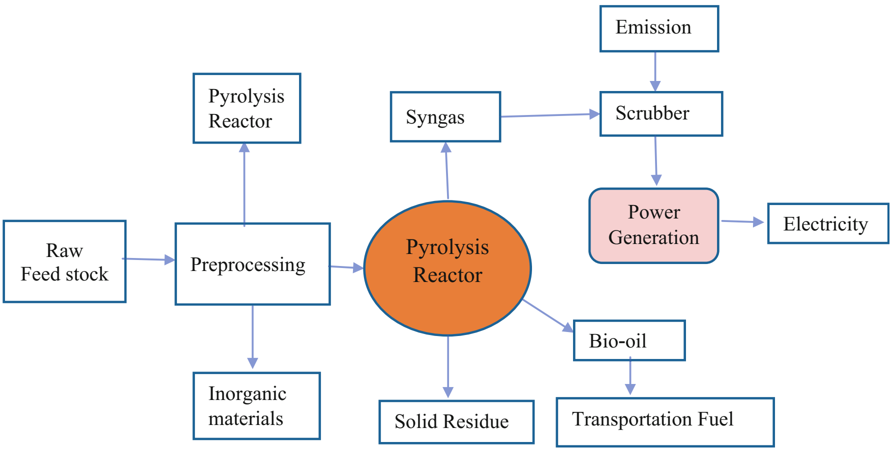

Fig. 2 Flow chart for pyrolysis of biomass

methane; hence, it balances fossil fuel energy production (Jeffry et al., 2021). However, the negative aspect of pyrolysis is that extra energy is required to produce syngas from the chemical reactions.

2.2.2 Gasification

Gasification of biomass is a process in which biomass is heated in a low-oxygen environment to produce a combustible gas known as producer gas or synthesis gas (syngas). This gas is a mixture of carbon monoxide (CO), hydrogen (H_2), carbon dioxide (CO_2), and other trace gases. It can be used as an alternative fuel to generate energy and heat in various applications such as power generation, transportation, cooking, and more (Shukla & Kumar, 2017). Gasification occurs at an 800 °C temperature and is performed in closed top or open top gasifiers. The approach for enhancing constant carbon substances derived from renewable carbon sources involves converting CO_2 from sources other than biomass species into synthetic fuels and organic intermediates. A handy approach of offering the desired strength and of concurrently decreasing the oxidation state is to reduce CO_2 with hydrogen (Patel et al., 2020). The end product, for example, may be methane (CH_4), the dominant element in biofuel line and the most effective hydrocarbon known, or different organic compounds.

A hydrogen-containing intermediate gas can also be produced from biomass through partial oxidation or steam reformation. Hydrogen might then successfully act as an energy provider from the biomass to CO_2 to yield an alternative or synthetic natural gas (Pandey et al., 2019). The production of different synthetic natural fuels may be finished in a comparable manner. For example, synthesis gas (syngas) is an aggregate of hydrogen and carbon oxides. It may be produced by biomass gasification techniques for next conversion to an extensive variety of chemical compounds and fuels (Speight, 2016). These consist of nonstop water splitting by electrochemical, biochemical, thermochemical, microbial, photolytic, and biophotolytic methods.

The primary idea of the use of biomass as a renewable energy resource includes the capture of solar power and carbon from ambient CO_2 in developing biomass that is transformed to different fuels (biofuels, syn fuels, and hydrogen) or is used directly as a source of thermal power or is converted to chemical substances or chemical intermediates as shown in Table 4.

2.2.3 Carbonization

This is a vintage pyrolytic method optimized for the production of charcoal. Traditional strategies use pilation of wood in the earth mounds or pits into which the wood is piled. The conversion rate of the conventional method is very low; it is generally estimated that on weight basis, 6–12 tonnes of wood is required for per tonne production of charcoal (Nizamuddin et al., 2017). During carbonization, unstable additives present in wood are eliminated, and this procedure is likewise called dry wood distillation. Due to reduction in degree of hydrogen and oxygen, carbon present in wood accumulates. The wood undergoes some of the physiochemical modifications because the temperature rises. As the temperature rises beyond

Table 4 Thermochemical conversion process overview

	Direct combustion	Pyrolysis	Gasification
Process conditions			
Temperature (°C)	>700	300–600	>600
Reaction time	–	1 s (fast), days (slow)	Several seconds to minutes
Air supply (λ^a)	$\lambda \geq 1$	$\lambda = 0$	$\lambda = 0.2–0.5$
Products			
Gaseous product	CO_2, H_2O, CO, C_XH_Y, NO_X, and SO_X	CO, CH_4, C_XH_Y, CO_2, H_2O, pyrolysis oil, N- and S-containing compounds	CO, H_2 CH_4, C_XH_Y, CO_2, H_2O, tars, NH_Y, NO_X, H_2S, and COS
Solid	Ash (N, S)	C_m, H_s, O_k, (N, S), and ash	C, (N, S), and ash

100 and 170 °C, most of the water vapor evaporates and CO and CO_2 condensable gases developed inside the pile (Rasul, 2016). These condensable vapors can be used for the production fuel after condensing and cleaning. An exothermic reaction develops from 270 °C and 280 °C which is detected with the help of using the spontaneous generation of heat. There are mainly three primary kinds of charcoal-making methods available: (a) internally heated: these charcoal kilns are the most common form of charcoal kiln. It is observed that 10–20% of wood (on weight basis) is sacrificed, a similarly 60% (on weight basis) is misplaced during the conversion and release of gases to the ecosystem from those kilns; (b) externally heated: in this system, an external fuel source is required which can be furnished from the producer gas as soon as initiation of pyrolysis happens; and (c) hot circulating gas: it is used for the production of chemicals. Recirculation of heated gas systems provide facility to generate big portions of charcoal and are related with the aid of using-products. However, this method is currently restricted due to excessive investment costs for large-scale plant. Figure 3 showing the schematic flow chart of the carbonization process.

2.3 Chemical Conversion

The chemical conversion of biomass involves breaking down biomass molecules into simpler molecules through chemical reactions such as transesterification and catalytic liquification (Naik et al., 2010). These processes can be used to produce fuels such as ethanol, methanol, and biodiesel, as well as other chemical products such as chemicals, fertilizers, and plastics. Transesterification is a chemical conversion process used for converting vegetable oils, animal fats, and greases into fatty acid methyl esters, which are further used to produce biodiesel (Gollakota et al., 2018). In the transesterification process, a glyceride reacts with an alcohol (typically methanol or ethanol) in the presence of a catalyst forming fatty acid alkyl esters and

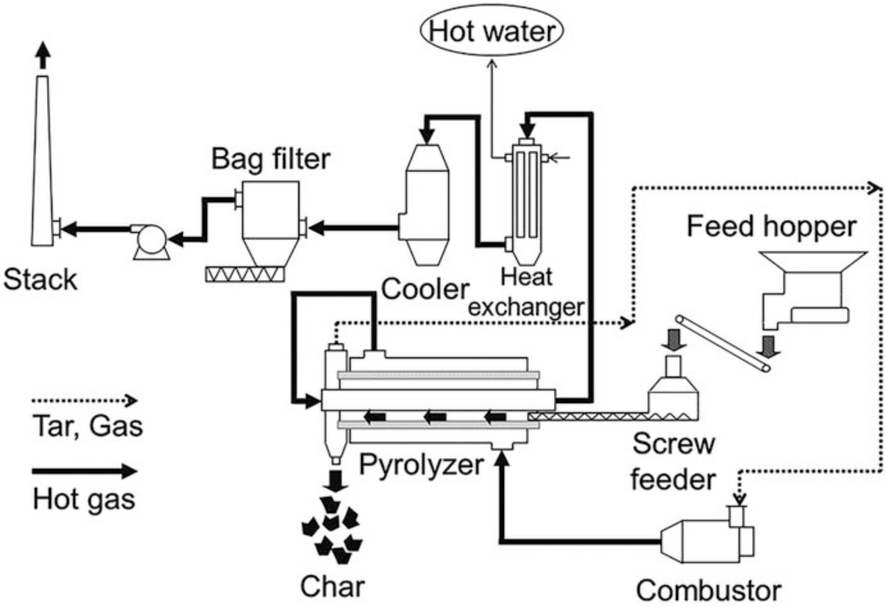

Fig. 3 Flow chart for carbonization of biomass (Okuma et al., 2015)

an alcohol. This technology provides better quality products of extra energy density. These products also require less processing to supply marketable products. This process is a low-temperature and excessive pressure thermochemical conversion method accomplished in the liquid phase. This method calls for both a catalyst and an excessive hydrogen partial pressure (Saxena et al., 2008). Technical problems associated with this technology limit the opportunities related to catalytic liquefaction.

2.4 Biochemical Conversion

Biochemical conversion includes the anaerobic digestion and fermentation in which enzymes, bacteria, or other microbes are used to break down biomass into liquids and gaseous feedstock.

1. Anaerobic digestion
2. Methane production in landfills
3. Ethanol fermentation

2.4.1 Anaerobic Digestion

Anaerobic digestion is the microbial digestion of feedstock which releases heat, methane, carbon dioxide, hydrogen gas (under specific conditions), and hydrogen sulfide. The digestion takes place in huge tanks over several days under suitable conditions. The gas released during this process is called biogas (Sorathia et al., 2012). The produced gas has been cleaned to remove the acidic compounds by condensation which is then used as a fuel. Anaerobic reactors are used for production of methane from human and animal manure and from crop residues as well. The biogas produced is a usable energy source for cooking and lighting (Li et al., 2016). However, the sludge produced after the manure has surpassed via the digester and is also nonpoisonous and odorless which is used as a fertilizer. This is because many of the nitrogen compounds in fresh manure turn out to be volatized while drying in the sun. During digestion, blended methanogenic bacterial cultures are utilized for growth which are characterized by finest temperature ranges (Noonari et al., 2019). These blended cultures permit digesters to be operated over an extensive temperature variety, i.e., above 0 °C as high as 60 °C. The microorganism converts approximately 90% of the feedstock into biogas (containing approximately 55% methane) during the full functioning of the digester. The benefit of anaerobic digestion is that it directly converts organic material into methane. Capturing and combusting the methane produces carbon dioxide that is a much less effective greenhouse gas (Wu et al., 2010). The disadvantage of anaerobic digestion is that the microbes possess a fitness hazard to humans and livestock. The microbes are very sensitive to adjust in the feedstock and in particular, the presence of antimicrobial compounds, require regular movement of reactor fluid, and a steady temperature and pH.

2.4.2 Methane Production in Landfills

Methane production in landfills occurs as a result of the anaerobic decomposition of organic materials. The organic materials break down into various compounds, such as methane, carbon dioxide, and hydrogen sulfide. Methane is a greenhouse gas that is 21 times more potent than carbon dioxide. Thus, landfills are major sources of methane emissions. Methane is captured from landfill sites through a series of pipes, which transport the gas to a flare or to a collection device (Kashyap et al., 2016). From there, the methane can be used as a fuel source or converted into other forms of energy, such as electricity. The great quantity of methane is being produced from dumped methane production from landfill areas. Commercial production of land gas is a useful resource with the leaching troubles as nowadays the problems related to landfills are increasing (Arancon et al., 2017). Local groups neighboring land fill sites are getting extra aware about the ability for heavy metals and vitamins to leach into aquifers. Landfill processing reduces the quantity of disposed sludge and nutrient content which facilitate proper disposal. The levels of organic matter produced per capita range from advanced to growing nations, e.g., the share of Municipal Solid Waste (MSW) in Sierra Leone is 90% as compared to approximately 60% for US MSW.

2.4.3 Ethanol Fermentation

Ethanol fermentation is a process by which sugars, typically derived from biomass and its derivatives, are converted to ethanol. This process is typically performed by microorganisms such as yeasts and bacteria (Dionisi et al., 2015). The sugars are usually obtained from biomass and its derivatives, such as cellulosic and starchy materials, including agricultural residues, food waste, and energy crops. The biomass is first converted into sugars through hydrolysis, followed by fermentation of the sugars to produce ethanol. The ethanol can then be distilled or used as a fuel or chemical feedstock. The substantial profits made during fermentation technology make the production of ethanol to be used as a petroleum replacement and fuel enhancer. The produced ethanol gives positive assumptions and lessens the dependence on the imported oil and energy supply (Wyman, 1999). The equation for ethanol production is as follows:

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$$

The most commonly used feedstock in growing nations for the production of ethanol is sugarcane due to its high productiveness which is supplied with enough water, and where water availability is limited, sweet sorghum or cassava may also become the desirable feedstock. Other benefits of sugarcane are that it provides excessive residue energy ability and current management practices make the production sustainable and environmentally benign while at the same time it permits continuous production of sugar. Other feed stocks consist of saccharide-rich sugar beet, carbohydrate-rich potatoes, wheat, and maize. As technology progresses, cellulosic feedstocks are now being used for production of alcohol, opening up the possibility of becoming economically competitive in the medium term.

2.5 Densification Techniques

The utilization of agricultural waste is often difficult due to its uneven characteristics. These are either not used or burnt inefficiently in their loose form which led to air pollution (Satlewal et al., 2018). Biomass is hard to utilize as a fuel as it is bulky, wet, and has a dispersed nature in the loose form. Due to low bulk density, crop residue is a too arduous job to handle and transport. Transforming the agriculture crop residue into high-densified fuel like briquettes and pellets provides an inexhaustible resource of energy. Biomass densification technology converts plants residues into a consolidated form of fuel generally known as pelleting and briquetting which change the management facilities of the material handling for transport and storage (Balan et al., 2013). This technology is used for many years in several countries. The process of densification or molding a biomass material into the shape of a pellet is called pelletizing. Pellets are made from a wide range of materials, including agricultural biomass residues, and animal compound feed, which can be used in the same manner as briquettes to generate heat. In addition to being too small and shaped in size and shape, briquettes do not emit pollutants like nitrogen oxide and sulfur oxides that cause pollution (Karkania et al., 2012). The principle of manufacturing process of pellets is mostly similar to the briquettes formation which are 4–5 times smaller than pellets, and their size varies from 4 to 7 cm.

Fig. 4 Different products of biomass densification techniques

Cubes are the rectangular-shaped material which are slightly denser and larger than pellets. The dimensions vary from 13 to 38 mm in cross-section and 25 to 102 mm in length. The process includes the compression of shredded biomass through a heavy press wheel which presses the biomass through dies to form cubes. Pucks have density similar to pellets and are made by using briquetter and resilient wet (Abdoli et al., 2018). As compared to palletization process, the production cost of pucks is very less. It is 75 mm in diameter and seems like a hockey puck. Wood chips are produced by wood chipper machine and are utilized in the accomplishment of cooking houses and industrial needs. The boilers plants require wood chips of 5–50 mm (0.2–2 in) in length. In context of feeding fuel, woodchips are cheaper in cost than coal (Young, 2007). Different products obtained from biomass densification techniques are shown in Fig. 4.

3 Indian Biomass Energy Conversion Policy

Nowadays, power consumption in India has been increasing at a relatively high rate due to population and financial boom. With rapid increase in urbanization and energy requirements of Indian residents, policy requirements elevate on regular basis. To complete the needs, the Government of India is making diverse plans and rules to strengthen the sector. Sustainable development is the biggest challenge of the world; consequently, renewable energy resources are considered for energy generation. Ministry of New & Renewable Energy of India has evolved many ventures and rules and offers diverse subsidies and incentives to undertake these technologies. In the 12th 5-year plan period 2012–2017, the government allocated overall Rs. 46.00 crores for a biomass gasifier scheme which incorporates promotional and different administrative activities (Manju & Sagar, 2017). Program implementation during the 12th 5-year plan period from 2012 to 2017 has covered the subsequent components:

- Off-grid/dispensed energy program primarily based on biomass gasifier, to fulfill the unmet demand of electricity in the rural region.
- At grid-level power application, 100% producer gas-based engines are supported at megawatt levels in biomass gasifiers.
- A power output of 2 MW can be achieved with boiler turbine generators (BTGs) based on biomass used.

Programs additionally cowl promotional activities, publicity, seminars/training applications, etc. The Indian Government offers many subsidies for enhancing the bioenergy market. They are making numerous patterns to attract and make investments in the bioenergy market, in each kind of scheme, i.e., off-grid and on-grid. MNRE offers numerous forms of subsidies for nonpublic and government sector.

4 Conclusion

Currently, using lignocellulosic biomass as raw material for the generation of bioenergy has obtained a significant interest for the improvement of sustainable approaches for production of energy. Most of the researches performed for biomass conversion technology head toward discovery of superior approaches to produce energy fuels with the intention to tackle its scarcity that the sector is facing. Also, the research is aimed toward reduction of greenhouse gases and different dangerous effects posed through fossil fuels to the environment. From the above, it could be concluded that biomass is an inexperienced supply of strength in current times. The observation additionally indicated that thermochemical and biochemical technology for the conversion of biomass into different energy products commenced several decades ago; however, it slowed down because of the invention of fossil fuels. Biomass conversion technology received momentum now due the reality that it is a clean, sustainable, and renewable source of power.

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Biomass

Sustainable Energy Solution from Agriculture

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Contents

Abstract

Biomass as energy source is being utilized since dawn of humans for various purposes like cooking, heating, and lighting. Prior to the nineteenth century, plant oil was the primary source of lighting fuel and wood was the primary fuel for cooking and heating. However, discovery of fossil fuel like coal and petroleum

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gradually reduced the use of biomass. Fossil fuels currently account for >80% of all energy use worldwide. With growing environmental concern and depleting fossil fuel resources, geophysical instability and climate change have changed the way biomass were thought of. The main benefits of biomass over other forms of renewable energy are that it is almost carbon neutral and that it is widely available. The environmental advantages of liquid biofuels, particularly biodiesel, have made them more appealing than biomass as a source of energy and wider use in automobile section. Production of biofuel domestically, and its use as alternate fuel, can help to reduce reliance on petroleum oil, decrease trade imbalances, air pollution, and GHG emissions. However, the second-generation biofuels, raw materials, high cost, marketing, and priority given to it all suggest that switching the energy demand from fossil fuels to biofuels will be difficult, at least for a few years. However, with demand and intervention of strong government policies, use of nonfood biomass will be a sustainable step toward reliving our reliance for fossil fuel. Moreover, it will help in achieving our goal in reducing carbon footprint.

Keywords

Biofuels · Biodiesel biomass · Climate change · Ethanol · Energy · Fossil fuel

1 Introduction

Sun is the ultimate source of energy for the earth ecosystem. However, it is directly utilized by only photosynthetic organisms and these organisms serve as source of energy for animals and human beings. Photosynthetic organism converts solar energy into the chemical energy like glucose or sugar which get stored in the form of plant biomass. Plant biomass is directly consumed (fruit, vegetables, grain, etc.) by animal and human being for energy requirement for their growth and development and being used as fuel (wood, dry leaves, crop straw, stalk, etc.) especially for cooking and heating. Bioenergy has been utilized as fuel source for domestic use like cooking, heating, and lighting since the dawn of humans. Before the nineteenth century, wood was the main source of energy for cooking and heating and plant oil for lighting. However, discovery of fossil fuel like coal and petroleum gradually reduced the use of biomass. Today, fossil fuel is the dominant energy source, meeting >80% of the world's energy demand (IEA, 2013). However, still in many developing and underdeveloped countries biomass serve as a major source of energy for cooking and heat generation. For example, in Europe until the 1950s about 20% of the land was devoted for the production of energy as fuel for dwellings or as feed for work animals. Only recently, and after the Second World War, oil became important alternative sources of energy (Sonnino, 1994). In India, about 32% of the total primary energy use is still derived from biomass on which more than 70% of the country's population depends for its energy needs (MNRE, 2021).

Continuous use of fossil fuel has led to rise in atmospheric concentration of carbon dioxide (CO_2) which is a major cause of global warming and climate change

(IPCC, 2014). It has been projected that consumption of energy at the global level will increase by 56% from 2010 to 2040 (524–820 quadrillion BTU), assuming "business as usual and no changes in the current laws and policy related to energy consumption" (Lim et al., 2012; Leahy et al., 2013). Furthermore, fossil fuel is expected to remain the primary source of energy through 2030 and well beyond and energy-related carbon dioxide emissions are projected to increase 46% by 2040, reaching 45 billion metric tonnes in 2040 (Sieminski, 2014). To stop global warming, growing interest has been placed in use of renewable energy, mainly utilization of available biomass for energy production. Therefore, the use of biomass fuels for transportation and electricity generation is increasing in many developed countries for reducing CO_2 emissions from fossil fuel use.

The progress in scientific knowledge has shown that biomass can not only be used as solid biofuels for combustion but can also be converted into forms similar to fossil fuel (like charcoal, biodiesel, and ethanol). Presently, solid biomass can be directly used for heat generation or can also be converted to liquid (biodiesel, ethanol, etc.) and gaseous fuels (Syn gas, biogas, etc.) through various processes. Growing concerns over greenhouse gas (GHG) emissions, uncertainty of future fossil fuel prices, geopolitical instability, and consumer preferences are few factors which are driving the development and use of biomass as a source of renewable energy (Bajwa et al. 2018). Biomass offers key advantages over other renewable energy sources, in terms of its carbon neutrality and availability (Leung et al., 2006). The energy stored in terrestrial biomass is three to four times greater than the current global energy demand (Guo et al., 2015).

Biomass combustion emits about the same amount of carbon dioxide as combustion of fossil fuels. However, burning of fossil fuel leads to emission of CO_2 which was captured and stored million years ago through the process of photosynthesis. On the other hand, biomass fuels are considered carbon-neutral because the CO_2 released during biomass combustion is equal to the CO_2 captured and stored in biomass during the plant growth. However, clearing forests to obtain biomass for fuel results in a carbon penalty that takes decades to recoup, so it is best to utilize waste biomass generated during processing of agricultural and forestry products and also growing trees on underutilized farmland. Large amount of agricultural waste biomass is generated at world platform and can be efficiently utilized for energy generation. Use of agricultural waste biomass for energy can significantly contribute to solve several problems, such as the pollution arising from use of fossil fuels, the dependency on import of energy products, the abandonment of land by farmers, use of marginal agricultural land, and the connected urbanization (Sonnino, 1994). Therefore, in this chapter we will be dealing with agricultural biomass and their utilization for energy generation.

2 Biomass and Its Characteristics

Biomass is a renewable organic resource synthesized by plants through photosynthetic process (Fig. 1). It includes whole plant body, i.e., both root and shoot. These materials are constituted of fibrous structural parts of plants, and which consist of cellulose, hemicellulose, and lignin. In general, biomass feedstocks contain cellulose

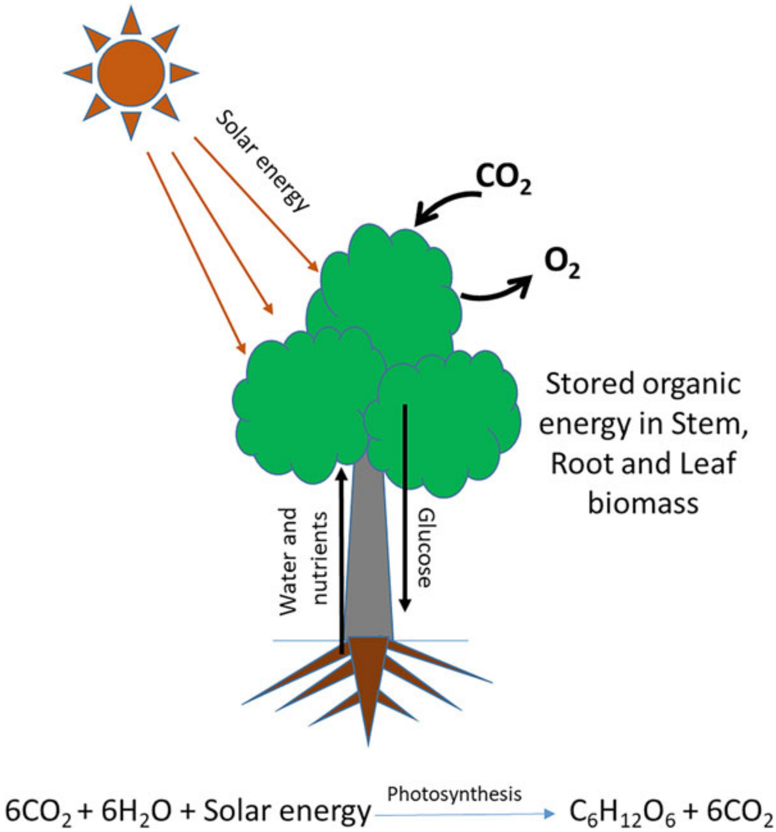


Fig. 1 Process of conversion of solar energy into biomass energy

in largest amount (40–50% by weight), followed by hemicellulose (20–40% by weight), and lignin (Bajwa et al., 2018). The hard surfaces of woody plants are mainly due to a high proportion of lignin which are tightly bonded with their fibers together, while nonwoody plants have a lower proportion of lignin leading to loosely bounded cellulose fibers, resulting into more pliable surfaces.

The relative proportion of cellulose and lignin in the biomass is one of the primary factors in identifying the suitability of plant species for energy crops (McKendry, 2002). Other key factors are calorific value, moisture content, fixed carbon/volatile compounds, ash content, and alkali metal content. Biomass differs from coal in many important ways. As compared to coal, biomass generally has less carbon, more oxygen, more silica and potassium, less aluminum and iron, higher moisture content, lower density and friability, and lower heating value (Demirbas, 2004) (Table 1).

These lignocellulose biomasses are the most abundant source of renewable carbon on Earth. The most commonly used biomass for energy generation include agricultural crop residues (like straw, corn cob/stover, pruned wood of horticultural tree, coconut shell and coir, crop and food-processing residues, etc.); forest residues (firewood, and

Table 1 Fuel properties of biomass and coal

Property	Units	Biomass	Coal
Fuel density	kg/m^3	500	1300
Ignition temperature	K	418–426	490–595
Peak temperature	K	560–575	–
Friability		Low	High
Dry heating value	MJ/kg^1	14–21	23–28
Particle size	mm	3	0.1
C content	Weight % of dry fuel	42–54	65–85
O content	Weight % of dry fuel	35–45	2–15
S content	Weight % of dry fuel	Max 0.5	0.5–7.5
SiO_2 content	Weight % of dry fuel	23–49	40–60
K_2O content	Weight % of dry fuel	4–48	2–6
Al_2O_3 content	Weight % of dry fuel	2.4–9.5	15–25
Fe_2O_3 content	Weight % of dry fuel	1.5–8.5	8–18

Source: Adopted from Demirbas (2004)

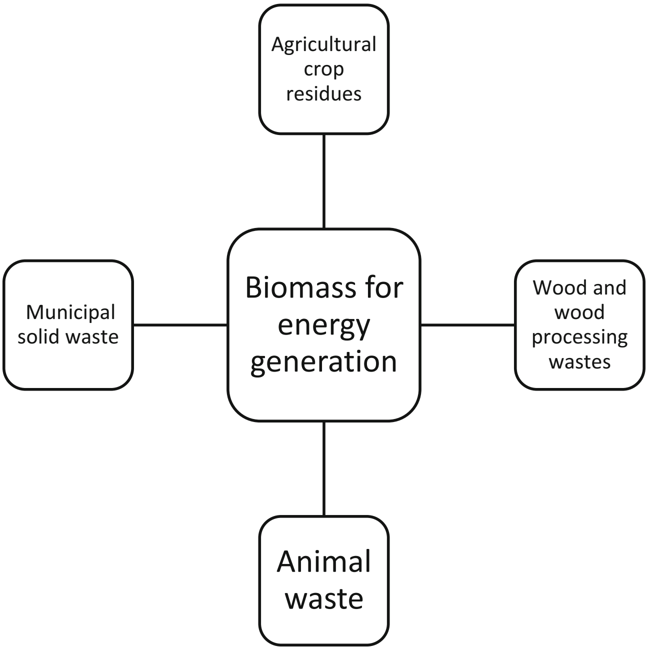


Fig. 2 Sources of biomass for energy generation

wood chips; lumber and furniture mill sawdust and waste); special crops cultivated specifically for energy use (such as willow trees, switchgrass, oil born tree, etc.); algae; animal manure and human sewage; and biogenic materials in municipal solid waste (cotton, paper, and wool products; and food, yard, and wood wastes) (Fig. 2). Corn

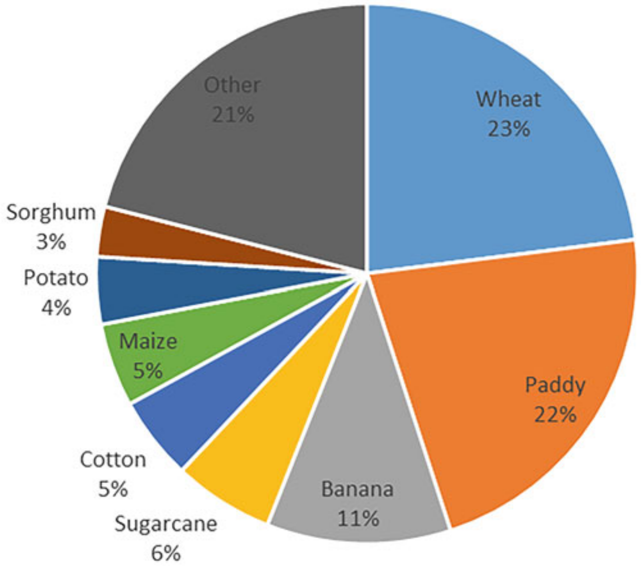


Fig. 3 Crop-wise contribution (%) of farm-level residues. (Adopted from Cardoen et al., 2015)

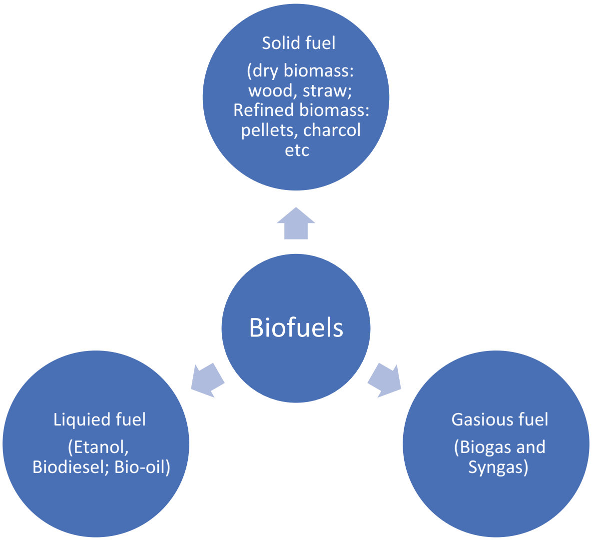
stover (stalks, leaves, husks, and cobs) accounts for about 80% of the agricultural residue in the USA; a significant amount of these materials can be used for producing biomass-based fuel like pellets, ethanol, chemicals, and process heat.

The availability of biomass in India is estimated at about 750 million metric tonnes per year including agricultural residues. According to Ministry of New and Renewable Energy (MNRE, 2021), Government of India, the estimated surplus available biomass is about 230 million metric tonnes per annum corresponding to a potential of about 28 GW. About 14 GW additional power could be generated using bagasse in the country's 550 sugar mills. In India, about 611 million metric tonnes of agricultural crop residues is generated per year, out of which about 158 million metric tonnes (25%) is considered surplus and is thus potentially available for a biobased industry (Cardoen et al., 2015). The crop-wise contribution of various farm residues in total available agricultural biomass in India has been depicted in Fig. 3. In India, about 47 million metric tonnes of chickpea, cotton, groundnut, maize, mustard, paddy, and pigeon pea residue is currently used per year as a domestic fuel. In India, the most important surplus agricultural residues are sugarcane bagasse (41 Mt./year), paddy straw (28 Mt./year), wheat straw (21 Mt./year), and cotton stalks (19 Mt./year) (Cardoen et al., 2015).

3 Forms of Biofuels

Biofuels are refined plant materials that can be burned to produce energy. Biofuels come in solid, liquid, and gaseous forms, just like fossil fuels (Fig. 4).

Fig. 4 Type of biofuels



3.1 Solid Biofuels

Solid biofuels include firewood, woodchips, dry agricultural crop residue (straw, maize stover, pigeon-pea stalk, horticultural crop pruned wood, etc.), wood pellets, and wood charcoal. Since the beginning of modern humankind, firewood and other plant products have been directly fired for warmth and cooking. Most dry plant products burn (flame) in the air at temperatures of 220–300 °C or higher, releasing the innate bioenergy present in heat and light. Air-dry firewood typically has 10–25% moisture, but well-seasoned firewood has an energy value of 15–50 MJ/kg, which is one-third to half that of fossil fuels (ORNL, 2013). In 2012, the USA, China, Japan, and India each used 308,185,400.8 million m^3 (FAO, 2013). Even today, approximately 40% (2.6 billion) of the world's population still uses firewood to meet their energy needs, with an annual consumption of 1730 million m^3 (mostly in rural parts of developing nations in Asia and sub-Saharan Africa) (FAO, 2013). By 2020, the market for solid biofuels (pellets and briquettes) has reached 40–50 million tonnes, a 300% increase from 2012. Averaging about 8% yearly, the usage of solid biofuels has expanded more quickly, with China, Japan, Germany, and the United Kingdom all experiencing strong increases in production (Bajwa et al., 2018).

3.1.1 Briquetting

Large amounts of solid biomass can be found in agricultural wastes, but they lack the density needed to be efficiently transported to energy production sites and also have less energy content as compared to wood biomass. The density and calorific value of some important agricultural residue has been given in Table 2. Therefore,

Table 2 Biomass feedstocks with their bulk density and average energy content

Biomass	Bulk density (kg/m^3)	Average heat value (MJ/kg)
Pine	420–670	30.20
Oak	600–900	19.26
Oat straw	46–136	17.8
Canola straw	24–121	17.4
Wheat straw	34–130	14.41
Corn stover	460–480	18.05
Switchgrass	68–323	17.36
Barley straw	30–47	14.70
Miscanthus grasses	130–150	19.08
Hazelnut husk	560	20.20
Oilseed wastes	544	23.2
Rice straw	50–120	15.17
Cotton stalk	150–250	18.1
Sugarcane bagasse	280–320	16.91

Source: Adopted from Bajwa et al. (2018)

agricultural residues like straw are subjected to densification for the formation of pellets and briquettes before their use. Energy requirements for biomass densification to enhance bulk and energy densities are comparatively low. This lowers transportation cost to the site of use and, if done carefully, can enhance the characteristics of biomass feedstock, increasing its effectiveness as an energy source (Bajwa et al., 2018). Preheating to 75 °C at 10–15% moisture content and conditioning to a water content of 15–20% (wet basis) are the ideal processes for producing high-quality densified pellets or briquettes at 25 °C. Cellulosic materials must reach a glass transition temperature of at least 75 °C for their binding components to become active (Bajwa et al. 2018).

Under high pressure, sawdust or other agricultural cellulosic wastes are often converted into pellets and briquettes. They are created from pulverized biomass material by compressing it in a compression cylinder using a hydraulic press, screw press, or punch press (Tumuluru et al., 2011). Pellets are cylindrical in shape with smooth surface with diameter ranging from 6 to 8 mm and length 18 to 24 mm (Bajwa et al., 2018). The rougher-surfaced sticks or blocks known as briquettes have various cross-sectional geometries (hexagonal, cylinder, or cuboid) with large diameter and length varying from 50 to 100 mm, and 60 to 200 mm, respectively. Moisture content of pellets and briquettes is between 12 and 18% and 15 and 30%, respectively. As a rule, pellets burn easily because of their huge surface area and improved heat transfer. In terms of uses, briquettes are only utilized in industrial settings, whereas pellets are largely used in household heating stoves, heating boilers, etc.

Briquettes are renewable energy fuel which is cheaper than coal. Ash content is low (1–3%) compared to coal (8–10%) which implies no fly ash when burning briquettes with high burning efficiency. Characteristics of biomass residues for briquetting are the moisture must be as low as feasible, often between 10 and 15%; low ash content biomass material is preferred to avoid condensation on tube during combustion. Ash content determines the flow characteristics (Grover & Mishra 1996).

3.1.2 Charcoal

Solid wood biofuels (fuelwood, woody biomass, and wood products) typically contain less energy than fossil fuels and burn at temperatures below 850 °C, making them incapable of melting many metals (Urbas & Parker, 1993). To address these problems, primitive man discovered ways to turn wood into charcoal, a porous, grayish-black substance that is rich in carbon. High-quality charcoal was produced by heating wood products in a kiln or retort at a temperature of about 400 °C until no visible volatiles remained. It burns without flame or smoke, reaching a maximum temperature of 2700 °C (Antal & Gronli, 2003). Approximately 35% of the original wood's dry mass may be converted into charcoal, and high-quality charcoal does have an energy content of 28–33 MJ/kg, which is higher than coals. Humans first used charcoal in metallurgy to process ores for copper and iron in the "Bronze Age" around 3000 B.C. Today, charcoal is still a significant fuel used for heating, air and water purification, art painting, and the production of steel. In 2012, 51 million tonnes of wood charcoal was produced worldwide, an increase of 5% over the 2008 total. African nations generated about 31 million tonnes. Brazil, India, China, the USA, and Russia produced 20 million in tonnes 2012 (FAO, 2013). From enormous logs to little, chipped bits of wood, charcoal can be produced. On a dry-yield basis, it typically takes 5 tonnes of wood to generate 1 tonne of charcoal. This sum will vary somewhat according to the temperature at which carbonization occurs and the rate at which biomass is heated (Demirbas et al., 2016).

3.1.3 Biochar

Using the pyrolysis process, biochar was created from varied agricultural waste at different temperatures of 250, 350, and 450 °C. Because of its porous nature and capacity for absorption, biochar can also serve as an inexpensive adsorbent material for absorbing CO_2 and turning it into fuels. The use of biochar in energy conversion technologies, as well as investigating its potential for carbon dioxide collection and catalytic conversions of carbon dioxide to fuels and energy, require further study. The biochar's wide range of mineralogical composition, high porosity, good thermal stability up to 900 °C, and alkaline pH (7.9–10.8) makes biochar appropriate for enhancing energy recovery technologies' processes. Because of its high heating values (HHV), which range from 23.08 to 24.0 MJ/kg^{1}, biochar can also be utilized as a source of energy (Waqas et al., 2018).

3.2 Liquid Biofuels

Liquid biofuels cover bioethanol, biodiesel, pyrolysis bio-oil, and crop-in transportation fuels. In order to augment the 22 billion gallons of bioethanol produced annually, primarily from food crops, commercial production of bioethanol from lignocellulosic materials has only recently started. The capacity for producing biodiesel from oilseeds has reached 5670 million gallons per year, with additional increase depending on the development of new feedstocks. The development of bio-oil and drop-in biofuels is still in its early stages due to difficulties with cost-effective conversion and upgrading. Because it is made from renewable resources and has positive effects on the environment, biodiesel has grown more appealing. The four main processes for producing biodiesel are microemulsion, pyrolysis, transesterification, and mixing. Transesterification of triglycerides (vegetable and animal fats) with alcohol when a catalyst is present is the technique that is most frequently used. Despite high cost government should promote these biofuels, as these cause less environmental pollution, global warming and being renewable resources. It can be promoted by providing incentives by government (Koh & Ghazi, 2011). Details of this have been discussed in another section of this chapter separately.

3.3 Gaseous Biofuels

Gaseous biofuels include syngas and biogas. In Europe and China, anaerobic digestion of organic wastes has been producing biogas at a rapid rate, with the potential to replace 25% of the world's current natural gas usage. In contrast, the creation of syngas through the gasification of biomass feedstocks is not economically viable and is only occasionally used. Globally, the production and use of bioenergy and biofuel will keep growing, especially in the fields of lignocellulosic bioethanol, biogas, and biopower. By 2050, 30% of the world's energy needs are anticipated to be met by bioenergy.

4 Agricultural Biomass As Source of New Energy

4.1 Ethanol

4.1.1 History of Ethanol Production

Ethanol has been produced about 1000 years back from wine, was known to be flammable, and was since then used as oil for lamps and as fuel for stove. In 1826, ethanol was used as an engine fuel for the first time, in the first internal combustion engine prototype in the USA. Ethanol became one of the most used fuels for lighting, replacing the costlier whale oil/ lard oil used at the time (Gustafson, 2008). However, imposition of tax on alcohol by the USA, to pay for the Civil War in the 1860s, increased the ethanol prices. In 1876, a German inventor, Nicolaus Otto, powered a modern four-cycle internal combustion engine using ethanol. The nineteenth century saw the continuation of the use of ethanol, after the tax was repealed, directly as fuel and also as blends with gasoline in Europe and the USA, making countries more fuel independent. In 1908, an early version of automobile "Model T" was run on an alcohol-gasoline mixture by its inventor, Henry Ford, who called this fuel mix "the fuel of the future." Fuel shortages during World War II increased demands for ethanol as fuel. Environmental concerns regarding leaded gasoline, research on finding uses for excess grains, and increase in prices for gasoline due to oil embargo spurred the current ethanol industry in the 1970s (EIA, 2021). It was also proved that leaded gasoline can be replaced with ethanol as an octane-boosting additive. In the USA, federal and state incentives led to establishment of several corn-based ethanol production plants, due to its ease of conversion to ethanol and abundant corn production. Ethanol demand continued to increase in 2000s, with phasing out of the oxygenate Methyl Tertiary Butyl Ether (MTBE), rising global demands for gasoline, and to decrease dependence on imported oil. Food-based biofuels were brought into focus in the late 2000s by the UN-FAO in the food versus fuel nexus, and foundation for more research on biofuels from other sources was laid.

4.1.2 Process of Ethanol Production

The process of ethanol production commonly uses yeasts for converting sugars in feedstock to ethanol. Based on feedstock used, ethanol may be classified into different categories (Table 3).

As described in Table 1, bioethanol obtained from agricultural biomass refers to second-generation ethanol. The plant biomass is composed of a matrix of cellulose, hemicelluloses, and lignin, which has to be broken down via appropriate methods into the constituent sugars, which can then be fermented to produce ethanol. Various factors restrict easy conversion of biomass into ethanol: strong and complex plant structure, which is resistant to breakdown; and release of different sugar types like pentoses and hexoses as end products for fermentation process, requiring organisms that efficiently ferment both sugars.

This process of breakdown of the plant matrix is a complicated process, which ultimately increases the production cost of this fuel. However, the upside of this generation of bioethanol is the availability of huge amounts of biomass feedstock (forestry wastes, grasses, agricultural residues, etc.), which does not need any arable land and also gives no competition with food sources.

A heterogeneous compound, lignocellulosic biomass contains about 40–50% cellulose, 25–35% hemicellulose, 15–20% lignin, and smaller quantities of minerals, oils, soluble sugars, and other constituents. Depending on the plant species involved, the relative ratios of the three main components (cellulose, hemicellulose, and lignin)

Table 3 Classification of bioethanol based on feedstock and its processing into ethanol

First generation		Second generation	Third generation	Fourth generation
Edible biomass		Nonedible biomass		
Sugary biomass (e.g., molasses)	Starchy biomass (e.g., corn)	Lignocellulosic biomass (e.g., agricultural residues such as straw, grass, and wood)	Algal biomass	Genetically modified cyanobacteria
	Hydrolysis	Pretreatment and hydrolysis	Pretreatment and hydrolysis	
		Fermentation		
		Ethanol		

in lignocellulosic feedstock vary. Pretreatment of feedstock and detoxification is followed by saccharification or enzymatic hydrolysis with the help of cellulolytic enzymes to produce sugar-rich hydrolysate, which is then fermented by yeasts to produce ethanol (Margeot et al., 2009). In an ethanol production facility, the unfermented lignin can be recovered and used for production of heat and electricity (Larson, 2008).

Pretreatment

The pretreatment method should be able to alter the crystalline structure of biomass, enhance sugar formation or the capacity to do so later through hydrolysis, prevent the formation of byproducts that would inhibit the subsequent hydrolysis and fermentation processes, prevent carbohydrate degradation or loss, and be economical (Balat & Balat, 2009). The complex crystalline cellulosic structure of lignocellulose, which is further strengthened by the presence of lignin and hemicellulose and resists degradation, presents a hurdle to its use as a substrate for the generation of ethanol. Without some sort of pretreatment, the enzymatic digestibility of cellulose is quite low (20%) for the majority of biomass types. Following are some examples of the numerous physical, chemical, and biological pretreatment techniques that have been used:

- Physical pretreatment: Freeze pretreatment, mechanical size reduction, irradiation, extrusion, etc. are some methods used for physical pretreatment of biomass. Employing physical pretreatment reduces cellulose's crystallinity and degree of polymerization while increasing the accessible surface area and pore size (Binod et al., 2010).
- Chemical pretreatment: In order to delignify cellulosic materials and generate high-quality paper products, chemical pretreatments were first developed and have been widely employed in the paper industry. It is currently the pretreatment approach for biofuel generation that has received the most scrutiny. Simple chemical pretreatments include soaking biomass in alkali or acid, while more complex ones involve treating the material with high-temperature steam or an ammonia explosion. Alkali or acid pretreatment with different concentrations of chemical at various temperature-pressure conditions, organoslov process, oxidative delignification, ozonolysis, and pretreatment with ionic liquids are some chemical methods.
- Physicochemical pretreatment: These pretreatments combine physical and chemical treatments, and they can be carried out through ultrasound pretreatment, ammonia fiber explosion (AFEX), CO_2 explosion, steam explosion, microwave-assisted chemical pretreatment, etc.
- Biological pretreatment: Lignocellulolytic species are often made use of for low-energy processes. Filamentous fungus, aerobic and anaerobic mesophilic bacteria, certain protozoa, actinomycetes, and alkaliphilic and thermophilic bacteria are among the organisms that use cellulose. The breakdown of organic materials in general and cellulosic substrate in particular is well recognized to be aided by fungi. Cellulose is more resistant to biological attack than the other

components of lignocelluloses, so cellulolytic fungi from the *Aspergillus* spp., *Fusarium* spp., and *Trichoderma* spp. families are widely used in biological pretreatment of lignocellulosic biomass. These fungi degrade lignin and hemicelluloses but only a small portion of cellulose (Taniguchi et al., 2005). In comparison to other pretreatment techniques, biological pretreatments are less hazardous, less energy-intensive, but slower (Talebnia et al., 2010). They also consume cellulose, hemicellulose, in addition to lignin.

Enzymatic Hydrolysis or Saccharification

In this process, enzymes are used to break down cellulose and hemicelluloses into monomer sugars that can then be fermented by yeasts to produce ethanol. While the amount and kind of pretreatment determine how much of the hemicellulose is hydrolyzed, cellulose hydrolysis requires an extra enzymatic hydrolysis step. Cellulase enzymes, which are extremely specific, perform cellulose's enzymatic hydrolysis. Numerous fungi, including *Aspergillus*, *Penicillium*, *Trichoderma*, and *T. emersonii*, have the capacity to produce significant quantities of extracellular and hemicellular cellulases. Endoglucanase, exoglucanase, and β-glucosidase, as well as a few auxiliary enzymes that attack hemicellulose, make up the trio of enzymes known as cellulases. Super strains created by genetic engineering are adept to ferment xylose and glucose to ethanol as well as hydrolyze cellulose and xylan.

Fermentation

In this step, particular microorganisms work to convert the fermentable sugars (both pentose and hexose sugars) released from the lignocellulosic feedstock to ethanol. In hemicellulose, dominated by pentoses, xylose contributes for the majority of sugars (14.8–20.2% of the straw). Therefore, it is hypothesized that fermentation of xylose is a crucial characteristic of microorganisms to use in large-scale fermentation of biomass hydrolyzates (Karimi et al., 2006). Equations (1) and (2) list the metabolic processes involved in the fermentation of pentose and hexose sugars to ethanol (2).

- According to the equation, every mole of hexose produces two moles of ethanol and CO_2:

$$C_6H_{12}O_6 \rightarrow 2\ C_2H_5OH + 2\ CO_2 + \text{energy (stored as ATP)} \ldots \quad (1)$$

- According to the equation, every three moles of pentose produce five moles of ethanol and CO_2 each:

$$3\ C_5H_{10}O_5 \rightarrow 5\ C_2H_5OH + 5\ CO_2 + \text{energy (stored as ATP)} \ldots \quad (2)$$

For fermentation, yeast, bacteria, and fungi can be employed. The process of fermenting glucose into ethanol most typically employs *Saccharomyces cerevisiae*, also referred to as Baker's yeast. A potential strain that can use both pentose and hexose sugars is *Pichia stipitis*.

Distillation

The fermented mass is subjected to distillation to get pure ethanol, which can be further used as a fuel. Distillation gives ethanol of about 96% purity, after which it undergoes dehydration to obtain a purer version (Anon, 2013).

4.1.3 Benefits and Disadvantages in Ethanol Production

Globally, Brazil and the USA are the prime producers and consumers of ethanol fuel, though their supply comes mainly from the first-generation bioethanol. Now, these and many other nations have turned their focus to the more sustainable second-generation feedstocks for their energy production. Most vehicles in these countries run on an ethanol-gasoline mix, which is more environment friendly compared to gasoline alone. The use of this fuel mixture can also help reduce imports of crude oil and make countries more independent. Of course, there are advantages and disadvantages to both the manufacturing and use of ethanol fuel.

Bioethanol production and use offers several benefits:

1. Environmental benefits:
   - (a) Being produced from crop biomass, ethanol can be classified as a renewable fuel.
   - (b) Agricultural waste burning can be minimized by using these wastes for bioethanol production. Thereby, emissions from biomass burning can be avoided.
   - (c) Blending of ethanol allows complete combustion in vehicle engine due to the presence of oxygen in ethanol (oxygenate fuel) that again results in fewer emissions like carbon monoxide. In 2016, use of bioethanol-gasoline blends was reported to reduce 43.5 MMT of CO_2-equivalent greenhouse gas emissions from transportation (RFA Releases 2017 Ethanol Industry Outlook, Pocket Guide, 2017).
   - (d) Use of waste biomass also lowers the life cycle greenhouse gas emissions, as compared to the first-generation biofuels. In comparison to gasoline, the cellulosic ethanol emits 90% lesser GHGs. It is also considered as carbon neutral.
   - (e) Production of ethanol from lignocellulosic materials like agricultural waste biomass, wood wastes, or energy crops like miscanthus or switchgrass leads to better energy balance of ethanol, as compared to that produced from sugar/starchy feedstock. This results from the lower use of fossil fuels and inputs needed for specifically producing these feedstocks.
   - (f) Pure ethanol is benign and biodegradable, unlike gasoline, and if spilled, it disintegrates into harmless chemicals very fast.
2. Economic and social benefits:
   - (a) Offers a source of extra income to farmers for agricultural waste.
   - (b) The cultivation of feedstock for the second-generation biofuels can be done on marginal or wastelands, providing a source of revenue.
   - (c) Characteristics such as high octane number render ethanol a high suitability for blending, which also improves drivability, reduces engine knocking, and

reduces deposits in vehicle, which all ultimately leads to better vehicle performance.

(d) Ethanol in fuel acts as an antifreeze, reducing problems during winter.

(e) Second-generation biofuels do not require separate arable lands for feedstock production, nor do they use edible material as feedstock. Hence these do not hamper food security of our country.

4.1.4 The Drawbacks of Ethanol Production and Use

1. Compared to the manufacture of ethanol from starchy or sugar-based feedstock, the method of producing ethanol from lignocellulosic biomass is more difficult.
2. There is lack of a standardized commercially viable procedure for production of this fuel.
3. Pretreatment is a costly process, due to higher power consumption.
4. An efficient microorganism, which can simultaneously ferment both the hexose and pentose sugars obtained after pretreatment and hydrolysis, is lacking.
5. Facilities for large-scale manufacturing of ethanol are limited in most countries.
6. Lower mileage: Bioethanol contains lesser energy gasoline. Per gallon, the ethanol fuel provides only 75% of the energy provided by gasoline, resulting in vehicle mileage reduction by 20–30%. Hence impact of ethanol on fuel economy will depend on the percent blend in the gasoline.
7. Ethanol has higher evaporative emission compared to gasoline, which is contributory to ground level ozone formation.

4.1.5 Current Status and Potential of Ethanol Production in the World

The 2000s saw approximately an 18% annual growth in biofuels, which slowed sharply to about 3.9% after 2010. The COVID-19 pandemic and further associated lockdown of the global economy further hampered the growth of biofuels in 2020 (Enerdata, 2021). Bioethanol accounts for two-thirds of the total biofuels produced globally.

Figure 5 gives the current trend of ethanol production by the leading producers from 2010 to 2020. Global bioethanol production has undergone significant advancements during the past few decades. The USA and Brazil manufacture 84% of all ethanol worldwide. These global ethanol producers, however, mainly utilize the first-generation feedstock such as maize in the USA and sugarcane in Brazil. The other major countries producing bioethanol are European Union, China, Canada, India, Thailand, and Argentina. Currently bioethanol production is mainly intended for meeting the domestic demands, and consequently, the main producers are also the main consumers, and trade is relatively less. North America accounted for 45% of total ethanol consumption in 2019. This region also exported about 2.2% of biofuels (Enerdata, 2021). The other exporters include Africa, Pakisthan, and Ukraine. The ethyl alcohol market was valued at $89.1 billion in 2019 globally (Clauser et al., 2021). The same report cited a compounded annual growth rate for lignocellulose-based bioethanol of 6.0% for the period 2020–2027.

Since it is blended with gasoline at a level of 5% and in certain countries at a level of 10%, bioethanol has mostly been employed as a biofuel for transportation. The

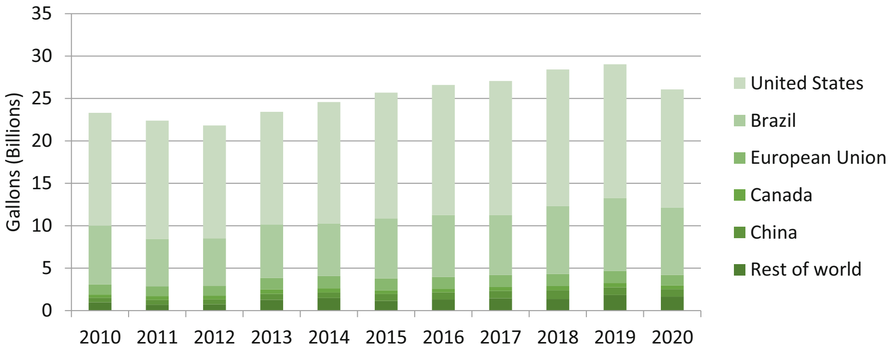


Fig. 5 Global ethanol production from 2010 to 2020. (Source: Renewable Fuels Association, 2021)

most widely used biofuel worldwide is bioethanol, which is combined with regular gasoline to power gasoline engines in road vehicles. It can also be used to make ethyl tertiary butyl ether (ETBE), an octane booster found in many different kinds of gasoline.

Crop leftovers, as a substrate for energy (ethanol) production, are appealing to industry since they are a low-cost resource. Furthermore, residue and food crop production are complementary, whereas producing crops specifically for energy use, rather than food production, can result in a reduction in food availability (Gallagher, 2006). Up to 33 EJ/year production of second-generation ethanol has been predicted in past studies by 2050 (Niphadkar et al. 2017). However, it will take a lot of technological advancements in the ethanol productivity and lowering of costs associated with pretreatment and enzyme costs, before the adoption of biomass-based ethanol becomes cost-effective. The corn-based ethanol industry has achieved great technological yield improvements which made the industry successful over the past two to three decades. A similar feat in case of the second-generation bioethanol would ensure ethanol yields above 90 gal/ton biomass. Additionally, availability of hydrolytic enzymes at lower rates could ensure the success of this industry. Even so, the high capital expenses of biomass-ethanol production in comparison to corn processing would continue. Availability of biomass at low-cost may offset the capital expenditures to some extent (Gallagher, 2006). Process optimization might also help to reduce the costs on second-generation bioethanol production. A comparative analysis of different alternatives for production of bioethanol indicated that an amalgamation of first- and second-generation ethanol production methods has the best economic performance, providing opportunity to reduce investment risks and increase revenues (Clauser et al., 2021).

The USA, Germany, and Scandinavian countries are the few developed and Brazil, China, India, and Thailand the developing countries that have undertaken research of improvement of the ethanol production process especially from ligno-cellulosic biomass. In order to increase production of second-generation gasoline to 60 billion liters by 2022 and 10% renewable energy in the transportation sector by

2020, respectively, the governments of the USA and the EU have agreed to pass biofuel support schemes (Niphadkar et al. 2017). The shortage of bioethanol production in these countries may present an opportunity for other producers, especially in Brazil, China, and to a lesser extent India, where pilot plants are already up and running and where the infrastructure permits the export of biofuels. The developing countries can also take advantage of the ever-increasing biomass market for second-generation biofuels, due to more availability of land for growing feedstock.

4.1.6 Future Perspective in Its Production

Diversion from fossil fuels to alternate renewable fuels has arisen out of the increasing consumption of the finite and fast-depleting fossil fuel resources as well as the increased concern for environment and climate change. Production of biofuel domestically, and its use as alternative fuel, can help to reduce reliance on petroleum oil, and decrease trade imbalances, air pollution, and GHG emissions. However, bioethanol production technology especially for the second-generation biofuels, high cost, raw materials, and priority toward it all indicate that a shift in focus to biofuels to meet our energy demands will be challenging, at least for a few years.

The main problem is producing ethanol at a reasonable cost. As reported by International Renewable Energy Agency, the bioethanol cost varied from 0.9 to 1.1 USD, 0.7 to 0.9 USD, and 1.04 to 1.45 USD per liter of gasoline-equivalent, when the substrates used were corn, sugarcane, and lignocellulosic biomass, respectively (Clauser et al., 2021). Hence, the selection of a good, abundant, and inexpensive raw material is critical. Optimization of an efficient pretreatment process, development of a microorganism capable of fermenting both the C5 and C6 sugars produced from lignocellulosic biomass, etc. are few steps which will enable significant savings in production costs (Abo et al., 2019). Many researchers are attempting to increase enzymatic hydrolysis and consequently the prospective output of biofuels by genetically engineering biomass. More advanced technologies like genetic modification and genome engineering are ideal solutions to change feedstock physiology (Ulaganathan et al., 2017; Lamichhane et al., 2021).

Some studies also predict a decline in global biofuel consumption due to many variables, including a decline in fuel demand, increased competition among transportation systems, and the decarbonization trend of public policies in 2029 (Enerdata, 2021). However, during the coming years, it is anticipated that rising crude prices, growing concern over greenhouse gas emissions, as well as favorable government legislation, would increase demand for ethanol in both industrialized and emerging nations. Growth is further aided by a focus on technological breakthroughs and the production of low-cost feedstock. The bioethanol industry includes businesses in the pharmaceutical, automotive and transportation, cosmetics and personal care, food and beverage, and other sectors. China is predicted to lead future growth in the bioethanol industry, emerging as the fastest expanding regional market. Globally, with a probable 45.1% share, the USA is the largest regional market for ethanol. By 2024, the bioethanol market is expected to be worth $45.3 billion (Anon, 2021). Regional governments in China, India, Vietnam, and Thailand are supporting the use of alternative fuels like ethanol due to rising environmental concerns and the threat posed by the depletion of fossil fuel sources to fuel supplies. More supporting policies, subsidies, and governmental actions will ensure that lignocellulosic biomass will also be a major player in the feedstock for ethanol production, which is otherwise expected to be again dominated by the first-generation feedstocks in the recent future (up to 2029) as per reports by Enerdata (2021).

4.1.7 Indian Case Study and Policy Measures

India, an agrarian country, has a lot of promise for producing ethanol from crop leftovers because cellulosic materials are widely available, plentiful, and relatively inexpensive (Prasad et al., 2007). Approximately 600 million tonnes of agricultural waste are produced annually in India. By 2012, these wastes may theoretically create 156 billion liters of ethanol, meeting 42% of India's oil needs. Therefore, the only predictable, practical, and long-lasting source of renewable fuel is lignocellulosic biomass.

Developing a cellulosic ethanol sector in India would assist both the environment and the economy. It could, for starters, assist in addressing the long-standing problem of crop burning. Second, domestically produced cellulosic ethanol will lessen fuel import demand, and improve India's energy security by contributing to the ethanol blend target. In addition, development of new industry will create more employment opportunities, and provide a source of income to farmers who can then sell the crop residues to the industry (Zhou et al., 2021).

For nearly two decades, India has promoted the blending of ethanol with transport fuels via a range of policy measures. The Indian government launched the Ethanol Blended Petrol (EBP) Program in 2003, under which a set percentage of ethanol is to be blended with gasoline. A National Policy on Biofuels was formed by the Ministry of New & Renewable Energy in 2008 to reduce the nation's future carbon footprint and reliance on imported crude. In accordance with this, a 5% bioethanol blend with gasoline was suggested starting in October 2008, with a 20% bioethanol blend objective by 2017. It also provided a schedule for the program's gradual rollout. The nationwide ethanol blend objective under the EBP is currently set to be 10% (E10) by 2022 and 20% (E20) by 2025. The ethanol mix target has increased over time (Sarwal et al., 2021). India now produces more ethanol and uses more gasoline ethanol as a result. The ethanol mix percentage in 2019 was 4.5% (Fig. 6).

Under the EBP, the government has also established ethanol buying policies. These laws mandate India's oil-selling companies to purchase ethanol for transportation from domestic sources alone. Since 2014, the Indian government has also routinely revised the ethanol price through another procurement regulation.

However, the major concern is that in India ethanol is mostly made from sugarcane molasses (i.e., first-generation ethanol), which is not a sustainable option to meet the increased demands for ethanol. Agricultural waste and municipal solid waste are examples of cellulosic biomass that can be used to make second-generation (2G) biofuels and have sparked interest in response to these concerns. The Indian government is encouraging 2G feedstocks in order to diversify ethanol feedstocks (Zhou et al., 2021). It has been estimated that if the currently burned crop residues (about 48 MT) are converted into bioethanol, 22 billion liters of ethanol can be produced annually (Sarwal et al., 2021). The Pradhan Mantri

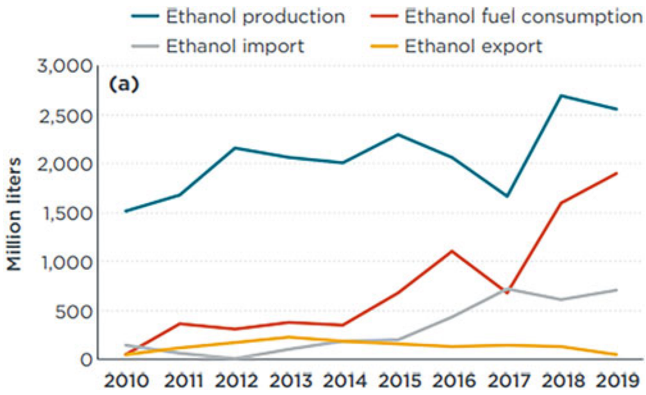


Fig. 6 Fuel use of ethanol in India between 2010 and 2019. (Table from Zhou et al., 2021)

Ji-Van Yojana initiative, which was launched in 2019, is a program run by the Indian government that provides Viability Gap Funding (VGF) to support the development of the cellulosic ethanol industry (Ministry of Petroleum & Natural Gas, 2019). From fiscal year 2018–2019 through 2023–2024, the government will provide a total of INR 19.7 billion (US$270 million) to fund 12 commercial initiatives and ten demonstration projects as part of this program.

An order for a second-generation bioethanol plant in Odisha, India, with a proposed production capacity of 100,000 liters per day, was given to TATA Projects by Bharat Petroleum Corporation Limited in February 2020. Currently, 4–5% ethanol is added to gasoline in India. By 2022, the government hopes to blend 10% ethanol into gasoline, and by 2030, 20%. The need for 3.3 billion liters of bioethanol to achieve this 10% blending is anticipated to increase commercial potential for Indian sugar mills in the ensuing years (Mordor Intelligence, 2021).

Commercializing cellulosic ethanol can be difficult from both a technological and financial standpoint, as can be observed from the experience from other regions, such as the USA and the European Union. Strong legislative support and policy measures are critical for the industry's success.

4.2 Biodiesel

Diesel fuel derived from either plant or animal source is referred as biodiesel. Chemically, these are long-chain fatty acid esters developed through the process of transesterification by reacting vegetable oil with an alcohol. It is used to fuel existing diesel engines in blended form with petro-diesel. Blending proportion of biodiesel with petro-diesel is generally kept less than 10%. Pure (100%) biofuel cannot be used in engines without appropriate modification. Biodiesel production gained momentum in the first decade of 2000 when European countries came up with favorable policies. In 2006, global production of biodiesel was around 5 million tonnes wherein contribution of Germany was more than half. In the recent years, Indonesia became the top supplier of biodiesel with annual production of 3.5 million tonnes of palm oil-based biodiesel. A variety of sources are used for biodiesel production. The most common ones are soybean and rapeseed oils. Other plant sources are *Jatropha*, mustard, sunflower, coconut, etc. Animal fats used for this purpose include chicken fat and rendered form of mutton or pig fats. Few other unconventional sources are algae, halophytes (slat-tolerant plants), and sewage sludge. In India, main source of biodiesel production is imported palm stearin oil. Used cooking oil available locally in bulk is also being promoted by Government of India as an alternate feedstock to minimize dependency on imports.

4.2.1 History

Steam engine of 1800s was inefficient and unsafe. There was a need to make an improvement. The first diesel engine designed by Rudolf Diesel was tested for the first time on peanut oil on 10 August 1893 in Augsburg, Germany. It had robust injection system that could run on many types of fuels including kerosene. It was the French government who had intense desire to build vegetable oil-based diesel engine with an intent to benefit their African colonies. Otto company was commissioned the by French Government that worked closely with Rudolf Diesel. Because of their joint effort, the first public demonstration of vegetable oil-based engine was done at the 1900 World's Fair. By the early 1900s, use of petroleum-derived diesel fuel had gained momentum. Many European countries including China, Brazil, Argentina and Japan still continue to use bio-diesel based internal combustion engine. Until then, petroleum availability across the globe became very common and cheap. Biofuel could not gain adequate attention, and engine design was thus modified to match the properties of petro-diesel. The result was an efficient and powerful machine. For the next couple of decades, diesel-powered engine remained to be an industry standard. Few instances in the history have reported interest toward using vegetable oils in diesel engines. These were World War II and the 1970s oil crisis. After 2000 when price of petroleum oil started soaring and concern over global warming increased, focus again shifted toward augmenting biodiesel production and distribution. Everything on this front, lies on the ability to grow feedstocks at a large scale and produce biodiesel at a competitive price.

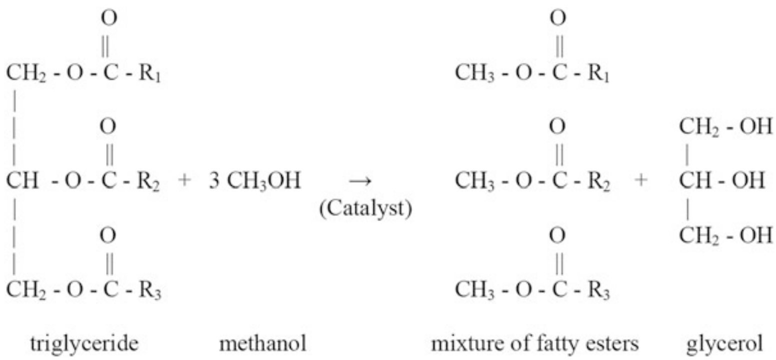
In India, cultivation of *Jatropha* (called *Jangliarandi* in Hindi) has been mainly associated with biofuel production. *Jatropha* seeds contain approximately 40% oil that is suitable for diesel engines. This oil can be used directly after extraction without refining. Several forest communities have been using *Jatropha* oil at smaller scale for many decades. To organize biofuel production and distribution, "National Biofuel Policy" was announced by the Indian Government in 2008 that aims to meet 20% of the country's diesel demand (Biswas et al., 2010). Recent development in India relates to producing biodiesel from waste of broiler chicken and dead poultry birds. John Abraham at the Veterinary College Wayaland under Kerala Veterinary and Animal Sciences University had pioneered this research in 2009 with funding from the Indian Council for Agricultural Research (NDTV, 2016). This produce is 40% cheaper than diesel and is equally efficient. Indian authority granted him patent for biodiesel from rendered chicken oil in July, 2021. His team is now working on a similar line on developing biodiesel from pig waste.

4.2.2 Production Process

European countries mostly use rapeseed and sunflower to produce biodiesel whereas production in the USA is based on soybean. *Jatropha* growing on wastelands is the topmost feedstock in India; the potential could not be fully harnessed due to several constraints. These are poor seed yield, unavailability of wastelands, and high plantation cost including shortage of seeds for plantation. According to Ministry of Petroleum and Natural Gas (MoP&NG), area planted with *Jatropha* in the country is around 0.5 million hectares and total annual production of biodiesel from all feedstock sources is approximately 150 million liters in 2017. Through 2014 to 2016, production of biodiesel in India increased from 130 to 140 million liters (Lahiry, 2018).

Chemical Reaction

Biodiesel is produced through transesterification process wherein vegetable oil or animal fat is mixed with alcohol in presence of either a strong base or strong acid, the catalyst (Verma & Sharma, 2016). Most used base substances in this process (particularly at industrial level) are caustic soda (NaOH) and caustic potash (KOH) due to low cost with better availability (Leung et al., 2010). If methanol is used as alcohol in the reaction, the biodiesel produced is known as fatty acid methyl ester (FAME). And if the ethanol is used rather than methanol, the resulting molecules are fatty acid ethyl esters (FAEE). Use of methanol in this process is highest because of its low cost. Methanol quickly reacts with triglyceride and base substance is easily dissolved (Romano & Sorichetti, 2010). For transesterification reaction to occur, the molar ratio of alcohol to triglyceride should be 3:1 (Kamrun et al., 2011). The reaction results in production of raw biodiesel and raw glycerol. As the next step of the process, these products are purified for final use. Transesterification reduces the viscosity of vegetable oil, and physical properties of FAME are very close to the petro-diesel. Chemical equation of transesterification reaction is given below.



4.2.3 Extraction from *Jatropha*

Jatropha curcas L. is a viable source of biodiesel and is considered a renewable energy source. CO_2 emission rate is 80% lower compared to petroleum diesel. *Jatropha* plant is drought-resistant and can tolerate soil salinity as well. It can be grown even on noncultivable wastelands so does not really compete for land with food crops. The plant grows up to 50 years and produces oil-bearing seeds with annual yield ranging from 7 to 12 tonnes per hectares. Raw *Jatropha* oil is filtered to remove foreign materials before blending it with a mixture of methanol (reagent) and caustic soda (catalyst). The mixture is agitated for a specific duration under ranged temperature and pressure. This is then sent to a settling tank. The ester is collected which is then purified through washing and drying to get the final product, pure biodiesel. Methanol gets recovered and can be reused. Glycerol is the byproduct of this process which can be refined for use in soap and candle industries (Mehar et al., 2006). Conversion yield of this process is 98% (1000 g of *Jatropha* oil produces 980 g of biodiesel). As India's biodiesel production is *Jatropha*-based, the following production process details are the is shown below in in schematic version (Fig. 7).

4.2.4 Other Production Processes

There are a few other processes through which biodiesel can be produced. But limitations are associated with these.

- Direct blending – crude vegetable oil is blended with petroleum diesel in certain ratio to get biodiesel. This product has concern over high viscosity and acid value.

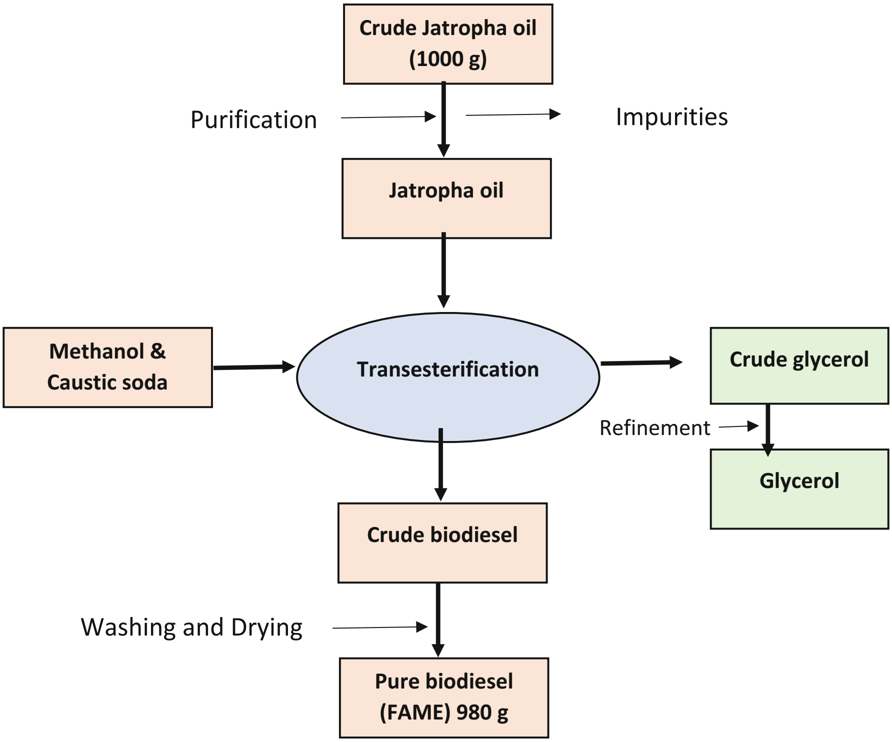


Fig. 7 Schematic showing conversion of *Jatropha* biomass into biodiesel

- Microemulsion – vegetable oil is mixed with appropriate emulsifying agents. It might be alcohol mainly methanol, ethanol, propanol, or butanol. The main lacuna associated with such type of biodiesel is incomplete combustion leading to carbon deposits in the engine.
- Catalytic cracking – conversion of vegetable oil or animal fat in the absence of oxygen to liquid product having properties alike diesel. This product holds high amount of sulfur and moisture.

In a new process, the transesterification reaction is catalyzed by mixed oxide of zinc and aluminum (Bournay et al., 2005). It promotes the reaction without loss of catalyst. Compared to methods based on homogeneous catalysis, this process is done at higher temperature and pressure. Methanol is also applied at excess.

4.2.5 Biodiesel Properties

Properties of biodiesel largely match those of petro-diesel although some differences exist. Molecules of biodiesel and petroleum diesel are of almost same size, but their chemical structures differ. Molecules of biodiesel contain unsaturated "olefin" components whereas petro-diesel consists of 95% saturated hydrocarbons. Specifications of FAME have been furnished below that provide a comparison with petroleum diesel.

This variation in composition results in several differences in their physical properties. Lubricity of biodiesel is higher that enhances engine life (Tziourtzioumis & Stamatelos, 2014). Absence of sulfur in biodiesel cuts pollution level. Higher oxygen content in biodiesel results in reduced pollution emission. But it is more likely to get oxidized and form a gel-like substance. This is one of the major negative sides of biodiesel making a concern in extended storage and in engines operated occasionally. There are variations in the quality of biodiesel depending upon oil crop being used for its production. Moreover, structure of alcohol reacted with the vegetable oil also determines biodiesel properties. There are three main properties that decide quality of biodiesel. These are:

- Length of molecule
- Amount of branching
- Saturation

Longer molecules increase heat of combustion, and a greater number of branching decreases the gel point. So, biodiesel having longer molecules and more branching is considered better in quality. The most interesting property of biodiesel is its blending nature. It very easily blends with petroleum diesel in different ratios. Depending upon the proportion of biodiesel blended in petro-diesel, it is named B5, B10, B20, etc. "B10" simply means that blend has 10% biodiesel and 90% petroleum diesel.

4.2.6 Advantages of Biodiesel Use

1. Reduces hazardous emissions of the most dangerous contaminants such as carbon monoxide and sulfur dioxide.
2. Degrades more quickly than diesel – environmental consequence arising out of biofuel spills is minimal.
3. Blended form of biodiesel and petroleum diesel in any proportion can be used in engines. Due to the better lubricating nature of biodiesel, it improves engine longevity.
4. Being a renewable source of fuel, it does not pose a threat on natural reserve.
5. Can use residues from meat (chicken, pig, etc.)-processing units as raw materials thereby help in absorbing waste materials.

The larger and long-term benefit of biodiesel is reduced risk of global warming. According to research done by the US Departments of Agriculture and Energy, biodiesel reduces CO_2 emissions into the environment by 78.5%.

4.2.7 Disadvantages of Biodiesel Use

1. Overall fuel requirement will be more due to lower calorific value of biodiesel.
2. Emission of nitrous oxide is greater than petroleum fuel.
3. Long-term storage is challenging due to tendency of forming gel-like substance.
4. Inconvenient for colder climate due to higher freezing point.

Overall, petroleum resources are rapidly depleting and fuel demand is continuously increasing (Purohit et al., 2014). It is creating a need to intensify the production of fuel through alternate sources. India's National Biofuel Policy in 2009 aimed to create enabling environment for large-scale development of the biofuel industry in the country. But *Jatropha*-based biodiesel production could not match the expectation due to bottlenecks mainly associated with slow growth in plantation area. Agricultural residues in India are another potential option that can meet feedstock demand. Again, its requirement in cattle feed sector stops any such diversion. In the short run, coverage under *Jatropha* should be scaled-out through stronger community participation, support to local entrepreneurs, and streamline supply chain under prevailing policy framework. These stepping stones would help in evolving and shaping up long-term strategy that should be around identification/targeting of suitable land, accelerating cultivation, and seed-pricing support to producers.

5 Process of Biomass Conversion to Energy

Various processes have been identified to generate energy from the biomass (Fig. 4). Heat is generated through direct combustion, thermochemical conversion of solid, gaseous, and liquid fuels, chemical conversion of liquid fuels, and biological conversion of liquid and gaseous fuels. All types of agricultural biomass can be converted to energy through all the foresaid processes; however, quantity, quality, and time taken in energy production depends on the quality of the biomass

Table 4 Comparison of diesel with biodiesel

Specifications	FAME (biodiesel)	Petroleum diesel
Density (15 °C) (kg/m^3)	865	825
Viscosity (40 °C) (cSt)	4.7	2.5
Water content (mg/kg)	330	–
Sulfur content	–	50
Iodine number (g/100 g)	117	–
Acid number (mg KOH/g)	0.16	–
Cold filter plugging point (°C)	−3	−12
Cetane number	55	50

feedstock. Therefore, selection of process and biomass is a most important requirement for efficient and quality energy production (Table 4).

5.1 Combustion

It is the process of burning biomass to produce heat while there is oxygen present. It is most frequently utilized to transform biomass into useable energy. All dry biomasses can be burned directly to produce power in steam turbines, heat industrial processes, and heat buildings and water. Most of the low-density biomass like crop straw and residue are subjected to densification for the enhancement of calorific value of the biomass. The direct use of combustion is in heating room, cooking, boiling water, electricity generation in thermal power plants, etc.

5.2 Thermochemical Conversion

It is a thermal decomposition process in which biomass materials are heated in closed, pressurized vessels at high temperatures in complete absence or limited amount of oxygen. It includes mainly two processes viz. pyrolysis and gasification. These both processes mainly differ in the process temperatures and amount of oxygen present during the conversion process.

5.2.1 Pyrolysis

Biomass is heated to 400–500 °C during pyrolysis, almost entirely without the presence of free oxygen. Biomass does not burn during the process because there is no oxygen present; instead, the biomass thermally decomposes into combustible gases and biochar. Some of these combustible gases (CO_2, CO, H_2, and light hydrocarbons), however, remain gases permanently. Most of these gases condensed into pyrolysis oil, also known as bio-oil. As a result, the pyrolysis of biomass yields three products: liquid bio-oil, solid biochar, and gaseous syngas (gas). The proportion of these products is influenced by several variables, such as the feedstock's composition and the process parameters. Under fast pyrolysis conditions (pyrolysis at fast heating rate 1000 °C/s) about 60–70 wt% bio-oil yields can be achieved from a typical biomass feedstock, with 15–25 wt% yields of biochar and 10–15 wt% syngas. The process of pyrolysis can be self-sustaining since the syngas and some biochar or oil can be burned to produce all the energy required to power the reaction. In order to create renewable diesel, renewable gasoline, and renewable jet fuel, the resulted bio-oil (produced through rapid pyrolysis) is treated with hydrogen under high pressures and temperatures in the middle of a catalyst. Syngas is a fuel that can be used for gas turbines that provide electricity, heating, and diesel engines. The hydrogen can then be burned or utilized in fuel cells after being processed to separate it from the gas. Utilizing the Fischer-Tropsch method, the syngas can be further processed to produce liquid fuels (Schulz, 1999).

5.2.2 Gasification

Gasification involves heating organic materials to 800–900 °C while injecting regulated quantities of free oxygen and/or steam into the tank to create synthesis gas, also known as syngas, which is a gas rich in hydrogen and carbon monoxide. The carbon monoxide then undergoes a water-gas shift reaction with water to produce carbon dioxide and additional hydrogen. The hydrogen in this gas stream can be extracted using adsorbers or certain membranes. Syngas is a fuel that can be used for gas turbines that provide electricity, heating, and diesel engines. Additionally, it can be processed to extract the hydrogen from the gas, which can then be burnt or used in fuel cells (USEIA, 2021). Utilizing the Fischer-Tropsch method, the syngas could be further processed to produce liquid fuels (Schulz, 1999).

$$C_6H_{12}O_6 + O_2 + H_2O \rightarrow CO + CO_2 + H_2 + \text{other species}$$

$$CO + H_2O \rightarrow CO_2 + H_2 + (\text{small amount of heat})$$

In order to produce a pure syngas mixture of H_2, CO and CO_2 are usually necessary to go through an additional step of reforming such hydrocarbons with a catalyst. The carbon monoxide is then changed to carbon dioxide in a shift reaction step using steam, precisely like in the gasification process used to produce hydrogen. The generated hydrogen is then sorted and cleaned.

5.3 Chemical Conversion

Vegetable oils, animal fats, and greases are converted chemically into fatty acid methyl esters (FAME), which are used to make biodiesel, through a process known as transesterification (USEIA, 2020).

Biological conversion entails anaerobic digestion to provide renewable natural gas and fermentation to turn biomass into ethanol. Vehicles run on ethanol as fuel. Anaerobic digesters are used to create renewable natural gas, also known as biogas or biomethane, at sewage treatment facilities as well as in dairy and animal operations. Landfills for solid waste are another place where it can form and be collected. Natural gas from renewable sources can be used in the same way as natural gas from fossil fuels.

6 Conclusion

Petroleum resources are rapidly depleting, and fuel demand is continuously increasing. It is creating a need to intensify the production of fuel through alternate sources. India's National Biofuel Policy in 2009 aimed to create enabling environment for large-scale development of the biofuel industry in the country. But plant biomass-based biodiesel production could not match the expectation due to bottlenecks mainly associated with slow growth in plantation area. Agricultural residues in India are another option that have potential to meet feedstock demand. Again, its requirement in cattle feed sector stops any such diversion. In the short run, coverage under biomass should be scaled-out through stronger community participation, support to local entrepreneurs, and streamline supply chain under prevailing policy framework. These stepping stones would help in evolving and shaping up long-term strategy that should be around identification/targeting of suitable land, accelerating cultivation, and seed-pricing support to producers.

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Biomass Technologies for Crop Residue Management

Ritu Dogra, Dhiraj Kumar, and Yadvika

Contents

Abstract

In India, large-scale agricultural farming practices are continuously performed from man immemorial. During crop harvesting, a huge quantity of its waste residues are produces, i.e., in view of cultivated former tedious jobs to collect

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and burn it in situ, which leads to disturbs to the soil fertility condition and its properties. Nowadays, these practices done by farmers become a major obstacle to handle it. This chapter tries to focus on crop residue (agricultural waste) management practices. Briquetting and pelletizing both are an emerging technology to overcome the mentioned constraint.

Keywords

Briquetting machine · Paddy straw · Densification · Pellets · Agricultural waste

1 Crop Residue Management Using Densification Techniques

Millions of tons of agricultural waste (residues) are produced each year from a variety of food grain crops. Agricultural waste is difficult to use because of its uneven and bothersome properties. These are either not used or are burnt inefficiently, resulting in air pollution. Due to its heavy, moist, and dispersed character, biomass in its loose state is rarely used as a fuel on a broad scale. Crop residue is difficult to handle and transport, owing to its low bulk density. Thus, by converting agricultural crop residue into high-density fuels such as briquettes and pellets, it can serve as an infinite source of energy. The process of transforming plant wastes into a consolidated form of fuel is known as biomass densification. This process, also known as pelleting or briquetting, alters the management of material handling for transportation and storage, and it has been in use in numerous nations for several years. The concept of biomass densification technology was first presented by William Smith (1880). Sawmill debris was densified by Smith. Baling, pelletization, extrusion, and briquetting are modern biomass handling procedures that are achieved using a baler, pelletizer, screw press, piston, or roller press machine. Pelletization and briquetting are the two most prevalent processes for biomass densification to a loose state at high pressure for the manufacture of solid or densified fuel. These “binderless” high-pressure densification procedures are often accomplished using a screw press or piston press machine (Sokhansanj et al. 2005). The manufacturing of briquettes is uniformly carried out in a screw press machine using a heated and tapered die. A screw press’s briquette qualities and manufacturing method are far superior to piston press technology. When examining the wear of parts in a piston press, such as a reciprocating arm and die, it becomes clear that the screw press parts required excessive patronage.

The interstitial hole drilled into the densified logs by a screw press allows for consistent and efficient combustion qualities, and the resulting logs can be quickly ignited by heat transfer. Many academics and experts have looked into the idea of using pellet and briquetting technologies to densify grasses and woody biomass. For example, Ndiema et al. (2002) discovered that die pressure had an effect on produced briquettes.

Challenges: The various challenges faced during crop residue management are listed below:

- Huge volume of crop residue.
- Collection and storage.
- Time window between harvesting and sowing of two (next) crops.
- Awareness, dissemination of technology, capacity building of technical manpower and those of farmers.
- Cost-effective mechanization, availability of appropriate machinery.
- Utilization of crop residue.
- Technology upgradation.

2 Biomass Briquetting: Densification Technology for Agricultural Waste

In the context of rising global energy demands, it is widely assumed that a lack of fossil fuels will lead to higher fuel costs as a result of increased dependency, as well as cause global warming and other environmental problems as a result of excessive use.

Plant photosynthesis and respiration compensate for the carbon dioxide (CO2) released by burning practices. As a result, biomass energies have received less attention as a potential alternative energy source. Agro-crop residues have become one of the most popular choices among the various types of accessible biomass. Agricultural waste (crop leftovers) plays a critical role in meeting the energy needs of developing countries by providing an alternative limitless fuel source. In general, varied crop wastes are abundant as a source of energy. However, because of bulky nature, low combustion qualities, and frequent release of toxic gases, it is difficult to store and manage. The direct combustion of agricultural leftovers in cooking households and manufacturing businesses is insignificant and is associated with widespread environmental contamination. It is important to densify agricultural wastes into compact pieces of specific shape and size without affecting their combustible qualities in order to gain more effective uses.

Briquetting is a method of densification in which loose biomass is compressed under extreme pressure, resulting in a high-quality combustible product with features such as high energy density, low moisture content, consistent shape and size, and good ignition properties.

3 Biomass Densification Technologies

It requires higher energy input powers and expensive costs of operation. A portion of the cost of operation is to be reduced by minimizing the proper management, collection, storage, transportation, better operability of the boiler, and burning practices. There are various densification technologies as described in Fig. 1.

Pellets (Fig. 2) are highly densified products formed by straw pelletizer machine. They are easier to collect than other densified goods. Pellets are erected by dismemberment process, implementing a piston press methodology, in which grinded material is inducted through round or square cross-sectional dies and cut into a

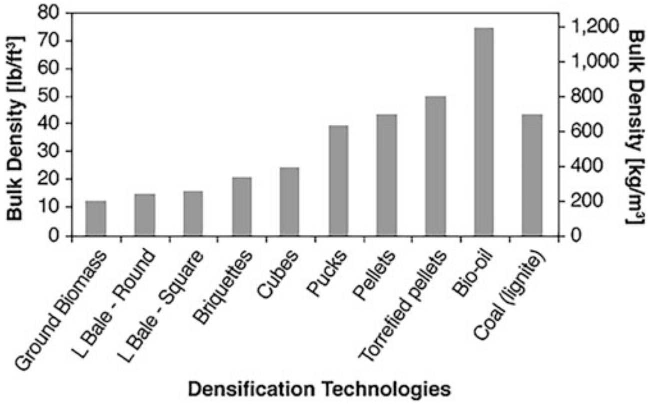


Fig. 1 Bulk densities of different shapes of briquettes using densification technologies

Fig. 2 Pellets

desired dimensional pieces. The pellets are in cylindrical form, having dimension of 38 mm (1.5 in.) in length and around 7 mm (0.3 in.) in diameter. Although uniformly shaped, pellets breakdown quickly during period of collection and handling. A good property of pellets varies in its energy and ash value.

Cubes are too large from pellets in size; usually it is produced in rectangular shape and slightly denser than pellets. Generally, its dimensions vary from 13 to 38 mm (0.5–1.5 in.) in cross section, ranging between 25 and 102 mm (1–4 in.) in length. The process of cubes production includes compressing a shredded biomass through a heavy press wheel, followed by pressing the biomass through dies to form cubes. Cubes are shown in Fig. 3.

Pucks (Fig. 4) have the external shape just like a hockey puck, with 75 mm (3 in.) diameter. It is built by using a briquette and hardy wet and having same density as pellets, with the benefits of lower production costs in comparison to pelletization process.

Wood chips are utilized in various operations for accomplishment of household cooking and industrial needs. Boiler plants require 5–50 mm (0.2–2 inch) of wood

Fig. 3 Cubes

Fig. 4 Pucks

Fig. 5 Wood chips

chips in length. Commercially, it is produced by wood chipper machine. In context of feeding fuel, wood chips (Fig. 5) are cheap in cost to coal.

Cost of biomass densification: The cost of biomass densification is influenced by various factors **which** are **listed below**:

- Size of densification plant (tons/year).
- Operating time (hours/day)
- Equipment cost
- Personnel cost
- Raw material costs

4 Briquetting Process

The following steps are included for densification/briquetting of agricultural residue:

1. Collection of raw materials
2. Size reduction by shredding machine
3. Compaction of material
4. Condensation and storage

4.1 Raw Materials Collection

Agricultural crop wastes, for instance, are suitable for briquetting because they are combustible but not in a regular shape, size, or form to be conveniently used as a fuel.

4.2 Size Reduction of Raw Materials

It includes the following terms discussed below.

4.2.1 Drying

It is the process of extraction of high moisture content from the harvested crops and having very high moisture contents during the harvesting period. Raw material drying practices can be done by direct sunlight and solar driers with hot air or with heater. Figure 6 shows the drying of biomass in open field and solar dryer.

4.2.2 Size Reduction

Firstly, reduce crop residue in size by cutting, milling, rolling, breaking, etc. until it reaches to a suitable size (1–10 mm). Materials available in size of 1–10 mm require no size reduction/shredding as the process consumes huge amount of energy. Figure 7 shows the shredder for size reduction of agricultural residue.

Fig. 6 Drying of biomass in open field and solar dryer

Fig. 7 Size reduction

4.3 Raw Material Mixing

It is the process of mixing two or more distinct kinds of crop residue or grasses in a certain proportion for the production of densified biomass product in form of pellets and briquettes. It is done in such a way that the product receives a great pressing pressure and retains high calorific value.

4.4 Compaction

It is to be done inside the briquetting machine and depends upon the adopted technology for briquetting.

4.5 Heat Reduction and Storage of Briquettes

Briquettes expelled out from the machines are in hot form with temperatures exceeding100 °C. It should need to be cool and stored in dry place.

5 Availability of Raw Materials

All agricultural crop residues can often be briquetted. In India, agricultural crop residues such as vegetable and cereal crops, sawdust, rice husks, castor, coffee, tapioca waste, cotton, pigeon pea, soybean, mustard stalks, sugarcane bagasse, and wood chips are primarily utilized as briquetting feedstock. All agricultural crop residues can be converted into briquettes, either with or without the use of chemical binders. Notably, numerous parameters such as water content, ash value, flow characteristics, regular size of material, and holding or availability in the neighborhood all influence the raw material selection criterion. The amount of moisture ranges from 10% to 15%, and for much greater moisture amounts, they will limit shredding and require more energy for moisture removal. In conjunction with the working conditions and ash mineral concentration, the briquette ash value impacts languish behavior. Biomass residues that retain up to 4% of their ash value can be used in briquetting. Briquettes are formed of shredded homogeneous components that may be carried simply by conveyers.

6 Factors Affecting Briquetting Process

The biomass briquetting process is influenced by a number of factors.

1. **Raw Material Types**

   Varied types of raw materials have different briquetting qualities. The choice of raw material has an impact on briquette quality, such as density, strength, and calorific value, as well as the briquetting machine's production and power consumption. Some plants, among a huge variety of agricultural and forestry wastes, are easier to compress and briquette after crushing, while others are more difficult. Fibrous plant straws and bark are easily briquetted and deformed under pressure, whereas wood debris is more difficult to briquette and deform under pressure. Figure 8 represents crop residue as a raw material for briquetting. When briquettes are made without heat, materials that are difficult to compress are

Fig. 8 Crop residue for briquetting (http://www.eia.doe.gov/cneaf/solar.renewables/page/biomass/biomass.html)

difficult to briquette; however, when heated, such as in the screw bio briquettes machine, wood waste is difficult to compress, but due to its high lignin content, it softens at high temperatures and allows the material to bond together easily. Plant stalks and bark have a low bonding ability, making briquette making difficult.

2. **Raw Material Moisture Content**

   During the biomass briquetting process, the moisture content of the raw material is a crucial quantity that must be managed. The briquetting effect can be improved by ensuring that the biomass material has the right moisture content. A moisture too high or too low is not conducive to briquetting. The steam created during the heating process cannot be smoothly released from the fuel center hole when the moisture content of the raw material is too high, causing surface cracking and, in severe situations, popping. Briquetting is difficult if the moisture content is too low, because trace moisture might cause lignin to soften and plasticize. In hot press forming, high moisture content reduces heat transfer and increases friction between the material and the mold. Gas obstruction will occur at high temperatures due to a considerable volume of steam; too little water content will impair the softening point of lignin. The raw materials' internal friction and compressive strength increase, resulting in excessive compression energy consumption. When the pressure is constant and the moisture content is within the required range, the compression density can reach a maximum as the moisture content increases. When the relaxation density is constant, as the water content increases, the required pressure becomes larger, and the maximum pressure value corresponds to the upper limit of the moisture content. The relaxation density of the compact decreases exponentially with the increase of moisture content.

   Although the lignin content of different raw materials varies, the appropriate moisture content for briquetting is essentially the same. There is still a significant discrepancy in the range of moisture content identified by the study based on current domestic and foreign literature. This is due to significant changes in the compression method, the briquetting mold, the briquetting method, and the process of the biomass raw material.

3. **Particle Size of the Raw Material**

   The particle size of the source material is another crucial aspect that affects briquetting. The shredded biomass is shown in Fig. 9. The particle size of the raw material should not exceed a set size for a specific briquetting procedure. Briquetting raw materials with small particle sizes is simple, while briquetting raw materials with high particle sizes is challenging.

   The relevant scholars discovered that when different particle size materials were briquetted at the same pressure and under the same conditions, the smaller the particle diameter of the raw material, the larger the elongation or deformation rate, implying that the smaller the particle diameter, the easier the briquetting. When using a briquetting method that requires a smaller particle size of the raw material, this tendency is more prominent.

   The efficiency of the briquetting machine and the quality of the briquettes are also affected by the particle size of the raw materials. The briquetting machine will not perform properly if the material size is too large; the energy consumption will

Fig. 9 Shredded biomass

be high, and the output will be low. When the particle size of the raw material is not uniform, especially when the morphological variation is substantial, cracks appear on the surface of the briquettes, lowering the density and strength. However, some briquetting procedures, such as stamping, demand a larger raw material with a longer fiber, and the raw material has a small particle size and is prone to falling off.

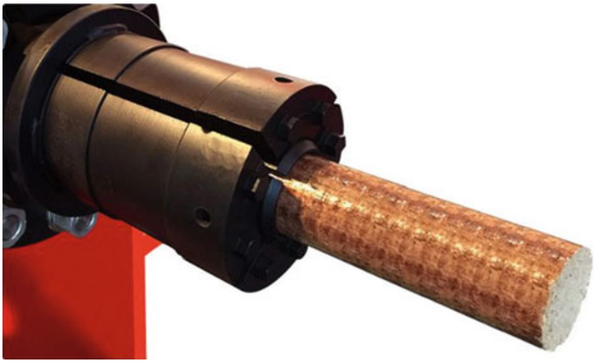
4. **Briquetting Pressure**

   The most basic prerequisite for briquetting biomass is briquetting pressure. The raw material can only be briquetted if enough pressure is applied. When the pressure is low, the density rises as the pressure increases. When the pressure reaches a particular level, the density of the briquette begins to increase slowly. Experiments have revealed that the pressure used during briquetting is largely proportional to the density of the fuel after it has been briquetted. If the pressure is too low, the briquette's density will be low or even impossible to form, but once the pressure reaches a certain level, the density will not considerably increase. Arrangement for pressing briquettes is shown in Fig. 10.

5. **Temperature**

   The temperature has an impact on briquetting as well. The lignin in the raw material can be softened and used as a binder by heating it. The raw material can also be softened and briquetted simply. Temperature influences not just the briquetting of raw materials but also the briquetting machine's efficiency. When the temperature is too low, the raw materials cannot be briquetted, and the motor's power consumption rises; when the temperature is too high, the motor's power consumption falls, but the briquetting pressure drops, and the particles are not squeezed. Its density decreases, making it simple to break. Furthermore, the briquette's surface will be hot, easy to burn, and produce a lot of smoke.

Fig. 10 Arrangement for pressing briquettes (http://www.briquettepress.eu/)



7 Methods of Briquetting

The briquette densification method can be done by adopting any of the mentioned following two methods:

1. **Direct compaction method.** The agricultural residues are mechanically densified by a machine into briquettes in the form of high bulk density than the raw material. As a result, the calorific value of the compacted fuel is increased multiple times on volume basis.

Binderless method using very high pressure. In this method, the biomass is compacted directly under high pressure in the order of 1200–1400 kg/cm^2. The job of compaction is accomplished by a machine, which is screw press type. Under such pressures, the residues get heated to a certain temperature of about 182 °C, and the lignin begins to pour out and act as a binder. Depending upon the availability of type of machine, the briquettes can be of any size varying from 65 mm in diameter and 120 mm length to 70–100 mm in diameter and 300–350 mm in length. Those have a production capacity of about 400 kg/h.

2. Compaction method using binder and low pressure. Biomass is compacted using binder like molasses to provide the required binding strength. Important characteristics of binder method are as follows:
   - They should be combustible and not produce smoke or gummy deposits.
   - Exposure to weather must not cause crumbling or excessive softening of briquettes.
   - They should be locally or cheaply available.

Natural gums and glues from biomass also offer very attractive possibilities of binders. Briquetting machines using this method operate at low pressure in the range of 500–1000 kg/cm^2 and are usually powered by electricity. These machines are available in capacity ranges of 0.1–0.4 t/h. Their calorific value is about 4000 kcal/kg. Steps involved are:

1. Collection of residues.
2. Size reduction of biomass for easy briquetting.
3. Removing excess moisture by drying.
4. Mixing of material with suitable binder.
5. Compaction/extrusion by suitable machine.
6. Cooling and storage.

8 Briquetting Technologies

Briquetting is the operation of conversion of low-bulk-density (60–180 kg/m^3) biomass into high bulk density (500–800 kg/m^3) and producing high energy densified fuel in the form of briquettes. Biomass briquette is an inexhaustible source of energy, renewable in nature, eco-friendly/non-polluting, and economical. Loading/unloading and transportation costs are quite less, minimal area is required for storage, and these can be transported for long distances.

The technologies which are used for briquetting of the agricultural crop residues are notably categorized into three classes: (1) high-pressure or compaction technology; (2) medium-pressure technology; and (3) low-pressure technology. In high compaction briquetting machines, the force is exerted to the value of 100 MPa and is most suitable for high lignin content residues. At this high compaction force, heat increases to about 200–250 °C, which is adequate to expel out the lignin from the residue, which works as a binder, and hence there is no necessity of using other binding materials. In medium-pressure type of machine, the exerting force varies from 5 to 100 MPa, which consequently lowers heat generation. Such kind of machines required an additional heating energy source for liberation of the lignin of the agro-residues which minimized the application of any kind of binder material. Generally, low-pressure machine functions at very low pressure, about 5 MPa, and ambient temperature. These kinds of machines require an additional source of binding materials and are also applicable for the carbonized materials due to absence of the lignin content.

The high-pressure technology can be classified into three classes:

(i) Piston press type.
(ii) Extrusion densification/screw briquetting press type.
(iii) Hydraulic or pneumatic type.

From above mentioned two technologies of briquette formation, piston press type was specially used for production of briquettes in India. The whole briquette production firms and enterprises usually use piston press technology for briquetting, chiefly in Tamil Nadu. Mostly cylindrical-shaped briquettes are produced in the range of 30–90 mm diameter.

(i) **Piston-ram press type:** In such machine, the material is introduced into a cylinder and pressed by the piston. Piston-ram press machine with 0.5–1.5 t/h capacities are commercially available and produce briquettes in the range of 5–9 cm diameter. The power required by such kinds of briquetting machines varies from 25 kW to 65 kW. A schematic view of piston press machine is shown in Fig. 11.

(ii) **Screw press type:** Material enshrined continuously into a screw designated chamber which conveys the material into cylindrical die and raises its temperature between 250 and 300 °C, making it soft and releasing lignin content. If die is not warmed, then temperature may not rise adequately causing lignin content to pour out and bind the material. The wear and tear (friction) of screw is increased and demands frequent reconditioning. Briquettes are of good quality than piston press unit. A schematic view of a screw press briquetting machine is shown in Fig. 12.

(iii) **Hydraulic pressing machine:** It consists of a hopper, hydraulic cylinder, piston, table, etc. The significantly good results can be achieved by double-piston hydraulic press, which produced about 25 kg/h of briquettes of density about 500 kg/m^3.

Schematic view of a hydraulic press briquetting machine is shown in Fig. 13. The precept of working is basically similar as mechanical piston press, but the basic

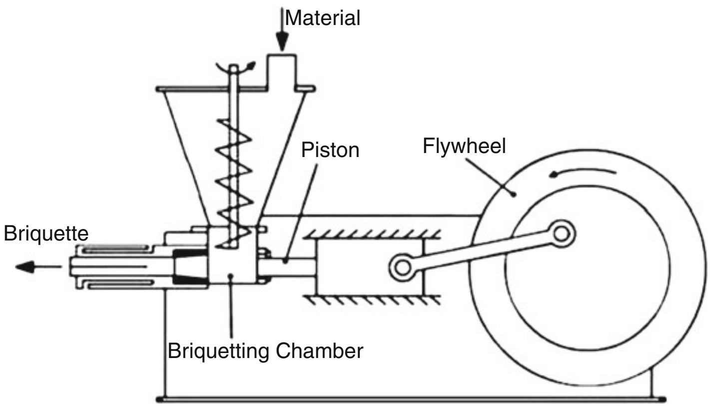


Fig. 11 Schematic view of a piston press briquetting machine (https://www.slideshare.net/sanjay0313/briquetting-248822750)

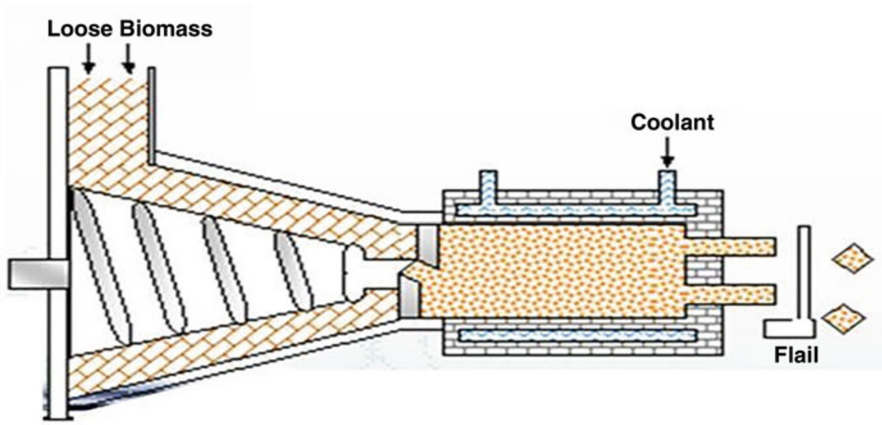


Fig. 12 Schematic view of a screw press briquetting machine

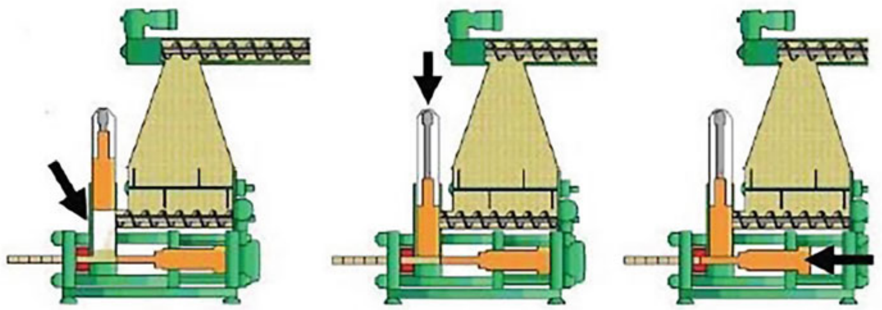


Fig. 13 Schematic view of a hydraulic press briquetting machine

contradict is that the energy to the piston is received by an electric motor by means of high-pressure hydraulic oil mechanism. The raw material is inducted from front side by a feeding cylinder. The entire process is managed through a set of programs, which can be changed on the basis of input material and desired product quality. The rotation of the cylinder press is too slow than mechanical press, which results in markedly minimum outputs.

9 Advantages of Briquettes

- Increases the net calorific value per unit volume.
- Eventual product is effortless to transport and store; uniform in size and quality.
- Helps in overcoming the constraint of agro-waste disposal.
- Controls deforestation by giving a sustainable substitute for fuel wood.
- It expels the possibility of spontaneous burning waste.

- Prevents from deterioration of residue.
- It can be easily introduced in gasification process for electricity generation.

10 Application of Briquettes

1. As domestic fuel, in cooking stoves, replacing cow dung cakes and coal.
2. As fuel for industrial boilers, furnaces, and brickkilns. Briquetted fuel can easily replace B and C grade coal in boilers and furnaces.
3. As fuel for producer gas unit, briquettes can be used for pyrolysis.
4. As animal feed in fodder.

11 Advantages

A) **As energy source:**
  (i) Briquettes are minimum-cost, available, biomass fuel than coal fuel.
  (ii) Exhaustive source of fuel like coal, on one time use, cannot be replenished or regenerated, but briquette can be produced every year because of bulk availability of agricultural crop residues.
  (iii) Briquettes have no sulfur content, which is becoming the cause of environmental pollution.
  (iv) It contains higher thermal value and produces minimum ash content (2–10%) than 20–40% in coal.
  (v) It has no fly ash while burning practices.
  (vi) It has high burning efficiency.
  (vii) Ignition is considerably steady compared to coal.

B) **As feed:** It will solve to a great extent the requirement of animal feed in fodder-deficit areas.

C) **Disposal of residue:** Problem is greatly resolved by biomass briquetting.

12 Basic Needs to Start a Briquette Production Unit

1. **Area requirement:** Requires at least one acre area for commencement of production unit and raw material storage for briquetting and its final product.
2. **Raw material:** Agricultural crop residues, shrubs, grasses, etc.
3. **Drying facility for extracting moisture content from raw materials:** The raw materials are ordinarily available in the form of higher moisture content. Thus, for extracting the moisture content from raw material, any one of the drying methods such as solar driers/heaters/hot air generator is used.
4. **Shredding machine:** It needs for proper operation a minimum of 5 hp. electric power motor for shredding to residues for briquetting.
5. **Briquetting machine:** Usually, hydraulic piston press machine exerts a very high pressure on raw materials, while operation is most suitable for production of

good-quality briquettes from agro-residues without binder, and it is usually driven by 50 hp. motor.

13 Pelletizing

Pelletizing is the process of densification or molding a biomass material into the shape of a pellet. A wide range of tremendous materials are pelletized including agricultural biomass residues and animal compound feed, i.e., used for heat generation similar to briquettes. It is too small in shape and size and free from environmental pollution like- nitrous oxide (NOx), sulfur oxide (SOx), etc. The principle of manufacturing pellets is mostly similar to briquette formation, and its size varies from 4 to 7 cm. The manufacturing unit in the pelletizing machine has distinct components like conical feed hopper, pellets manufacturing unit (two pressing rollers and flat die), main shaft, shredding unit (bevel gear, 1:2.75, and pulleys 1: 4), frame, and axial wheels. It is generally driven by one-phase electric motor of 0.75 kW, at a speed of 1440 rpm. A schematic view of pellet machine is shown in Fig. 14.

14 Conclusion

The low-energy density of biomass fuel by its volume, in position with other fossil fuels, consequently enhances its managing costs. In this way, biomass is most economically feasible and compatible when used close to the source. The new emerging biomass conversion technologies for better utilization and crop residue management of dispersed or loose form play a vital role in the proper managing and improvement of its combustible properties. Biomass conversion (briquetting and pelleting) technologies provide an alternate option for accomplishment of future

Fig. 14 Schematic view of pellet machine (http://www.pellet-making.com/products/electric-motor/mobile-pellet-machine.html)

needs of fuel at domestic and industrial level in producing a uniform product with a higher calorific value and energy density. These technologies would also overcome the costs of handling, storage, as well as transportation through densification.

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Internet of Things (IoT) Framework to Support Sustainable Food Production

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Contents

Abstract

Faced with the challenges posed by the effects of climate change, a decrease in resources in agro-ecosystems and strengthening of the sustainability of agricultural communities, the Fourth Industrial Revolution puts the Internet of Things (IoT) at the service of the agricultural sector as an alternative solution to configure resilient production systems. This chapter presents an empirical study of an agricultural IoT framework deployed in a food production system to collect microclimate data in plantations, transmission through wireless networks, storage, and analysis of the dataset with computational algorithms to support farmers

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in data-driven decision processes. The agricultural IoT framework enables the configuration of flexible, data-driven agricultural production systems focused on productivity improvement, labor optimization, input use efficiency, and agro-ecosystem sustainability.

1 Introduction

The 2030 Agenda for Sustainable Development offers a vision of a more just and peaceful world (UN, 2015). The purpose of the agenda is to eradicate poverty and hunger, combat climate change, and protect natural resources, food, and agriculture (Colglazier, 2015).

To achieve this, member countries have adopted and committed to the fulfillment of the 17 Sustainable Development Goals (SDG) (UNa,2015), each including a set of targets, 169 in total, and 230 indicators for monitoring and verifying results.

The agricultural sector is linked, to a greater or lesser extent, to actions to meet the projected targets for the SDGs. Food and Agriculture Organization (FAO) statistics describe that the cultivated agricultural area has not changed in the last 20 years, standing at around 1.5 billion hectares, just over 11% of dry land (FAO, 2017).

The conservation of terrestrial ecosystems requires productive and profitable agriculture that does not deplete soil and water. Therefore, it is important to increase productivity and adapt diets to this supply.

The Agricultural Outlook 2021–2030 (OECD/FAO, 2021) estimates that the average food availability per person in the world will grow by 4% over the next 10 years, reaching just over 3025 kcal/day in 2030. World agricultural production will be expected to increase by 1.4% per year, a figure that will correspond mainly to production in emerging economies and low-income countries.

The Organization for Economic Co-operation and Development (OECD), together with the FAO, describe a wider access to inputs, increased investments in technology, infrastructure, and agricultural training to improve productivity as drivers for agricultural development (OECD/FAO, 2021).

In the SDG 2 ‘Zero Hunger’, target 2.4 is to ensure the sustainability of food production systems and apply resilient agricultural practices that increase productivity and production, contribute to the maintenance of ecosystems, strengthen resilience to climate change, and progressively improve land and soil quality (UNa, 2015).

Sustainable agriculture as an economic activity, a source of livelihoods, and a provider and user of environmental services places agricultural producers at the heart of the food production system. In this perspective, an agricultural plantation must be economically profitable, resilient to external shocks, and provide wellbeing to those who work it.

In the face of current challenges, technological innovation is a key element for feeding the world in a sustainable way (Sung, 2018). The Fourth Industrial Revolution (4IR) provides the agricultural sector with different technologies as an alternative to configure resilient, efficient, and sustainable production systems (Kamilaris et al., 2017; Sharma et al., 2020; Mtshali & Akinola, 2021).

Integration of global positioning systems (GPS), wireless communication, internet of things (IoT), and big data technologies transforms agricultural production systems to optimize the use of natural resources, increase crop yields, decrease costs, and reduce waste (Ane & Yasmin, 2019; Ayentimi, 2020).

Agriculture 4.0 provides the opportunity for crop data analytics to help farmers make decisions under uncertainty in the local context (Rose & Chilvers, 2018; Raj, 2021). This chapter describes an agricultural IoT framework deployed in an open field food production system to collect microclimate data in the crop and provide the ability of farmers to make data-driven decisions that describe what is happening in their plantings.

2 Innovation in the Agricultural Sector

Over the last 100 years, agriculture has undergone many changes and many innovations have been implemented to help producers improve yields and increase economic benefits (Howkins, 2005).

In the face of the challenges posed by world population growth, the effects of climate change, diminishing resources in agro-ecosystems, and strengthening of the sustainability of agricultural communities, it is necessary to use all available technological advances.

Innovation in the agricultural sector is a key element for improving the productivity, sustainability, and resilience of the world's food production systems (OECD/FAO, 2021).

Revolutionary changes in agriculture date back as far as 10,000 years ago, when the first hunter-gatherers decided to start domesticating wild plants and leave nomadic life to settle and produce food, through the green revolution to the present day with the development of Agriculture 4.0.

Evolution of agriculture has been characterized by the use of transformative and disruptive technological innovations in food production processes with the purpose of contributing to the reduction of costs and time, speeding up work, improving productivity, and making this millenary task easier.

2.1 Green Revolution

The Green Revolution (FAO, 1996) was one of the great events that took place in the twentieth century, driven by the scientific work of Norman Borlaug (who received the Nobel Peace Prize in 1970) focused on achieving greater production per hectare cultivated.

This revolution adapted and transformed agriculture by making it possible to obtain high levels of crop production through the use of improved seed varieties, fertilizers, and chemical pesticides to control pests and diseases.

2.2 Process Mechanization

This stage was characterized by the mechanization of agricultural processes through the use of vehicles and machinery in the fields. A technological incursion in agriculture was made with the objective of reducing the time and costs of food production. The use of agricultural machinery and tractors was generalized for planting and harvesting activities; more tasks can be carried out at the right time and large areas of land can be worked.

Mechanization of agricultural production processes has made it possible to increase the food supply in the main food-producing countries and international food marketing.

2.3 Precision Agriculture

Incursion of technological advances in electronics and computing in the agricultural sector allowed better machinery that enables the automation of planting and harvesting processes. The use of GPS systems coupled with software services favored the emergence of precision agriculture (Paustian & Theuvsen, 2017; Say et al., 2018).

The precision agriculture paradigm was characterized by studying the variability of factors affecting agricultural production, such as variation in soil attributes, pest attacks, and disease occurrence.

The main purpose was to optimize the use of resources based on the variability of factors by delimiting management zones for the application of fertilizers with variable rates as well as pesticides and herbicides depending on the presence of pests, weeds, or diseases in crops.

2.4 Agriculture 4.0

Agriculture 4.0 is related to the digital era in which we live. It is characterized by the use of technologies in agricultural production processes, production chains, and in the industrialization of products with the purpose of achieving increased efficiency in production (Rose & Chilvers, 2018; Raj, 2021).

This paradigm proposes monitoring the entire production process and the use of more advanced technologies to make this possible (Yahya, 2018).

Use of the dataset generated by sensors, communicated through wireless networks, stored in virtual repositories, and analyzed by computational algorithms allows decision making without loss of time for the benefit of producers to reduce costs and production times, as well as the efficient use of resources.

3 4IR Technologies for Agriculture

The Fourth Industrial Revolution (4IR) is changing the way in which actors in the agricultural sector produce food and other products (Nijhuis & Herrmann, 2019). Expansion of the use of artificial intelligence (AI), drones, and IoT technologies in agriculture is intended to increase profitability, decrease production costs, and reduce environmental impact (Zhai et al., 2020).

These technologies also empower agricultural producers by discovering new planting patterns that are more resilient to adverse weather and climate change.

Use of these technologies makes possible the transformation from an agriculture that was intensive in phytosanitary products, water, and fertilizers to a knowledge-intensive agriculture that will use a significant amount of data that is transformed into valuable information.

3.1 Artificial Intelligence

Artificial intelligence provides the agricultural sector with a smarter and more efficient approach to improving production systems. Sensing and analytics technologies enable the implementation of data-driven agriculture (De Clercq et al., 2018; Sharma et al., 2020).

In the agricultural sector, AI can fulfill different functions, e.g., optimize or even develop some activities, increase productivity, improve working conditions, and the use of natural resources efficiently through better knowledge management in the planning, management, and evaluation of plantations.

Most relevant applications of AI in the agricultural sector can be classified into: a) robots to perform basic agricultural tasks such as planting, harvesting, weed control, and spraying; b) crop and soil monitoring using machine vision and learning algorithms to process data to monitor crop and soil health; and, c) predictive analytics with machine-learning models to monitor and predict impacts of environmental conditions on crop yields.

3.2 Drones

Drones are causing a revolution in the agricultural sector from the top down. The planning and configuration of flight plans allow collection of aerial images for soil, water, and crop monitoring at a significantly faster speed than from the ground (Raj et al., 2021).

Unmanned aircraft are fast, simple, and efficient; bringing multiple benefits to the agricultural sector, e.g., topographic assessment, plant counting and density, species identification, weed monitoring, phytotoxicity damage control, and yield estimation, among others.

Aerial images collected by drones are analyzed by computational algorithms to calculate vegetation indices that quantify some crop characteristics. Estimation of loss of biochemical constituents of chlorophyll or water, detection of changes in leaf pigments, or chlorophyll fluorescence are some of the applications.

3.3 Internet of Things

Rapid advancement of sensor technologies, communication networks, and computing power increases the capacity of computer systems to collect and analyze datasets at a high speed (Cornejo-Velazquez et al., 2019).

The IoT is an alternative to transform agricultural production systems in the tasks of a) sensing and monitoring of production, b) monitoring of specific crop conditions, c) remote control of crop operations, and d) food traceability.

From an optimistic approach, the implementation of IoT solutions in the agricultural sector favors the transformation toward a micro-precision model in food production systems.

4 Agricultural IoT Framework

'Heavy' digitization (Mazzetto et al., 2019) of agricultural production systems through the agricultural IoT framework was based on low-cost hardware devices for the deployment of the microclimate monitoring network and software services for the storage, analysis, and visualization of results.

The monitoring network consists of Agricultural Microclimate Automatic Monitoring Stations (AMAMs), which were responsible for observing variables of interest using sensors to obtain measurements that were communicated through a wireless network to be stored and analyzed with small time scales.

Raw datasets were subjected to a process of transformation, normalization, and evaluation to ensure the quality and validity of the set that was used by the other components of the system.

4.1 Agricultural IoT Framework Architecture

Ontological definition of the agricultural IoT framework is presented in Fig. 1. Semantic definitions for sensors and their observations were extended from the standard W3C SSN ontology (Compton et al., 2012). Definition of the temporal concepts of observations and measurements was employed in the W3C Time ontology (Cox et al., 2017). In addition, the OGC GeoSPARQL ontology (Perry & Herring, 2012) was extended to define the spatial location of platforms, sensors, and observations.

Functional design of the agricultural IoT framework includes a three-layer architecture as presented in Fig. 2. The lower level includes the AMAMs as edge devices; the middle level includes a data concentrator node; and the top level includes the storage space for the dataset.

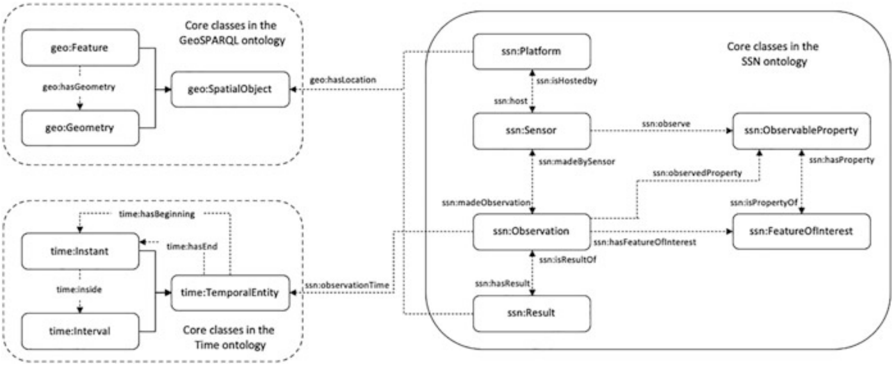

Fig. 1 Extended ontology of agricultural internet of things framework

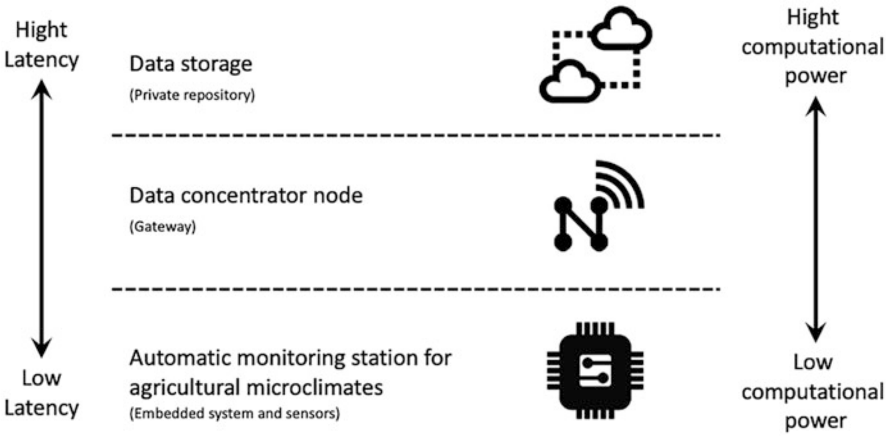

Fig. 2 Architecture of agricultural internet of things framework

Architecture of the agricultural IoT framework has a low latency at the lower level and high latency at the upper level, which guarantees the efficiency of communication and datasets processing. On the other hand, the lower level of the architecture has low computational power, but with the ability to filter and analyze sensor measurements, whereas the upper level has high computational power that enables the implementation of computational algorithms for data analysis and visualization of results.

4.2 IoT Deployment in Crops

The conceptual model of AMAMs integrates a low-power microcontroller connected to sensor blocks and connectivity, as presented in Fig. 3.

Soil sensors, microclimate sensors, and connectivity blocks implement sensing, smart, scalable, and sustainable (S^4) capabilities through physical devices and software components as follows:

- **Sensing**: digital and analog sensors were used to measure soil properties and microclimates in the plantation.
- **Smart**: a communication module was used to link and transmit the measurements taken to the data concentrator node within the agricultural IoT framework. With the software components deployed on the microcontroller, data analysis, and normalization functions were implemented.
- **Scalable**: the agricultural IoT framework allows the configuration and deployment of the required number of AMAMs based on the extension, geographical characteristics of the plantation, and configuration of monitoring quadrants. At a logical level, each AMAM has a unique identification within the system.
- **Sustainable**: this was achieved at the economic level with A choice of durable and low-cost materials; at the operational level, by efficient location within the crop field so as not to interfere with field practices and to achieve efficient communication rates of the observed datasets.

The data concentrator node (DCN), which was responsible for the reception of the raw data observed by the AMAM network, adds a timestamp to each block of received observations and performs the communication of the dataset to the storage layer.

A conceptual model of the DCN, as presented in Fig. 4, integrates a low-power microcontroller connected to the components that enable the functional capabilities of receiving, tagging, and sending datasets to the configured storage space.

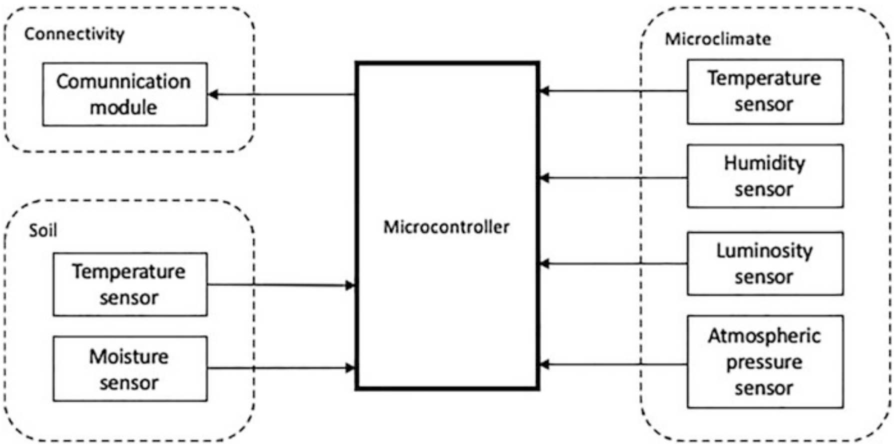

Fig. 3 Conceptual model of agricultural microclimate automatic monitoring stations

4.3 Software Services

Semantic definitions of the agricultural IoT framework establish the design requirements for the private storage repository of datasets generated by the system. Based on the classes, subclasses, and properties of the ontology, the entities, relationships, and attributes of the implemented relational database were defined.

Figure 5 shows the relational model of the database implemented within the agricultural IoT framework. Each entity in the relational model defines the set of attributes, semantic description, and domain constraints for each attribute.

The relational model presents the relationships between entities and defines the data integrity rules in correspondence with the semantic rules of the ontology. This ensures efficient data storage and retrieval, while guaranteeing the integrity, quality, and validity of the processed data.

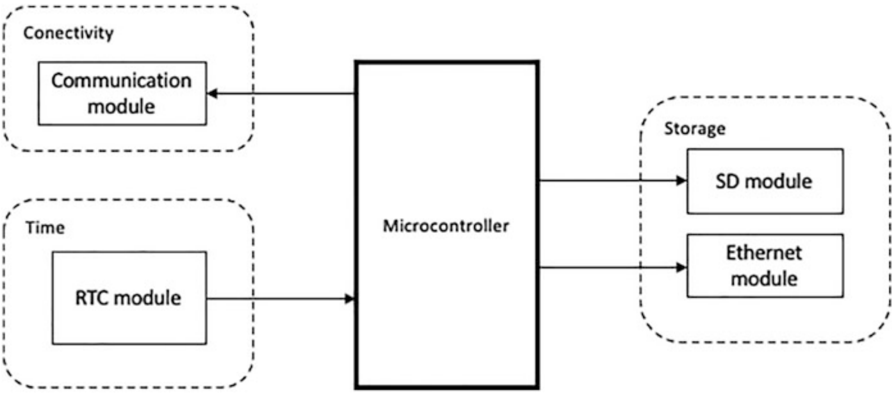

Fig. 4 Conceptual model of the data concentrator node

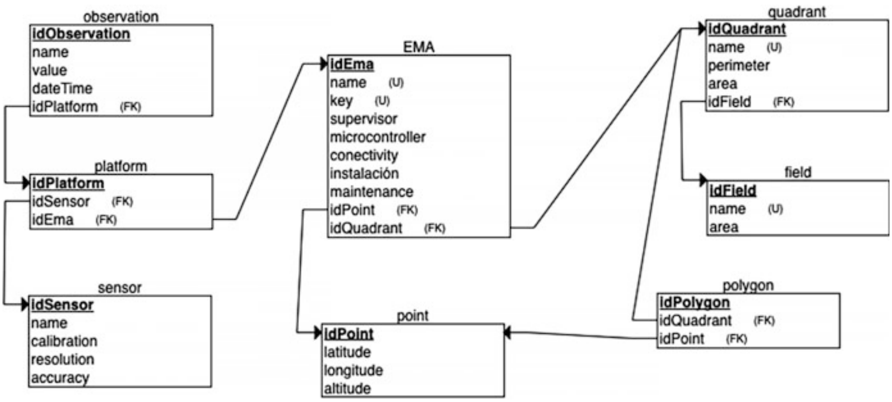

Fig. 5 Relational model

Data analysis components were based on software services that handle the processing of the datasets of data generated by the system. The software-as-service paradigm was used with the implementation of a Web representational state transfer application programming interface (REST API)-based architecture through which the data reception, storage, and processing functions were available to the system components by means of calls to software services in the Web environment.

Finally, data processing was divided into the stages of:

- ***Data entry*** – upon receiving the data generated by the system, components were transformed, normalized, and evaluated to ensure reliability and efficient data integration.
- ***Query processing*** – in charge of processing the requests from the system users based on the ontological definitions to give semantic consistency to the results generated and presented.
- ***Results visualization*** presents results to system users through visualization technologies to display tables, graphs, and widgets to describe values for key indicators and indices for monitoring the agricultural production process.

5 IoT Technology for Sustainable Food Production

The agricultural IoT framework described in this chapter is an alternative solution to the challenges faced by the agricultural sector for food production. Through the described architecture it is possible to configure agricultural production systems to be monitored at different stages of crop development to obtain real-time data to support data-driven decision-making processes for the benefit of producers.

With sensor technologies, wireless networks, and software services it is possible to configure flexible data-driven food production systems. With the results of the agricultural IoT framework, it is possible to direct the application of agricultural practices and the decision making of producers to improve productivity, optimize work, use inputs efficiently, reduce production costs, optimize times, and strengthen the sustainability of agro-ecosystems.

Agriculture 4.0 makes it possible to implement resilient, efficient, and sustainable food production systems. Resilient to the challenges faced by the agricultural sector, efficient in the use of available resources and inputs, and sustainable in economic, social, and environmental dimensions.

6 Conclusions

The agricultural IoT framework presented in this work is linked to the Sustainable Development Goals through the systematization and automation of agricultural production processes using digital technologies. The technological strategy associated with the implementation of technological services allows transforming the traditional agricultural management into a more flexible and dynamic model.

Based on data collection of variables of interest and uses the data set in the tasks of planning and data-driven decision making.

The integration of the proposed ontology to the agricultural IoT framework architecture favors the collection, transmission, storage, and processing of data from food production systems oriented to improve yields and productivity for the benefit of farmers.

There are still many challenges to be solved in the transformation of crop fields to achieve the digitization of production processes. Therefore, the scientific community can continue to search for solutions that strengthen the competitiveness of the agricultural sector.

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Application of Gasification Technology in Agriculture for Power Generation

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Abstract

Gasification is the process of producing fuel gas from biomass for power generation. The fuel gas is utilized in internal combustion engines to produce mechanical or electrical power. The abundantly available agriculture residues have the potential to generate enough power to sustain agricultural system in a carbon-neutral way. Major energy-intensive stationary operations can be performed using electrical or mechanical power generated through gasifier-engine combination. Many such systems have been installed and operated as models for proliferation of this technology. A brief account of gasification technology and its application in agriculture has been collated in this chapter.

1 Introduction

The industrial energy demands increased rapidly over the past few decades and imposed a burden upon the conventional energy resources. These situations paved the path for utilization of nonconventional energy resources. The utilization of biomass as nonconventional energy resource is essential since it can eliminate the factors responsible for global warming and climate change (Nunes et al., 2016). Biomass energy or bioenergy can be defined as the energy produced from transforming any biomass. Bioenergy is implemented for electricity, space heating, and transportation (Anonymous, 2020a, b) and is a sustainable alternative to the global fossil fuel requirement (Ribeiro Teixeira et al., 2018). The share of renewable energy in total global energy production was approximated as 23.7% in the year 2015. There was 8.45% proportion of biomass energy in the total renewable energy consumption, which contributes about 2% to global electricity demand. The raw biomass consists of carbon, nitrogen, hydrogen, and oxygen compounds and can be obtained as by-product from forests and agricultural industries. Biomass is a renewable and carbon-neutral energy resource since it generates equal amount of carbon during energy generation as it was sequestered during its growth period (Anonymous, 2021).

Considering India as an agriculture-dominated country, the bioenergy sector primarily depends upon Indian agriculture. Approximately half of the country's population depends solely on agriculture and its allied sectors for living. However, the share of agriculture sector in Indian gross domestic product (GDP) reduced from 48.9% (in 2011–2012) to 17.32% (in 2017–2018), as stated by National Sample Survey Office (NSSO) (Anonymous 2012a, b, 2017a, b, c). The country possesses a variety of geographical regions such as high mountains, wetlands, numerous river systems, and plains. It thus has significant fraction available as fertile land for growing food crops. India is the second largest in the world in terms of cultivated land (about 159.7 million hectares or 394.6 million acres) and has highest irrigated crop area (82.6 million hectares or 215.6 million acres) (Anonymous, 2020a, b). Thus, the huge amount of crop residues generated can be utilized for power generation for agriculture itself.

The thermochemical conversion of dried biomass converts the carbonaceous material into syngas or producer gas (Balat et al., 2009), which can be utilized in engine generator for production of electricity. The small-scale biomass-based gasifiers can be a feasible solution for effective utilization of biomass and electricity generation in hilly terrain and remote village areas (Debajit & Sanjay, 2007). This chapter explores the necessity and potential of small-scale biomass gasification-based electricity generation plants with investigating biomass availability, sustainability, and gasification process and its application in agriculture. There are many installations in different parts of the country, but not all of them are in published materials. Therefore, some items have been added in reference to information available to the authors. It also elaborates the present installations as well as government's initiatives and policies for expansion of energy production through biomass gasification.

2 Indian Energy Scenario

The total energy generation in India by using thermal (coal, natural gas, and diesel), nuclear, large hydro, and renewable resources is estimated as 222.91 GW, 6.78 GW, 45.29 GW, and 69.78 GW, respectively (Anonymous, 2018a). Thermal-operated power plants are leading contributors followed by renewable energy resources and hydro and nuclear power-based plants. India assured to reduce the emission levels by 33–35% by 2030 in the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC) held at Paris, France. They have also stated to replace about 40% of fossil fuel-based electricity generation plants with renewable energy resources (Anonymous, 2018b). At present, only 20% of electric power plants are powered through renewable sources. India has a commendable bioenergy generation potential of about 25 GW using commercially exploitable resources (Anonymous, 2016). Despite all this, the major energy generation fraction is achieved by coal in Indian electricity generation scenario. The bagasse cogeneration provides about 8.7 GW in Indian bioenergy sector presently. However, only 0.662 GW and 0.16 GW are contributed with non-bagasse in grid connected mode and captive/off grid mode to the Indian bioenergy sector (Anonymous, 2017a).

For over two decades, TERI (The Energy and Resources Institute, New Delhi) has been working on the development of various biomass gasifier designs (downdraft, updraft, and natural draft) for both thermal applications and for decentralized power generation. So far, more than 350 TERI gasifier systems have been successfully installed in the field throughout India with a cumulative installed capacity of over 13 MWth.

3 Global Bioenergy Scenario

The total forest biomass and agricultural biomass (animal by-products, agricultural by-products, and energy crops) contribute about 87% and 10%, respectively, to the global bioenergy sector. The rest (3%) of the biomass requirement are supplied by municipal solid waste (MSW) and landfill gas. The major contribution in global bioenergy is from solid biomass, which contributes 77% and 71% in heat generation and electricity production, respectively. The contribution of MSW, biogas, and biofuel in global bioenergy heat generation accounts for 4, 18, and 1%, respectively. In global electricity production using bioenergy, the share of biogas, MSW, and biofuel is 20, 8, and 1%, respectively (Anonymous, 2021).

4 Advantages of Bioenergy

The advantages of using biomass as source of energy are as follows:

1. Biomass is generated through photosynthesis; hence, it is renewable.
2. The use of biomass as energy resource reduces environmental pollution due to burning of fossil fuels.
3. Biomass is abundantly available everywhere, which reduces the requirement of transportation to power plants.
4. Due to the composition, it can be used for generation of all three types of fuels, i.e., solid, liquid, and gaseous (Asadullah et al., 2014).

5 Gasification Mechanism

Gasification process is a thermochemical conversion of biomass involving several chemical reactions at high temperature, which depends on heat, type of feedstock, and pressure. Earlier, gasification of solid fuel is used to harness energy in the form of combustible gases. Nowadays, this process is also being utilized to transform complex liquid hydrocarbons into gases and chemicals (Baruah & Baruah, 2014). The combustible gas produced in gasification is known as producer gas or syngas and is a mixture of CO, H_2, CO_2, and CH_4. The calorific value of syngas is about 4–10 MJ/m^3.

Thermochemical conversion of agricultural biomass is a complex chemical and physical process. In the first stage of gasification, vaporization of water content in the feedstock takes place when heat is applied. This zone in a gasifier is called drying zone. In the next phase, when the temperature of feedstock reached to a critical level, devolatilization of biomass takes place. This stage is called as pyrolysis or devolatilization stage of gasification and pyrolysis zone in a gasifier. Char and volatiles are the end product of this stage. These volatiles are usually long-chain hydrocarbons in liquid or gaseous phase. In the next phase, cracking of tar occurs with the application of more heat. The heat and several other reactions such as water shift reaction crack the tars. Due to cracking of tar, some heterogeneous reactions on the active sites of solid char and some homogeneous reactions in gaseous phase take place. This happens in oxidation zone. After cracking of tar, reduction reactions take place in which char react with the gas in a heterogeneous manner. The devolatilization gases and gases produced from cracking of tar also react with oxidants as a homogeneous reaction. This zone is called reduction zone.

Char reactions

$$C + 1/2O_2 \rightarrow CO - 110.6\ \text{kJ/mol}$$

$$C + O_2 \rightarrow CO_2 - 393.6\ \text{kJ/mol}$$

Boudouard reactions

$C + CO_2 \leftrightarrow 2CO + 172$ kJ/mol

Water-gas reaction

$C + H_2O \leftrightarrow CO + H_2 + 122.9$ kJ/mol

Methanation

$C + 2H_2 \leftrightarrow CH_4 + 74.9$ kJ/mol

Shift reaction

$CO + H_2O \leftrightarrow CO_2 + H_2 - 41.4$ kJ/mol

Steam reforming

$CH_4 + H_2O \leftrightarrow CO + 3H_2 + 206$ kJ/mol

6 Types of Gasifiers

Gasifiers are broadly classified into three principal types: (1) fixed or moving bed, (2) fluidized bed, and (3) entrained flow. Fixed or moving bed gasifiers are further subdivided as updraft, downdraft, and cross-draft gasifiers. Fluidized bed gasifiers are subdivided as bubbling, circulating, and twin-bed gasifiers, and entrained flow gasifiers are subdivided as coaxial downflow and opposed jet gasifiers. A detail description of these gasifiers can be found in (Basu, 2010). A comparison has been shown in Table 1.

Updraft gasifier is one of the simplest and oldest of all gasifier types. In these types of gasifiers, gasification reactions (oxidation zone) take place near the bottom, while gas is drawn out from the top of the fuel bed. As the producer gas passes through the fuel bed, it picks up volatile matter (tars) and moisture from the fuel. Therefore, the gas from the updraft gasifier contains condensable amount of tar. Updraft gasifiers are suitable for high-ash (up to 25%), high-moisture (up to 60%) biomass. In downdraft gasifiers, product gas flows downward (giving the name *downdraft*) and leaves through a bed of hot ash due to which tar content in gas is considerably low. Biomass is fed at the top and air at the middle or top. Tar content varies from 0.015 to 3 g/Nm^3 (Basu, 2010) (Fig. 1).

In fluidized bed gasifiers, the air is blown upward through the biomass bed, making it behave like boiling fluid. Sand or any inert material is used as bed material. The operating temperature of the bed is maintained within the range of 750–950 °C. There are two principal fluidized bed types: bubbling (BFB) and circulating (CFB). BFB is most common type and suitable for medium-sized units (<25 MW). The BFB and CFB differ significantly in hydrodynamic principals. CFB is especially suitable for fuels with high volatiles. Unlike BFB, a CFB typically comprises a riser,

Table 1 Comparison of some commercial gasifiers (Basu, 2010)

Parameters	Fixed/moving bed	Fluidized bed	Entrained bed
Feed size	<51 mm	<6 mm	<0.15 mm
Exit gas temperature	450–650 °C	800–1000 °C	>1260 °C
Biomass suitability	Not very suitable, forms clinkers	Good for biomass	Unsuitable for biomass
Oxidant requirements	Low	Moderate	High
Oxidation zone temperature	900–1100 °C	800–1000 °C	1800–2000 °C
Cold-gas efficiency	80%	89%	80%
Application	Small capacities	Medium-size units	Large capacities
Problem areas	Tar production and utilization of fines	Carbon conversion	Raw-gas cooling

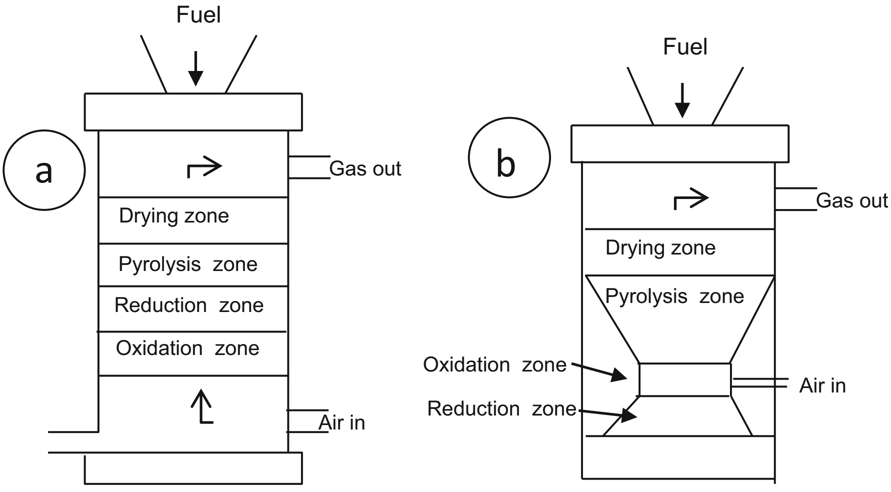

Fig. 1 (**a**) Updraft and (**b**) downdraft gasifiers

a cyclone, and a solid recycle device. The fluidization velocity in a CFB is much higher (3.5–5.5 m/s) than that in a bubbling bed (0.5–1.0 m/s).

7 Feedstock for Gasifier

The agricultural by-products obtained from crop processing and harvesting are classified as primary and secondary residues. So based on this categorization, sugarcane tops and rice straw are primary residues, and bagasse and rice husk are secondary residues (Murali et al., 2007). India has become one of the three major producers of wheat, paddy, cotton, pulses, peanuts, fruits, and vegetable crops.

Therefore, the utilization of available waste biomass to bioenergy can be beneficial due to abundant availability of raw biomass (Anonymous, 2018c). Nowadays, bagasse is the major contributor in Indian bioenergy sector, which is a by-product of sugarcane industries. The utilization of bagasse avails waste to energy (WtE), additional electricity generation, and implementation of agricultural residues for biomass gasification.

An electronic atlas for outlook of biomass resources has also been developed by the Ministry of New and Renewable Energy (MNRE) and the Indian Institute of Science (IISc). State- and crop-wise biomass availability for electricity generation have been illustrated in Tables 2 and 3. The waste biomass residue obtained from wheat, maize, ragi, jowar, and bajra is generally used as fodder and the woody biomass as fuel for household purposes. There are several crop residues burnt in farms due to their unsuitability as fodder. In India, there is approximately 511.04 million tons of biomass residue generated annually from about a 143.54-million-hectare area. Out of which, about 145.02 million tons of biomass residue get utilized for power generation annually (Anonymous, 2018d). The other abundantly available biomass wastes are still not efficiently utilized in Indian bioenergy sector (Singh, 2016). A significant portion of the available biomass remains unused and cause environmental pollution. So the utilization of vastly available biomass in Indian energy sector will be beneficial in terms of energy security and will support the sustainable development of ecosystem.

8 Forest Biomass

By-products of forest such as tree branches, leaves, tops, stumps, roots, split logs, and harvesting wastes are considered as forest biomass. Fuel wood available from forests is vastly used as a primary energy source for direct burning. Woody biomass is assumed as a superior raw material for power generation, since the utilization of agricultural biomass conflicts with national food security interests (Singh, 2016). The conversion of forest residues in power generation industries also minimize forest fire hazards, reduce air pollution, and conserve soil flora/fauna (Anonymous, 2002). As per the Forest Survey of India (FSI) in 2017, forest covers about 24% of total geographical area, which is approximated as 80.21 million hectares (Anonymous, 2017b). The abundant availability of forest biomass in India can be a potential energy source but is limited to household purposes and small-scale industries (Skipper et al., 2003). Recently, the direct burning of woody biomass for cooking purposes has been reduced due to the use of LPG for cooking in rural India (Singh, 2016). This paved the path for utilization of woody biomass for energy production in upcoming years. The total forest biomass potential for electricity generation has been presented in Table 2. The total annual forest biomass and surplus forest biomass for power generation were approximated as 89.11 million tons and 59.68 million tons, respectively (Anonymous, 2018d).

Table 2 Agriculture and forest biomass availability in India

State	Biomass production (MT/year)	Surplus biomass (MT/year)
Uttar Pradesh	60.3	13.7
Punjab	50.8	24.8
Maharashtra	47.6	14.8
Andhra Pradesh and Telangana	43.9	7.0
West Bengal	36.0	4.3
Karnataka	34.2	9.0
Madhya Pradesh	33.3	10.3
Rajasthan	29.9	8.6
Gujarat	29.0	9.1
Haryana	29.0	11.3
Bihar	25.8	5.1
Tamil Nadu	22.5	8.9
Orissa	20.1	3.7
Kerala	11.6	6.4
Assam	11.4	2.3
Chhattisgarh	11.3	2.1
Jharkhand	3.6	0.9
Himachal Pradesh	2.9	1.0
Uttarakhand	2.9	0.6
Jammu and Kashmir	1.6	0.3
Manipur	0.9	0.1
Manipur	0.9	0.1
Goa	0.7	0.2
Meghalaya	0.5	0.1
Nagaland	0.5	0.1
Arunachal Pradesh	0.4	0.1
Mizoram	0.1	0.1
Sikkim	0.1	0.1
Tripura	0.4	0.2
India	511.0	145.0

9 Fuel Properties of Biomass

Generally, a solid fuel is characterized on the basis of proximate analysis and ultimate analysis. Proximate analysis characterize the fuel on the basis of fixed carbon, volatile matter, moisture content, and ash content, whereas ultimate analysis depicts the elemental characterization of a biomass. The primary elements (C, H, O, N, S, and minerals) influence the thermochemical reactions of a solid fuel. For instance, the minerals available in fuel are oxidized into ash, which decrease the effective specific energy of biomass as these minerals are generally inert material. Furthermore, higher ash and tar contents in the gasification of agricultural or forest biomass bear several technical difficulties such as sintering of ash, removal of tar, and bed bridging (Gai & Dong, 2012; Guo et al., 2014). Table 3 depicts the

Table 3 Fuel properties of different agricultural and forest biomass

Feedstock	Proximate (% as received)				Ultimate (% ash-free)					High heating value (MJ/kg)	Density (kg/m^3)	References
	FC	VM	M	Ash	C	H	O	N	S			
Paddy straw	11.8	72.7	8.25	15.5	35.97	5.28	43.08	0.17	–	16.28	75	Parikh et al. (2005); Mandal et al. (2017)
Pine needles	26.3	71.58	7.78	2.08	44.99	5.46	48.55	0.99	–	17.67	–	Mandal et al. (2018)
Cotton gin waste	20.8	68.7	11.8	10.5	45.14	4.93	40.4	1.16	0.29	16.6	390	Samy (2013)
Sugarcane bagasse	31.0	65	9.4	3.6	49.4	6.3	43.9	0.3	0.07	18.9	68	Jordan and Akay (2012)
Oil palm empty fruit bunch	8.79	82.58	5.18	3.45	46.62	6.45	45.6	1.21	0.035	17.02	1422	Mohammed et al. (2012)
Switchgrass	16.8	76.9	6.0	6.3	47.9	6.2	45.0	0.8	0.1	19.6	115.4	Masnadi et al. (2014); Mani et al. (2006)
Cattle manure	11.15	59.05	13.08	29.8	35.4	5.04	27.5	1.79	0.4	15.93	–	Magnilao et al. (2015)
Corncobs	18.54	80.10	NA	1.36	46.58	5.87	45.4	0.93	0.16	18.77	282	Jenkins and Ebeling (1985)
Rice hulls	16.67	65.47	NA	17.86	40.96	4.3	35.8	0.4	0.02	16.14	70–145	Jenkins and Ebeling (1985)
Sawdust	16.27	82.45	NA	1.28	50.26	6.14	42.2	0.07	0.05	20.47	210	Lapuerta et al. (2008)
Macadamia shells	23.68	75.92	NA	0.40	54.41	4.99	39.6	0.36	0.01	21.01	680	Jenkins and Ebeling (1985)
Coconut shells	21.38	77.82	NA	0.8	49.62	7.31	42.75	0.22	0.10	20.8	–	Iqbaldin et al. (2013)
Redwood	19.92	79.72	NA	0.36	50.64	5.98	42.88	0.05	0.03	20.72	481	Jenkins and Ebeling (1985)

proximate and ultimate characteristics of different biomass available in India. The higher carbon content in biomass implies that the biomass has high energy content. On the other hand, high moisture and ash content depicts that biomass has low effective energy content. Also, the content in biomass is not the only variable to influence the process of gasification. The hydrogen and oxygen content available in the moisture reacts and thus forms hydrogen, CO, and CH_4, which are primary gases in the syngas composition. Moreover, bulk density of fuel is another variable that influences the gasification process. Unlike coal, agriculture biomass has low bulk densities, which causes severe problems in handling biomass when feeding to gasifier. Biomass contains alkali and alkaline metals such as K, Na, Ca, and Mg along with some other minerals like Fe, Si, Al, Cl, and P. These minerals are responsible for ash formation in the gasification process. Though formation of ash hinders the efficiency of gasification, for some biomass, alkali or alkaline earth metals may act as a catalyst and thus increase the quality of syngas. The presence of alkali and alkaline earth metals can crack the tar forming in gasification process, subsequently enhancing the quality of syngas.

10 Process of Biomass Gasification

10.1 Collection and Densification of Biomass

As discussed earlier, agriculture or forest biomass has low bulk density along with non-uniform shape and dimension, which creates difficulties in collection, transportation, and handling of biomass in loose form. Therefore, densification and pretreatment of biomass is important for its utilization as a solid fuel in gasifier. Nowadays, tractor-operated balers are available to densify the biomass in cylindrical or cuboid shape. Torrefaction of biomass and pelleting are generally two routes to increase the bulk density and energy content of loose biomass. These routes also enhance the specific energy content in biomass along with bulk density.

10.2 Size Reduction of Biomass

Size reduction of biomass for obtaining appropriate particle size is required to increase the efficiency of gasification process. The irregular size and shape of agricultural biomass make it necessary to reduce the particle size. Generally, smaller particle size associated with high surface area of biomass results in fast and even heat transfer. The fast heat transfer increases the reaction rate of gasification. The particle size of 1 μm to 1 cm is recommended for gasification; however, it varies on the type of gasifier (Souza-Santos, 2010). For example, a fine-size feedstock is generally required for gasification in the fluidized bed gasifier to improve the fluidization of biomass and maximize the contact area of biomass with the oxidant. On the other hand, larger particle size is required for fixed-bed gasifiers because for effective devolatization of biomass, delaying of rapid combustion of biomass is required. Therefore, to achieve slower reduction, larger particle size in the range of 1 cm is recommended. Similarly, finer particle size of biomass is recommended for entrained bed-type gasifiers.

The size of biomass is generally reduced using hammer mills, ball mill, rotary blade cutter, or grinders. The performance of these tools is a function of size reduction ratio and nature of biomass such as moisture content and fiber content. Knife cutters are recommended to use for size reduction of biomass having high fiber content instead of grinders, as grinders increase the ratio of chopped biomass, having broom-like ends (Souza-Santos, 2010). This type of chopped biomass can intertwin and thus can clump in the feeder unit.

10.3 Drying

Agricultural or forest biomass usually has high moisture content; therefore, drying of biomass is often required to decrease the moisture content to 10–15% (Basu, 2010). Some biomass such as cotton gin waste has low moisture content and therefore do not require drying. On contrary, some biomass such as vegetable waste has moisture content of more than 50% and require drying before gasification. Drying of biomass is an energy-consuming process and therefore reduces the overall efficiency of gasification. The energy consumption to vaporize 1 kg moisture is about 2300 kJ (Basu, 2010). This energy can be achieved using heat generated during gasification or by any other medium such as solar drying.

10.4 Pelleting or Briquetting

Pelletizing or briquetting is another way to increase specific energy of biomass. The main aim is to increase the density of agricultural biomass by pelletizing. Pellets with a grain size of about 1–2 cm are typically best for combustion in fixed-bed biomass gasifiers. For many years, biomass pellets, especially wood pellets, have been easily available in the local market commercially. Pelletizing as a process mainly serves to increase the density of biomass, but it is also able to increase its thermochemical conversion efficiency. Compared to raw heterogeneous material combustion, agricultural biomass combustion produces lesser ash content in pellet form. It was reported by Holt et al. (Holt et al., 2006) that on combustion, cotton gin waste pellets resulted in a reduced ash product by two to three times when in comparison to combustion of un-pelleted biomass. Pelletizing of biomass may also make sense for heating purposes in industries, particularly with respect to the operation of infeed system. This is due to the fact that the irregular shapes and sizes of raw agricultural biomass and the combustion or gasification of pellets can present fewer control problems than raw biomass. This is because raw non-woody biomass has a tendency to clump together. When pellets are burned or gasified, the combustion and gasification can be unstable, resulting in higher emissions and lower efficiency. Controls in pelletized form are comparable to those in liquid/gas-fueled systems. Because wood pellets have similar sizes and water content, they may be more convenient to process, store, and transport (Vinterbäck, 2004). Briquettes made of wood have proven productive in domestic heating systems in the European and US markets. For these regions, the standard-quality parameters for fuel pellets are considerably different; however, they are both predicated on the amount of ash in the fuel (Duca et al., 2014; Holt et al., 2006; Toscano et al., 2013; Vinterbäck, 2004). However, another category of lower-grade fuel pellets for industrial applications has also been considered (Vinterbäck, 2004). In order to handle the lower fuel quality, emission control systems may need to be more flexible to cope with the production of emissions within acceptable limits. Despite the availability of wood pellets from waste for some time, biomass properties differ widely, which makes it challenging to develop pelleting technologies that are suitable for a wide range of feedstocks. Pelletizing is basically a means of compressing raw materials. Screw extruders or die pellet mills are the standard tools used in the process. It is important to keep in mind that the efficiency of the tools is affected by temperature of die, roller configuration, die and roller pressure, feed rate, moisture content, and feedstock properties (Holt et al., 2006; Uslu et al., 2008). In a recent study, it was examined how add-on binder materials impacted extrusion temperature, pressure, and moisture content, as well as the effects of binder addition or additive materials. The studies examined primarily the properties of the developed fuel pellets and the biomass associated with them. Pellet binders in general can include natural lignin, protein, starch, and water-soluble carbohydrates (Lu et al., 2014). A lignocellulosic matrix is formed when lignin is bonded together. Pelleting is similar to bonding, in that lignin softens, flows, and hardens. By combining pressure and heat, a polymer softens and passes from a glassy to a plastic state. Due to the unique lignocellulosic composition and bond structure of each non-woody biomass, pretreatment may be required to change the lignin, cellulose, and hemicellulose bonds before pressing. Pretreatment enables the production of pellets that have uniform durability and stable structure. Biological fermentation or steam explosion can be used as one or combinations of methods for bond modification (Agbor et al., 2011). Frequently, steam explosions are used on an industrial scale (Shahrukh et al., 2016). It involves applying steam to rupture cellular structure at 180–240 °C. Fermentation through biological means is promising but still a challenge to achieve on a large scale for colder applications (Agbor et al., 2011). For some non-woody biomass pelleting processes, bond modification still is inadequate (Sultana et al., 2010). The pellets can then be strengthened, coated, and thermochemically altered with additives to improve strength, durability, and other properties. For further improvement of mechanical structures, additional starch, lignosulfonate, or bentonite may be added. Pellet fuel can be improved by adding a number of substances during pelletization to improve its heating value and thermochemical properties (Holt et al., 2006; Jordan & Akay, 2013; Lu et al., 2014). Additionally, oil, glycerol, and calcium catalysts were found to improve thermochemical properties and overall process efficiency. A number of these substances could however have detrimental effects on the durability and density of pellets, for example, oil added to cotton gin trash (Holt et al., 2006). In this area, a number of researches are underway.

10.5 Criteria for Selecting Suitable Gasifier

A gasifier is the reactor unit used for heat transfer to biomass. These gasifiers can be distinguished according to the flow pattern of biomass, heating method, and type of produced gases. The fixed-bed gasifiers are easy to construct and operate. In these gasifier, feedstock flow naturally through the various zones of gasification such as drying, pyrolysis, gasification and combustion (Piechocki et al., 2014). There are no exact physical boundaries exists between these zones but these zones are controlled by oxidant and quantity of feedstock (Souza-Santos, 2010). This type of gasifiers provide intimate contact of feed and gases. On the other hand, the fluidised bed reactors provides more contact between feed and oxidisers. In similar fashion, entrained bed type gasifier use finer fuel particles which give high surface contact with oxidants. Other than these categories, gasifiers can also be categorised as allo-thermal and auto-thermal. In allo thermal reactors, the heating of feedstock is externally sourced whereas in case of auto-thermal gasifiers heat is generated due to incomplete combustion of feedstock.

The problem of lesser density of agricultural biomass can be overcome by selecting a suitable gasifier design. The selection criteria of different gasifier is summarized in Table 4. Application of pretreatments such as size reduction and pelleting are useful for fluidised bed, entrained flow or cyclone type gasifiers however, the high mineral content in agricultural biomass can restrict the operation in fluidized bed reactors. The minerals present in the biomass produce ash having low melting point such as alkali silicate. The generation of this sticky glassy melt may result in particle agglomeration in the bed, resulting in fluidization failure and overall operational failure (Fryda et al., 2008). For typical agricultural and forest biomass a fixed-bed reactor is rarely effective to employ it as feedstock. This is due to the fact that a fixed-bed reactor generally requires natural flow of fuel in each zone

Table 4 Selection criteria for gasifiers

	Fixed bed		Fluidised bed		Entrained flow
Particulars	Downdraft	Updraft	Bubbling bed	Circulating fluidised	
Capacity of gasifier	Small-medium	Small-medium	Small-large	Medium-large	Medium-large
Tars	Less	High	Moderate	Moderate	Very low
Temperature Range	700–1200	700–900	<900	1450	1450
Type of heating	Auto heating	Auto heating	Both auto and allo heating	Both auto and allo heating	Allo-heating
Biomass pretreatment	Very important	Important	Less important	Less important	Only fine particles
Feedstock particle size	More than 1 cm	More than 1 cm	1 um–1 cm	1 um–1 cm	1 um–1 cm

of drying, pyrolysis, combustion and gasification. On the other hand agricultural biomass due to their irregular shape and size have low flow ability. The low flow ability of raw low density feedstock may hinder oxidant infiltration, resulting in zones of partial oxidation and disrupted airflow patterns. The disrupted air pattern may alter the stoichiometry ratio of air and biomass. The unbalanced air fuel ratio may restrict to achieve the optimized zone conditions. Therefore, fixed-bed reactors are usually unsuitable for agricultural biomass if not pre-treated and densified properly. Jordan and Akay (2012) investigated sugarcane bagasse pellets as a feedstock in downdraft gasifier. The study reported that the quantity of tar was low because of pelleting of biomass and cracking of tar in the pyrolysis zone of the gasifier. On the other hand, gasification of unpelleted sugarcane bagasse produced tars which were condensable easily at low temperatures. In similar fashion, Mandal et al. used briquetted pine needles in updraft gasifier and found that briquetted pine needles have better combustion characteristics (Mandal et al., 2019). To overcome the problem of tar generation, granular CaO acts as a catalyst for tar cracking if mixed with pellets.

10.6 Co-gasification of Agricultural Biomass

In regards to the utilization of non-woody biomass, there are two approaches. Firstly, the gasifier must be modified to suit the non-woody properties, and secondly, the non-woody properties as solid fuel must be improved. For accelerated commercialization of biomass, it might be better to first focus on improving the quality of non-woody biomass so that it can be fed into existing thermochemical energy converters or gasifiers without many modifications. Upgrading nonwoody sources into good quality pellet fuel may be the best way to improve their quality as solid fuels. Studies have been conducted using fluidized bed and entrained gasifier types to investigate biomass and coal co-gasification (Howaniec & Smoliński, 2014; Pan et al., 2000; Pinto et al., 2003; Xu, 2013). Some researchers have also conducted trials using fixed-bed plants (Kumabe et al., 2007; Rizkiana et al., 2014). As opposed to fluidized systems, a fixed bed may be more suitable and more controllable for small- to medium-scale plants. Fixed beds may provide better conditions for synergistic effects during co-gasification than fluidized ones, since they provide closer contact between adjacent fuel particles. An adequate time in residence is another factor affecting the likelihood that synergistic effects will occur. Gasification occurs in a reduction zone when downdraft types are used. With co-gasification of coal, greater stability is created within the zone, making tars and chars more prone to cracking and becoming reactive due to the slower process. A study by Collot et al. (2009) examined a fluidized and a fixed-bed co-gasification process. While the researchers found that fluidized reactors did not show synergy, they did observe a slight, but not significant, increase in tar cracking on fixed beds. Research on co-gasification of biomass and coal has utilized either biomass as a supplement to coal gasification (Zhu et al., 2008) or vice versa, in the sense that coal served as a supplement to biomass gasification (Nemanova et al., 2014). The use of highly volatile coal (low to medium rank coals) in coal co-gasification with biomass can lead to higher gas conversion efficiencies than that of using high rank coal (Nemanova et al., 2014; Rizkiana et al., 2014). Despite having higher energy content, use of high-ranked coal resulted in more char residue rather than a higher amount of carbon converted to combustion gases. The difference is because high-ranked coal is more inert than lower ranks. The high-ranking coals were less catalytic than low-ranking coals during coal gasification (Tchapda & Pisupati, 2014). High-ranking coals typically contain calcium in the form of calcite, resulting in decreased catalytic activity. Also present is potassium, which forms potassium aluminosilicate glass. Consequently, biomass can serve as a better source of natural mineral catalysts than coal for co-gasification. The use of blended coal and biomass may allow for an energy plant to operate more economically and reliably. But the issue concerning the released mixed char should be handled carefully to avoid soil contamination. Mixing biochar with biomass could be another use for it. Biochar has many characteristics similar to coal in that it contains high fixed carbon but is potentially more volatile and reactive than high-ranking coals, contains less ash and sulfur than low-ranking coals, and more importantly has fewer heavy metals like mercury than coal.

10.7 Application of Gasifier in Agricultural Operations

Gasifiers in agriculture can be applicable in three modes:

- Electrical power generation.
- Mechanical power generation.
- Thermal applications.

11 Electrical Power Generation

This has been one of the important modes of using gasifiers in agriculture for many decades. However, cost of electrical power generation in gasification mode is considered higher when solar power has been very cheap.

In 1998, gasifier was employed in rice mill for electricity generation. Rice husk generated as a by-product of rice processing was used as feedstock. The unit cost of electricity using rice husk gasifier-based power generation systems has been calculated and its financial feasibility assessed in comparison with utility-supplied and diesel-generated electricity. The cost of power generated by the gasification system was lower than diesel-based power generation (Kapur et al., 1998).

Decentralized power generation systems based on the biomass gasifier were implemented in Hosahalli and Hanumanthanagara villages in of Kunigal taluk, Tumkur district in Karnataka. Installed capacity was 20 kW in both villages. A mixed species forestry biomass was used as feedstock. In Hosahalli village, lighting, drinking water, irrigation water, and flour-milling services are provided using power derived from the biomass gasifier-based power generation system. The biomass power system has functioned for over 14 years (1988–2004), meeting all the electricity needs of the village. Lighting and piped drinking water supply using biomass electricity were provided for over 85% of the days during the 6 years. Fuel, operation, and maintenance cost ranged from Rs 5.85/kWh at a load of 5 kW to Rs 3.34/kWh at a load of 20 kW. There were few technical problems associated with the grate repair, filter replacement, and fuel quality (Ravindranath et al., 2004).

A 20 kW power generation unit has been tested for stationary farm operations (Nevase et al., 2013). The volumetric percentage of carbon monoxide (CO), hydrogen (H_2), carbon dioxide (CO_2), methane (CH_4), and nitrogen (N_2) at 20 kW load was 18.4, 13.8, 11.1, 2.40, and 54.2%, respectively. The calorific value, density, and tar of producer gas varied from 4.17 to 4.85 MJ m^{-3}, 1.16 to 1.56 kg m^{-3}, and 10.2–10.0 mg m^{-3}, respectively, with the increase of load from 5 to 20 kW. The biomass consumption rate, specific biomass consumption rate, specific gasification rate, specific gas production rate, equivalence ratio, and gasification efficiency varied from 11 to 28 kg/h, 2.20 to 1.40 kg/kWh, 29.63 to 75.43 kg/(m^2 h), 103.7 to 257.43 m^3/(h m^2), 0.32 to 0.47, and 79.26 to 89.90, respectively, as the engine load increased from 5 to 20 kW.

In central India, a 125 kW electrical power generation plant was installed for pumping water for the Bhopal City in Mana village of Raisen district, and a similar plant of 125 kW was installed in Udaipura village of the same district for electricity supply to the village. Both the plan was operated by downdraft gasifiers, which were fed by briquettes made from agricultural residues. On an average, 1 kg of briquette required for production of 1 kW-h of electrical power. Major hurdle in the operation was faced due to varying physical and moisture conditions in the feedstock (Anonymous, 2012a, b).

12 Mechanical Power Generation

In 1989, a study was conducted on the use of gasifier-engine system for water pumping (Rajvanshi & Joshi, 1989). Operational experience with a topless hybrid wood gasifier powering a 3.75 kW diesel engine pumpset was detailed. The gasifier-engine pumpset was operated for 250 h. The fuel was *Leucaena leucocephala* wood from trees 1–2 years old. Average diesel substitution varied between 50% and 78% depending on load. On average, the gasifier consumed 1.33 kg of wood and 125 ml of diesel to produce 1 kWh of mechanical energy for water pumping.

In a study, use of downdraft gasifier for irrigation pump operation was undertaken to replace diesel engine (Gangil & Dubey, 2004). A diesel engine of 5 hp. was used for production of mechanical power to drive the irrigation pump. The engine was operated for 750 h. The engine operation faced few operational constraints due to tar deposition at engine parts. The study identified the problems/faults occurred during dual fuel operation of the engine along with their reason. The study explored that use of dual fuel in diesel engine is feasible, provided the producer gas used is clean from tar.

A successful demonstration of gasifier-based water pumping in agriculture was made by Homdoung et al. (2015). The biomass gasifier-engine system was designed, built, and tested with waste woods from the furniture-making industry. A downdraft, throat-type, fixed-bed gasifier was used for producing the gas for engine. The engine power rating was 5.5 kW. The engine performance was evaluated over a fixed load and variable speeds between 1000 and 2000 rpm. Results showed that dual operation was able to produce slightly higher power output than normal diesel operation, with similar thermal efficiency. Producer gas substitution or diesel replacement of about 60–70% by mass was achieved. The producer gas powered water pumpset was later installed, which could deliver water yield of 60% of nominal value.

13 Thermal Application

Commodity drying has been the major application of gasification or biomass energy system in agriculture. In an experiment, gasifiers were proposed as an alternative method of providing the hot air used for drying in tea (Jayah et al. 2007). A downdraft gasifier was tested and found to have a conversation efficiency of 80% of biomass heat. The heat loss was found between 11.5% and 14% of the input energy. Wood consumption is also reduced by 12% in comparable to wood burner.

More than 150 gasifier-based drying systems were installed in Sikkim in collaboration with the state horticulture department for drying of large cardamom. Through extensive field performance monitoring, it was observed that use of gasifier not only resulted in more than 62% fuel wood saving but also resulted in improving the quality of the product, as the dried cardamom retained 35% more volatile oils and natural reddish color compared to local drying system (Dasappa et al., 2003). TERI also developed an integrated gasifier-based system for boiling and drying of areca nut. The gasifier with a wood consumption rate of about 20 kg/hr. capacity was used for boiling areca nut in the existing boiling pan and also utilized the hot flue gases for drying. The gasifier could also be operated successfully using waste areca nut husk (a by-product during de-husking operation) that made this system more energy- and cost-attractive.

Efforts were made to replace diesel fuel with the use of coconut shell-fed gasifiers for chemical extraction from marigold flowers. Two types of heating systems were studied: low temperature and a high temperature industrial heat requirement. The gasification system for these applications consisted of an open top-down draft reburn reactor lined with ceramic. Necessary cooling and cleaning systems are incorporated in the package to meet the end use requirements. The other elements included are the fuel conveyor, water treatment plant for recirculating the cooling water, and adequate automation to start, shut down, and control the operations of the gasifier system. Drying of marigold flower, a low-temperature application, was carried out to replace diesel fuel in the range of 125–150 l/h. Gas from the 500 kg/h gasifier system was piped into the producer gas burners fixed in the combustion chamber with the downstream process similar to the diesel burner. The high-temperature application was for a heat treatment furnace in the temperature range of 600–920 °C. A gasifier of 300 kg/h of biomass consumption capacity replaced 2000 liters of diesel per day completely. The systems were operated over 140 h per week on a nearly nonstop operation and over 4000 h of operation replacing fossil fuel completely (Pathak et al., 2008).

A 125 kg/h biomass gasifier of modular design was developed at the Sardar Patel Renewable Energy Research Institute (SPRERI) and tested on the thermal mode to test the concept. Based on the design, a scaled-up version having capacity of 375 kg/h modular throat-type, downdraft gasifier system was designed, developed, and tested. The smaller gasifier when tested at a wood consumption rate of 55 kg/h gave a gas calorific value of 4.24 MJ N m^{-3} and cold gas gasification efficiency of 63%. The larger gasifier system was operated for about 50 h using agro-residue briquettes at gas flow rates of 213 and 278 N m^3/ h. The cold gas efficiency was in the range of 70–73% (Pathak et al., 2008).

14 Economics and Sustainability of Gasification Technology

Energy utilization of biomass resources can be an encouraging and sustainable method in order to encounter the problem of depletion of fossil fuels and coal. The consumption of coal can be minimized in thermal applications by consuming biomass in an efficient manner. India has about 145 Mt./year surplus biomass, which can lower the demand of coal in power generation. Biomass can be either solely utilized or mixed with biochar to overcome the drawbacks of coal power plant. The International Energy Agency (IEA) emphasizes on the utilization of biomass in power generation to reduce the CO_2 emission to cope with climate change. It is also estimated that utilization of biomass can drastically decrease the environmental emissions (World Energy Outlook, 2012). Moreover, the practice will also avoid the issue of crop residue burning in India and other developing nations. Thus, the utilization of biomass in gasification is a sustainable approach as it saves natural resources like coal and fossil fuel but also helpful to mitigate climate change.

Considering the economic side of gasification technology, it can be observed that with growing population and industrial development, the demand of energy in India has increased significantly over the decade. To cope with the increased demand of energy, biomass energy can be a viable option since it is environment-friendly and economical. Power generation using decentralized biomass-based energy system can be more economic because it has minimal transmission and distribution losses. In addition, biomass is abundantly available in remote locations in India, which is a positive factor to design a decentralized biomass-based gasification system.

15 Conclusion

Gasification is process to convert biomass into gaseous fuel and subsequently into energy. There are numerous agricultural and forest biomass available in India, which accounts for a total of 145 million tons of surplus biomass available annually for gasification. This type of biomass has a great deal of potential for utilization, given that it is abundant and widely available. In contrast to standard combustion, gasification provides a better conversion efficiency while also reducing pollutants. This type of biomass material is, however, impractical for gasification due to low density and high silicate content. This chapter provides the brief insight for selection and improvement of gasifier designs to take into account the low density and lack of woody properties. Yet there have been reports of some technical difficulties, like issue of fluidization or consumption of higher energy. Densification and briquetting of agricultural biomass could be a viable option for feeding into gasifiers. This technique is equally well suited to the even simplest designs of gasifier like updraft or downdraft gasifiers. By torrefying or briquetting/pelleting the biomass, it is possible to enhance the density of feedstock. Pelletizing can be made more efficient by adding some catalytic materials or materials with higher heating values in addition to the binding agent. Pelletizing biomass only consumes about 15–20% of the pellet energy and improves the quality of feedstock and overall efficiency of gasification. The most of biomass co-gasification research is focused on combining biomass with coal. The natural catalyst in biomass may produce catalytic gasification, whereas thermal energy from coal may crack the tar. Despite its apparent synergy, co-gasification requires additional testing on a larger scale and with a wider range of feedstocks and product ratios. It is also feasible to replace coal with biochar briquettes by adding some suitable binder. Thus, the upgradation of the quality of agricultural biomass might enhance gasification process. In co-mixed and pelletized form, biomass as a fuel can provide the better control for auto-thermal gasification. The process controls are comparable with liquid/gas-fueled system. Densified non-woody waste solid pellets could well provide a reliable alternative energy source for achieving energy independence and decentralized energy in the future.

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Optimizing Solar Photovoltaic Cells

Improving Green Energy Harvest for Agriculture

Subhadip Paul and Amitava Rakshit

Contents

Abstract

Replacement of fossil fuel-based energy sources in agriculture becomes necessary because of its restricted supply and impact on the environment. In this aspect, different renewable energy sources have been analyzed for good alternatives. Solar energy has gained more attention among these renewable energy sources. The photovoltaic cells harness this solar energy and convert them into electricity. Global market is mainly dominated by silicon-based photovoltaic cells because of its cheapness and high electricity production efficiency. However, it lacks more spectral regions for capturing photons. Scientists have taken heed on enhancing the silicon cells' spectral region to increase the photon capture. Three spectral conversion processes, namely, *upconversion*, *downconversion*, and *downshifting*, have been performed in developing revolutionary photovoltaic cells that have

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geared up the efficiency of silicon-based solar cells. Lanthanides are very promising luminescent elements, used as dopants in these spectral conversion processes. These advanced technologies can provide more electricity for sustainable farm operations while curbing the greenhouse gas emission. Hence, the upgraded solar cells held an outstanding potential to supply power for precision farming. Still, challenges remain to remove the barriers among laboratory results, broad-scale farm application, knowledge of environmental concerns, and economy.

Keywords

Photovoltaic cell · Spectral conversion · Upconversion · Downconversion · Downshifting

1 Introduction

Combustion of fossil fuels (petroleum, coal, liquefied petroleum gas, etc.) releases a high amount of greenhouse gases (GHGs) in the atmosphere and delivers a global threat to the climate change. Over several decades, a price hike of fossil fuels became prominent due to the depletion from continuous use. According to the IPCC report in 2014, the agriculture sector contributes 24% of the global GHG emission, second to electricity and power production sector (25%), followed by industrial emission (21%), transportation (14%), and emissions from other economic sectors (16%) (Lee et al., 2018). The CGIAR (Consultative Group on International Agricultural Research) stated that about 19–29% of GHG emission occurs from consuming about 30% of global energy, generated through fossil fuels (Gorjian et al., 2021). Out of various agricultural operations, power generation contributes 79% of the total *carbon footprint* (Jaiswal & Agrawal, 2020). For large-scale farming activities (i.e., irrigation, harvesting, soil inversion, sowing, and spraying) and high-load machinery operations (i.e., tractor, power tillers, drip system, sprinkler system, dryer, threshers, etc.), power requirement is very high. Thus, scientists have searched for different alternatives to mitigate these problems. Major focus is given on renewable energy sources, but lower efficiency and high maintenance cost made these sources ineffective. Nowadays, renewable energy shares nearly 19.2% of global power consumption (Lee et al., 2018). This figure is extensively low as compared to fossil fuels which operate nearly 78.3% of global power consumption (Lee et al., 2018). The maximum share within renewable energy comes from traditional biomass combustion (89%) which is used for cooking, heating, and other household purposes, while biofuels and hydro-energy accounted for nearly 8% and 39% of the renewable energy (Lee et al., 2018). The major assumption behind the popularity of biomass/biofuels is that these are thought to be *carbon-neutral fuels* as the plants/crops grown on field capture atmospheric carbon and release the same amount upon combustion. Thus, more lands are currently occupied by the biofuel crops. However, the error lies within the calculation of *carbon opportunity cost* (Creutzig et al., 2014). The *carbon opportunity cost* for altering surplus lands/abandoned lands/forest lands/agricultural lands into lands for bioenergy crop production can liberate soil reserve carbons into the atmosphere in the form of CO_2. These indirect land use changes were reported to contribute nearly 3.8 g CO_2 equivalent MJ^{-1} and 26.5 g CO_2 equivalent MJ^{-1} emissions from corn and sugarcane fields, respectively, used for bioethanol production (Mekonnen et al., 2018). Hence, neither biomasses nor the biofuels are considered sustainable/green technology for power generations. Energy from the waste is now given importance, but the anaerobic digestion of agricultural or other kinds of organic wastes yields very little fuel as compared to the energy consumption during the process (Pavlas et al., 2010). Hydropower supplies nearly 20% of global electricity, but major disadvantages in its implementation lie within countries' geomorphology, i.e., geography with higher river torrents (Azarpour et al., 2012). Furthermore, it also carries risks of collapsing dam structure and flooding. Wind power can provide substantial amount of energy, but its installation over large areas can alter the local habitats. Besides, only arid areas (preferably areas near deserts) with no physical obstruction are chosen for installing wind turbines. Energy, generated during the formation of earth and spontaneous natural radioactive decays, is stored as geothermal energy within or below the earth's crust. The risk associated with geothermal power grid is that it enhances the micro-seismicity which can induce earthquake or landslides (Majer et al., 2007).

Solar energy accounted the cheapest among all other renewable energy sources. The most important part is that during the light harvest, solar modules do not emit GHGs. Higher solar intensity in terrestrial lands appraises the deployment of solar energy harvesting modules. Photovoltaic cells are the most widely used solar energy harvester. Here, only manufacturing capital shares the major production cost. The *stand-alone* and *grid-connected* systems are deployed for agricultural operations. The former one is more utilizable in small farms; but the *grid-connected* system is more prevalent in reducing cost due to the elimination of storage unit (Gorjian et al., 2021). The growing demand for *precision agriculture* in the world employs the automation of machineries and implementation of different sensing technologies. The automation of agricultural machineries and robotic technologies necessitates *autonomous mobile robots* in which *unmanned ground vehicles* and *manipulators* possess a high energy demand, giving opportunity for harnessing abundant solar power (Gorjian et al., 2020). Until 2010, nearly 40 GW of energy demand is met by solar power alone, but in 2019, renewable energy sources are found to enhance 72% expansion in electrical power, out of which solar energy accounted 90 GW (Hosseini, 2020). Scientists and research institutions are now working on developing high-efficiency photovoltaic cells for farm uses at various scales.

2 Photovoltaic Cells

The photovoltaic cells devised the conversion of incoming photon (solar spectrum) energy into electricity through photovoltaic (PV) effect of semiconducting materials. In 1839, Alexandre-Edmond Becquerel discovered the PV effect at atomic level.

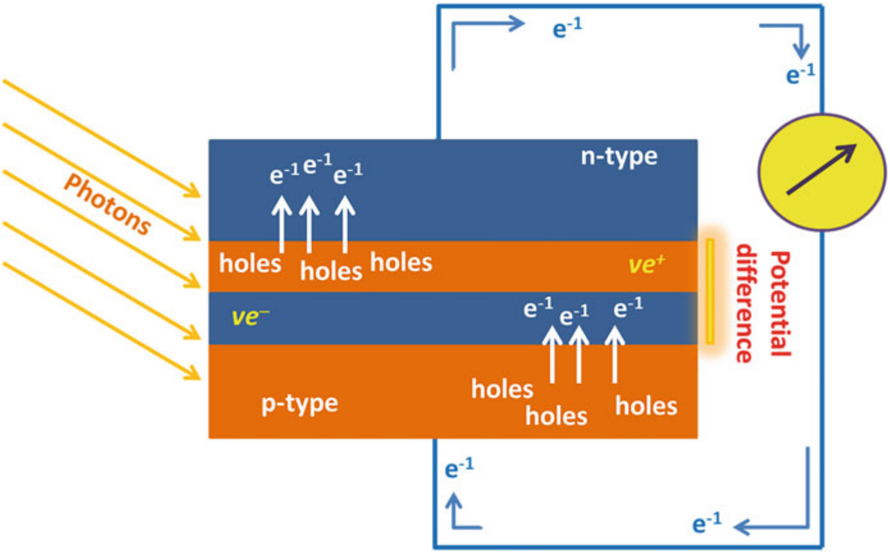

Fig. 1 Generalized photovoltaic cell with p-n-type doping

Elements, exhibiting photoelectric property (i.e., semiconductors), absorb photons from sunlight and release electrons (e^{-1}) from their outermost shells, creating e^{-1}-hole pairs in the material. Integrating p-type (i.e., more holes; positively charged) with n-type (i.e., more e^{-1}; negatively charged) semiconductors (i.e., doping) causes further distribution of holes and e^{-1} on the both sides of junction (Fig. 1). This difference in potential due to charge separation (electrons and holes) at p-n junction provides electricity for running farm machinery (Fig. 1).

However, traditional first-generation silicon (Si) wafer-based modules are less efficient in contributing the power requirements for mechanized farming activities (Srinivas et al., 2015). Theoretical maximum efficiency (nearly 30%) of this Si-PV can be obtainable using the Shockley-Queisser model (1961). Again, storage of this power has not been successfully implemented yet. There exists a loss in power conversion efficiency (*PCE*) of Si-PV ($E_G \sim 1.12$ eV) due to spectral mismatch between incident solar radiation (incidental photon energy, E) and energy band gap (E_G) of the material (Shockley & Queisser, 1961). Today, nearly 86% of PV cell markets are covered with Si-PVs (Singh et al., 2021). When the photon energy, E, is less than the band gap energy, E_G, the photons will pass through the PV cell without an output. Though photocurrent will be generated when $E > E_G$, the valence e^{-1} (charge carriers) will receive more kinetic energy that gets wasted in the form of heat, i.e., band edge thermalization loss (Proctor et al., 2013). Again, recombination of charge carriers causes loss in conversion efficiency (Proctor et al., 2013). Practically, the optical loses are even greater due to shading, reflection, shunt resistance, parasitic series resistance, and incomplete absorption (Müller et al., 2004; Singh & Ravindra, 2012). Over the decades, researchers have successfully developed multi-junction PV cells. Different solar spectrum regions can be absorbed using multiple stacking of different cells (varying E_G) to create a multi-junction in a single structure (Kinsey et al., 2008). The theoretical maximum *PCE* for multi-junction PV cells can be achievable up to 86% if concentrated sunlight is to fall over an infinite stacking (De Vos, 1980; Araújo & Martí, 1994). As 20% of photon energy falls below the *global spectrum* (AM1.5G), the maximum *PCE* lies between ~47.7% (un-concentrated solar spectrum) and ~63.17% under maximal solar spectrum concentration at terrestrial bodies (Trupke et al., 2002; Goldschmidt et al., 2011). Modulation of incident spectral properties can aid this output gap.

3 Optimization of Photovoltaic Cells

The spectral conversion of incidental photon properties is performed nowadays to maximize the *PCE* of PV cells. Three methods are followed in spectral conversion: (**i**) *upconversion* (*UC*), (**ii**) *downconversion* (*DC*), and (**iii**) *downshifting* (*DS*) (Fig. 2). Within AM1.5G, ~49% incoming solar spectrum is absorbed by Si-PV cells; however, out of the rest non-utilizable 51% spectral region, *UC* and *DC* can help to gain 13% and 10% more spectra which fall at infrared (IR) and ultraviolet (UV) regions, respectively (Yu et al., 2014).

3.1 Upconversion

Energies of two incidental photons ($E < E_G$) are merged into a single photon ($E > E_G$) that can generate the e^{-1}-hole pairs in the junction points leading to more current production (Fig. 2a). Because of the ladder-like energy structure of

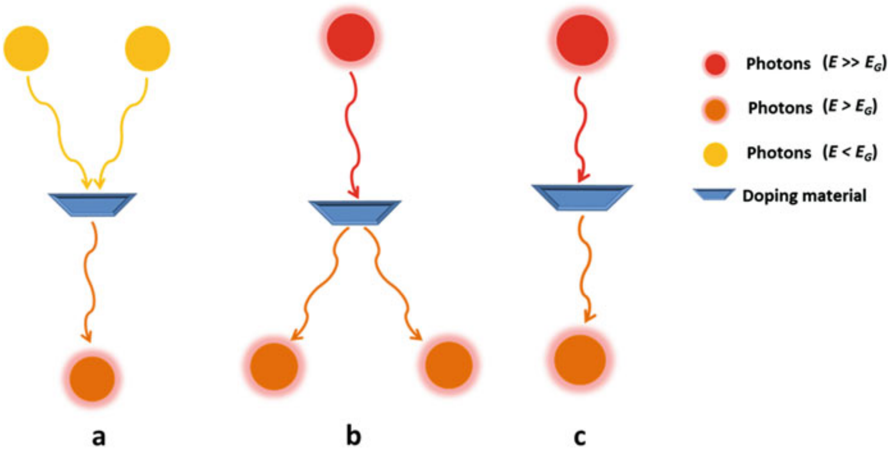

Fig. 2 Schematic diagram of (**a**) *upconversion*, (**b**) *downconversion*, and (**c**) *downshifting*

trivalent rare-earth metals (lanthanides; electron configuration $4f^n$; $n = 0$–14), they can be operated in a wide range of absorption-emission process. Thus, lanthanides were found to be promising luminescent elements to be doped in PV cells for integrating low-energy photons. The *UC* efficiency can be presented by *internal photoluminescence quantum yield* (*iPLQY*) and *external photoluminescence quantum yield* (*ePLQY*), such that:

$$\mathrm{iPLQY} = \frac{\text{no. of emitted photons}}{\text{no. of absorbed photons}}$$

$$\mathrm{ePLQY} = \frac{\text{no. of emitted photons}}{\text{no. of incidental photons}}$$

In a generalized term, these efficiencies can also be referred to as *upconversion quantum yield* (*UCQY*). For a perfect absorption and merging of two low-energy photons into one ($E > E_G$), the *ePLQY* reaches 50% value (Johnson et al., 2007). Erbium (Er^{3+})-doped fluoride glass can reach 12.7% *UCQY* (Shalav et al., 2007). Sun et al. (2015) showed that ytterbium (Yb^{3+}) doping can marvelously sensitize another sensitizer/activator at near-infrared spectrum (~50% *UCQY*). Day et al. (2019) mentioned that five principle mechanisms are involved in *UC* process with rare-earth doping:

(a) **Ground-state absorption and excited-state absorption (GSA/ESA)**
When one ion absorbs a photon, its outermost orbital-e^{-1} (ground state) reaches an excited state. It can even reach a second excited state when absorbing a second photon. During the dissipation of all energy, the e^{-1} emits a higher-energy photon that can overcome the band gap energy (E_G).

(b) **Photon avalanche (PE)**
Cross-relaxation resonance of intermediately excited ion-population can lead to a certain release of energy via single-photon emission. This is a very rare phenomenon.

(c) **Energy transfer upconversion (ETU)**
Here, one excited ion (sensitizer) transfers its energy to another excited ion (activator). This results in the emission of a high-energy photon (E > EG) from the outer shell electron, forcing the sensitizer to return to its ground state.

(d) **Cooperative energy transfer (CET)**
Two sensitizer ions transfer their energy into one ground-state element (activator) which after excitation releases one photon with energy more than E_G.

(e) **Energy migration upconversion (EMU)**
It is a four-step process where a sensitizer collects the photon into one surrounding the accumulator from where one migrator harvests the excitation and traps one activator for transferring the energy. This mechanism is more pronounced with nano-ranged doping of lanthanides into PV cells.

The emission spectrum moves toward a higher-frequency range when application of thermal radiation increases the surface temperature of PV material (Wang et al., 2014b). Rare-earth doping is also necessary for the absorption of heat. The emitted photons are used to generate more electron-hole pairs. Infrared (IR) spectra of the sun carry very-low-energy photons than can overlap the band gap, but as nearly 49% of incidental solar spectra fall under IR region, a great amount of solar spectrum remained non-utilizable in Si-PV cells (Wang et al., 2014b). When rare-earth or transition metals are doped as sensitizer into the oxide-based hosts, absorption of thermal IR photons jumped up to a higher level (Auzel, 2004). This energy is then transferred to oxide hosts through *multiphonon relaxation*, magnifying the host temperature to furnish high-energy photons than incident ones (Binnemans, 2009). Nearly 16% *PCE* can be achieved by doping Yb^{3+}-doped (28 mol%) ZrO_4 when laser-based (976 nm) thermal excitation was used (Wang et al., 2014b). Boriskina and Chen (2014) demonstrated nearly 73% *PCE* when Si-PV is upconverted with hybrid thermal PV under low concentrated sunlight.

Low excitation energy can also be used for *UC* materials like organometallic compounds via sensitized *triplet-triplet annihilation* (*TTA*) procedure. A *triplet* state condition avails two unpaired e^{-1}s, carrying similar/parallel spins at separate orbitals. Parker and Hatchard first performed sensitized *TTA* procedure on 1962 (Parker, 1963). In *TTA*, a chromophore group (donor/sensitizer) is chosen based on their *triplet* state, higher than the acceptor or emitter, but their *singlet* state remains below it. The greater the state difference, the more favorable will be the *triplet* state energy transfer. So, they require low-energy excitation for absorbing visible to near-infrared (NIR) spectra and maintain their *triplet* state for a longer time period (microseconds). The metallic component in these chromophores helps the spin-orbit coupling of *singlet-triplet* excited orbitals via *intersystem crossing*, giving rise to the first *triplet* state sensitizer. Through the *triplet energy transfer* (*TET*) process, the first *triplet* state sensitizer shifts its *triplet* state to a ground-state emitter which again undergoes *collisional complex* with another excited *triplet* state emitter, generating one higher *singlet* state emitter and one ground-state donor. This *singlet* state releases one high-energy photon and returns to ground state. Iodophenyl-bearing boron dipyrromethene derivatives (*BODIPY* chromophores; *BD*) showed the highest *UCQY* among all chromophoric fluorescence groups due to large energy gap (~1.6 eV) in its *singlet-triplet* state (Azov et al., 2006). Thus, *BODIPY* chromophores can be an excellent doping material for *UC* of PV cells.

Dye-sensitized solar cell (*DSSC*), because of its facile fabrication and higher conversion efficiency under visible-NIR region (max. 920 nm), carries low cost of application. The first nano-sized crystalline *DSSC* (*PCE* ~80%) was made by O'regan and Grätzel (O'regan & Grätzel, 1991). This semiconducting PV cell consists of five arrays of units (Gong et al., 2012): (**a**) oxide layer coated with transparent anode; (**b**) mesoporous TiO_2 layer (electronic conduction activator of anode); (**c**) a monolayer dye, coated over mesoporous TiO_2 layer; (**d**) a redox couple of iodide/tri-iodide (I^-/I_3^-) in organic solvent; and (**e**) a Pt-made cathode (Fig. 3).

When incoming photons strike the *DSSC*, excited TiO_2 photo-anode releases e^{-1}s which are being channeled within the mesoporous monolayer dye and consequently

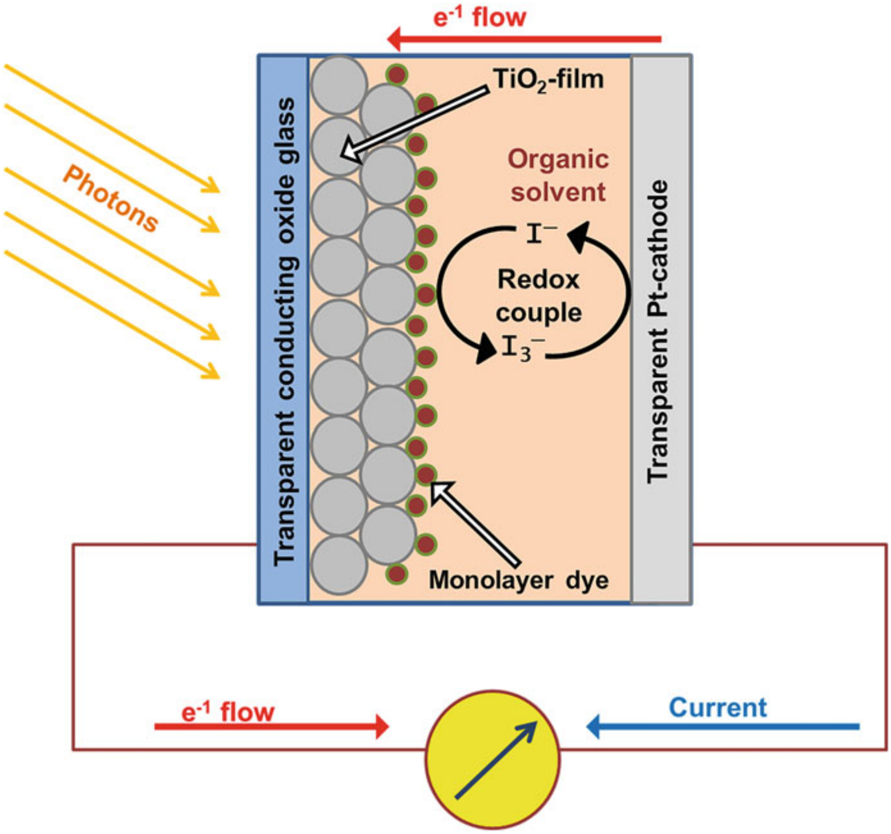

Fig. 3 Schematic diagram of a dye-sensitized solar cell (*DSSC*)

get absorbed by Pt cathode via wiring. The absorbed e^{-1} in the cathode is then liberated to I^-/I_3^- redox complex. These collected e^{-1}s then repeat the cycle to generate electricity. Tin-doped indium oxide (In_2O_3:Sn; 80% transmittance) and tin oxide doped with fluorine (SnO_2:F; 70–80% transmittance) are more preferred transparent conducting oxide glass than others (Tahar et al., 1998; Yang, 2008). However, due to their mechanical abrasion, limited availability, and sensitivity towards photons, alternative materials are now under investigation. The graphene ultrathin films are about to replace In_2O_3:Sn and SnO_2:F in solid-state *DSSC*. Zinc oxide (ZnO) and SnO_2 are also assessed as semiconducting photo-anode materials alongside TiO_2 film for greater range of sensitivity (Law et al., 2005; Qian et al., 2009). The dye (monolayer) should be chosen in such a way that back-transfer of e^{-1} to the sensitizer will remain at minimum. The Zn-porphyrin dye (YD2-*o*-C8) is found efficient in this aspect, yielding 12.3% *PCE* at AM1.5G (Yella et al., 2011). The room temperature ionic liquids (consist of pyridinium, imidazolium, and halide/

pseudo-halide ions) now served as the best liquid-state electrolytes for redox couple-mediated e^{-1} transfer (Zakeeruddin & Grätzel, 2009). Also, p-type solid-state and quasi-solid-state electrolytes are gaining importance.

No matter how much one PV material is fabricated, there will always be some band gap regions (1050–1350 nm or 1580–1800 nm) within AM1.5G that cannot be utilized by the cells. Quantum dot (QD) and quantum dot (artificial atom) sensitized solar cell (QDSC) are treated as third-generation PV cells that can regulate their band gap energy based on their sizes. The *QD*s are nano-crystalline semiconductors, used in multi-junction solar cells to reduce the presence of bulky PV materials and enhance the photon absorption. When applied to Si-PV cells, *QD* can increase the *PCE* up to 60% even under IR regions. Pan et al. (2010) doped PbS *QD* with Yb^{3+} and Er^{3+} and found higher efficiency due to broadening of spectral regions. However, to activate this kind of *UC*, more terrestrial solar concentrations are required, leading *QDSC* application to a disadvantage. Besides *QD*'s *plasmonic resonance* of lanthanide nano-materials, *photonic crystals*, *perovskite* PV (inorganic-organic hybrid solar cell), and other *core-shell nano-structure* materials are becoming popular in upconverting Si-PV technology. In the case of *UC*, the doping material's concentration should be operated in such a scale that the layer thickness of Si-PV must not encourage the self-absorption of emitted photons that can result in lower *PCE*.

3.2 Downconversion

Conventional Si-PV and *UC* of Si-PV can only use the visible-IR window of solar spectrum, but ultraviolet (UV) region contains a significant amount of high-energy photons. If harvested, these photons can be of great use in generating electricity, but as these photons carry far more energy than band gap ($E >> E_G$), a significant portion is dissipated as heating PV cells besides the generation of high-energy e^{-1}-hole pairs. This results in a loss of Si-PV cells' efficiency. The *downconversion* (*DC*) is a *quantum-cutting* process where this highly energized incoming photons' energy ($E >> E_G$) is transformed into two or more low-energy photons with $E > E_G$ that can intensify the e^{-1} delivery to the anode, resulting in higher flow in electricity (Fig. 2b). Dexter first theoretically summarized that if the energy of UV photon is to be incorporated into two visible photons, there will be a possibility of a quantum yield greater than unity (Dexter, 1957). This process reduces the energy loss from thermalization. Generally, three major processes are involved in *DC*:

(a) **Reverse cooperative energy transfer (RCET)**

In this process, a high-energy photon is being absorbed by one luminescent ion (sensitizer) and subsequently gets split into two additional ions (activators), promoting them to high-energy states. Then, these low-energy photons ($E > E_G$) get emitted, generating two high-energy e^{-1}-hole pairs.

(b) **Reverse ground-state absorption and reverse excited-state absorption (RGSA/RESA)**

Here, one ion receives a high-energy photon, stimulating one ground-state e^{-1} to a secondary excited state. The e^{-1} loses its energy by two-step dissipation, generating two high-energy photons ($E > E_G$) at NIR region.

(c) **Resonance energy transfer (RET)**

Resonance energy transfer (*RET*) is an optical process in which energy is shared between donor and acceptor molecules by dipole-dipole coupling. The energy from the valence e^{-1} of donor molecule is shifted to an acceptor molecule via virtual photon transfer. In 1922, Cario and Franck carried out a spectroscopic experiment in which they had taken Hg-Tl vapor and found that fluorescence spectrum from Tl was absorbed by Hg vapor (Cario & Franck, 1922). This was the first documentation of *RET* experiment. Since then, many scientists have tried to update the theory but Förster simplified the phenomenon, specifically and developed R^{-6} distance-dependence law for quantifying short-range resonance energy transfer (Förster, 1946, 1948).

Huang and Zhang (2009) reported that more than 150% *ePLQY* can be achieved through *DC*. Lanthanide phosphor groups ($(Y,Yb)PO_4:Tb^{3+}$), lanthanide-doped fluorides ($LiGdF_4:Er^{3+}$, Tb^{3+}), nano-structured carbon materials, nano-phosphor groups ($SmPO_4$-doped TiO_2), quantum dots (CdS, CuS, PbS, InP, etc.), and *perovskite* cells are considered excellent *DC* materials but for the Si-PV cells, lanthanide-doped optical glasses were found more favorable (De la Mora et al., 2017). However, the *DC* approach still carries very little practical utility despite its higher quantum yield. This is because stratospheric ozone layer blocks the majority of incoming UV light.

3.3 Downshifting

The luminescent *downshifting* (*DS*) is another *quantum-cutting* process in which one incoming short-wave photon is absorbed by luminescent elements and reemitted as a long-wave photon, preferably within visible-NIR region, before reaching the PV module. Here, quantum yields are much lower compared to *DC* because on the absorption of a high-energy photon ($E> > E_G$), there is only one low-energy photon ($E > E_G$) output, and the excess energy is lost from thermalization. Some other physical unavoidable losses are also associated with *DS* (Klampaftis et al., 2009):

(a) Parasitic absorption of host
(b) Reabsorption from luminescent species
(c) Direction of emission from the side of *DS* layer

The main difference between *DS* and *DC* is that in *DC*, output contains two photons ($E > E_G$), but only one photon ($E > E_G$) output is associated with *DS*, imparting lower conversion efficiency (Fig. 2b, c). The choice of luminescent

Table 1 Use of lanthanides for spectral conversion in silicon photovoltaic cell

Spectral conversion	Rare-earth doping	Solar cell	Device response	Reference
Upconversion	$BaCl_2:Er^{3+}$	Amorphous Si	+0.6 mA cm^{-2} SCCD	Chen et al. (2015)
	β-$NaYF_4:Er^{3+}$	Crystalline Si	+16.2 ± 0.5% PLQY	MacDougall et al. (2012)
	$BaY_2F_8:Er^{3+}$	Crystalline Si	+17.2 ± 3 mA cm^{-2} SCCD and 10.1 ± 1.6% PLQY	Fischer et al. (2015)
Downconversion	$TeO_2:Tb^{3+}$	Crystalline Si	+7.47% PCE	Florêncio et al. (2016)
	$Y(OH)_3:Eu^{3+}$	Monocrystalline Si	+17.2% PCE	Cheng and Yang (2012)
	$Y_2O_3:Bi^{3+}$, Yb^{3+}	Crystalline Si	+173.8% PLQY	Huang et al. (2011)
Downshifting	$SrAl_2O_4:Eu^{2+}$, Dy^{3+}	Crystalline Si	+4.6% PCE	Wang et al. (2014a)
	$YVO_4:Eu^{3+}$	Crystalline Si	+15.71% PCE	Chander et al. (2015)
	Eu^{2+}-doped SiO_2	Crystalline Si	+19.85% SCCD and 16% PCE	Ho et al. (2016)

PCE, power conversion efficiency; PLQY, photoluminescent quantum yield; SCCD, short-circuit current density

material is based on (**a**) higher absorption coefficient, (**b**) low reabsorber, (**c**) coinciding band gap emission as compared to host, (**d**) near-unity *ePLQY*, and (**e**) higher *PCE* (Klampaftis et al., 2009). Thus, these materials generally come under organic dye (organic dye-sensitized poly(methyl methacrylate)), rare-earth-doped complexes (fluoride glasses doped with Tm^{3+}), and *QD*s (ZnS/CdS/CdTe) (De la Mora et al., 2017; Day et al., 2019). The *downshifting* process is still under consideration for large-scale adoption.

The rare-earth dopants have been found best for spectral conversions. Till date, higher *PCE* was obtained using lanthanides as doping materials in Si-PV cells through *UC*, *DC*, and *DS* processes (Table 1).

Arrangement of dopants or converting layers in host cell carries another important feature for increasing the efficiency of spectral conversion. The spectral modified layer should be put beneath the PV cells in the case of *UC*, while a thin *DC* or *DS* layering is done over the PV cell for increasing light harnessing power (Fig. 4).

4 Development of Upgraded Solar Cells

Depending upon stages of up-gradation, PV cells are characterized as first-, second-, third-, and fourth-generation solar cells.

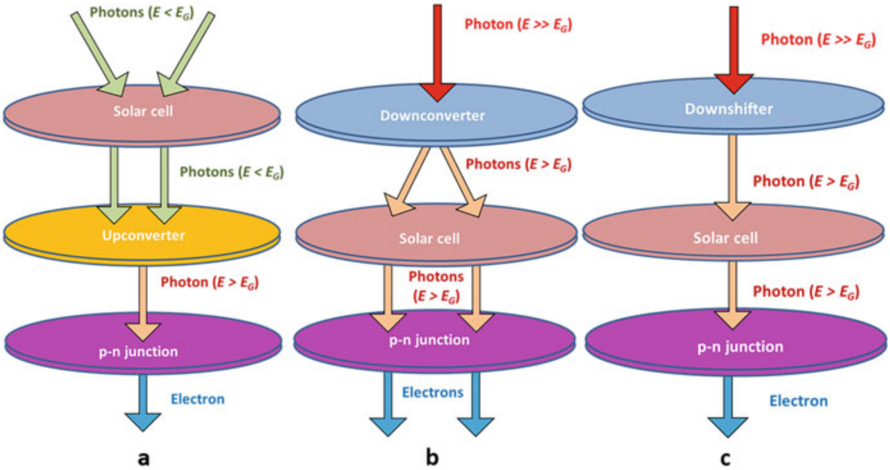

Fig. 4 Arrangement of layers in (**a**) *upconversion*, (**b**) *downconversion*, and (**c**) *downshifting* processes

First-generation photovoltaics

Crystalline silicon (Si)-based PV cells come under this along with gallium arsenide (GaAs) cells. Both mono- and polycrystalline PV come under this. Their cost of manufacturing is high, but high *PCE* and ease of availability of raw material have made it popular (Bertolli, 2008).

Second-generation photovoltaics

The application of thin film PV layers is seen in this evolutionary stage. Among the materials used, microcrystalline Si-PV, amorphous Si-PV, CdTe, CdS, and copper indium gallium selenide solar cells are comparatively cheaper to fabricate. Thus, their application can be comparable with fossil fuel-generated electricity (Singh et al., 2021).

Third-generation photovoltaics

The PV fabrication is much easier than previous generations. This are also called triple-junction solar cell. Major organometallic compounds, organic dyes (*DSSC*), polymer-coated PV, *QD*s, and *perovskite* cells are considered third-generation PVs. These materials' manufacturing cost is further cheaper and flexible than second generations, but the low mobility of organic charge carriers (in the case of organometallics and *DSSC*s) and more reabsorption of emitted photons (*QD*s) carry some disadvantages. Tunable band gap energy materials are started to be manufactured in this generation.

Fourth-generation photovoltaics

Graphene and its derivatives, carbon nano-structured materials, *QD* sensitized with *DSSC*, hetero-junction solar PV, methylammonium lead halide *perovskite*-sensitized PV, etc. are taken as fourth-generation PV technology, also known as *nano-photovoltaics* (Singh et al., 2021).

Table 2 Generation-wise photovoltaic cell advancement

Generation	Photovoltaic cell	PCE	Reference
First	1. Monocrystalline Si	25%	Kivambe et al. (2017)
	2. Polycrystalline Si	21%	Kivambe et al. (2017)
	3. Gallium arsenide	18–29%	Kivambe et al. (2017)
Second	4. Microcrystalline Si	12–14%	Green et al. (2017)
	5. Amorphous Si	13%	Kivambe et al. (2017)
	6. Cadmium telluride/cadmium sulfide	15.8%	Britt and Ferekides (1993)
	7. Copper indium gallium selenide	22.3%	Green et al. (2017)
Third	8. Quantum dot solar cell	11–17%	Almosni et al. (2018)
	9. Dye-sensitized solar cell	5–20%	Gong et al. (2012)
	10. Perovskite solar cell	22%	Green et al. (2017)
Fourth	11. Graphene oxide poly(3,4-ethylenedioxythiophene)/poly(styrene sulfonate)-sensitized perovskite cell	6–12%	Huang et al. (2016)
	12. Eu^{3+}-Dy^{3+} co-doped graphene-loaded ZnO acted on dye-sensitized solar cell	3.18% (245% relative)	Yao et al. (2014)
	13. Tm^{3+}-Yb^{3+}-Er^{3+} co-doped NaYF4 in quantum dot solar cell	0.73% (20% relative)	Wang et al. (2017)

PCE, power conversion efficiency

A general trend has to be mentioned that with advancement, cheaper fabrication and lightweight materials are incorporated into existing cells (Table 2).

5 Challenges

As the *PCE* of Si-PV modules are directly dependent upon radiation intensity, high humidity/water droplet accumulation, cloudy sky, dust accumulation, and bird fouling can limit the maximum output. Cloudy day (rainy season) blocks the high energy incidence of solar spectra. Thus, the solar modules' working hours decreased automatically, reducing the efficiency of spectral conversions. An increase in 50% shading was reported to cut off 45% power generation, while ~7.5% and ~9% decrease in power production are associated with bird fouling and dust accumulation, respectively (Gorjian et al., 2021). Cleaning of PV module surfaces also needs clean water. Thus, a higher proportion of clean water wastage will always be associated with the maintenance of solar grids. Water droplets on the PV module surface can diffract the incidental solar radiation, giving less output as compared to clean surface modules. A decrease in 3.2 W power productions was observed by Sohani et al. (2020) when there was an increase in 20% relative humidity. Surface temperature of PV modules is another important fact to consider as ~0.5% decrease in *PCE* can be achieved from increasing 1 °C surface temperature (Said et al., 2018). Further, cost reduction of PV grids for small farming communities needs much government incentives for future endeavor.

6 Conclusions

The agri-food chain generates a high proportion of GHGs and consumes more electricity than most of the economic sector. As the future agriculture needs more precise input allocations and sustainability, the GHG emissions from agricultural sectors need to be cut out. Alteration of traditional non-renewable as well as renewable energy sources into solar energy should be put to more focus. Today, more researchers have been developing efficient PV cells to reduce both module weight and module cost and to achieve higher efficiency than existing ones. Reduction of *carbon footprint* from the farming sector seemed possible with advanced solar grids. The PV cells have given promising results in sustaining renewable power supply along with a trim in GHG emission. However, certain gaps still remained between PV-developing industries and farming communities. Implementing suitable government policy and economic improvements of farming communities should fill this gap. For more details, readers are suggested to see also Trupke et al. (2002), Gong et al. (2012), and Day et al. (2019).

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Photovoltaic-Integrated Greenhouses for Sustainable Crop Production in the Tropics

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Abstract

Food and energy requirements are rising, and their security has become a significant concern worldwide with an increased aspiration for development and an increasing global population. Electricity generation from conventional fossil fuels poses a challenge for both the economy and the environment in many countries. Thus, the long-term viability of energy and food systems has become a serious issue across the world. Therefore, the worldwide shift to create low-carbon energy technologies, including renewable energy, has accelerated greater than ever before. Photovoltaic systems (PV) represent a clean electricity generation strategy for many industries, including agriculture. Controlled environmental agriculture, particularly greenhouse agriculture, is in the spotlight due to increasing food demand, decreasing natural resources, climate change, shrinking agricultural lands, and environmental and health concerns. Microclimate controls and other management operations powered by fossil fuels and grid electricity can boost crop yields and quality while costing farmers money and harming the environment. Therefore, PV-integrated greenhouse systems are recognized as one of the most energy-efficient systems for food and energy sustainability in future agriculture. This chapter describes the most critical features of greenhouse farming, such as greenhouse electricity requirements, and the current applications of PV technologies in greenhouses.

Keywords

Photovoltaic · Greenhouse · Electricity · Renewable energy · Solar energy · Shading

1 Introduction

Food and energy consumption is rising rapidly, and their security has become a worldwide concern. Global food systems are getting more and more insecure due to population expansion, diminishing natural resources, climate change, and shrinking cultivable lands (Hassanien et al., 2016). Conventional fossil-fuel-based energy generation has become an economic and environmental challenge, and it has a negative impact on global warming, threatening future generations. Moreover, fossil fuel is being rapidly depleted. As a result, following the 2015 Paris agreement and in accordance with the Sustainable Development Goal (SDG) 7, people are concerned about the generation of electricity from renewable energy sources. Consequently, the transition to a low-carbon economy and zero or low-emission of CO_2 and other greenhouse gases has grown faster worldwide than ever before. Therefore, these controversial issues have led researchers to use alternate energy sources of food production and energy technologies.

Renewable energy plays a significant role in providing this growing energy demand in a sustainable and eco-friendly manner. Solar energy is the most abundant and prevalent source of all renewable energies, and it is safe, reliable, and clean (Dupraz et al., 2011). Technological advancements have continued in recent years, providing a more stable and cost-effective solar photovoltaic (PV) technology and making it more accessible. Setting up PV panels in locations such as car parks, rooftops, and agricultural lands provides dual-use options that maximize land usage productivity.

Green technologies with zero-carbon emissions continue to evolve in many industries, and agriculture and allied sectors also need to comply. Hence, modern farming and food systems should be more productive in quantity, efficiency, climate resilience, and long-term sustainability (Chamara et al., 2020). Control of environmental agriculture, particularly greenhouse agriculture, is becoming more popular due to global food security, health, and environmental issues (Hassanien et al., 2016). It offers improved resource use efficiency, reduced production risk, year-round production, and clean, pesticide-free food production (Stanghellini et al., 2003).

In consideration of the future demand for increased energy and food production, agrivoltaic systems (AVS) have been recognized as a combined method that integrates PV with agriculture at the same time in the same land (Dupraz et al., 2011; Santra et al., 2018). It is one of the most efficient energy systems for sustainable food and energy usage in future agriculture. Integrating PV panels with existing greenhouses has become increasingly popular, especially in rural regions where electricity from the primary grid is unavailable. The approach to land usage minimizes the footprint for a broad scale of mounted PV systems (Trommsdorff et al., 2022). Greenhouse provides ideal opportunities for dual-use lands since solar panels may be deliberately positioned to supply electricity while enabling continued productive agricultural use of the site. A good open space with abundant sunlight in tropical areas is ideal for AVS for generating solar electricity and food through photosynthesis.

This chapter first highlights the fundamental features of PV electricity generation, greenhouse horticulture, and power requirements. The different applied solar PV technologies in the agricultural/greenhouse sector are then reviewed and classified. The shading effects of PV are also explored on the greenhouse plants. Finally, opportunities are examined for the increased usage of PV technology in greenhouses, especially in the tropical region.

2 Photovoltaic Electricity Generation

The PV function is among the most fundamental ways to convert solar energy to electricity. An electric voltage is created between two electrodes attached to a semiconductor device under strong incident sunlight. PV devices are also known as solar cells and contain a diode (pn junction) in the semiconductor that allows current flow (Fig. 1). Electron hole pairs are formed when the semiconductor materials absorb light quanta. An electrical voltage is created due to the inhibition of their recombination (Goetzberger et al., 2003). Amorphous silicon, crystalline

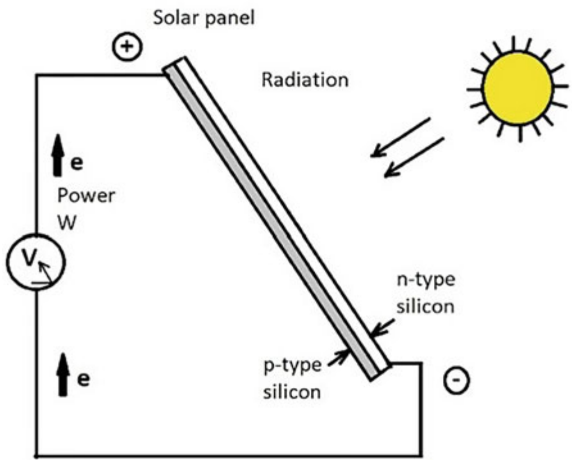


Fig. 1 Schematic diagram of a solar PV panel

silicon, cadmium telluride (CdTe), and cadmium sulfide (CdS) are mainly used as PV materials; however, silicon is the standard material, and the global market is dominated by crystalline silicon (Goetzberger et al., 2003; Parida et al., 2011). Efficiencies and electricity generation performance and their price vary significantly according to employed materials and methods (Green et al., 2021; Kim & Ferreira, 2008).

PV cells are integrated into modules in commercial applications and then combined into panels, finally assembled to create panels. These solar panels can produce electricity from a few microwatts' outputs to many megawatts when combined as a vast array of applications (Parida et al., 2011). The panel's output is shown in Watts (W) and indicates the theoretical power generation of the panel under optimal circumstances of sunlight and temperature. Today, most home solar panels have a power output of 250 to 400 watts, and higher power values are often preferable to lower power levels (Energysage, 2021). AC load systems require a DC-AC inverter. Stand-alone systems may feature an energy storage battery component. The grid is not connected to stand-alone systems, and utilities integrated systems can supply the grid with energy and use it if necessary. Power output is an important consideration to be measured when considering the productivity of solar panels. The solar panel's productivity is characterized by the power generated from the unit area per unit time. Many design characteristics such as PV panel strip number, length, inclination, spacing, size of individual PVP shading, and sun hours are significant when considering productivity (Dupraz et al., 2011; Chamara & Beneragama, 2020). High-performance solar panels sold in the market are about 15% efficient under the midday sun on a clear day (Dupraz et al., 2011; Kim & Ferreira, 2008). Peak Watt is around 1 W under 1 kW/m^2 of solar radiation (Kim & Ferreira, 2008).

Building PV arrays on the exposed sunny field or mounting PV modules on the greenhouse rooftop is appropriate for combining these two. Planning the density of PV panels is crucial because the number of solar panels or the area covered by the solar panels in each land determines the amount of light received by the crops grown below or between the panels (Dupraz et al., 2011). That is why the arrangement and orientation of PV modules on the roofs must be studied carefully to give considerable electricity with a minimum shade of the plants (Chamara & Beneragama, 2020).

When mounting the solar panels, it is essential to calculate the solar position angle or sun path to intercept light perpendicular to the surface. Solar panels are typically placed on a mounting structure at an elevated height from the ground with an inclination of 25° facing the South, which corresponds to the location's latitude since the efficiency of electricity generation continually rises to perpendicular incident light (Santra et al., 2018). Because of this angle of solar panels, a shade of PV modules is created at the leeward side by shading neighboring PV modules, lowering the efficiency of the shaded panel. Therefore, PV arrays with spacing between two arrays should be created. The placement and orientation of PV strips is an important aspect. Straight lines of PV arrays positioned east-west, on the south roof of an east-west greenhouse, are appropriate for energy production. Several previous reports (Chamara & Beneragama, 2020; Yano et al., 2010) highlight the connection between the position and orientation and energy generation of greenhouse-based PV cells.

3 Greenhouse Overview

Horticulture crop production in agriculture is a critical component of the global food supply with potential for expansion. The demand for fruits, vegetables, and ornamentals is expected to increase in the coming decades, demanding more production (Dijk et al., 2021; Saeed et al., 2021). Both open fields and covered fields are used to grow fruits and vegetables. On the other hand, greenhouses are shown to be highly efficient in producing abundant and high-quality food by maximizing the use of resources such as water and mineral nutrients while minimizing use of pesticides. Crop quality can be improved by maintaining optimal environmental conditions, and water and fertilizer usage is either low or comparable to that of field cultivation. Greenhouses, in general, can shorten the cultivation period, intensify crop cycles, dramatically boost crop yields, and widen the choice of crop species (Gao et al., 2010; Lamont, 2009; Stanghellini et al., 2003). Furthermore, the harvesting of greenhouse crops may be modified to match market demands until it is lucrative for producers. Pesticide usage can be minimized because the cover materials protect against insect infestations, thereby supplying consumers with healthy foods.

As reported previously, there are millions of hectares of greenhouses around the world (Lamont, 2009; Savvas et al., 2014), and marginal agricultural lands are being rapidly transformed into protected cultivation in many parts of the world (Stanghellini et al., 2003). On the other hand, growers, designers, and researchers in each location regularly evaluate aspects such as structure, cover materials, climate-control systems, irrigation, and fertilization equipment to enhance efficiency, minimize inputs, and limit negative environmental impacts. The "cleanliness" of the production process in environmentally friendly manufacturing is recognized as a significant benefit of long-term energy management. Thus, PV-integrated greenhouse systems are recognized as one of the most energy-efficient systems for food and energy sustainability in future agriculture.

3.1 PV-Integrated Greenhouse

Solar energy is required for electricity generation in PV panels and food production in crop plants; thus, adequate sunlight is critical for crop photosynthesis and electricity generation in the PV-integrated greenhouse. Both are generally constructed on open fields with abundant sunlight (Chamara & Beneragama, 2020; Yano & Cossu, 2019). PV-integrated greenhouses are a practical and ecologically friendly concept in AVS where renewable energy and plant production can be combined successfully on the same land unit. Although certain PV technologies have been used in greenhouse sectors, optimizing crops and power output remains a priority since incorrect installation and design can result in excessive shading and low electric yield.

3.2 Environmental Control in PV-Integrated Greenhouse

Greenhouse plant production is a method of cultivating plants in which the interior cultivation environment is controlled and optimized for crop growth and development. Traditional techniques employ fuel and electricity to regulate the greenhouse indoor environment and other management practices that increase or sustain crop yields and quality. However, rising energy prices undermine farmers' income while threatening the environment. As a result, farmers struggle to maximize crop yield while reducing their reliance on fuel and electricity. If renewable energy sources such as sunlight could be exploited actively in greenhouses, the use of fossil fuels and grid electricity may be reduced. Consequently, greenhouse gas emissions by the agricultural sector can be further reduced. These concerns over green energy usage and energy security have provided a chance to use renewable energies in greenhouse agriculture. Solar energy technology applications for greenhouse crop production can be considered a sustainable solution for both energy consumption and the environment's well-being.

3.3 Electrical Energy Demand for Greenhouse Environment Management

The major factors determining plant growth and productivity are temperature, light, humidity, carbon dioxide (CO_2) concentration, and plant nutrition. These conditions affect the physiological activities of plants, such as photosynthesis, transpiration, respiration, assimilation, flowering, and fruit development. Therefore, different modifications are applied in a greenhouse to improve crop growth and achieve optimal crop production.

According to Campiotti et al. (2008), a typical Mediterranean greenhouse (14.74 m^2) consumes 315 kWh of electricity/day/ha for cooling (using foggers) during summer. Souliotis et al. (2006) stated that 2.2 MWh electricity was consumed for cooling with fans and spraying water inside the greenhouse (500 m^2) during May–September in Greece. Electricity consumption of 35.792 kWh/day was recorded in a Saudi Arabian greenhouse (351 m^2) for a fan-based cooling system (Al-Ibrahim et al., 2004). Campiotti et al. (2008) stated that 231 kWh of electricity day/ha was consumed for heating a typical Mediterranean greenhouse (14.74 m^2) during the winter. According to Tong et al. (2012), Japanese greenhouse (151.2 m^2) consumes around 0.1–0.2 kWh/m^2 for 2 months to operate heat pumps. In Italy, the electricity of 134–209 kWh/m^2 during 5 months was consumed in a greenhouse of 400 m^2, according to Fabrizio (2012). Bakker (2009) stated that electricity consumption of 140, 527.78, 416.67, and 138.8–444.4 kWh/m/year was recorded in Sweden, Finland, the Netherlands, and southern France for cooling, ventilation, and lighting purposes.

3.3.1 Temperature Control

Temperature affects all the metabolic processes related to plant growth and development (Sidaway-Lee et al., 2010). Most greenhouse plants' growth, yield, and quality are considered optimum between 12 and 30 °C temperatures (Castilla & Hernandez, 2006). Quantity and yield quality can be adversely affected when the plants are not in optimum condition (Hassanien et al., 2016). In warm tropics, cooling systems lower the air temperatures exceeding the levels that plants cannot tolerate during summer or reduce heat accumulation during the daytime. On the other hand, greenhouses in the temperate region use heating systems to increase the air temperature during cold winters (Sethi & Sharma, 2008).

Heating and cooling (temperature control) are critical cost components in the greenhouse industry, where energy plays an important role. Expenditure on heating and cooling demands 30–60% of the total production cost, which is a crucial determinant in the final output product price (Martzopoulou et al., 2020). On the other hand, conventional greenhouse systems burn vast amounts of diesel, natural gas, and LPG like fossil fuel, releasing many greenhouse gases, including CO_2, into the atmosphere. The clean energy generated from PV greenhouses reduces CO_2 emissions (Chel & Kaushik, 2011). Most importantly, PV heating/cooling systems demand less energy requirement, resulting in lower energy costs than conventional heating systems (Lazaar et al., 2015). Several solar energy applications are used in the heating and cooling of PV greenhouses. They are listed out in Table 1 along with electricity generation.

3.3.2 Light Control

Another vital application of PV systems is supplementary lighting, which can significantly increase crop productivity and extend working hours. Different plants require different quantities of light energy to optimize their growth and development.

Table 1 Electric energy requirements for temperature control in greenhouses at different locations

Authors	Region/country	Application (cooling/heating)	PV design/or type	Electricity production	Season/time
Yano et al. (2014)	Japan	Heating and cooling	A semi-transparent PV module	110 kWh/m^2/year	NA[a]
Urena-Sanchez et al. (2012)	Spain	Heating and cooling	A flexible thin-film PV module	2766 kWh/crop-cycle	Sept 2009–May 2010
Perez-Alonso et al. (2012)	Spain	Heating and cooling	A flexible thin-film PV module	8.25 kWh/m^2/year	Oct 2011–June 2012
Xu et al. (2014)	China	Heating	Seasonal thermal energy storage	331.9 GJ/year	April 2012–Mar 2013
Ozturk (2005)	Turkey	Heating	A flat plate solar air collector with the latent heat storage technique	NA	NA
Sethi and Sharma (2007)	India	Heating	Earth-tube heat exchanger system	NA	Winter and summer (2004–2005)
Esen and Yuksel (2013)	Turkey	Heating	A flat-plate solar collector	NA	Nov 2009–Mar 2010
Russo et al. (2014)	Italy	Heating	A PV-geothermal heat-pump integrated system	8013.6 MJ/year	Nov 2001–March 2012

Joudi and Farhan (2014)	Iraq	Heating	Solar air heaters on the roof	NA	Dec 2012–Mar 2013
Bouadila et al. (2014)	Tunisia	Heating	Solar air heater using a packed bed of spherical capsule with the latent heat storage system	1800 kW/year	Jan–April 2013
Sonneveld et al. (2010b)	Netherlands	Heating	Hybrid PV cell/thermal collector	31 $kWh/m^2/year$	Sept 2008–Sept 2009
Sonneveld et al. (2010a)	Netherlands	Cooling	Seasonal storage	32.5 $kWh/m^2/year$	NA
Mongkon et al. (2014)	Thailand	Cooling	Horizontal Earth Tube System (HETS) bedded in underground	19.26 kW/day	Dec 2009
Yano et al. (2007)	Japan	Cooling	Side ventilation is driven by PV energy	Cumulative 2.84 MJ	Mar 16–May 28, 2004
Al-ibrahim et al. (2004)	Saudi Arabia	Cooling	PV greenhouse	Cumulative 392.62 kWh	Jun 11–16 2002

[a] *NA* not available

Based on the required light intensity, plants are categorized as long- or short-day plants (Hassanien et al., 2016). Additional light can lengthen the day for short days, allowing flowering in long-day plants. Mainly, LEDs are being extensively used by greenhouse farmers due to their better control of plant growth and reduced energy consumption compared to other light types (Zhang et al., 2017).

Lighting using PV systems eliminates the expensive operation of running electrical wiring to greenhouses from the grid. Moreover, PV systems are cost-effective alternatives to conventional flashlights or fixtures powered by batteries and fuel-based lighting. Supplement of artificial lighting is critical for crop production during low-light days and cloudy days to extend the day length or photoperiod to manipulate flowering (Hassanien et al., 2016). PV lighting systems can supply high-quality light according to the plant's demand. For example, long-day floriculture crops are grown under supplementary artificial lighting at night. Power generation using irradiance outside the photosynthetically active radiation (PAR) is another reliable application of PV systems (Lopez-Marin et al., 2012) (Fig. 2).

3.3.3 Humidity Control

Humidity control is essential to achieve a high-quality crop yield. However, higher relative humidity (RH) levels cause diseases and plant development disturbances and hamper the pollination process (Korner & Challa, 2003). In contrast, lower RH levels cause higher transpiration rates in plants (Jochum et al., 2006). Humidity is not that easy to control inside a greenhouse since it has a complex relationship with temperature. Therefore, it is considered the most challenging environmental factor in controlling the greenhouse environment since management practices such as insulation, shading, and controlling air exchanging rates are closely associated with changing humidity levels (Rabbi et al., 2019). Moreover, shading caused by PV panels harms microclimate controlling inside the greenhouse. Generally, daily mean relative humidity around PV equipped zone is higher than in areas without PV equipment (Urena-Sanchez et al., 2012).

Humidification in conventional greenhouses is done through water addition using misting/fogging or evaporative pads (Rabbi et al., 2019). Therefore, several cooling systems can be used in the humidification of PV greenhouses, such as hybrid solar PV/thermal (PV/T) systems cooled by water spraying, hybrid solar PV/T systems cooled by water circulating, and floating tracking concentrating cooling systems (FTCC) (Siecker et al., 2017). Likewise, heating and ventilation systems can be used to dehumidify the greenhouse environment. Hybrid solar PV/T systems that generate forced air, solar air heaters, and hybrid PV/T collectors can dehumidify PV greenhouses. Marucci & Cappuccini (2016) reported that average relative humidity values inside PV greenhouses ranged from 60 to 90%.

3.3.4 CO_2 Enrichment

CO_2 concentration is another essential factor that affects plant growth. The ambient CO_2 concentration level for crop growth is considered as 380 ppm by volume. The photosynthetic capacity of greenhouse crops can be enhanced by raising the CO_2 level from 380 to 1000 ppm (Martzopoulou et al., 2020). Increased CO_2

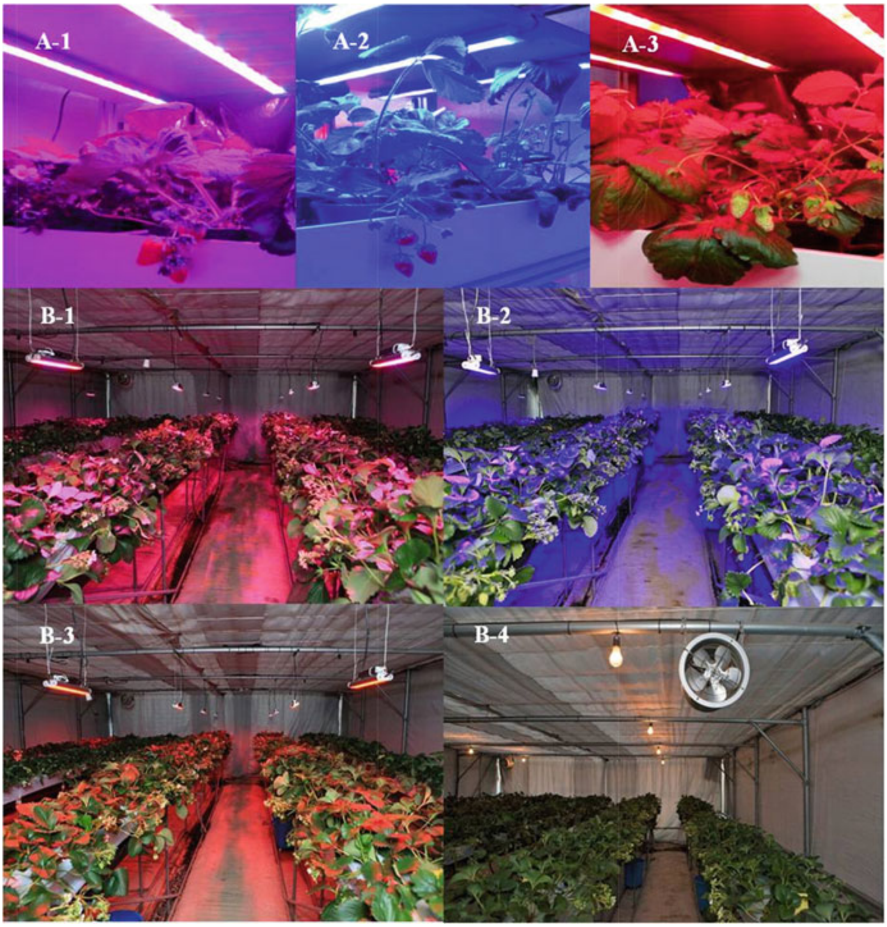


Fig. 2 Growing plants under the illumination of LED lighting. (Source: Choi et al., 2015)

concentrations (380–1000 ppm) have increased crop yields by 12–25% (Minguez et al., 2014). CO_2 can be a limiting factor of photosynthesis during daytime, reaching lower concentrations around 200 ppm in the greenhouses.

As a solution, CO_2 enrichment (introducing CO_2) or ventilation (allowing the entry of outside air) could be practiced in greenhouses (Martzopoulou et al., 2020). Most of the crops that are cultivated in greenhouses are C3 plants. They require a temperature in the range of 16–25 °C during daytime and 14–18 °C during nighttime, indicating the necessity of daytime cooling and nighttime heating inside greenhouses. It reduces the duration of ventilation, emphasizing solar systems to save energy with CO_2 enrichment. In addition, this energy saving in passive solar systems is higher when it is compared with conventional systems (Martzopoulou et al., 2020).

3.4 Solar PV Water Pumping in Protected Agriculture for Irrigation and Fertigation

Nowadays, optimum water utilization has become a vital issue in greenhouse crop production and open field cultivation. Both irrigation and fertigation demand energy and water as they are scarce and expensive (Pardo-Picazo et al., 2018). The conventional way of supplying electricity to this irrigation/fertigation system is through grid electricity or fuel motors like diesel engines (Chel & Kaushik, 2011), leading to an increase in greenhouse gas (GHG) emission (Garcia et al., 2018). To mitigate these harmful effects, people are now moving to environmentally friendly, clean, and sustainable renewable energy sources as alternatives. Pumping water requires much power, which is not always accessible in distant places. Hence, one of the most effective alternatives is to use PV electricity to pump water, replacing the conventional energy supplying methods.

Solar photovoltaic water pumping systems (SPWPS) are becoming popular as reliable irrigation systems, especially in the desert, remote, isolated, and non-electrified areas where no reliable electricity supply is available for agriculture (Haddad et al., 2015). This SPWPSS is more economical than diesel generators or expanding the electrical grid, and it allows for high-frequency and low-volume irrigation while saving water (Chel & Kaushik, 2011) Moreover, there are many benefits of SPWPSs, namely, the zero greenhouse gas emissions (CO_2), low maintenance costs, simple installation, and operation without fuel (Rathore et al., 2018). Many studies have proven that achieving the optimum solar energy and water management utilization is possible using SPWPSs than conventional diesel-powered pumping methods (Mahmoud & Nather, 2003), because these PV pumping systems reduce the overall system cost by having the added advantage of storing water to utilize during the dark periods, eliminating the need for batteries to run the pumps. It enhances the simplicity of the systems (Chel & Kaushik, 2011). Developed modules can measure hourly air temperature and solar irradiation to predict the hourly flow rate over potential sunshine hours (Hassanien et al., 2016), where SPWPSs operate more effectively than traditional irrigation systems (Mahmoud & Nather, 2003).

PV pumping systems can have significantly higher efficiency than diesel pumps, and the price of diesel fuel has grown significantly over time. In most common stand-alone solar irrigation systems, groundwater or surface water is pumped to an elevated storage tank and then distributed by gravity according to demand (Reca et al., 2016). As shown in Fig. 3, PV panels, a motor pump, and a storage tank are necessary components for these pumping systems. Motors are used in PV water pumping systems with appropriate power conditioning equipment. Series and parallel combinations of PV modules provide the required voltage. A motor converts electrical energy into mechanical energy, and a pump converts that mechanical energy into hydraulic energy. AC-DC inverters with DC motors and AC-AC inverters with AC motors are used as power conditioning equipment (Hamidat & Benyoucef, 2009) (Fig. 3).

Khaled et al. (2015) have conducted a case study in Algeria to improve the performance of a PV pumping system in irrigation. A maximum power point

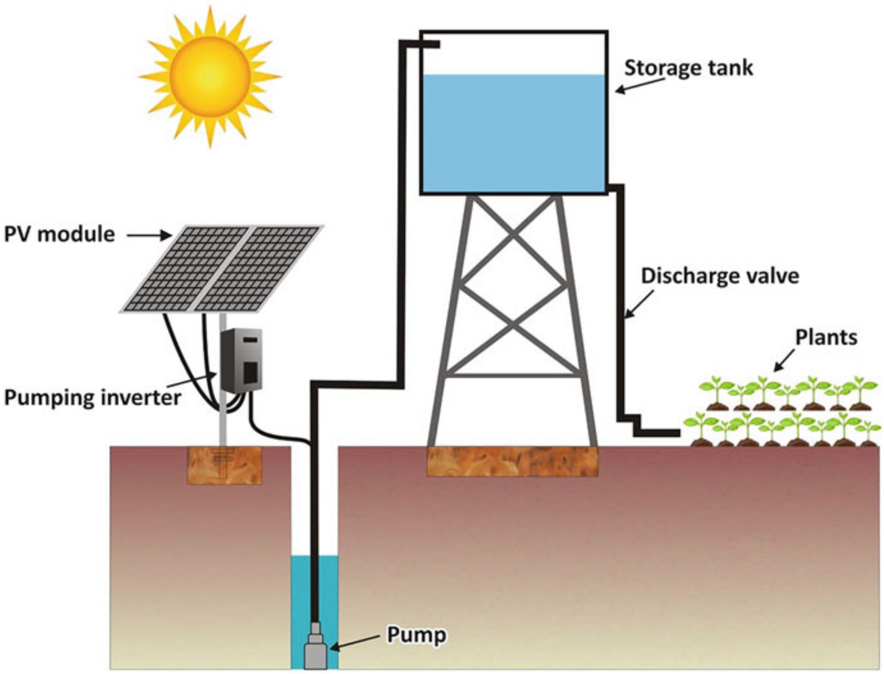


Fig. 3 Schematic diagram of a PV water pumping system with conventional irrigation system, which may be modified in greenhouses

tracking controller has been installed with a DC converter to improve efficiency and save system costs. Water must be pushed to the appropriate pressure to operate emitters in drip irrigation systems. Hence, drip irrigation systems may be used on flatlands with direct PV pumping systems. By enabling the discharge rate to be changed, a combination of variable frequency pumps and non-compensating emitters may adjust the irrigation system's power consumption to the PV power (Reca et al., 2016). Moreover, dividing the farmed area into appropriate subsectors showed the technical and economic viability of stand-alone direct pumping drip irrigation systems in greenhouses.

Sprinkler systems can even be effectively operated with solar pumping systems. The use of several filters can extend the pump's life and reduce clogging in sprinkler emitters and tubes. Systems need minimal attention and maintenance as they are self-controlling (Shinde & Wandre, 2015). Even though PV panels directly linked to the load produce the most effective solar energy, water pumping performance is often dependent on the inclusion of a battery bank as an intermediary phase to store energy since the system can pump outside of daylight hours (Shinde & Wandre, 2015). The most efficient usage of a PV pumping system may be achieved by having a solid understanding of the system's features and adequately estimating the amount of water required. The overall water head and solar array sizes affect the pumping system's electrical and hydraulic performance. When assessing the performance, the area that has to be irrigated, the water volume that needs to be pumped in, and the water requirement of the selected crops to fulfill food standards should be considered. Peak volt average, unanticipated solar radiation variations, and uneven water demand are primary problems of running PV water pumps. However, hybrid pumping systems and net metering billing policies can be used to alleviate these issues (Reca et al., 2016). Several solar PV water pumping applications are listed out in Table 2 along with electricity demand.

Rathore et al. (2018) reported that 21 million irrigation pumps running on diesel and electricity are used for irrigation in the agriculture sector in India. Replacing these pumps with more efficient PV pumps has the potential of annual energy saving of 131.96 billion kWh, where the GHG emission will be reduced by 45 million tons of CO_2 annually. India has the potential to have 9 to 70 million solar PV pump sets for irrigation, which can save at least 255 billion liters/year of diesel according to estimated values (Shinde & Wandre, 2015). Moreover, Mehmood et al. (2015) reported that installing a single 4.48 kW DC solar water pump resulted in 7–8 MWh electric power saving in irrigation and 1.2–1.4 t CO_2 gas emission reduction produced due to fuel combustion for generating electric power.

4 Shading Effects on Plants in the PV-Integrated Greenhouse

Greenhouses are complex installations that require the optimal balance of solar irradiation, heating, cooling, and ventilation to grow high-quality crops on a consistent and stable timeline. Greenhouse energy consumption is crucial in profitability, and PV panels are considered an alternate method for meeting their electrical requirements. On the other hand, PV panels on the greenhouse roof limit solar radiation that passes through the roof covering, resulting in intermittent shading and a reduction in the crop's average available light, which is far below the requirement (Chamara & Beneragama, 2020; Marrou et al., 2013). The crop productivity in the greenhouse is also primarily decided by the light availability under the PV panels (Niinemets, 2010). This reduction may impact plant lighting; therefore, it should be investigated in terms of the best installation to optimize solar irradiance entering the greenhouse interior area. Therefore, crop selection and panel design that maximize energy efficiency and crop production are critical. They should be handled with care by a crop specialist knowledgeable about the shade effect on crops.

By contrast, roof whitening and shading nets are commonly employed in high-insolation locations to reduce excessive summer sunlight for greenhouses by reflecting some solar radiation. Photosynthetic photon flux density (PPFD) exceeds 2000 μmol/m^2/s around noon on sunny summer days (Hindersin et al., 2013). In comparison, photosynthetic light saturation points of most agricultural C_3 plants are 500–1500 μmol/m^2/s (Larcher, 1995). Many crop species may not grow optimally in the environment with the high solar radiation available. For these reasons, crops may be anticipated to get more light in ideal forms, thus improving crop production and

Table 2 Electric energy demand for PV water pumping at different locations

Authors	Region/country	Application PV design	Electricity energy demand	Season/ time	Discharge	Extent
Pande et al. (2003)	India	Drip irrigation for orchards	NA[a]	NA	3.4–3.8 L/h	5 ha
Urena-Sanchez et al. (2012)	Southeastern Spain	Window opening pumps fans, irrigation, and fertigation	P 2766 kWh C 768 kWh 3 kWh/m^2/year	Crop cycle 8 months	NA	NA
Pardo-Picazo et al. (2018)	Western Mediterranean area of Spain	Irrigation to orchard	C 428.74 kWh/day	July	NA	168 ha
Yildirim et al. (2018)	Turkey	Drip irrigation in greenhouse	NA	May–Sept	2000 L/ 40 min	93.1 m^2
Garcia et al. (2018)	Southern Spain	Smart PV irrigation manager – a real-time model	P 2500–3900 kWh/ month	April–Sept	NA	13.4 ha
Bostan et al. (2019)	Republic of Moldova	Irrigation is done by the dropping method	C 44 MWh/season	NA	NA	0.88 ha

P energy production, *C* energy consumption
[a]*NA* not available

quality if PV modules can only shade excessive sunlight that is less than photosynthetically optimal.

The reflected sunlight can be turned into energy for greenhouse climate control and other management practices if PV components with a moderate shading rate are employed instead of shading materials (Urena-Sanchez et al., 2012). These might be semi-transparent PV panels that allow less solar radiation to flow through, affecting crop development on purpose. This scenario would theoretically allow the creation of electrical energy and agricultural output to cooperate. Semi-transparent PV panel shading has also been observed to reduce temperatures below PV panels on a roof compared to unshaded.

4.1 Crop Shading Mitigation with PV Panel Design and Semi-transparent Technology

The amount of light available in a PV-integrated greenhouse significantly depends on whether the PV modules are placed in a single array or scattered across the roof. Figures 4 and 5 show that PV panels have several field arrangements such as opaque PV modules, continuous rows, staggered rows, and checkerboard (Yano et al., 2014). The different designs create different spatial and temporal radiation distribution in a day under the panels. Apart from that, electricity generation also varies with the type of design. Of all, the most appropriate design which creates a more uniform radiation distribution is checkerboard.

Compared to the straight formation, it provides a better distribution of solar radiation on the PV greenhouse space. It creates intermittent shadows on plants, and the places that get shadows may vary with the time of the day according to the sun's position (Chamara & Beneragama, 2020; Yano et al., 2014). Therefore, all the plants under the panel receive uniform light, and this design reduces the inhibitory growth effects of the shading. In contrast, when the straight lines of PV modules are oriented north-south, all plants in the greenhouse receive equal, direct sunshine on a sunny day (Yano & Cossu, 2019). However, other designs create shadows on the same groups of plants continuously during cultivation. Nevertheless, the capacity of the PV system may vary with the radiation availability of the area, the energy conversion efficiency of the solar panels, and the design.

4.2 Semi-transparent PV Technology

Traditional photovoltaic silicon-based solar PV is not transparent and does not allow solar radiation to enter the greenhouse. Consequently, cultivation becomes challenging while achieving the greenhouse effect required to establish crop microclimatic conditions difficult. As solar energy is restricted and highly inhomogeneous in the PV-integrated greenhouses, the ability to grow plants in closed and protected environments is harmed by this approach. This is beneficial for energy generation, but it is incompatible with biomass production, as this portion of the spectrum is vital

Fig. 4 Possible field arrangements of PV panels (**a**–**c**) opaque PV modules (Xue, 2017; Cossu et al., 2016a), (**d**, **e**) continuous rows (Ezzaeri et al., 2020; Allardyce et al., 2017), (**f**, **g**) checkerboard (Marucci et al., 2018)

for photosynthesis. Furthermore, the PV film has no transmittance in the infrared long-wavelength region. As a result, it impacts attaining the greenhouse effect in temperate regions, particularly during the winter.

Researchers are working on panels with partially transparent materials in flexible sheets or semi-transparent rigid panels to overcome that problem. These panels allow for the passage of sunlight, essential for plant development in protected settings. Semi-transparent PV can be used to enable solar energy, which is required for crop growth, to enter the greenhouse with light transmissivity since they only shade a small portion of the incident light, allowing the plants to get the remaining radiation (Cossu et al., 2016b; Wang et al., 2017). Semi-transparent PV reduces the electricity required by interior lighting and heating loads because of solar radiation penetration through the roof.

Glass-glass monocrystalline building-integrated PV modules, optimized for high transparency, have been developed by varying the cell arrangement. These PV modules are ideal for creating little shade while allowing sunlight to enter. This is feasible because manufacturing facilities allow variable cell spacing, allowing the

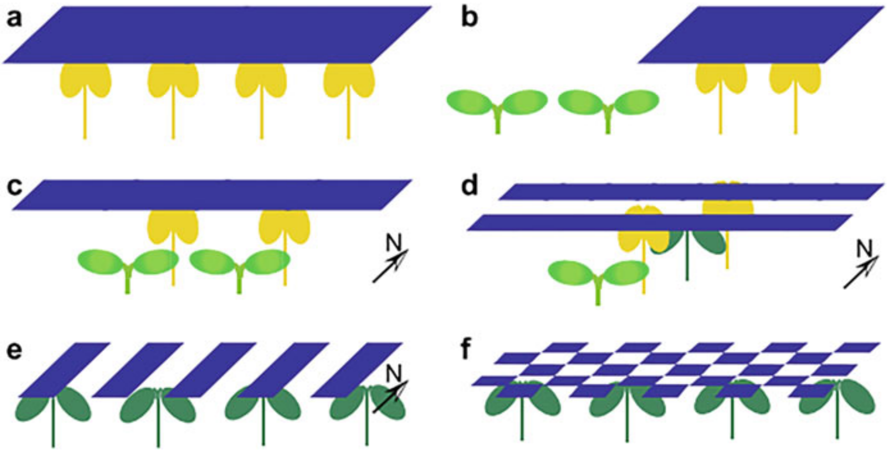


Fig. 5 Some examples of possible opaque PV module arrangements above greenhouse crops: (**a**) 100% coverage; (**b**) concentrated partial coverage; (**c**) east-west straight; (**d**) stripe along east-west; (**e**) stripe along north-south; (**f**) checkerboard. Non-shaded, intermediately shaded, or heavily shaded plants are presented as bright green, dark green, and yellow plants. (Source: Yano & Cossu, 2019)

number of cells per cell row or cell rows per module to be changed. The variants include a 32-cell panel with 51% transparency, a 48-cell product with 27% transparency, and a 54-cell version with the transparent part spanning just 19% of the panel's total surface area. The panels are excellent for PV-integrated greenhouses and verandas, pergolas, awnings, carports, swimming pools, halls, and facades due to their transparency (PV Magazine, 2020).

Organic photovoltaics (OPV) is an emerging solar power technology that can maximize photosynthetically important light to reach the plants while utilizing unused wavelengths for generating energy and different specialized application potential, particularly in greenhouses. A broad range of semiconducting polymer materials allows OPV to absorb light, which is unnecessary for plant development. OPV materials are not yet unique for producing considerable power with a low impact on crops in a PV greenhouse (Emmott et al., 2015). In fact, the entire sunshine spectrum is not essential for plant photosynthesis. Ultraviolet, PAR, and near-infrared are available from the global solar radiation that enters the greenhouse interior. The PAR from 400 nm to 700 nm is just what plants need for photosynthesis (Hernandez, 2013).

Initially, Emmott et al. (2015) examined OPV operational efficiency for PV greenhouse technology with a systematic techno-economic study in 2015. The efficiency and spectrum transparency of five widely accessible OPV polymer materials have been investigated. Four of them showed peaks for the usual absorption of plants, showing their capability for light collection, which is not essential for plants to develop. The visible transparent OPV tandem photonic crystal was later disclosed by Yang et al. (2015), with an absorption efficiency of 51.5% and 40.3% in the PAR band. Results reveal that thanks to the significantly increased transmission spectrum, the sunlight for crops may be maximized, and the crop growth factor may reach 41.9%. However, modern OPV technologies are not yet ready to be fully included in modern greenhouses. Nevertheless, OPV materials will be developed with more efficiency and transparency due to their low weight and transparency, flexibility, and rapid, roll-to-roll manufacture of existing greenhouse designs (Wang et al., 2017) (Fig. 6).

4.3 Crop Yield and Quality Improvement Through Crop Selection

Light limitation is the main eco-physiological restriction for crop production in the PV-integrated greenhouse. Therefore, cultivation may drop, and in conditions such as concentrated PV panels designs, specific crop species with low-light saturation in photosynthesis may be selected. Since most crop species in shade conditions are not sufficiently informed, it is challenging to recommend specific plants for their shading. To the best of the authors' knowledge, little information about productivity and quality has been reported in the literature on greenhouse vegetables covered by PV modules. Therefore, shading (PV) panels require additional crop-specific studies to determine the optimal fraction and arrangement of panels that do not decrease agricultural productivity (Chamara & Beneragama, 2020). This section examines and highlights the research gaps in the selection of appropriate greenhouse crops.

Shade tolerance is the plant trait that describes the capacity in plant ecology to survive and develop under low light conditions (Dupraz et al., 2011). However, the term shade tolerance is used in various fields outside ecology, including plant physiology, forestry, agriculture, landscaping, and gardening (Valladares Niinemets, 2008). Limited information on shade tolerance of most crop species is available because few screening studies have been conducted on crop shade tolerance.

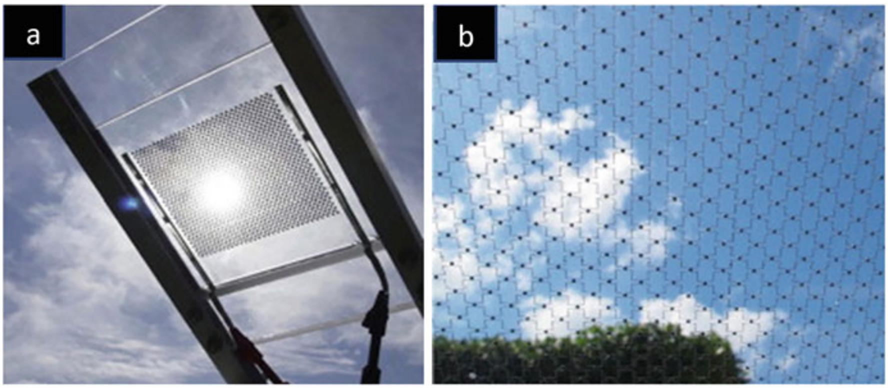


Fig. 6 Look-up view of the semi-transparent PV. (Source: Yano et al., 2014 (**a**); Cossu et al., 2016b (**b**))

PV modules restrict PAR under it and the ideal balance between shade reduction and energy generation needs to be achieved to maintain optimal photosynthesis levels. According to the design of the PV panel, there are two main areas based on the amount of light received by crops, between panels with full sunlight and under shaded panels. Crops that have different shade-tolerant abilities can be selected for both areas. More shade-tolerant crops should be selected below the panels and vice versa (Chamara & Beneragama, 2020). Nevertheless, the balance between power generation and the permissible shade should vary by plant species, region, weather, season, and greenhouse features.

Tolerance to any given stress depends on specific structural and physiological traits, but it is also strongly affected by the status of other environmental factors, most importantly, the light. When we adopt the PV greenhouse, it is vital to know how various plant morphological and physiological features contribute to photosynthesis under low-light environments. Different plant species show different adaptations to shade. A specific plant can show different shade tolerances and improves plant performance through morphological and physiological acclimatization to the light surroundings (Valladares & Niinemets, 2008). Some plants can create more than one phenotype in different conditions of the environment. In response to a unique environment, the change in phenotype could be in relation to behavior, morphology, and physiology. Phenotypic plasticity is a vital mechanism that makes organisms adaptable to the changing environment. Plasticity can be remarkable for specific plant characteristics, especially for morphological features that optimize light absorption. Various plant strategies have been reported previously to intercept radiation at low irradiance and enhance radiation use efficiency. Morphological changes involve increased total leaf area and optimized leaf area arrangements to capture radiation more efficiently (Marrou et al., 2013).

The photosynthetic light response of leaves acclimated to different light levels must be determined when adopting species in the PV greenhouses. In light harvesting by plants, light-driven plasticity is a critical trait that alters radiation interception among different shade-tolerant species (Niinemets, 2010). The whole plant's light harvesting depends on several parameters. Mainly, foliage chlorophyll content governs leaf absorbance; hence, foliage chlorophyll content per unit dry mass increases with decreasing light availability. Branching architecture, foliage inclination angle, and leaf area distribution can also importantly decide the arrangements of leaves, thereby the efficiency of foliage exposure to light (Iio et al., 2005).

5 Refrigeration Facilities for Cool Storage by PV Energy

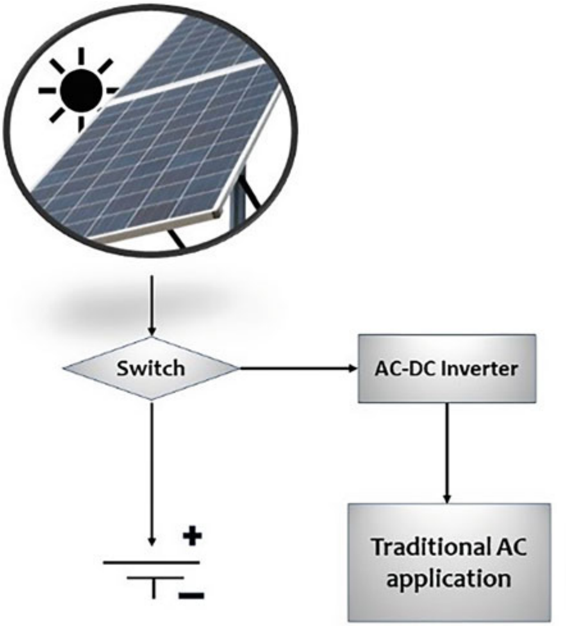
Horticultural products are required to be stored at a lower temperature because they are highly perishable. Reduction in post-harvest losses, which are present in the range of 25–30%, might significantly influence consumer availability of fruits and vegetables (Eltawil & Samuuel, 2007; Mekhilef et al., 2013). Low-temperature storage of agricultural products helps reduce microbial activity and respiration, which influences the time of extended storage and maintains the quality. Moreover, refrigeration helps reduce the field heat and storage if the market has low demand and price, mainly when the products are exported in fresh form. Since cooling is an expensive process, including the initial capital investment, solar PV power can be used to refrigerate freshly harvested vegetables sustainably, reduce post-harvest losses, and prevent distress sales. This system provides benefits in rural or remote areas where grid electricity is almost unavailable. On the other hand, traditional cooling methods are not economically viable due to high electric power consumption and operating expenses (Mekhilef et al., 2013). When coupled with a traditional vapor compression system, the main advantage of having solar panels for refrigeration is the easy construction and high overall efficiency. Therefore, the system is particularly suited to village power systems since they need a small amount of specialized work to install and maintain (Eltawil & Samuuel, 2007; Kim & Ferreira, 2008).

PV panels and an electrical refrigeration device are the primary components of a solar electric refrigeration system. First, the systems should be equipped with some means to cope with altering the rate of producing electricity with time, such as an electric battery, mixed use of solar grid electricity, or a compressor with variable capacity (Mekhilef et al., 2013). Various technologies for delivering refrigeration from solar energy include solar electric, thermo-mechanical, sorption, and some newer technologies (Kim & Ferreira, 2008). The energy consumption of a refrigeration system is determined by the refrigeration capacity and the difference between the condensation and evaporation temperatures. Therefore, the cooling load to be met by the PV-generator depends essentially on the ambient temperature and the refrigerator's room temperature (Eltawil & Samuuel, 2007). PV arrays must generate satisfactory current and voltage to run the applications. They can be coupled in series or parallel to provide the desired voltage and current.

Eltawil and Samuuel (2007) designed a solar PV-powered vapor compression refrigeration system to provide favorable conditions for potato storage. It consisted of PV panels, a lead-acid battery, an inverter, and a vapor compression refrigeration system. Modi et al. (2009) explored the possibility of using a solar PV system to power a household electric refrigerator. They used a standard home refrigerator and modified it by adding a battery bank, inverter, and transformer powered by solar PV panels. Del Pero et al. (2016) have introduced a novel, self-constructible refrigerator driven by solar (PV) energy and is suitable for food preservation. A thermally insulated cover with thermal energy storage has been created with existing resources and integrated with technological components, DC compressor, heat exchangers, and PV module. De Blas et al. (2003) designed a refrigeration plant to cool down an estimated daily supply of milk that can also be applied for vegetable storage with slight modifications. The solar energy generated during daytime hours is kept in a tank surrounding a milk container as sensible and latent heat of frozen water.

Navigant (2006) has provided a systematic overview of the many technologies available for using solar energy for refrigeration, including solar electrical, thermo-mechanical, sorption, and some newly developing technologies. He has also evaluated the capabilities of these various technologies in terms of producing competitive, long-term solutions. Moreover, he suggested employing photovoltaic-powered

Fig. 7 Schematic diagram of a solar PV cooling system



vapor compression systems and continuous and intermittent liquid or solid absorption systems and adsorption systems for refrigeration (Fig. 7).

6 PV Energy-Powered Electric Vehicles in Greenhouse Management

Conventional fossil fuel-powered internal combustion engines cause economic hardship due to fluctuating fuel prices, pollute the environment, and endanger the community's health. Not only that, but most current fuel supplies are expected to run out long before the end of the century, forcing people to turn to alternative options such as renewable energy-powered vehicles. As a result, there is a growing need for environmentally friendly transportation systems such as electric vehicles (EV) because anthropogenic greenhouse gas emissions should minimize in all sectors, including agriculture, during the transition toward the low-carbon economy. Therefore, a gradual shift of machinery and other vehicles is critical in the agricultural sector, and greenhouse agriculture is no exception.

Electrification of transportation provides an opportunity to reduce petroleum consumption and shift to renewable energy sources with battery-powered electric vehicles. Incorporating PV into the EV charging system has increased due to numerous causes, including ongoing price reductions in PV modules, rapid development in EVs, and concern about greenhouse gas impacts.

PV battery-powered electric vehicles charged with a solar PV array provide additional benefits, particularly in mountainous and isolated locations with no grid connection, no maintenance facilities, and no filling stations. This system is more economically viable in locations with high solar irradiation. Different battery types can be found in the electric vehicle industry, which may be utilized for automated and lightweight vehicles in agriculture. Many different aspects, such as energy storage efficiency, physical features, cost price, safety, and battery life, should be considered when selecting suitable batteries for these vehicles. This technology can replace fossil-fuel-powered tractors for lesser agricultural activities, relieving internal combustion engine vehicles for more power jobs. More efficient electrical energy storage systems with quicker charging times and longer lifespans with lower costs must be introduced to enhance the adoption of battery-powered electric vehicles in greenhouse agriculture.

In addition to the above, the use of PV technology in unmanned aerial vehicles (UAV) targeting various functionalities in greenhouse management, autonomous surface vehicles (ASV) for water quality and greenhouse gas emission monitoring (Dunbabin & Grinham, 2010), and electric farm machinery and agricultural robots (Gorjian et al., 2021) has also been reported previously.

7 Synthesis and Way Forward

Increasing food and energy demands linked to population expansion is significant, particularly in the current climate change predicament. The green energy strategy toward the green economy is a solution to these challenges so that solar power can play a pivotal role in sustainable energy. Therefore, this chapter aimed to elucidate the characteristics of the PV-integrated greenhouse, the use of PV energy for greenhouse environmental management, the use of various PV systems in greenhouses, and the impact of PV shadowing on plants.

The usage of PV-integrated greenhouses in the same land unit, especially in the tropics, is predicted to be beneficial if PV electricity provides improved growing conditions for plants without harmful shadowing effects. The selection of crops that are capable of resisting shadow is crucial. Shade-tolerant plants with high plasticity are best suited for growing, particularly in heavily shaded situations. Microclimatic effects on crops should also be investigated, and energy-efficient machines will give an added advantage in energy conservation. Examining the microclimatic impacts of crops and energy-efficient machines is also necessary to add energy conservation. Productivity of crops and cultural practices in different climatic conditions should also be explored. Minimum change should be recommended to facilitate the transition from typical greenhouse to PV-assisted greenhouse cultivation, and light reduction mitigation should be given the most attention. Although crop yield is modest compared to the conventional greenhouse in most cases, power generation can attain a high land equivalent ratio (LER).

Future PV module designs should reduce heterogeneity by optimizing the placement of panels to create spatially uniform shade patterns such as checkerboard design and semi-transparent PV panels, resulting in an even accumulation of biomass. PV electricity generation should be introduced in advanced manufacturing like plant factories where PV may be used over 100% of the impervious roof area to maximize electricity production. Furthermore, this renewable energy technology needs to be incorporated into policy decision levels, especially in low-income tropical countries, where this kind of approach has a year-round benefit so that financial assistance, training, and technology transfer can be mandated under relevant authorities. To sum up, this system enhances farmers' economic income and solves the electricity shortage problem while protecting the environment in a low-carbon economy.

8 Conclusion

Greenhouse crop production provides a promising solution to the challenges faced by modern agriculture, such as population growth, depleting natural resources, and climate change, while ensuring the production of quality food. However, optimal crop growth and resource utilization require precise environmental control within greenhouses, including temperature, humidity, lighting, CO_2 enrichment, irrigation, and fertigation. Despite its benefits, intensive greenhouse crop production is associated with significant environmental impacts due to high energy consumption from fossil fuel-based energy sources. Therefore, transitioning to renewable energy sources is crucial to achieving sustainable greenhouse crop production. The integration of photovoltaic technology in greenhouses offers an efficient energy system for sustainable food and energy usage in agriculture. The use of semi-transparent PV technology and proper panel-arranging systems can improve light transmissivity for crops while selecting appropriate crops with some shade-tolerant ability. In addition to improving environmental control, PV energy can also power cool storage facilities and light vehicles for greenhouse management, especially in remote areas where grid electricity is unavailable. Finally, the adoption of renewable energy technology in greenhouse crop production has year-round benefits, enhances farmers' economic income, solves the electricity shortage problem, and protects the environment. Policymakers and stakeholders must support the transition to renewable energy sources to achieve sustainable greenhouse crop production.

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Energy Conservation in Farm Operations for Climate-Smart Agriculture

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Abstract

Farm mechanization was considered one of the seven wonders of the twentieth century. Even in the twenty-first century, agricultural mechanization remains significant. With climate change issues, we are entrusted to practice conservation agriculture by reducing intensive cultivation. Though it is advocated to reduce tillage operations, other field operations have become more machine-dependent for enhancing input use efficiency and conserving energy, environment, and equity.

Efforts have been put to discuss the important topics of stubble burning and crop residue management and related machines in this chapter. For conserving natural resources while sustaining agricultural production for the ever-increasing population, site-specific machines must be selected and used by skilled operators. Though in India food security issue has been addressed to a satisfactory extent, efforts toward adaptation of climate-smart approach in crop production by the farmers need to go a long way.

Global as well as Indian population is increasing exponentially, but agricultural land remains unchanged for several decades. To fulfill the world food security, crop productivity has to be increased. Higher energy demand has to be rationalized and optimized as the cost of energy resources has increased significantly in recent days. Evaluating the energy usage patterns for various cropping systems is crucial for effective management of input energy in crop production systems. Different energy consumption for crop production has been discussed, and methods of parametric assessment have also been presented in this chapter.

1 Introduction

Agricultural practices in recent decades are taking a paradigm shift by taking different terms like intensive agriculture, sustainable agriculture, and conservation agriculture. Recently, we are faced with another term called "climate-smart agriculture" (CSA) that seems to be a combination of sustainable agriculture and conservation agriculture. Very recently, stubble burning, an age-old practice, has become a global issue. The usage of appropriate machineries for crop residue management is a must for providing an alternative solution to the farmers. Governments across the globe have taken serious cognizance of this issue and are banning stubble burning with environmental laws. West Bengal is not an exception; "anti-stubble burning" day is being observed on November 4 since 2019.

The agricultural focus in the twentieth century was on maximizing food productivity, and it shifted toward maximizing profitability toward the end of the century. Environment quality issues have forced agriculture to examine material flow, particularly nutrient flows, and this, to a large extent, is the reason for the current interest in sustainable agriculture (Pierce & Lal, 1991). Sustainable agriculture encompasses various farming approaches such as organic farming, low-input farming, biological, and other alternative approaches, among others (National Research Council, 2010). Degradation of the soil is a significant issue on a global scale. According to Karlen and

Rice (2015), about 40% of the world's agriculture is badly deteriorated, according to new research from the International Food Policy Research Institute (IFPRI).

The relationship between agriculture and climate change is one of interdependence as they both have an impact on and are affected heavily by recent climate changes. According to the Intergovernmental Panel on Climate Change (IPCC), the global temperature is expected to increase by 1.4–5.8 °C during this century. Agriculture is solely responsible for around 13.5% of the global greenhouse gas (GHG) emissions that equates to approximately 6.6 GT of CO_2 equivalent per year, which is 1.8 GT of C-equivalent per year. The main contributors to greenhouse gas emissions in agriculture are the production of methane (CH_4) and nitrous oxide (N_2O) from fertilized soils, fermentation, burning of biomass, and the use of manure and fertilizers (Jat et al., 2020). To address these issues, carbon sequestration practices such as reduced tillage, use of cover crops, residue management, composting, green manuring, precise application of fertilizers, control of biomass burning, and agroforestry have been identified as important goals of CSA.

In the early twenty-first century, global organizations related to agriculture and the environment developed the concept of climate-smart agriculture (CSA). It was created to focus on mitigating food security in African nations, where a large portion of the agricultural land is made up of small and marginal fields. In India, the eastern region of the country as well as most of the northeastern states has a majority of their land classified as marginal or small holdings. In West Bengal, about 94% of the cultivable lands comes under the category of small and marginal fields (MoA, GoI, 2019). In recent years, with the government's strong initiatives, farm mechanization has taken a commanding role in cultivation practices with several farmers' friendly schemes. The selection and operation of crop-specific machinery have not been fully optimized for CSA. However, these challenges can be prioritized within the context of CSA. The chapter in question specifically deals with the use of machinery to achieve the objectives of CSA, with a focus on smallholder farming.

2 Stubble Burning and Environmental Issues

According to IPCC (2007), agriculture contributes to about 14% of total greenhouse gas emissions among all other sectors, with conventional energy supply contributing nearly 26%. In the agricultural sector, though enteric fermentation and soil management are responsible for 32% and 38% of emissions, respectively, the contribution of biomass burning is not at all insignificant as it stands at 12% (Fig. 1).

Stubble burning has been an age-old practice among the farmers. In the paddy fields, burning rice or wheat straw emits greenhouse gases that exacerbate climate change problems. On November 6, 2019, the Supreme Court of India ordered that the states must give free of cost machinery tools like the happy seeder, hydraulically reversible MB plow, and paddy straw cutter to small and marginal farmers who cannot afford them for helping them to take care of crop residue and stubbles. The Supreme Court of India has directed the governments of Haryana, Punjab, and Uttar

Fig. 1 Rampant stubble burning cases

Pradesh to offer financial assistance to small and marginal farmers who are growing paddy (except Basmati) as an incentive of INR 100 per quintal.

Now having realized the environmental issues, governments across the globe are banning stubble burning and advocating alternate solutions to excess crop residue. In an effort to reduce air pollution, West Bengal's state environment department has outlawed burning rice stubble in fields there. Those who burn paddy straw in field and violate the air (Prevention and Control of Pollution) Act, 1981) may face prosecution and imprisonment. The governments of north and western states have enforced laws that prevent sale of combined harvesters without straw management system (SMS).

The state is rife with paddy stubble burning, especially after the Kharif crop is harvested in October or November. In West Bengal, November 4 is being observed as an "anti-stubble burning day" since 2019. Thus, management practices for crop residue management and development of site-specific equipment are the essence of these days.

3 Concept of Climate-Smart Agriculture

According to the World Bank (2012), the objective of the climate-smart agriculture (CSA) approach is to enhance agricultural productivity in the long term, enhance the resilience of farmers, reduce greenhouse gas emissions from agriculture, and promote carbon sequestration. Besides delivering environmental benefits, it strengthens

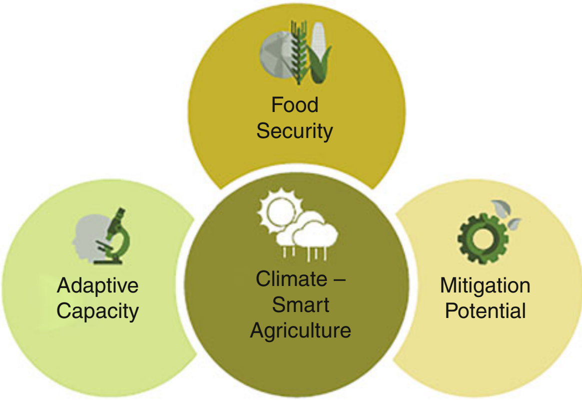

Fig. 2 Foundations of climate-smart agriculture. (Jat et al., 2020)

food security (Fig. 2). Due to climate change, agriculture is adversely affected by variable rainfall, higher temperatures, and greater water requirement through the manifestations of heatwaves, floods, and droughts.

The Food and Agriculture Organization (FAO) of the United Nations, the African Union, CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), International Fund for Agricultural Development (IFAD), United Nations Environment Programme (UNEP), and World Food Programme (WFP) have extensively documented the concept of climate-smart agriculture (CSA). CSA practices include crop diversification, usage of GIS, integrated crop and livestock management, crop-specific machinery, intercropping, conservation agriculture, improved grazing, agroforestry, and mulching. In addition to technological interventions, management strategies, including timely weather forecasts, choosing robust crop types, and ensuring that farmers have access to government support in the form of crop insurance coverage, must be associated with CSA. To optimize the input use efficiency, selection of farm equipment with matching power sources is one of the most important factors in climate-smart agriculture.

The major operational feature of CSA centers on increasing input energy efficiency with a focus on carbon sequestration with nutrient management by the application of site-specific smart technologies toward achieving environment-friendly cultivation (Fig. 3).

4 Conservation Agriculture (CA)

Conservation agriculture (CA) is an approach to agriculture that aims to combine sustainable crop production with resource conservation. It involves three main principles: minimum soil disturbance, permanent soil cover, and crop rotation. By reducing soil disturbance, keeping the soil covered with vegetation or organic materials, and alternating crops, CA aims to create a more sustainable and resilient form of agriculture

Fig. 3 Portfolio of climate-smart agriculture. (Jat et al., 2020)

that can help to meet the food needs of a growing population while also protecting natural resources and reducing negative environmental impacts (Gonzalez-Sanchez et al., 2015). The use of conservation tillage, which includes reduced tillage or no-till practices, along with long-lasting organic soil cover, is a key component of conservation agriculture. This combination can significantly improve soil moisture retention, increase soil organic matter, and reduce soil erosion and runoff. The organic soil cover helps to protect the soil, retain moisture, and provide a source of nutrients for the crops, while the presence of living plant roots and associated microorganisms can help to improve soil structure and increase the soil's ability to store water and nutrients. Overall, conservation tillage and organic soil cover can improve soil health, increase crop yields, reduce negative environmental impacts, and promote sustainable food production (Palm et al., 2014). CA is an approach to agriculture that aims to improve and conserve natural resources such as soil, water, and air by combining the management of people, machinery, and energy. This approach can help to increase agricultural productivity, enhance food security, reduce poverty, and improve the standard of living of farming communities. By reducing soil disturbance, conserving soil moisture, and improving soil health, conservation agriculture can improve crop yields and help farmers adapt to changing climatic conditions. Overall, CA is a unique and effective technique that promotes sustainable use of natural resources and can benefit both the environment and society.

The CA practice focuses on conserving natural resources, enhancing productivity, and mitigating the effects of global warming. Minimum soil disturbance involves reducing or eliminating tillage operations, crop residue retention involves leaving plant materials on the soil surface, and appropriate crop rotation involves alternating crops to maintain soil fertility and reduce the build-up of pests and diseases. By implementing these practices, CA can improve soil health, enhance productivity, and provide a sustainable and resilient approach to food production, even in small-scale farming systems.

5 Impacts of CA on Agriculture and Environment

Conservation agriculture (CA) benefits both the agriculture and the environment, and it can be "win-win" condition for both. However, many individuals involved in food production worldwide have yet to recognize some of the unexpected advantages it provides. Recently, conservation agriculture has gained popularity as a climate-smart agricultural approach that offers a practical alternative to traditional farming practices. By enhancing the productivity of various agricultural inputs, such as land, labor, water, nutrients, soil organic matter, energy, and equity, conservation agriculture can improve crop yields and provide benefits to farmers. The use of a conservation agriculture system can also increase cropping intensity in multiple ways.

Scientific research has documented the numerous benefits of conservation agriculture, establishing it as a sustainable and effective option for agricultural production.

Various sources, including FAO, IFAD, and numerous research studies (e.g., Hagga-blade & Tembo, 2003; Baker et al., 2007; Hobbs et al., 2008; Wall, 2008; Bhattacharyya et al., 2012; Llewellyn et al., 2012; Ogle et al., 2012; Ngwira et al., 2013; Derpsch et al., 2014; Palm et al., 2014; Sithole et al., 2016), have highlighted the following important benefits of CA practices:

(a) The implementation of reduced tillage and mulching practices in agriculture can lead to reduced greenhouse gas emissions, which helps to mitigate the impact of climate change by increasing in carbon sequestration.
(b) Organic mulching by left out residue of previous crop on soil surface can reduce extensive soil erosion caused by runoff water and wind, while also suppressing weed growth.
(c) Less soil and water erosion control land degradation and desertification.
(d) Inorganic fertilizers and pesticides are less likely to pollute natural resources when there is residue cover on the soil.
(e) CA practices that involve soil cover can enhance soil organic matter and lead to improved soil fertility over time. This is because CA practice increases soil organic carbon, which is a crucial factor in enhancing soil health and productivity.
(f) Improved soil structure augments water infiltration and retention.
(g) Agro-biodiversity is improved due to the stimulation of the biological activity in the soil.
(h) Improved soil conditions resulting from conservation agriculture practices can create a healthier root environment for crops, which can in turn reduce the risk of crop loss due to drought and other natural disasters.
(i) Crop rotation is an effective method for breaking the cycle of weeds, disease, and insect pests. Additionally, CA practices such as mulching by residue of cover crops can contribute significant amounts of organic carbon as well as other macro- and micro-nutrient to the soil and aid in nitrogen fixation.

In areas with semi-arid rainfall and high climate-induced risks, it is especially important to implement site-specific CA methods that consider local soil and climatic conditions. CA practices can help maintain the critical functions of the agro-ecosystem even in unfavorable conditions.

6 Crop Diversification

The conventional methods of agriculture have become a major source of concern due to the constantly rising demand for the growing population and the overtaxed natural resources, where the current cropping system poses difficulties for economic viability. The prevalence of rice-wheat system in South Asia has led to a number of ecological and socioeconomic challenges, including a decline in the productivity of groundwater resources and soil fertility. Thus, it is crucial to rethink alternate cropping systems in light of the resources at hand. In this era of farm mechanization, resource optimization can be accomplished by the selection and effective use of appropriate machinery. Reduced tillage, multi-crop planter, drip and sprinkler irrigation systems, weed-controlling tools, and reaper with residue management system should be made part and parcel of the cropping systems.

7 Mechanization in CA for Energy Conservation

Energy is required at different stages of crop production in agriculture to produce crop yield. Thus, it is a user as well as a producer of energy. However, from environmental, social, and economic perspective, the output energy is expected to surpass the total input energy. Agricultural operations require energy input in different forms like human energy, animal energy, seeds, chemicals, fertilizers, water, machineries, fuels, and electricity. One of the major objectives of CSA or CA is to conserve the energy input to the farm operations through energy budgeting and optimizing the input parameters.

8 Energy Used in Crop Production

Energy input in crop production varies with types of crop production, level of mechanization, socioeconomic condition of the farmer, and agro-climatic condition of the region. The energy input to crop production is categorized on the basis of various sources and usage pattern. Energy systems can be categorized as direct or indirect depending on how they are used. For crop production, direct energies are released directly from power sources, whereas indirect energies are lost via different conversion processes during operations like manufacture, storage, and distribution, among other things (Singh & Mittal, 1992). Energy consumption in crop production can be classified into two types.

8.1 Direct Energy Consumptions

The energy expenditure in physical work during field operations is considered a form of direct energy consumption in crop production. Direct energy requirements cover the energy needed for clearing the land, planting, irrigation, cultivating, harvesting, processing the produce once it has been picked, producing food, storing it, and transporting it for use in agriculture. In agricultural production, field operations use a lot of energy, with fuel use accounting for the majority of consumption (Bowers, 1992). Direct energy inputs in agriculture are typically defined as physical energy, which includes human labor, draft animal power, and mechanical power sources. In order to accurately estimate energy inputs, values for energy equivalents are necessary.

(a) ***Human labor***: Human muscle power has been a power source for agriculture since time immemorial. Even in this era of modern farm mechanization, human labor cannot be ignored, though its use has been reduced. In practical applications, an input of 74.6 W is often used to represent human labor energy in agricultural operations.
(b) ***Draft animal***: With the development of small farm machines, draft animal power has been dependable for carrying out farm operations for decades. Even today, bullock- or buffalo-drawn indigenous plow is being used in many developing countries for tillage and threshing purposes. For a pair of bullocks, 746 W power is taken into consideration.
(c) ***Mechanical power***: With the advent of intensive agriculture, farm mechanization became an indispensable tool for farm operations. With the development of medium- and large-scale machines, engine-generated mechanical power became popular in field operations. Power tiller or hand tractor, four-wheel tractors, irrigation pumpsets, and other self-propelled machines for tillage, sowing, harvesting, and threshing are all used as mechanical power input to cultivation. Power equivalence of the mechanical power sources depends on their work capacity and size. Besides these prime movers, fuel used to run engines of these machines is also considered mechanical power. Rated power for power tillers varies from 3.0 to 10.5 kW while that for tractors mostly used in Asian countries varies from 22.5 to 56 kW. These days mini tractors with power capacity as low as 13.5 kW are also available for small and marginal farms. Power capacity for stationary engines for pumping and threshing may vary from 0.38 to 3.75 kW.
(d) ***Electrical power***: Electricity is also a very important source of power on farms. It is mostly used for irrigation purposes. Nowadays, electrical power is also used for running power threshers.
(e) ***Renewable power***: Renewable energy sources such as wind, solar, and biofuels are increasingly being used in agricultural operations, primarily for irrigation purposes, in an effort to use energy more sustainably. By utilizing renewable energy in agriculture, farmers can reduce their carbon footprint, lower their energy costs, and increase their energy independence.

8.2 Indirect Energy Consumptions

The energy required to generate power in the prime movers and used for other farm services as agricultural input is considered indirect energy consumption. Indirect energy consumption can be of different forms like physical, biological, and chemical energy inputs.

(a) ***Physical energy***: Energy required for manufacturing, transportation, distribution, repair, and maintenance of machinery and equipment as well as considered as energy sequestered by raw materials and enlisted as indirect physical energy input. These are mostly associated with mechanical, electrical, and renewable power sources.

The standard measure of energy in production is measured in MJ kg^{-1} of the finished good (Bowers, 1992). To estimate the energy required for the manufacturing of agricultural machinery, including tractor or power tiller tires, one could use an energy equivalent value of 86.76 MJ kg^{-1}. Repairs and maintenance are usually thought to make up 1% of energy consumption in manufacturing, and that transportation and distribution of materials are estimated to require 8.8 MJ kg^{-1} (Pimentel et al., 1973).

(b) ***Biological energy***: Biological energy inputs are often measured to include seeds, organic fertilizers, and hormones.

(c) ***Chemical energy***: Inorganic fertilizers, pesticides, herbicides, etc., used for spraying and dusting are considered as input chemical energy. In general, nitrogen equivalent is the standard unit of measurement used to determine the amount of chemical fertilizer used (N-Eq Energy). The energy equivalent values for N, P_2O_5, and K_2O are considered 78.1, 17.4, and 13.8 MJ kg^{-1}, respectively (Mudahar & Hignett, 1987). In terms of raw and diluted insecticides, energy coefficients of 119.8 and 10.1 MJ kg^{-1} may be employed, respectively, for estimation (Singh & Mittal, 1992).

8.3 Energy Outputs

Energy output from crop production consists of mainly products and by-products. Crop grain and fruits are the product and considered yield energy, while straw, bagasse, and crop residues are considered by-products. The values of energy equivalent to these power sources are given in Table 1.

9 Estimation of Input Energy

Human Labor Energy: Any type of fieldwork involves laborers to run machinery or work independently. To determine the amount of human energy required (E_h, MJ h^{-1}) for crop cultivation, one can calculate the total number of man-hours (H_h, h ha^{-1}) needed to complete all operations involved in the process.

$$\text{Human energy} = \text{human} - \text{hour worked} \times \text{energy coefficient of human} \quad (1)$$

Seed Energy: To calculate the input energy from seed, one can use the quantity of seed (M_s, kg ha^{-1}) required for sowing or planting and the energy coefficient value of seed (E_S, MJ kg^{-1}).

Table 1 Energy coefficient for different input–output parameters

Particulars		Unit	Energy coefficient (MJ $unit^{-1}$)
Tractor		kg	138.00
Farm machinery			
	Disc harrow	kg	149.00
	Rotavator	kg	148.00
	Leveler	kg	149.00
	Seed cum fertilizer drill	kg	133.00
	Sprayer	kg	129.00
	Combine	kg	83.50
Diesel		kg	56.31
Human		Human-h	1.96
Seed			
	Rice	kg	14.70
	Wheat	kg	15.70
	Green gram	kg	13.96
	Maize	kg	14.70
	Soybean	kg	25.00
Fertilizer			
	N	kg	60.60
	$P - P_2O_5$	kg	11.10
	$K - K_2O$	kg	6.70
Chemicals			
	Herbicide	kg	238.00
	Fungicide	kg	216.00
	Insecticide	kg	199.00
Electricity		kW	11.93
Water		M^3	1.02
Straw			
	Rice/wheat/green gram	kg	12.51

Source: Binning et al. (1983); Mittal and Dhawan (1988); Singh and Mittal (1992); Kitani and Jungbluth (1999); Devasenapathy (2008); Chaudhary et al. (2009); Tipi et al. (2009); Pishgar-Komleh et al. (2012); Elhami et al. (2016); Singh et al. (2019)

$$\text{Seed energy} = \text{amount of seed} \times \text{energy coefficient of seed} = M_S \times E_S \quad (2)$$

Fuel Energy: To determine the total amount of diesel fuel (V_F, L ha^{-1}) used by all primary movers during crop production, either a volumetric approach or gravimetric method can be utilized. It is crucial to evaluate the quantity of fuel consumed throughout all crop production. The fuel energy can be obtained from the amount of fuel used and energy equivalent of respective fuels (E_F, MJ l^{-1}) as per Eq. 2.

$$\text{Fuel energy} = \text{Amount of fuel} \times \text{Energy coefficient of fuel} = V_F \times E_F \quad (3)$$

Water Energy: Irrigation requires a huge amount of energy consumption in plant growth and maturity, particularly in dry-land agriculture. To estimate the energy input for irrigation, it is necessary to track and measure the total volume of water delivered to the field using various types of flow meters. The water energy input for irrigation can then be determined from the volume of water supplied into the field for irrigation (V_W, $m^3\ ha^{-1}$) and the water energy coefficient (E_W, $MJ\ m^{-3}$) using the following equation:

$$\begin{aligned}\text{Water energy} &= \text{Volume of water supplied into field} \\ &\quad \times \text{energy coefficient of water} \\ &= V_W \times E_W \end{aligned} \tag{4}$$

Electrical Energy: Electricity is primarily utilized for operating irrigation pumps during cultivation, and its usage (kW-h) can be measured using an energy meter. The electrical energy input can be determined from electricity consumption per unit area and the energy equivalent (E_e, MJ-kW h^{-1}) using the following equation:

$$\text{Electric energy} = \text{Electric power consumption } (\text{kW} - \text{h}) \times E_E \tag{5}$$

Machinery Energy: Depending on the cropping system and cultivation practices, different types of farm machinery are used at different phases of cropping season. Every machine and implement has been assigned with specific energy equivalent. The machinery energy input can be determined from operating time of the prime movers and the respective machinery implements (T_M, $h\ ha^{-1}$) by their respective machinery energy equivalents (E_M, $MJ\ h^{-1}$) as per the following equation:

$$\begin{aligned}\text{Machinery energy} &= \text{Time fo machinery operation} \\ &\quad \times \text{energy coefficient value of respective machinery} \\ &= \sum\nolimits_{i=1}^{n} T_{Mi} \times E_{Mi} \end{aligned} \tag{6}$$

Fertilizer Energy: Fields often receive applications of nitrogen (N), phosphorus pentoxide (P_2O_5), and potassium oxide (K) as inorganic fertilizers (K_2O). The fertilizer energy input can be determined from the quantity of fertilizer used for crop production (Q_N, Q_P, and Q_K kg ha^{-1}) and their respective energy coefficients (E_N, E_P, and E_K MJ kg^{-1}) as per the following equation:

$$\begin{aligned}\text{Fertilizer energy} &= \text{Quantity of fertilizer used} \\ &\quad \times \text{energy coefficient value of respective fertilizer} \\ &= (Q_N \times E_N) + (Q_P \times E_P) + (Q_K \times E_K) \end{aligned} \tag{7}$$

Chemical Energy: Indirect energy input occurs when pesticides like fungicides, insecticides, and herbicides are applied. The energy equivalent values for the various compounds (E_H, E_I, and E_F in MJ kg^{-1}) are readily available. To calculate the chemical energy input (MJ ha^{-1}), one can use the following equation, which takes into account the quantity of chemicals sprayed (insecticide Q_I, herbicide Q_H, and fungicide Q_F kg ha^{-1}) and their respective energy coefficients.

$$\begin{aligned}\text{Energy of chemical} &= \text{Quantity of chemicals used} \\ &\quad \times \text{energy coefficient value of respective chemicals} \\ &= (Q_H \times E_H) + (Q_I \times E_I) + (Q_F \times E_F)\end{aligned} \tag{8}$$

9.1 Total Energy Inputs

The amount of energy required for any crop production, from field preparation to harvesting and threshing, is total energy input, and it can be calculated as per the following equation:

$$\begin{aligned}\text{Total energy inputs} = (&\text{Human energy} + \text{Seed energy} + \text{Fertilizer energy} \\ &+ \text{Chemical energy} + \text{Machinery energy} \\ &+ \text{Fuel energy} + \text{Water energy} + \text{Electrical energy}\end{aligned} \tag{9}$$

9.2 Estimation of Energy Outputs

Yield Energy: Each grain species has its respective energy equivalent, as do vegetables, fruits, spices, etc. (E_y, MJ kg^{-1}). The energy from yield (MJ ha^{-1}) can be determined by using the yield of specific crop (M_y, kg ha^{-1}) and their corresponding energy coefficient:

$$\begin{aligned}\text{Yield energy} &= \text{Quantity of yield} \times \text{energy equivalent of yield} \\ &= M_Y \times E_Y\end{aligned} \tag{10}$$

Straw Energy: Like crop yield energy, the straw from the crops also contains energy. The energy from straw (MJ ha^{-1}) can be determined from the quantity of straw, chaff (M_{st}, kg ha^{-1}), and the energy coefficient value of straw (E_{st}, MJ kg^{-1}).

$$\begin{aligned}\text{Straw energy} &= \text{Quantity of straw produced} \times \text{energy equivalent of straw} \\ &= M_{ST} \times E_{ST}\end{aligned} \tag{11}$$

$$\text{Total energy output} = \text{Yield energy} + \text{Straw energy} \tag{12}$$

9.3 Energy Indices

Energy indices for the crop production include "specific energy (S_E, MJ kg^{-1}), energy productivity (E_P, kg MJ^{-1}), energy profitability, energy use efficiency (EUE), net energy gain (NEG, MJ ha^{-1}), renewable energy productivity (REP, kg MJ^{-1}), nonrenewable energy productivity (NEP, kg MJ^{-1})," and other similar parameters (Bhunia et al., 2021). To compute these parameters for the energy used in agricultural operations and energy from yield and straw, the following equations can be used. Specific energy, energy productivity energy use efficiency (EUE), net energy gains renewable energy productivity nonrenewable energy productivity energy profitability (PE), and other parameters are included in a cropping system's energy indices. The following relationships can be used to compute those parameters for energy use in agricultural operations and output energy from grain as well as straw (Choudhary et al., 2017).

$$\text{Specific energy}\left(\text{SE, MJ kg}^{-1}\right) = \frac{\text{Total input energy}\left(\text{MJ ha}^{-1}\right)}{\text{Grain yield}\left(\text{kg ha}^{-1}\right)} \tag{13}$$

$$\text{Energy productivity}\left(\text{EP, kg ha}^{-1}\right) = \frac{\text{Grain yield}\left(\text{kg ha}^{-1}\right)}{\text{Total input energy}\left(\text{MJ ha}^{-1}\right)} \tag{14}$$

$$\text{Energy use efficiency (EUE)} = \frac{\text{Total output energy}\left(\text{MJ ha}^{-1}\right)}{\text{Total input energy}\left(\text{MJ ha}^{-1}\right)} \tag{15}$$

$$\begin{aligned}\text{Net energy gain}\left(\text{NEG, MJ ha}^{-1}\right) &= \text{Total output energy}\left(\text{MJ ha}^{-1}\right)\\ &\quad - \text{Total input energy}\left(\text{MJ ha}^{-1}\right)\end{aligned} \tag{16}$$

$$\begin{aligned}&\text{Renewable energy productivity}\left(\text{REP, kg MJ}^{-1}\right)\\ &= \frac{\text{Grain yield}\left(\text{kg ha}^{-1}\right)}{\text{Total renewable input energy}\left(\text{MJ ha}^{-1}\right)}\end{aligned} \tag{17}$$

$$\begin{aligned}&\text{Non} - \text{renewable energy productivity}\left(\text{NEP, kg MJ}^{-1}\right)\\ &= \frac{\text{Grain yield}\left(\text{kg ha}^{-1}\right)}{\text{Total non} - \text{renewable input energy}\left(\text{MJ ha}^{-1}\right)}\end{aligned} \tag{18}$$

$$\text{Energy profitability} = \frac{\text{Net energy return}\left(\text{MJ ha}^{-1}\right)}{\text{Total input energy}\left(\text{MJ ha}^{-1}\right)} \tag{19}$$

10 Machinery for CSA

Mechanization is a crucial component of CA, and smallholder farmers frequently struggle to choose the right machinery with compatible prime movers. Few countries across the globe have been practicing conservation agriculture extensively for the last few decades and thus CA has become a trend in their crop production system. The adoption of conservation agriculture (CA) agricultural practices has been widespread in Australia, making it one of the top five countries in the globe in this regard (Kassam et al., 2015). Zero tillage (ZT) practice, in particular, has gained popularity in Australia and currently covers 80–90% of agricultural land in several areas with continued expansion (Llewellyn et al., 2012). The machinery for CA systems has rapidly evolved as a result of this unparalleled rate of development.

The principal mechanization requirements for conservation agriculture include tools for minimum soil disturbance during tillage and sowing, and machines for crop residue management during sowing and harvesting. Considering the practice of CSA, the major focus is given to the machinery that ensures operations with minimum emission of GHGs. The important technologies that should be adopted toward effectively practicing climate-smart agriculture for adaptation, food security, and mitigation are enlisted below (Jat et al., 2020):

(a) Laser land leveling
(b) Happy seeder with SMS
(c) Spatial zero-till drill
(d) Permanent beds
(e) Direct seeded rice
(f) Crop diversification
(g) Farm design and integrated farming systems
(h) Green seeker
(i) Nutrient expert tool
(j) Sub-surface drip irrigation
(k) Intercropping
(l) Solar power pumps

Tools for low soil disturbances and stubble management equipment are given due importance. Stubble burning can be avoided by mechanically processing the straw using balers and other machines. Though there has been much discussion of reduced or no-tillage system, adoption of strip-tillage can serve the purpose of CA as well as CSA. The effectiveness of conservation agriculture (CA) relies heavily on the efficient utilization of resources such as seeds, fertilizers, irrigation, and various energy sources. Irrigation efficiency can be enhanced by making proper slope in the field prior to cultivation. This can be done using a laser land leveler. Turbo seeders can serve the purpose of precision planting as well as managing crop residue for incorporation. Straw management system (SMS) with a combine harvester also serves the purpose of crop residue management by making the stubble finely chopped and spreading over the field uniformly. Operational details of the important equipment are discussed below.

10.1 Laser Land Leveler

One of the most important climate-smart interventions is a laser land leveler, which smoothens out terrain with accuracy. Earth-moving buckets fitted with lasers are used in the laser land leveling procedure to produce a surface (± 2 cm). Global positioning systems (GPS) and laser-guided equipment are used in this procedure.

Crops can be adversely affected in terms of germination, growth, and yield by undulated soil surfaces that cause disparities in soil moisture and water distribution.

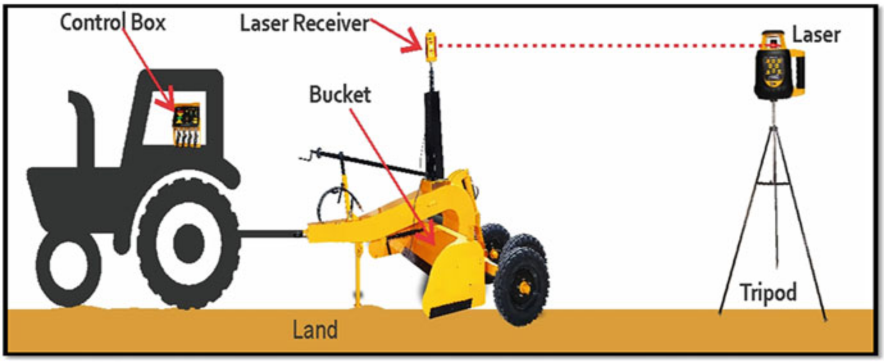

Fig. 4 Components of laser land leveler (https://celec.com)

Hence, leveling the ground is a necessary first step in excellent crop, soil, and agronomic management, especially in conservation agriculture (Fig. 4).

Despite the fact that laser land leveling technology has a number of direct and indirect advantages, the farming community has not yet adopted it. It is, however, encouraging that the government of West Bengal has included this tool in the subsidy schemes under Custom Hiring Centres (CHCs) and other programs. Efforts are required from people associated with agricultural extension to make it usable and accessible to even small and marginal farmers for increasing input use efficiency.

10.2 Machinery for Direct Seeding

Any planting and fertilizing technique that does not include plowing to prepare the soil beforehand is known as "direct seed farming." This applies to both one-pass systems that fertilize and plant straight into undisturbed soil and two-pass systems that fertilize and plant first. The direct seed cropping systems are identified by the use of longer crop rotations, limited to no soil disturbance during seeding, and retaining most of the crop residues over the soil surface.

Direct seeded rice (DSR) is a practice of rice seeding directly in dry or puddled field using zero-till seed drill or happy seeder. Because of its effective crop establishment and superior agronomic, soil, and crop management approaches that increase input usage efficiency, the DSR practice has gained popularity. In the target region, subsurface drip irrigation in highly automated fields and relay cropping of pulses in DSR fields are improving system productivity and profitability, as well as enhancing soil quality and crop diversification (Sidhu et al., 2015). DSR appears to be a commercially feasible substitute for transplanted rice as a way to address the new issues of labor, water scarcity, and high production costs.

10.3 Happy Seeder

It is exceedingly difficult for farmers to manage 8–10 t ha^{-1} leftovers in a rice-based cropping system efficiently and cheaply, especially when it comes to planting wheat crops on schedule. Because of its technological and financial advantages, zero-till (ZT) technique for wheat sowing has gained a lot of popularity. Nevertheless, utilizing the ordinary ZT seed drill to directly drill wheat into rice fields that had been harvested by combines still presented several challenges.

To address the abovementioned issues, a 9-row "Turbo Happy Seeder" was developed at BISA, Ludhiana. It has the feature of sowing the seeds along lines similar to that of zero-till seed drill following harvest of previous crop with a special provision to chop the standing straw. This turbo seeder is operated by tractor PTO to control rotating blades for crop residue management. Without any prior tillage, it offers surface retention of leftovers as mulch. Despite providing various benefits to farmers, planting wheat directly into rice residues using the Turbo Happy Seeder has been shown to produce grain yields comparable to or higher than those achieved by conventional tillage through rice residue burning (Sidhu et al., 2015) (Fig. 5).

From the perspective of marginal and small farms of West Bengal, we need to have a similar turbo seeder that could be operated by power tiller or hand tractor. Efforts are going on at BCKV, Mohanpur, toward the development of such site-specific machines. The concept of strip tillage must be implemented to have less than 30% soil disturbance during sowing operation. Power tiller-operated strip tillage machine would serve the smallholders farming with energy efficacy and environmental benefits.

Fig. 5 Happy seeder in operation. (CIMMYT.org)

10.4 Combine Harvester with SMS

Harvesting of paddy and wheat using a combine harvester has taken the driver's seat in farm mechanization due to timeliness and cost-effectiveness. However, serious problems were being encountered by the farmers due to huge straw and standing stubble left behind by the harvester. This has encouraged stubble burning among the farmers that had consequently led to air pollution (Fig. 6).

Combine harvesters are now equipped with a Super Straw Management System (Super SMS) to chop and distribute straw evenly. The Super SMS is an emerging machine that provides a practical solution to straw problems. It is attached to the combine harvester and chops paddy straw into small pieces, which are then scattered across the field as a form of mechanical mulching. This makes it easier to operate other machines on the field. By directly sowing wheat seeds following paddy harvesting with the SMS, sowing machines can avoid clogging due to surface residue, making stubble burning unnecessary.

From the perspective of small and marginal farms of West Bengal and other states, 6.7-m-wide cutter bar-based large combine harvester poses difficulty in operation and maintenance. There are mini combine harvesters available in the market that have similar widths to that of power reaper or power tiller. Hence, it is recommended that straw management systems compatible with mini combine be developed for making them popular among small and marginal farmers.

Fig. 6 Chopped stubble being spread by SMS

Fig. 7 Straw baler is in operation

10.5 Straw Baler

Another option for managing crop residue left after harvesting by combine harvester is to make bales out of the excess straw over the field. With a machine, compact bales of chopped and raked straw are created that are simple to handle, move, and store.

The round baler is currently the most used form of baler in industrialized nations. It creates "rolled" or "round" bales in the form of cylinders. In recent years, rectangular bales are also being formed by compacting the loose materials. Rectangular bale is easy to transport in comparison to round bales (Fig. 7).

Balers are typically driven by the PTO of a tractor. The assembly includes reel-style straw pick-up equipment, straw compaction, and tying components. The equipment automatically collects the leftover straw from the field using a reel, and then feeds it into the bale chamber using a feeder. The straw is compressed into a compact mass of varied lengths by the reciprocating ram. Also, the baler automatically makes the knots out of nylon rope or metal wire.

11 Energy Optimization

To achieve energy conservation through modern practices, it is crucial to assess how different energy sources are used and how well they affect the output. This analysis can be done by energy budgeting using optimization techniques. Optimizing energy consumption is essential for efficient management of finite natural resources and economical use of various inputs.

There exist several methods of optimization. Theoretical classification is based on the characteristics of the independent variables. The general classification is mentioned below:

1. Classical optimization techniques
   (a) Single-variable functions
   (b) Multivariable functions with no constraints
   (c) Multivariable functions with both equality and inequality constraints
2. Numerical methods of optimization
   (a) Linear programming
   (b) Nonlinear programming
   (c) Quadratic programming
   (d) Integer programming
   (e) Dynamic programming
   (f) Stochastic programming
   (g) Combinatorial optimization
   (h) Infinite-dimensional optimization

Currently there are many commercially available software and applications available based on the abovementioned techniques. A few of the parametric application-based programs are mentioned below:

(a) Data envelopment analysis (DEA)
(b) Distribution-free approach (DFA)
(c) Stochastic frontier analysis (SFA)
(d) Artificial neural networks (ANN) and fuzzy logic
(e) Neuro-fuzzy inference system (NFIS)

Aiming for yield productivity and environmental sustainability, energy utilization optimization is being conducted for different cropping systems and levels of mechanization in terms of agricultural input parameters.

12 Energy Conserved Through CA and CSA

In a traditional tillage system, merely the till-age process (seedbed preparation) often requires more than 50–70% of the entire fuel energy input (Safa et al., 2010; Houshyar & Grundmann, 2017). The use of decreased tillage in climate-wise agriculture and conservation agriculture saves a significant amount of energy compared to traditional tillage. Besides tillage energy, energy consumed as fuel, machinery, and irrigation can be saved to a large extent by practicing CA and CSA.

Conventional and reduced tillage used 69% and 115% more equipment energy, respectively, compared to no tillage (Hobbs et al., 2008). Recent studies by Bhunia et al. (2021) on different cropping systems found that about 16% of machinery energy and 15% of fuel energy could be saved in conservation agriculture. The amount of irrigation needed was significantly decreased by rice residue on the field. By reducing evaporation, drainage, and surface runoff, zero tillage practices and residual mulch minimize water losses and the energy needed for irrigation (Pal et al., 2010; Gaydon et al., 2011; Fu et al., 2018; Chakraborty et al., 2008).

13 Conclusions

The concept of climate-smart agriculture aims to ensure food security while also adapting technology to promote conservation agriculture and mitigate greenhouse gas emissions. Combined efforts by the government, private sector, researchers, extension agents, cooperative bodies, and farmers in an integrated approach will serve the need for CSA. Direct seeding, strip tillage, raised bed planting, turbo seeding, and crop residue management are among the technologies that have been found to greatly impact productivity, profitability, input use efficiency, energy efficiency, carbon sequestration, and greenhouse gas (GHG) mitigation.

Application of techniques like reduced and zero-tillage, combined tillage and sowing, and crop residue management has been found to contribute significantly to energy conservation. It is important to extend such technologies to the small and marginal landholders for achieving sustainable goals of climate-smart agriculture.

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Efficient Management of Energy in Agriculture

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Abstract

The agricultural sector's energy use is expected to skyrocket in the future decades. The estimated growth in food demand is outstripping the anticipated increase in energy capacity, which necessitates an increase in energy usage. Energy efficiency refers to the use of less energy to provide the same amount of output and services. Greater energy efficiency in food production systems is required since the projected energy production growth is inadequate and conventional energy sources are limited. Energy is consumed on farms directly as electricity or fuel to power farm activities and indirectly as fertilizers and other agricultural pesticides produced off-farm. Around 18.5 percent of India's overall energy consumption is spent by agriculture. Processing and transportation of agricultural goods and inputs consume more energy in high-income countries, while cooking consumes the most in low-income countries. The possibilities for increasing energy efficiency in agricultural through the implementation of innovative techniques and practices without compromising agriculture's high production are needed to be identified for each and every crop and ecology. Conservation agriculture, organic farming, preserving agro-biodiversity, improved soil and water management, integrated pest management, and plant fertilization are some of the strategies and practices that can help the agriculture sector progress toward higher energy use efficiency and sustainability. A higher level of mechanization and advanced food-processing technologies are also important. Rural people are at risk of being left behind unless energy policies are tailored precisely to their requirements.

Keywords

Energy budget · Energy efficiency · Energy equivalents

Abbreviations

BP	Bed planting
CO_2	Carbon dioxide
DSR	Direct seeded rice
EUE	Energy use efficiency
FAO	Food and Agriculture Organization
FYM	Farmyard manure
GHG	Greenhouse gas
IFS	Integrated farming system
IGP	Indo-Gangetic plains
MJ	Megajoule
N	Nitrogen
RCT	Resource conservation technologies
REY	Rice equivalent yield
RWCS	Rice-wheat cropping system
SE	Specific energy
ST	Strip tillage
TPR	Puddled transplanted rice
ZT	Zero-till

1 Introduction

According to the United Nations' Food and Agriculture Organization (FAO), food production will need to jump by 70% by 2050 to nourish the projected increasing population. It also predicted a 30% increase in energy production by 2050 (FAO, 2011). It shows the estimated growth in food demand is outstripping the anticipated increase in energy capacity. In the agricultural sector, energy is one of the precious inputs, and it is both a consumer and a producer of energy in the form of bio-energy. It needs energy as a crucial input for production, improving food and nutritional security, value addition, and rural socioeconomic development. To nourish the growing population and satisfy other economic and social goals, the amount of energy required in agricultural production, processing, and distribution is greatly increased. A significant portion of energy in production process in terms of human labor, fertilizers, fossil fuels, and electricity is utilized in the agricultural sector. Over the years, the energy usage pattern of Indian agriculture has changed due to factors such as increased gross and net area under cultivation, mechanized agriculture, expanded irrigation facilities, and the use of improved crop production technologies. Agriculture contributes to greenhouse gas (GHG) emissions through consuming energy (e.g., electricity, fuel, and heating/refrigerating) and is the end user of a number of energy-intensive inputs (e.g., fertilizers, pesticides). Constantly increasing costs, growing share of commercial energy (fossil fuels) in total agricultural energy input, and an increasing paucity of commercial energy sources have demanded more effective use of these sources in agriculture (Singh et al., 1997). Inefficient production processes cause overuse of these scarce energy resources, resulting in undesired outputs including agricultural waste and GHG emissions. Cutting GHG emissions from agriculture is critical for mitigating climate change. The increasing fuel prices and emission of GHG due to fuel use in agriculture lead to increasing awareness about energy efficiency in crop production. Primary agriculture and fishery production represent for around 1/5 of total energy demand, but 2/3 of GHG emissions. Beyond the farm gate, CO_2 emissions from food manufacture, transportation, and house-associated activities (e.g., cooking, refrigeration) are the highest in the developed world, whereas packaging, retail, and catering are substantial but significantly lower in comparison to developing nations (FAO, 2011). Of late, excessive use of natural resources (water, soil) has severely impaired the nonrenewable soil resource base, which caused adverse environmental effects (Cohen et al., 2006) and led to declining system productivity (Ghosh et al., 2015). There is lot of room for improvement of energy efficiency in agricultural input manufacturing and supply and food industry. Developing an alternative method, which is energy-, water-, and labor efficient, along with a capability of preserving soil and environment while producing more for less money and resource, is the emerging challenge for researchers (Gupta & Seth, 2007). To improve agricultural productivity, sufficient supply of the appropriate energy, as well as its effective and efficient utilization, is essential. Proficient energy use in agriculture will boost productivity and production, saves money, reduces harmful effects on environment, conserves natural resources, and facilitates long-term sustainable growth of agriculture. Finding energy-efficient technology/process/methods with low GWP and high returns is vital for safeguarding the agricultural sustainability.

1.1 Classification of Energy

Energy is classified into direct or indirect energies depending upon its sources (Fig. 1). Direct sources of energy are those that release the energy directly, which include manpower, bullocks, and immovable and moving mechanical or electric power units, such as diesel engines, power tillers, electric motors, and tractors, among others. The direct sources of energy are further classified as renewable and nonrenewable sources of energy depending upon their replenishment. Humans, animals, solar and wind energy, fuel wood, agricultural wastes, and other energy sources that are direct in nature yet can be renewed are known as renewable direct sources of energy. Nonrenewable direct sources of energy are direct energy sources that are not renewable within the next 100 years. The indirect sources of energy are those which do not release energy directly but release it by conversion process. Some energy is spent in producing indirect sources of energy. Examples for indirect

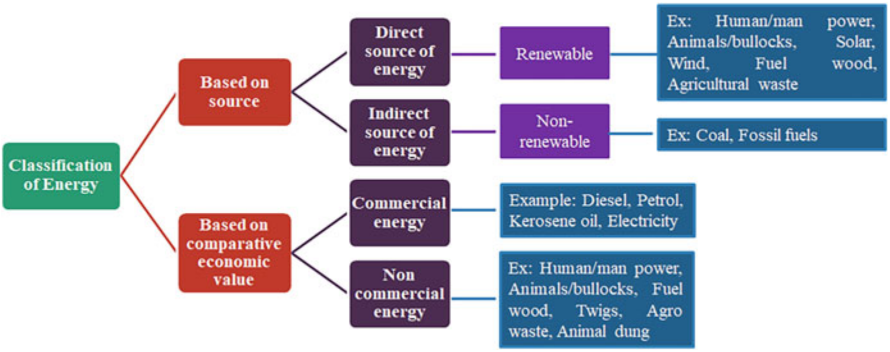

Fig. 1 Classification of energy

sources of energy are seeds, manures (farmyard and poultry), pesticides, fertilizers, machinery, etc. The indirect source of energy can be subdivided into two groups based on their replenishment: renewable and nonrenewable. Seeds and manures are examples of renewable indirect sources of energy since they may be regenerated over time. Energy sources that cannot be replenished such as chemicals, fertilizers, and machinery manufacturing are nonrenewable indirect energy sources.

1.2 Necessity for Energy Audit

For efficient use of scarce resources along with increased production and productivity, energy budgeting based on farm size is important. All of the characteristics, including energy source, energy indicators, and energy use efficiency, should be evaluated for the impact of farm size variation. A complete energy study at the farm level could reveal ways to reduce energy consumption. In addition, increasing concerns of climate change have heightened interest in agriculture energy use, in addition to its efficiency, because farming contributes to climate change through emission of GHG. GHG emissions from agricultural energy consumption account for around 20 percent of overall CO_2eq emissions from agricultural production. This paved the door for the development and dissemination of energy-efficient farm implements/crop management practices. However, farming and crop production patterns differ around the world, and these differences constitute a danger to agricultural energy efficiency. Apart from increasing farm output, the primary goal of mechanizing crop production is to eliminate human drudgery. This can only be accomplished by replenishing traditional energy inputs, such as human labor with farm machinery, as well as use of modern agricultural inputs such as synthetic fertilizers and crop protection chemicals such as weedicide, insecticide, and fungicide, expanding efficient irrigation methods and irrigation area, and soil and water conservation measures, among other things. These inputs and methods reflect a variety of direct and indirect energy sources that must be examined in order to establish their efficacy. As a result, energy analysis is a technique for managing farm and allied resources efficiently in agriculture. Understanding energy use patterns and evaluating energy balance are required to lessen reliance on increasingly finite fossil-based energy resources. Energy auditing will aid in understanding how energy and fuel are used as well as finding waste and opportunities for improvement. It also provides a favorable direction for lowering energy costs, determining an acceptable energy mix, identifying energy saving technology, and retrofit for energy-efficient farm implements and equipment. Thus, increasing energy efficiency in food production systems is critical. The goal is to produce the same or more food while using less energy.

1.3 Relation Between Agriculture and Energy

In contrast to traditional agricultural production system, modern production systems are characterized by intensive use of energy within the farm as well as outside the farm (transportation and processing). The available labor/human power will be scarce in the coming years, and energy will be the most reliable source of crop production. The proficient use of energy and other inputs in agriculture is crucial in the context of climate change, increasing cost of fertilizers, fuel, pesticides, and other inputs. To do so, we must examine the amount of energy required for each operation. Energy auditing is a critical technique for determining the energy needs of animals, humans, and machines. Improving energy efficiency in agricultural systems helps with two major issues: boosting agricultural output and maintaining environmental sustainability. Improvements in energy efficiency are achievable even in the face of rising energy use, in turn implying that food production can rise dramatically. Energy inefficiencies are mainly present in agricultural production in advanced nations, while they are present in the food industry in undeveloped nations.

1.4 Energy Use in Agriculture

Crop productivity is a function of output to input from unit of area. The energy input-energy output relationship is gaining more importance over the last few years especially in highly intensified rice-wheat cropping system (RWCS) of Indo-Gangetic Plains (IGP) due to decreasing resource availability. The energy use in agriculture has surged significantly with the progress of technology. Low input energy requiring traditional farming system is slowly substituted by high input energy demanding modern farming system. Agriculture consumes a substantial quantity of non-commercial energy like FYM and animal energy, as well as commercial energy like diesel/petrol, power, chemical fertilizer, pesticides, irrigation water, machinery, and seed. Fuel and human labor were included in direct energy consumption, which made up a minor fraction of total energy consumption. Seed, energy consumed to manufacture farm machinery, fertilizers, plant protection chemicals, and irrigation were included in indirect energy consumption, which account for a large share of total energy use. Fertilizer accounted for 48–49 percent, tillage 12–14 percent, irrigation 15–19 percent, and plant protection 19–21 percent of total energy consumption when rice crop is grown under un-puddled transplanting (Islam et al., 2013). In bed planting, fertilizer came on top, and tillage came in fourth as input energy. The crop yield could be enhanced by up to 30% through optimal use of various input energy (Sidhu et al., 2004; Chaudhary et al., 2006). Improved productivity, income, sustainable economy, and sustainable livelihood are the benefits of efficient use of various energy sources.

2 Major Characteristics of Energy-Efficient Farming

Energy efficient farm strives to reduce energy consumption, minimize waste, and implement sustainable practices that benefit both the environment and the farmer's bottom line (Fig. 2).

Fig. 2 Major characteristics of energy-efficient farming

2.1 Least Negative Impact on Environment

Energy consumption is usually used as a proxy for environmental performance. Enhancing energy efficiency in agricultural will have the effect of lowering GHG emissions (Varone & Aebischer, 2001). GHG emissions from agricultural energy consumption account for around 20 percent of overall CO_2eq emissions from agricultural production. Machinery that is well maintained consumes less fuel and operates more efficiently. Similarly, well-maintained farm equipment will use less energy than equipment that has been neglected. It has been proved that replacing older pumps with new pumps and servicing worn-out pumps save electricity/gasoline, thereby reducing GHG emission. Similarly, drip irrigation systems reduce total energy consumption, thereby reducing GHG emission and protecting the environment.

2.2 Reduced Human Drudgery

Switching from manual to mechanical cultivation will result in better resource utilization and economic gains. Apart from increasing farm output, the primary goal of mechanizing crop production is to eliminate human drudgery. Gender-friendly equipment will significantly minimize human drudgery, and it also increases total productivity and EUE. When compared to traditional tools, the introduction of ergonomically designed tools and equipment, as well as an adequate power source, will help lessen human drudgery besides reducing energy loss.

2.3 Minimal Energy Waste

High energy-intensive inputs are used in agriculture. Efficient use of these inputs like fertilizers, electricity, diesel, pesticides, etc. minimizes energy waste and increases energy use efficiency. The integrated farming system (IFS) minimizes energy loss in agriculture through utilizing the input energy for the production of various components of farming system. Similarly, many improved crop management practices like zero tillage, minimum tillage, mechanization in sowing and harvesting, seed drill-based crop sowing, and drip irrigation reduce energy loss in agriculture.

2.4 Lower Energy Cost

Energy efficiency methods have resulted in cost savings in capital and labor that are even bigger than energy savings (Worrell et al., 2000). For example, in RWCS, farmers very often go for thorough dry tillage and planking in order to prepare an ideal seedbed for wheat crop after rice harvest. These tillage operations are energy intensive and accounted for 25–30% cost of the total wheat production costs, resulting in a lower benefit/cost ratio (Saharawat et al., 2011). It also causes delay in sowing of succeeding wheat crop, which in turn reduces wheat yield (Bhushan et al., 2008; Jat et al., 2009), whereas minimal tillage, on the other hand, needs less total energy to attain the same crop yield levels as conventional tillage methods (Smith et al., 2002).

2.5 Maximum Energy Use Efficiency

Mechanization, resource conservation technologies, and improved input management practices not only reduce input energy requirement, but it also maximizes EUE by increasing crop yield. Wheat crop sow through zero tillage increased specific energy by 17 percent and energy usage efficiency by 13 percent when compared to conventional tillage (Kumar et al., 2013).

2.6 Maximum Production

Mechanization of agriculture eliminates human drudgery, ensures timely completion of agricultural operations, and boosts farm yield. Improvements in energy use efficiency helps enhance profits during the periods of elevated energy price, besides improving consumer perception of their product and hence increasing sales (Verghese et al., 2012). However, many poor countries' agricultural sector continues to rely heavily on animal and human energy, because there is inadequate electrical and mechanical energy supply for the agriculture sector. The potential improvements in agricultural productivity that could be obtained by deploying modern energy services are not being realized in many underdeveloped nations.

3 Factors Affecting Energy Use in Agriculture

3.1 Mechanization

Mechanical energy's share to operational energy in Indian agriculture grew from a low of 11 percent in 1970–1971 to a high of 76 percent in 2000–2001 (Kulkarni, 2010). The input of mechanical energy increases significantly, resulting in a corresponding increase in the usage of fossil fuels, primarily diesel. Besides mechanization, irrigation for crop production accounted for a large portion of the energy input from fuel and electricity. As a result, expanding efficient irrigation techniques through increased investment and scientific innovation can reduce energy waste and input while increasing energy use efficiency (EUE). Increasing spending on rural infrastructure and transferring subsidies directly to farmers on purchases of seed machinery and implements will reduce agricultural production costs and increase farmer's income through increasing agricultural productivity. Rice crop requires more energy (15.4 GJ/ha) than wheat (10.8 GJ/ha) in RWCS due to more number of farm operations in rice crop compared to wheat (Sarkar, 1997). In recent years, farmers in the IGP are increasingly adopting zero-till (ZT) in wheat alongside other RCTs using recently developed drills and planters. ZT seed-cum-fertilizer drill, happy seeder, raised bed planter, rotovator, and other drills/planters ensure efficient management of expensive resources such as diesel/petrol, inorganic fertilizers, and irrigation water and assist in saving energy and production costs.

3.2 Conservation Tillage

Tillage procedures are commonly utilized in arable agricultural systems, which often demand the most energy. Mechanized tillage has been linked with augmented soil fertility in the past because of the mineralization of soil nutrients. Moreover, it facilitates higher working depths as well as the use of instruments like ploughs, disc harrows, and rotary cultivators. Tillage reduces soil organic matter over time, and most soils deteriorate under long-term intensive arable agriculture, with particularly negative consequences on soil structure. Under tropical climate, this process is substantial, but it can be seen all over the world. Deep tillage consumes more fuel than shallow tillage and isn't always required. Secondary tillage should be shallower than primary tillage to make the most efficient use of fuel and time. Secondary tillage should really only 50 percent depth of the primary tillage. There are ways to save energy by reducing or eliminating tillage, such as minimum, strip, or no-till.

The analysis of energy balance of rice production under various tillage practices revealed minimum tillage requires significantly lower amount of energy in comparison to conventional tillage. Minimum tillage ranked fourth, and conventional tillage ranked second based on the share of input tillage energy on total input energy (Islam et al., 2013). Zero tillage reduces energy consumption by 56% and carbon footprints by 39% along with reduction of nitrous oxide emission by 20% lower than conventional tillage (Lal et al., 2019). In South Asia, tillage and crop establishment account 25–30% of the total cost of wheat production in RWCS (Saharawat et al., 2011). Conservation agriculture-based crop establishment methods are a feasible option for farmers not just in terms of energy and time efficiency but also in terms of higher productivity and profitability, as evidenced by the increased net income in zero tillage (33%) and reduced tillage (20%) compared to conventional tillage (CT) (Kumar et al., 2013).

3.3 Fertilizer and Other Pesticides

Historically, inputs like fertilizers and other agricultural pesticides have been proven vital in enhancing food production in all parts of the world. Inorganic fertilizers and chemical pesticides, viz., insecticides, fungicides, and herbicides, all need energy in their manufacture, transport, and distribution. Pesticides are the most energy-intensive agricultural inputs, whereas inorganic fertilizers account the largest share of these energy inputs to agriculture (on a per kg basis of chemical). Fertilizers, particularly nitrogen fertilizers, are responsible for 30–50% of yield (Stewart et al., 2005; Subramanian et al., 2020). Although nitrogen fertilizer production has become more energy efficient over time, it remains the most important energy-consuming part of modern intensive agriculture. N fertilizer production requires ten times higher energy as compared to phosphorus and potassium fertilizers (Khan & Hanjra, 2009). In RWCS, nitrogen fertilizer accounted for the major share of total energy input (26–37%) followed by irrigation (17–33%). Energy input for chemical fertilizers accounted the major part of total input energy (39–52%) in un-puddled transplanted rice (Islam et al., 2013). 4R nutrient stewardship (right dose, right time, right place, right source)-based nutrient management will reduce inorganic fertilizer application and increase nutrient use efficiency (Vijayakumar et al., 2021b). Split application of 60 kg K_2O/ha (50% at basal +50% at panicle initiation) recorded the highest total output energy (337×10^3 MJ/ha), net energy (300.6×10^3 MJ/ha), energy productivity (0.30 kg REY/MJ), energy profitability (8.17), and energy use efficiency (9.2) (Vijayakumar et al., 2019). Similarly, the use of pesticides including insecticides and fungicides can be decreased by increasing the use of pest control measures based on integrated pest management principles. Many agronomic management practices like intercropping, border row planting, and crop rotation reduce the pest intensity in most of the cropping system. Identifying and adopting idea agronomic management practices will reduce pest pressure, which in turn reduces the demand for energy-intensive pesticides. Under dry directed seeded rice system, the sequential application of pendimethalin followed by bispyribac-sodium provides higher energy use efficiency (4.35) and energy productivity (0.3 kg/MJ) over other herbicide treatments (Pooja et al., 2021).

3.4 Farm Size

The environmental and economic effectiveness of smaller farms versus larger farms has always been a source of contention. In many Asian countries, marginal and small farmers own the majority of the agricultural land. Unfortunately, this region also has highest population growth. As a result, the operation land holding size keeps on reducing, and agricultural lands are fragmented into several small fields. The potential for agricultural mechanization is reduced in this region due to small land holding size. Nevertheless, farmers are increasingly adopting agricultural mechanization in these areas, due to growing labor shortage and increasing labor wage (Vijayakumar et al., 2021c). Thus, developing new machineries and implements for small and marginal farmers will transform the agriculture into more energy efficient in South Asian countries. On contrary, farmers who practice IFS and organic farming will have high EUE compared to modern conventional farming. Thus, EUE is highly influenced by farm size.

3.5 Minimize Turning Time

Use of fuel during turning at the ends of a field and going around things in the middle is wasteful that provides no return on investment. Fields should be large and long in order to save turning time. Any obstacles in the field such as fence or ditches that tractor will have to navigate must be cleared if possible. This technique will save time and money by reducing the amount of time and gasoline use.

3.6 Irrigation

Every irrigation system uses a substantial amount of energy. The majority are electrically driven; however, there are a few diesel-powered pumps that require a large amount of gasoline as a source of energy. The EUE of any cropping system varies highly with irrigation system. For example, drip irrigation, sprinkler irrigation, aerobic rice, alternate wetting, and drying will have higher EUE compared to conventional flooding (Vijayakumar et al., 2018). Drip irrigation system reduces the need for pumping energy besides conserving precious irrigation water (Subramanian et al., 2021). The input energy requirement for irrigation varies with season within the year. For example, rice grown in summer season requires more energy (21,000 MJ/ha) than wet-season rice (13,000 MJ/ha), due to higher energy expenditure in rice for land preparation, irrigation, and nitrogen fertilization (Biswas et al., 2006). It has been proved that replacing older pumps with new pumps and servicing worn-out pumps save electricity/gasoline, and thereby it will also reduce GHG emission. The Ministry of Power in India has introduced the National Energy Efficient Agriculture Pumps Program in order to make the nation more energy efficient. This program will assist farmers in replacing antiquated, energy-guzzling agricultural pumps with modern, energy-efficient agricultural pumps that have a 5-star rating across the nation. These pumps will be equipped with a smart control panel and a SIM card, allowing farmers to turn on and off the pumps from their smartphones.

3.7 Efficient Crop Harvest

Crops that are too moist or soil that are too wet require more fuel/energy. So harvesting the crops under ideal conditions can increase the efficiency of harvest and save fuel. In developing nations, farmers using mechanical harvester/combined harvester in cereals are increasing as it saves cost and energy and ensure timely harvest with very less yield loss compared to conventional manual harvest and threshing.

3.8 Consistent Wheel Traffic Pattern

Having consolidated soil compaction rather than some compaction all over allows the crops to grow better in locations where there is no compaction. Driving on compacted soil is easier, increases machine efficiency, and helps reduce fuel consumption. Thus, having consolidated soil compaction will provide energy benefit as well as high yield.

3.9 Organic Agriculture

Organic farming saves 20 percent more energy on average than conventional farming. Organic agriculture uses a higher proportion of renewable energy and has a lower environmental impact. It also does not rely on energy-intensive nitrogen fertilizers and pesticides that help the crops thrive. Organic farming excludes use of fertilizers, pesticides, and other growth hormones and thereby saves the energy used in the manufacture, transport, packing, and distribution. Because of the larger system diversity and manual weed control on organic agriculture, human energy input requirements are considerably higher. Organic agriculture is distinguished by lower energy use, which is particularly noticeable per hectare of land; however, the energy use per kilogram of product is the polar opposite (Lynch et al., 2011). Organic wheat and corn production was 29–70% more energy efficient than conventional production (Pimentel et al., 1983). Organic agriculture production system provides higher efficiency due to its focus on sustainable production methods. Due to the production of forage in grass-clover leys, bovine production systems under organic agriculture appear to be more energy efficient. Organic poultry, on the other hand, tend to require more energy due to greater feed conversion ratios and fatality rates than conventional completely contained or free-range systems (Smith et al., 2015). Although there are some significant exceptions, organic agricultural techniques are much more energy efficient than their conventional ones. Policymakers should pay attention to this because energy consumption associated with input supply accounts for a large portion of total consumption.

3.10 Food Processing and Transportation

The food and beverage business are infamous for its excessive energy usage. The food sector relies extensively on fossil energy and contributes significantly to GHG emissions. The most energy-dense foods include instant coffee, milk powder, french fries, crisps, and bread. The thermal processes used in their production accounted for a significant amount of the total processing energy. Due to improved hygiene standards and cleaning requirements in the meat and dairy processing industries, energy and water consumption has grown. Furthermore, meat products are processed – and often overprocessed – to a larger degree for consumer convenience, all of which increases the corresponding energy consumption during manufacturing. There is a lot of scope to improve energy efficiency in food processing and transportation sector. Some of it are making refrigeration and temperature control systems more energy efficient; use variable speed drives for electrically driven machinery, which can save up to 50% on running costs; wherever practical, use alternative energy methods and sources (wind and solar); and use energy-saving lighting technology such as light-emitting diodes (LED).

3.11 Animal Husbandry

Human and animal labor is likely to continue to be used as agricultural inputs in underdeveloped nations for the near future. Animal can reduce human hardship while also increasing agricultural output. Animals are used in agricultural processes such as ploughing, threshing, transportation, etc. Draught animal populations are estimated over 400 million worldwide. The power output varies from 200 W for donkey to over 500 W for buffalo, and daily working hours vary from 4 h for a donkey to 10 h for a horse. However, during lean season (dry season), the performance of animal is reduced due to short supply of feed and water. Modernization of animal-drawn agricultural equipment, better breeding and animal husbandry, feeding, and veterinary care will increase animal efficiency.

3.12 Use of Renewable Energy as an Energy Input

Renewable energy is much more efficient than nonrenewable energy in most cases. The burning of fossil fuels for energy emits a large amount of GHG, which contributes to global warming. Even when considering the whole life cycle of technologies, the majority of renewable energy sources produce little to no emissions. Diesel engines and electricity are utilized to substitute human and animal labor in agriculture and industry. In case rural electrification is not available or is too expensive, diesel generators can be used instead. Otherwise, renewable energy solutions such as wind mills and solar panel are viable solutions for well water extraction for small farms. Many countries around the world are blessed with abundant sunshine. This can be potentially utilized to generate electricity using solar panels. Doing so also helps electrification of remote areas where rural electrification is costly and difficult due to natural geographical creation.

3.13 Conservation Agriculture

Reduced mechanical tillage and increased soil organic matter through permanent soil cover are two approaches to reversing soil deterioration and other environmental consequences of intensive mechanized tillage. It also facilitates higher agricultural production on a truly sustainable basis. This method is known as “conservation agriculture,” and it involves replacing mechanical soil tillage with biological tillage. Conservation agriculture (CA) has been shown to save energy and other resources, increase output and revenue, and address rising environmental and soil health issues (Saharawat et al., 2011; Kumar et al., 2015). It guarantees field operations are completed on time, lowers production costs, minimizes labor, lowers weather risk in shifting climate scenarios, and increases productivity, environmental quality, and sustainability (Kumar et al., 2014). Crop residues left on the soil surface form a layer of mulch, which protects the soil from the physical effects of rain and wind while also stabilizing the temperature and moisture content of the surface soil (Das et al., 2017). This zone creates a home for a variety of organisms that decompose the mulch into humus. Agriculture with minimal mechanical tillage is possible only when soil organisms take over the duty of tilling the soil. This has ramifications on the use of chemical inputs, as synthetic insecticides and mineral fertilizers must be applied in a manner that does not destroy soil life. All agronomic aspects must be controlled equally well for conservation agriculture to work.

3.14 Unmanned Aerial Vehicle

In recent years, use of unmanned aerial vehicle (UAV) in the agriculture sector is gaining popularity. Drones are used in many agricultural operation including crop sowing, crop health monitoring, weed mapping, pest identification, nutritional disorder identification, foliar spray of herbicide and other pesticides, etc. Use of drone/UAV is found more economical and makes many agricultural operations easier. For example, drone can spray pesticide precisely without much overlapping and cover large area in quicker time. It avoids the exposure of agricultural labor to toxic chemical and human drudgery associated with pesticide spray (Kumar et al., 2020). It is anticipated that in the coming decades, drones will transform the agriculture in developing and developed nations through its diverse applications.

3.15 Agricultural Waste Recycling

The agricultural sector produces a huge quantity of recyclable waste every year. It is possible to produce significant amount of renewable energy using these resources. Crop residue, livestock waste, and agro-industrial waste can be utilized for production of organic manures. This will eliminate energy-intensive inorganic fertilizer use in agriculture. Similarly, use of agricultural waste for biogas production will exclude use of fossil-based energy in agriculture (Vijayakumar et al., 2021a). This is a win-win procedure to protect our environment and soil.

4 Energy Indicators, Budgeting, and Equivalents

4.1 Energy Indicators

Input energy in the form of human and animal energy; use of machinery and other agricultural equipment; diesel oil and gasoline consumption; fertilizer and other agrochemical production; usage of organic manure such as FYM, vermicompost,

Table 1 Management practices involved in the cropping system and their corresponding energy source

Management practice	Energy input source
Tillage	Human, animal, equipment, fuel
Nursery raising	Seeds, fertilizer, FYM, agrochemicals, human, equipment, electricity, fuel
Transplanting	Human, fuel, machineries, electricity, agrochemicals
Seeding/planting	Seeds, tubers, human, equipment, fuel, FYM, agrochemicals, electricity, fertilizer
Plant protection	Human, agrochemicals, equipment, fuel
Irrigation	Human, electricity, equipment
Fertilization	Human, fertilizer, FYM
Soil loading	Human, equipment
Weeding	Human
Harvesting	Human, equipment, fuel
Winnowing and threshing	Human, animal, equipment, fuel, electricity

green manures, and green leaf manures; and seed inputs are energy indicators. The total amount of biomass produced and the energy content of useable biomass (grains, straw, and tubers) were used to compute the output energy. Current management practices and the energy input source used in each of the crop activities are summarized in Table 1.

Crops are categorized into two types based on market price and energy content per unit weight: (1) low-value and high-energy crops, e.g., cereals, potato, pulses, (2) high-value and low-energy crops, e.g., oilseeds, cotton, fruits, vegetables, sugar beet, tea, and tobacco. The area under cultivation of these crops is largely controlled by government policy and people's diet. For example, in China, the low-value and high-energy crop production increased from 436.2 MT in 1991 to 589.8 MT in 2012, with an average annual growth rate of 1.45 percent. Similarly, the high-value and low-energy crop production increased from 335.7 MT in 1991 to 1130.7 MT in 2012 with an average annual growth rate of 5.95 percent (Yuan & Peng, 2017). Similarly, in India, the pattern of energy consumption has shifted dramatically, with a large shift away from animal and human power and toward machines, electricity, and diesel. The total input energy of Indian agriculture has surged from 425.4×10^9 MJ in 1980–1981 to 2592.8×10^9 MJ in 2006–2007 (Jha et al., 2021).

4.2 Energy Budgeting

In recent years, computing energy budget is gaining more momentum due to persistence change in climate. The agricultural sector has become a major energy consumer in order to supply more food to the teeming billions and provide enough and adequate nutrition (Samavatean et al., 2011). Energy budgeting in agriculture will ensure efficient utilization of input energy (Vijayakumar et al., 2019). Energy

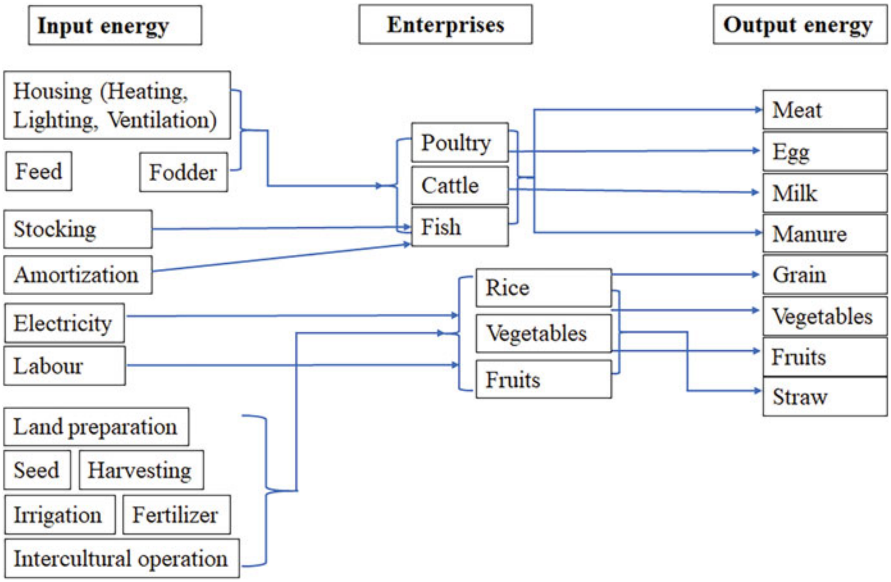

Fig. 3 Conceptual diagram showing energy flow in IFS

efficiency improvements contribute to the reductions of emissions and climate change (Varone & Aebischer, 2001). The input energy is utilized to produce many enterprises due to incorporation of many enterprises simultaneously in integrated farming system (IFS) (Vijayakumar et al., 2021a). The conceptual diagram showing energy flow in IFS is presented in Fig. 3. Thus, computing energy budget of IFS is a complicated task compared to single enterprise. To overcome this difficulty, we had collected energy equivalence of various inputs and outputs of IFS from various literatures available in the Internet (Table 2).

5 Methodology of Calculating Energetics

5.1 Energy Use Efficiency (EUE)

EUE is one of the energy indices that measure the efficiency of a crop production system in terms of energy input and output (main product and by-product). Alternatively, it expresses the inefficiency of agricultural production systems. Any increase in EUE implies that available energy is being used efficiently for agricultural purposes, and vice versa. Increasing energy use efficiency is the most effective strategy to reduce the environmental hazard caused by energy use.

$$\text{Energy use efficiency} = \frac{\text{Energy output (MJ/ha)}}{\text{Energy input (MJ/ha)}}$$

Table 2 Energy equivalents of various components of rice-based farming systems

Input	Unit	Equivalent energy (MJ/unit)	References
1. Rice-based system			
Adult man	Man-hour	1.96	Singh and Mittal (1992)
Woman	Woman-hour	1.57	
Child	Child-hour	0.98	
Diesel	1 L	56.31	
Petrol	1 L	48.23	
Electricity	KWh	11.93	
Electric motor	hr	64.80	
Farm machinery including self-propelled machines	hr	62.70	
Ploughing by power tiller	ha	563	
Ploughing by tractor	ha	637	
Ploughing by bullock	ha	100	
Transplanting	ha	550	
Sowing	ha	19.76	
Pesticide application	ha	91.1	
Weeding	ha	553	
Zero-till seeder	ha	338.8	
Cultivator	ha	220	
Water	m^3	1.02	
N	kg	60.6	
P_2O_5	kg	11.1	
K_2O	kg	6.7	
Zinc sulphate	kg	20.9	
Gypsum	kg	10	
FYM	kg	0.3	
Herbicide	kg	237	
Insecticide	kg	288	
Harvesting by labor	ha	711.36	
Harvesting by machinery	ha	2158.6	
Manual			
Spade	(MJ/h)	0.314	Nassiri and Singh (2009)
Sickle	(MJ/h)	0.031	
Sprayer	(MJ/h)	0.502	
Tractor			
Moldboard plough	(MJ/h)	2.508	Nassiri and Singh (2009)
Cultivator	(MJ/h)	3.135	
Disk plough	(MJ/h)	3.762	
Planter	(MJ/h)	9.405	
Disk harrow	(MJ/h)	7.336	

(continued)

Table 2 (continued)

Input	Unit	Equivalent energy (MJ/unit)	References
Seed drill/planter	(MJ/h)	8.653	
Reaper	(MJ/h)	5.518	
Rotavator	(MJ/h)	10.283	
Combine harvester	(MJ/h)	47.025	
Others			
Thresher/sheller	(MJ/h)	7.524	Nassiri and Singh (2009)
Centrifugal pump	(MJ/h)	1.75	
Electric motor 35 hp	(MJ/h)	0.343	
Electric motor (others)	(MJ/h)	0.216	
Diesel engine	(MJ/h)	0.581	
Tractor (>45 hp)	(MJ/h)	16.416	
Tractor (others)	(MJ/h)	10.944	
Self-propelled combine harvester	(MJ/h)	171.000	
Output			
Paddy, wheat, maize, sorghum, bajra	kg	14.7	Singh and Mittal (1992)
Green gram, red gram, soybean, lentil, peas, beans	kg	14.7	
Cotton seed, ground nut pod (not shelled), sesame, rape seed, mustard, sunflower	kg	25	
Sugarcane	kg	5.3	
Colocasia, potato	kg	3.6	
Carrot, radish, onion, beetroot	kg	1.6	
Tomato, chillies, green papaya, drumstick, pumpkin, gourd family, cucumber family	kg	0.8	
Cabbage, spinach	kg	0.8	
Tamarind, grapes	kg	11.8	
Guava, mango, amla, apple, citrus, cashew fruit	kg	1.9	
Cotton, sunn hemp, jute	kg	11.8	
Fodder (berseem, lucerne, maize, pearl millet, napier, cowpea, sorghum)	kg	18	
Stover (maize)	kg	18	
Straw (wheat, green gram, and okra)	kg	12.5	
Stalks (cotton)	kg	17.4	
Pea	kg	14.6	
Mustard	kg	19.4	
Bottle gourd and onion	kg	19.4	
2. Dairy farming			
Concentrate feed	(MJ/kg)[b]	13.6	Frorip et al. (2012)

(continued)

Table 2 (continued)

Input	Unit	Equivalent energy (MJ/unit)	References
Meat	MJ/kg[a]	9.22	Frorip et al. (2012)
Milk	MJ/kg	2.7	NRC (2001)
Maize silage	MJ/kg	10.41	NRC (2001)
Cow manure	MJ/kg dry matter	0.3	Singh and Mittal (1992)
3. Poultry farming			
Chicks	(MJ/kg)	10.33	Heidari et al. (2011)
Water	MJ/L	2.63	Atilgan and Koknaroglu (2006)
Feed	MJ/kg	12.98	Anonymous (2014)
Egg	MJ/g	0.327	Anonymous (2002)
Manure	MJ/kg	8.83	Bock (1999)
Electricity	MJ/kWh	5.65	Uzal (2012)
Bird	MJ/kg	10.33	Celik (2003)
Human labor	MJ/h	2.2	Fluck (1992)
Local heating (broilers)	Watt hour/bird/day	13–20	World Bank (2007), EU (2003)
Feeding (broilers)	Watt hour/bird/day	0.4–0.6	
Ventilation (broilers)	Watt hour/bird/day	0.10–0.14	
Feeding (layers)	Watt hour/egg/day	0.5–0.8	
Ventilation (layers)	Watt hour/egg/day	0.13–0.45	
Lighting	Watt hour/egg/day	0.15–0.40	
Egg preservation	Watt hour/egg/day	0.30–0.35	
4. Fish farming			
Fingerling	MJ/kg	55.6	Charrondiere et al. (2004)
FYM	MJ/kg	0.3	Oladimeji et al. (2016)
Water	MJ/m^3	1.02	Oladimeji et al. (2016)
Maize (feed)	MJ/kg	7.9	Amid et al. (2016)
Output			
Fish	MJ/kg	55.6	Charrondiere et al. (2004)

[a]Live weight
[b]Metabolizable energy

5.2 Net Energy

The quantity of energy gained through harvesting an energy source is referred to as energy output. Net energy is the total amount of energy gained from harvesting the crop after deducting the amount of energy that was spent to produce it. High values of net energy reveal efficient production system and vice versa.

$$\text{Net energy} = \text{Energy output (MJ/ha)} - \text{Energy input (MJ/ha)}$$

5.3 Energy Productivity

Energy productivity is a measure of the economic benefit/yield received from each unit of energy consumed. It is calculated by dividing crop yield or gross return by the amount of energy consumed. High values of energy productivity reveal efficient production system and vice versa.

$$\text{Energy productivity} = \frac{\text{REY (kg/ha)}}{\text{Energy input (MJ/ha)}}$$

5.4 Specific Energy (SE)

Specific energy (SE) estimates the amount of energy used to produce a specific quantity of yield and used regularly to compare various farm. SE with a higher value denotes a less efficient production and vice versa. All the techniques/methods which lower SE will help increase EUE, and vice versa.

$$\text{Specific energy} = \frac{\text{Energy input (MJ/ha)}}{\text{REY (kg/ha)}}$$

5.5 Energy Intensity

Energy intensity is a measure of the energy inefficiency of a production system. It is calculated as units of energy per unit of cost spent. The unit of energy intensity is mega joule (MJ) per Rupee invested. High energy intensiveness indicates a high price or cost of converting energy into return (cost). Alternatively, low energy intensity indicates a lower price or cost of converting energy into return.

$$\text{Energy intensiveness} = \frac{\text{Input energy (MJ/ha)}}{\text{Total cost of cultivation (Rs./ha)}}$$

5.6 Energy Profitability

Energy profitability is the measure of the net energy produced for every 1 unit of input energy. It is a unit-less measurement. A higher value of energy profitability symbolizes a more efficient cropping system.

$$\text{Energy profitability} = \frac{\text{Net energy (MJ/ha)}}{\text{Input energy (MJ/ha)}}$$

5.7 Energy Output Efficiency

Energy profitability is the measure of the amount of energy produced per day. It is calculated by dividing output energy by total duration of the system and expressed as MJ/ha/day.

$$\text{Energy output efficiency} = \frac{\text{Energy output (MJ/ha)}}{\text{Duration of the system (days)}}$$

6 Energy-Saving Techniques and Practices in Rice-Based Systems

In the lowland rice production system of Malaysia, tillage accounted highest average operational energy consumption (1.75 GJ/ha), which is about 48.6 percent of the total operational energy consumption (3.6 GJ/ha), followed by harvesting (1.17 GJ/ha, 32.6 percent) and planting (0.56 GJ/ha, 15.7 percent) (Bockari-Gevao et al., 2005). Site-specific tillage has potential to reduce costs, labor, fuel, and energy requirements. In a loamy sand soil type, site-specific tillage resulted in saving 50 percent energy and 30 percent fuel as compared to uniform-depth tillage (Alimardani et al., 2007).

When soil tillage activities were curtailed, the energy output/input ratio tended to rise (Islam et al., 2013). Rice establishment using un-puddled transplanting [bed planting (BP) and strip tillage (ST)] method is a recent concept in rice establishment and found as a promising technology in terms of irrigation water conservation, tillage reduction, and cost reduction without sacrificing grain yield (Islam et al., 2012). In terms of energy expenses and energy produced in rice production, bed planting and strip tillage appeared to be energy efficient. In rice, un-puddled transplanting reduced direct fuel use and indirect machinery use and saved 20% input energy and increased energy productivity and energy output/input ratio by 8–12 percent and 22–24 percent, respectively, over conventional puddled transplanted rice (Islam et al., 2013). Un-puddled transplanting had the highest energy output/input ratio compared to puddled transplanting. When compared to CT, the energy output/input ratio in SPWT, BP, and ST was 15%, 22%, and 24% higher, respectively. With a strip tillage system, fuel usage for production might be decreased by 2 to 3 times when compared to traditional tillage system (Islam et al., 2012).

Direct seeded rice (DSR) is found to be highly efficient in terms of energy and economics, and it is also a climate-smart production system compared to puddled transplanted rice (TPR). In central China, Yuan et al. (2021) reported higher total input energy for TPR (31.5 GJ/ha) primarily due to extra energy use for nursery beds and transplanting and lower total energy inputs for DSR (22.8 GJ/ha), while the output energy was higher for DSR (202.5 GJ/ha) over TPR (187.7 GJ/ha) due to a slightly higher yield from DSR. The lower specific energy of DSR (2.78 MJ/kg) compared to TPR (4.02 MJ/kg) indicated that adopting DSR might cut the energy necessary to produce per unit of rice grain by 30.8 percent. Thus, increasing EUE and economic return will reduce environmental footprint associated with rice cultivation.

6.1 Case Study: Comparison of Energy Budget of Rice-Wheat and Rice-Potato System

Rice-wheat and rice-potatoes systems are two cropping systems popular among farmers in the middle IGP, and these systems require a lot of agricultural mechanization, insecticides, fertilizers, and other pesticides (Vijayakumar et al., 2019). The RWCS was more energy efficient in the middle IGP, with energy use efficiency (EUE) of 6.87 ± 1.7 compared to 3.61 ± 0.58 for the rice-potatoes system. The rice-wheat system had a higher energy efficiency ratio (3.94 ± 1.30) and SE (4.39 ± 2.06) than the rice-potatoes system, which had 2.62 ± 0.47 and 2.15 ± 0.35, respectively (Soni et al., 2018). Fertilizer use was the most energy-intensive input in both systems, accounting for 58 percent and 51 percent of the energy consumed in the rice-wheat and rice-potatoes systems, respectively. Diesel/ petrol, seeds, and electricity were the next most energy-intensive inputs in both systems (Soni et al., 2018).

The highest contributor of fertilizer input was nitrogen, followed by phosphorus, while potash made the smallest amount. Fuel was the second-largest contributor, accounting for 22% and 15% of total energy inputs in the rice-wheat and rice-potatoes systems, respectively. The majority of the fuel-based energy inputs were attributed to the use of diesel in various farm operations, with gasoline usage mostly related to plant protection spraying operations. In comparison to the rice-potatoes system, the rice-wheat system consumes more fuel because of increased mechanization. In the rice-potatoes and rice-wheat cropping systems, seeds accounted for 14 percent and 6 percent of the energy input, respectively.

The rice-potatoes system had a higher energy input in the form of human power since farmers relied heavily on human labor to harvest potatoes and avoid tuber damage. In comparison to the extremely little amount of seeds used for rice and wheat sowing, large quantities of potato seeds (32 t/ha) were used for planting. Electricity was another significant contributor to input energy, accounting for between 5% and 6% of total input energy, primarily for irrigation purposes. In the rice-potatoes system, FYM and plant production chemicals each contributed about 3% of the input energy, but in the rice-wheat system, the figures were 0.05 percent and 0.4 percent, respectively. Farmers that followed the rice-potatoes cropping method used a lot of FYM and plant production chemicals for the potato crop and didn't feel the need to use a lot of fertilizers in the paddy rice after the potato was harvested because the soil was nutrient rich due to the earlier fertilizer application.

In terms of direct and nonrenewable energy contributions, the rice-wheat and rice-potato systems were equivalent, but the rice-potato system used more renewable and indirect energy. In the rice-wheat and rice-potatoes cropping systems, direct energy accounted for 30.81 percent and 24.84 percent of total energy input, respectively. Rice-potato systems used more renewable energy, with a contribution of 21.66 percent compared to 9.59 percent in rice-wheat systems. The larger human and animal energy intake in the rice-potato system can be explained by the higher renewable energy input.

The paddy rice-wheat (PW) system (22.02 percent) used more fuel as a source of energy than the paddy rice-potato (PP) system (15.37 percent), which was due to the PW system's larger usage of renewable energy, which accounted for 9.59 percent and 21.66 percent, respectively, in the two systems. In both systems, marginal farms had the lowest input energy while medium farms had the greatest. In terms of numerous energy indicators, it was also discovered that smaller farms were more energy efficient than larger ones. In the rice-wheat system, the usage of human power decreased as farm size increased, indicating a greater reliance on mechanical farming methods as farm size expanded. In the rice-wheat system, the eco-efficiency values were greater for larger farms, and the mean values differed significantly; however, there was no discernible trend in the rice-potato system.

The PP system's output energy (236.95 ± 22.66 GJ/ha) was lower than the rice-wheat system's (250.89 ± 40.13 GJ/ha). The tendency was inverted in terms of input energy, with the rice-wheat system consuming less than the rice-potato system. When compared to the rice-potatoes system, the higher output energy of the rice-wheat system can be attributable to the diverse forms of yield. On average, the rice-wheat system contributed the same amount of energy from straw and grains, whereas the rice-potato system did not.

7 Conclusion

In agricultural sector, both energy use and production cost are increasing over the years due to increased use of inputs (fertilizers and agrochemicals), irrigation (pumping), and adaption of mechanization (tillage, harvesting, threshing, cleaning, transportation, etc.). The demand for energy in agriculture is increasing globally to meet the food demand of >7 billion people. As a result, increasing energy efficiency has become a top priority for both producers and lawmakers, and the agricultural sector, as both a user and a supplier of energy, plays a significant role. Energy budgeting for agro-ecosystems is the need of the hour since energy is also one of the indicators of crop performance (Tuti et al., 2011). Quantification of the net energy of a cropping system offers scope for sound planning of sustainable cropping systems, keeping in view the rise in the share of agriculture in national energy consumption over the last three decades. Based on the available records, the yield of different crops could be increased up to 30% by using optimal level of energy inputs (Chaudhary et al., 2006). In the long run, farmers will need to embrace energy-saving technologies in order to remain profitable. Effective energy usage is one of the requirements for long-term sustainable agricultural production since it saves money, preserves fossil resources, and reduces pollution. Energy efficiency in agriculture will reduce pollution from greenhouse gas emissions while simultaneously ensuring the long-term profitability of the agricultural system. The government should strengthen agricultural mechanization and support the development and use of renewable energy in crop production to improve energy efficiency, energy balance, and the level of harmony in the energy consumption system.

Agriculture's energy issues and solutions should always be led by local economic, environmental, and social factors. National energy development policies should be aligned with locally perceived priorities in the formulation of energy policies. In developing countries, a greater emphasis on non-fossil fuel alternatives to provide energy services in agriculture is required. These include improved biomass conversion (including liquid biofuels, biogas, and gasification), solar energy (PV), wind and geothermal energy, and small-scale hydropower, as well as lower-energy intensity industries, material and energy recycling, and better ways of using traditional energy sources, such as improved cooking stoves. In addition, mechanical equipment, as well as drying and separating operations, must be more energy efficient. It may appear that lowering your energy use is a difficult task, but the small steps we take along the way can make a large difference.

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Energy Management in Agriculture

Patent Applications and Network Analysis

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Contents

Abstract

Due to the strategic position of the agricultural sector, its energy management is a relevant issue; on the one hand, agriculture requires energy to carry out its activities, but, on the other hand, agriculture can also be used to produce energy. Consequently, energy management involves optimizing consumption, production, and efficiency. In the present study, we conducted a network (co-occurrence) analysis based on bibliographic information, as well as a patent application analysis, to determine trends in relation to research and technological development in this knowledge area. Our results show scientific and technological production in the area over time, the main nodes and thematic clusters around the role of energy in agriculture, as well as the most relevant jurisdictions, applicants, and technological sectors, as a starting point to better understand energy management in the agricultural field.

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1 Introduction

1.1 Energy, Technological Progress, and Agriculture

The efficient use of energy in the agricultural sector is linked to technological advances in machinery, irrigation systems, agrochemicals, and other elements related to the improvement of crops and livestock through genetic engineering (Schneider & Smith, 2009). Although genetically modified crops have been associated with technical, environmental, and social welfare benefits conducive to positive impacts on small-scale production in developing countries, it is also true that experiences regarding the adoption of this type of technology in this context are still scarce and stances vary widely with respect to the sustainability, adoption, price, accessibility, quality control, and availability of information on these crops (Azadi et al., 2016; Barragán-Ocaña et al., 2019; Ervin et al., 2010). It has also been pointed out that transgenic crops, maize, for example, have inhibited practices and agroecologies traditionally carried out by small-scale producers (Fischer, 2016) and that their adoption in developing countries has resulted in widespread controversy (Qaim, 2005).

Moreover, in general, technological progress, optimized use of resources, efficient application of agrochemicals, and policies in favor of sustainability allow for the mitigation of greenhouse gases (GHG) emitted by agricultural activities (Smith et al., 2007). However, actions aimed at reducing these emissions can motivate an increase in the price of fossil fuels and agricultural inputs, but, at the same time, promote the use of renewable sources to supply energy needs (Schneider & McCarl, 2005). In agriculture, energy demand is determined by geographical and environmental factors and the very nature of the crops, in addition to the needs derived from the use of machinery and lighting, heating, and hydraulic systems. This highlights the need to use smart agriculture in combination with clean energy sources (Liu et al., 2018).

In this context, the energy input provides added value to agricultural activities throughout the production chain. Thus, energy requirements are direct when the energy is used in activities related to the cultivation and harvesting processes and in the transfer of products and indirect when these needs are related to the entire machinery and input production process, from manufacturing to delivery (Ozkan et al., 2004; Sebri & Abid, 2012). However, the scarcity of both energy and water at a global level, together with the intensification of agriculture and its technological modernization to address food security problems, results in increased energy demands and the need to improve planning to face the negative effects of climate change (Ahmad & Khan, 2017).

1.2 Energy Management and Agricultural Sustainability

There are different sustainable alternatives for meeting energy needs in agriculture; among them are increasingly advanced sensors that optimize agricultural activity through the use of wind energy (Nayak et al., 2014; Aqueel-ur-Rehman et al., 2014) and the drying of agricultural products as part of their processing using solar technology (Fadhel et al., 2011). Other alternatives related to renewable energy and their multiple applications in agriculture are biofuels and hydroelectric and geothermal energy sources (Jebli & Youssef, 2017). The range of available options highlights the potential of the use and adoption of technologies in the context of agricultural practices, although, of course, the economic, social, and environmental implications that motivate their implementation will have to be considered and evaluated for each case.

On the other hand, developing countries lack information and public policies in promoting the development of alternative energy solutions and government support for rural areas as strategic factors for rural development and social and economic advancement (Karkacier et al., 2006). For instance, support must be strategically planned and allocated because the energy used by machinery, intensive agriculture, excessive use of chemical products, and a deficient management of irrigation systems result in significant negative effects on the environment (Jat et al., 2019), for example, the negative direct effects of increased energy costs on the operation of irrigation systems (Zilberman et al., 2008). Thus, as an energy user and an energy producer, the agricultural sector represents a priority axis requiring special attention in its migration toward sustainable energy management (Lansink et al., 2002).

In this regard, conservation agriculture provides an energy-saving alternative based on concrete actions such as the use of agricultural residues, crop rotation and diversification, efficient irrigation management, and minimum tillage (Jat et al., 2020). Among other options, organic agriculture and their sustainable agricultural practices represent a valuable alternative for a significant number of crops in terms of energy efficiency (Smith et al., 2015). Sustainable agriculture tends to demand less energy and improves the quality of life of farmers who embrace technology (Srisruthi et al., 2016). Organic agriculture can represent an opportunity for the economic and social well-being of small-scale farmers who carry out their activities in developing countries, and it also decreases their environmental impact; nevertheless, there are important productivity and regulatory challenges as well as market factors that this group of producers will have to face in this area (Jouzi et al., 2017). Additionally, the benefits of organic and small-scale agriculture can help to promote biodiversity and provide important ecological services (Happe et al., 2018).

As an energy source, agriculture provides inputs for fuel development. However, first-generation biofuels have raised a debate around their technical feasibility and the risk that their development poses for food security. On the other hand, second-generation biofuels, obtained from lignocellulosic sources, promise positive results in environmental and efficiency terms, although they still face technical difficulties for their industrial-scale production, as well as issues related to the production of these energy crops (López-Bellido et al., 2014). Nevertheless, biomass value is directly associated with its molecular characteristics (McKendry, 2002). However, the accelerated pace of climate change requires efficient global solutions in agriculture and energy (Asumadu-Sarkodie & Owusu, 2017). Energy is certainly a fundamental input for economic growth; nonetheless, to guarantee its sustainable supply, it will be necessary to promote the use of renewable energies (Paramati et al., 2018).

Due to its rapid advancement, bioenergy is an important area of opportunity, but its management must be framed by a comprehensive scheme to guarantee its viability (Muller, 2009). The main goals are to facilitate greater economic growth with less carbon emissions and to deploy sustainable public policies based on the promotion of technology to achieve these purposes. In the case of agriculture, the objectives are twofold: reducing energy consumption and GHG emissions (Norse, 2012). Energy management is today a general concern, both globally and locally. Consequently, in order to achieve sustainable development, we must not fail to consider its complexity and its many institutional, technical, political, and other elements that complicate the decisions made by the different stakeholders (Mardani et al., 2017). Thus, to define an energy management plan for the agricultural sector, a diagnosis must be presented, and strategies aimed at reducing energy consumption must be established. As a starting point, these strategies may include location, production, consumption, and energy-saving measures, among others (Gulkis & Clarke, 2010).

2 Methodology

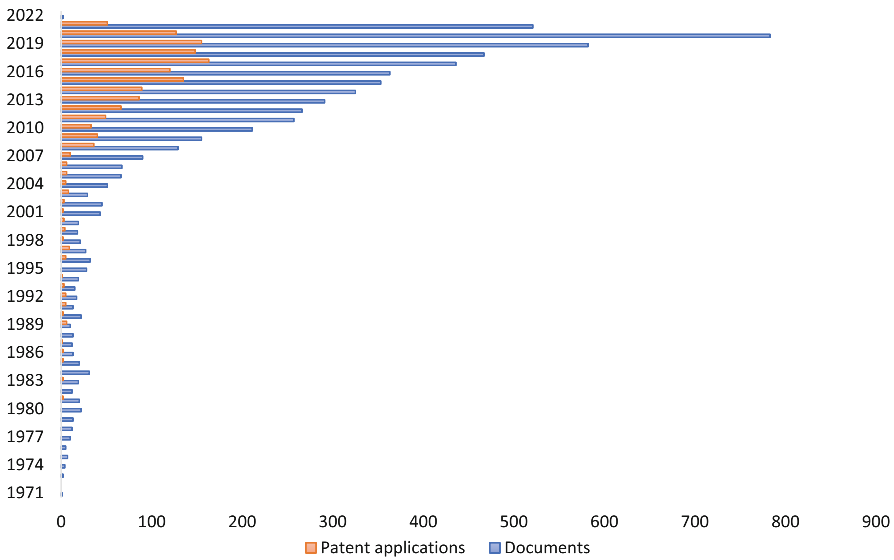
With the purpose of documenting and analyzing basic research and technological development related to energy management in agriculture from a scientific and technological point of view, we analyzed patent applications and conducted a network analysis. For this purpose, and considering their robustness and academic reliability, we used the Scopus (2021a) database, as well as the Lens (2021) database, whose main data partners are the US Patent and Trademark Office (USPTO), the European Patent Office (EPO), the World Intellectual Property Organization (WIPO), and IP Australia. The term "agriculture" was included in each search, in addition to the following concepts: (1) energy management, (2) energy production, (3) energy consumption, and (4) energy efficiency. In the case of academic documents, we searched for documents containing the search terms in the title, abstract, or keywords, whereas in the case of patent applications, the searched documents contained the terms in the title, abstract, or claims sections (see Table 1).

As shown by Graphic 1, academic document production begins in 1971, while in the case of patent applications, it begins in 1981, that is, 10 years later. The early twenty-first century is clearly characterized by the increased production of academic documents and patent applications, although technological production is always behind basic science production in this area of knowledge (see Graph 1). The documents obtained via Scopus (2021b) were arranged in descending order by publication date. Then, considering the first 2000 of 5989 identified documents, we conducted a co-occurrence analysis using the following analysis criteria:

Table 1 Queries in Scopus and Lens

No.	Database	Query	Documents
1	Scopus	TITLE-ABS-KEY((agriculture) AND ((“energy management”) OR (“energy production”) OR (“energy consumption”) OR (“energy efficiency”)))	5989
2	Lens	Patents (1392) = (Title: (agriculture) OR (Abstract: (agriculture) OR Claims: (agriculture))) AND ((Title: (“energy management”) OR (Abstract: (“energy management”) OR Claims: (“energy management”))) OR ((Title: (“energy production”) OR (Abstract: (“energy production”) OR Claims: (“energy production”))) OR ((Title: (“energy consumption”) OR (Abstract: (“energy consumption”) OR Claims: (“energy consumption”))) OR (Title: (“energy efficiency”) OR (Abstract: (“energy efficiency”) OR Claims: (“energy efficiency”))))))	1392

Source: Elaborated by the authors based on Scopus (2021b) and Lens (2021)



Graph 1 Documents and patent applications. (Source: Elaborated by the authors based on Scopus (2021b) and Lens (2021)).

1. Type of analysis: co-occurrence
2. Unit of analysis: author keywords
3. Counting method: full counting

This procedure resulted in 5711 keywords, although only 182 presented an occurrence (O) equal to or greater than 5.

With this information, a network map was obtained consisting of 10 clusters, 182 nodes, and 1202 links (L), with a total link strength (TLS) of 1838 (see Annex). Thus, to highlight relevant examples in the network, the three most important nodes based on the number of occurrences in each cluster are indicated below. In this way, the results for clusters 1–5 (under the following order L/TLS/O) were as follows:

Cluster 1 (red): (a) energy efficiency, 81/169/130; (b) IoT, 42/103/63; and (c) Internet of Things, 39/96/58
Cluster 2 (green): (a) energy consumption, 67/131/89; (b) economic growth, 26/58/24; and (c) CO_2 emissions, 18/39/20
Cluster 3 (dark blue): (a) biomass, 31/56/40; (b) biogas, 23/43/27; and (c) anaerobic digestion, 16/25/25
Cluster 4 (yellow): (a) agriculture, 94/223/117; (b) sustainability, 52/92/65; and (c) climate change, 30/42/30
Cluster 5 (purple): (a) renewable energy, 43/88/65; (b) life cycle assessment, 34/50/38; and (c) sustainable agriculture, 24/30/21

In the case of clusters 6–10, results were as follows:

Cluster 6 (light blue): (a) energy, 55/89/52; (b) efficiency, 17/25/19; and (c) simulation, 21/24/13
Cluster 7 (orange): (a) UAV, 17/20/9; (b) greenhouses, 9/11/7; and (c) controlled environment agriculture, 6/7/7
Cluster 8 (brown): (a) solar energy, 14/20/18; (b) energy saving, 12/11/13; and (c) photovoltaic, 7/8/9
Cluster 9 (fuchsia): (a) irrigation, 25/33/23; (b) water, 12/16/10; and (c) water-energy nexus, 8/9/7
Cluster 10 (pink) included only one node: (a) energy conservation, 4/6/6

Remarkably, certain high-occurrence nodes presented interesting links with other terms, such as energy efficiency, whose 81 links are related to items such as Internet of Things (IoT), renewable energy, sustainability, biomass, and wireless sensor networks, as well as agriculture, whose 94 links connect it with several similar terms to those previously mentioned and other relevant terms such as economic growth, biogas, biofuels, CO $emissions_2$, and greenhouse gases (see Fig. 1).

Regarding the search for patents on the Lens platform, no filters were included for the search period, jurisdictions, applicants, or inventors, among others. Filters were used only to identify English language documents, IPC classifications, lexemes, and patent applications. A top ten analysis shows the main patent applications by jurisdiction and applicants. In the first case, China and the United States are the undisputed leaders in the field, followed by PCT applications administered by the WIPO. However, the case of Korea stands out: its patent applications exceed European's. An analysis of applicants reveals the contributions of the academic institutions in this field of knowledge, especially Chinese universities, which represent the highest proportion of applicants in this ranking, a fact that reaffirms its

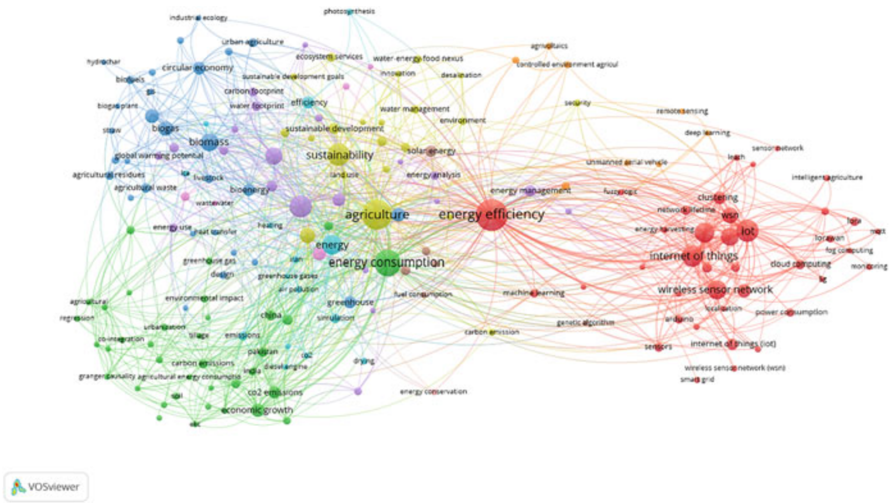


Fig. 1 Keyword co-occurrence analysis. (Source: Elaborated by the authors based on Scopus (2021b) and VOSviewer (2021))

Table 2 Jurisdictions and patent applicants

No.	Jurisdiction	Documents	Applicants	Documents
1	China	1092	Univ China Agricultural	28
2	United States	109	Univ Jiangsu	18
3	WO – WIPO	89	Univ Jilin	17
4	Korea, Republic of	31	Univ Kunming Science and Tech	13
5	European atents	23	Xinyi Hegou Ind Concentration District Construction Development Co LTD	12
6	Russia	14	Univ Shihezi	9
7	Japan	11	Agnetix INC	8
8	Germany	6	Univ Jiangnan	7
9	Canada	5	Univ Northeast Agricultural	7
10	Australia	4	Univ Henan Science and Tech	6

Source: Elaborated by the authors based on Lens (2021)

leadership as a country; the fourth and seventh places correspond to private companies (see Table 2).

In the case of patent applications identified using the WIPO International Patent Classification (IPC), the main technology sectors include inventions related to greenhouses or receptacles associated with heating, irrigation, or ventilation issues, as well as structures. Other technologies focus on fertilizers and their combination with additives (e.g., soil conditioners), drying, cloisters (greenhouses), composts, machinery, and devices that optimize different agricultural activities. An important

Table 3 Patent applications by IPC classification

No.	IPC classification	Description	Documents
1	A01G9/24	"A01G 9/00 Cultivation in receptacles, forcing-frames or greenhouses . . . Edging for beds, lawn or the like. . .- A01G9/24Devices for heating, ventilating, regulating temperature, or watering, in greenhouses, forcing-frames, or the like. . ."	55
2	C05G3/00	"Mixtures of one or more fertilisers with additives not having a specifically fertilising activity. . ."	50
3	F26B21/00	"Arrangements for supplying or controlling air or gases for drying solid materials or objects (air-conditioning or ventilation in general. . ."	49
4	C05G3/80	"C05G 3/00 Mixtures of one or more fertilisers with additives not having a specifically fertilising activity. . .- C05G3/80 Soil conditioners. . ."	33
5	A01G9/14	"A01G 9/00 Cultivation in receptacles, forcing-frames or greenhouses. . . Edging for beds, lawn or the like . . .- A01G9/14 Greenhouses (cloches. . ."	27
6	C05F17/00	"Preparation of fertilisers characterised by biological or biochemical treatment steps, e.g. composting or fermentation. . ."	27
7	F26B9/06	"F26B 9/00 Machines or apparatus for drying solid materials or objects at rest or with only local agitation; Domestic airing cupboards- F26B 9/06 in stationary drums or chambers"	26
8	A01M7/00	"Special adaptations or arrangements of liquid-spraying apparatus for purposes covered by this subclass. . ."	23
9	C12M1/107	"C12M 1/00 Apparatus for enzymology or microbiology-C12M1/107 with means for collecting fermentation gases, e.g. methane (producing methane by anaerobic treatment of sludge. . ."	23
10	C12N1/20	"C12N 1/00 Microorganisms, e.g. protozoa; Compositions thereof . . . Processes of propagating, maintaining or preserving microorganisms or compositions thereof; Processes of preparing or isolating a composition containing a microorganism; Culture media therefor. . .-C12N1/20 Bacteria; Culture media therefor. . ."	22

Source: Elaborated by the authors based on Lens (2021) and WIPO (2021)

aspect of the technological trends identified in this ranking shows that the technologies developed are related to gas capture means, for example, to capture methane, and others related to microbiology (see Table 3). These results underscore the multiple opportunities that technology can offer not only to agricultural development but also to the management of energy in this very relevant primary sector.

Energy management has become a central topic of discussion in the agricultural sector given the demand for food and other inputs generated by the significant population growth around the world. In this context, energy management depends mainly on its demand, its production, and how efficiently energy is used. Therefore,

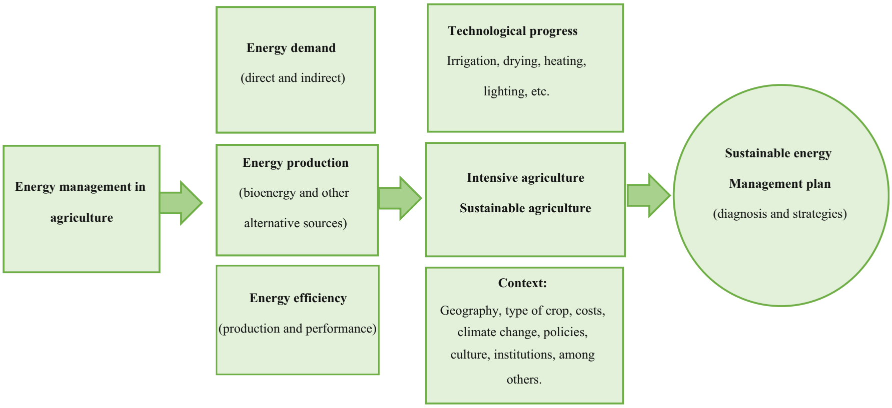


Fig. 2 Toward the construction of a sustainable energy management plan. (Source: Elaborated by the authors)

the sector ought to consider technological solutions that can maximize energy use and production. Of course, however, everything will depend on the agricultural model used and the different elements of the context where crops are produced, including public policies, regulatory and institutional frameworks, environmental and geographical factors, etc. That is, only based on these analysis elements will a sustainable energy management plan be established that, through an adequate diagnosis and the inclusion of relevant strategies, will contribute to the development of the agricultural sector, especially in developing countries (see Fig. 2).

3 Conclusions

As a primary sector, agriculture has a strategic priority due to the increasing demand for food and other inputs provided by the sector. Intensive farming, agrochemicals, poor irrigation management systems, and increased energy demand, among other elements, reflect an unsustainable production model. In addition to these are issues related to geography, biodiversity, climate change, type of crop, and energy costs. However, this context includes cultural elements too and a political, normative, and institutional structure that must be factored in the elaboration of a sustainable energy management plan for the agricultural and rural environments. These plans may be oriented toward the development of intensive agricultural systems, although sustainable agricultural models such as those based on organic agriculture or conservation agriculture should be favored as much as possible if the environmental and social impacts of agricultural activities are to be minimized. All these elements must be taken care of, especially in developing countries, whose economic conditions tend to be adverse.

Annex

Cluster 1				Cluster 2				Cluster 3				Cluster 4			
items				items				items				items			
	links	Total link strength	occurrences		links	Total link strength	occurrences		links	Total link streght	occurrences		links	Total link streght	occurrences
5g	8	9	5	agricultural	11	15	6	agricultural machinery	6	6	6	agriculture	94	223	117
Arduino	16	17	9	agricultural energy consumption	5	5	5	agricultural residues	8	11	11	carbon emission	10	13	7
cloud computing	13	27	11	ardl	13	16	5	agricultural waste	10	11	12	climate change	30	42	30
Clustering	19	43	22	carbon emissions	21	23	11	anaerobic digestion	16	25	25	desalination	7	10	5
edge computing	13	16	8	china	16	27	14	biochar	6	6	5	ecosystem services	5	5	11
energy efficiency	81	169	130	co-integration	14	18	6	bioeconomy	10	17	8	electric vehicles	3	3	5
energy efficient	5	5	5	co2 emission	20	27	14	bioenergy	23	28	20	energy policy	7	8	6
energy harvesting	10	11	6	co2 emissions	18	39	20	biofuel	7	7	6	environment	12	14	8
fog computing	7	10	5	ecological footprint	8	8	6	biofuels	11	12	9	fertilizer	6	7	6
fuzzy logic	8	9	6	economic growth	26	58	24	biogas	23	43	27	food security	11	13	11
intelligent agriculture	5	6	6	ekc	12	14	5	biogas plant	6	7	5	ghg emissions	10	10	7
internet of things	39	96	58	electricity	15	19	6	biomass	31	56	40	innovation	8	10	6
internet of things (iot)	16	21	17	electricity consumption	14	14	5	circular economy	26	38	21	land use	10	11	7
Iot	42	103	63	energy balance	15	17	10	design	4	5	8	modeling	14	17	10
Leach	9	13	6	energy consumption	67	131	89	experiment	6	6	6	modelling	9	10	6
Localization	6	8	5	energy demand	7	7	5	gasification	8	12	8	renewable energy sources	6	7	13
Lora	11	17	10	energy intensity	13	15	10	gis	7	8	6	security	8	11	7
Lorawan	10	14	8	energy production	17	20	9	greenhouse	24	31	20	sustainability	52	92	65
machine learning	13	14	9	energy sector	12	15	5	heat transfer	3	3	6	sustainable development	19	23	15

Monitoring	5	6	6	environmental degradation	11	12	7	hydrochar	2	2	5	sustainable development goals	8	9	7
Mqtt	6	9	5	environmental impact	8	9	8	industrial ecology	5	8	5	water management	13	15	9
network lifetime	14	27	12	environmental kuznets curve	11	21	8	life cycle assessment (lca)	6	7	7	water-energy-food nexus	11	12	8
power consumption	8	10	9	forecasting	9	9	6	livestock	16	20	11				
precision agriculture	37	92	51	granger causality	13	16	6	optimization	26	36	23				
precision farming	11	14	6	greenhouse gas	10	10	7	pollution	8	8	5				
raspberry pi	5	6	5	india	12	16	8	pyrolysis	4	4	6				
routing protocol	14	27	11	input-output analysis	3	3	6	straw	6	8	6				
routing protocols	8	12	5	mathematical model	2	2	5	urban agriculture	7	13	10				
rpl	5	8	6	pakistan	16	22	12	waste management	8	8	7				
sensor network	8	8	5	regression	8	10	6								
sensors	17	23	11	soil	7	7	7								
smart agriculture	21	34	24	soil compaction	3	3	5								
smart farming	16	25	12	structural decomposition analysis	6	6	5								
smart grid	5	5	6	tillage	5	5	6								
wireless sensor network	32	75	46	time series analysis	15	22	5								
wireless sensor network (wsn)	6	6	6	urbanization	11	11	7								
wireless sensor networks	32	71	42												
wsn	30	59	32												
zigbee	12	15	6												

Cluster 5				Cluster 6				Cluster 7				Cluster 8			
items				items				items				items			
	links	Total link strength	occurrences		links	Total link strength	occurrences		links	Total link streght	occurrences		links	Total link streght	occurrences
carbon footprint	10	14	10	air pollution	10	11	7	agrivoltaics	4	4	7	diesel generator	6	7	6
data envelopment analysis	9	9	8	co2	8	12	6	controlled environment agriculture	6	7	7	energy saving	11	12	13
economic analysis	15	20	10	diesel engine	4	5	5	deep learning	5	6	5	fuel consumption	5	5	6
energy analysis	10	13	10	drying	2	2	7	greenhouses	9	11	7	genetic algorithm	5	6	5
energy indices	8	8	5	efficiency	17	25	19	remote sensing	7	7	5	photovoltaic	7	8	9
energy management	19	24	17	emission	9	11	5	throughput	8	9	5	solar energy	14	20	18
energy optimization	11	11	6	emissions	12	15	11	uav	17	20	9				
energy productivity	9	10	7	energy	55	89	52	unmanned aerial vehicle	6	7	6				
energy use	14	18	10	environmental impacts	7	11	5								
energy use efficiency	16	19	15	greenhouse gases	6	6	5								
environmental pollution	5	5	5	heating	7	12	5								
european union	8	10	5	iran	12	16	7								
ghg emission	6	6	6	lca	9	13	6								
global warming potential	9	15	9	photosynthesis	4	4	6								
greenhouse gas emissions	9	13	12	simulation	21	24	13								
life cycle assessment	34	50	38												
renewable energy	43	88	65												
renewable energy consumption	8	13	8												
sustainable agriculture	24	30	21												
water footprint	9	13	12												
wheat	7	8	5												

Cluster 9				Cluster 10			
items				items			
	links	Total link streght	occurrences		links	Total link streght	occurrences
hydropower	3	4	5	energy conservation	4	6	6
irrigation	25	33	23				
wastewater	3	3	5				
water	12	16	10				
water-energy nexus	8	9	7				

The problem of energy management must be analyzed from the amount of energy required to carry out agricultural activities and transport production (direct demand), but energy costs related to the production of inputs and machinery and their transportation to production sites must also be taken into account. Given the increased costs and the challenges related to the production of energy, the role of technology and the development of plans for adequate energy management are essential. The implementation of new technological solutions will certainly involve new energy requirements, but their technical and economic feasibilities have to be measured in terms of agricultural production and performance (energy efficiency). Alternative energies for agricultural applications are numerous, and they include sources such as wind, solar, hydroelectric, and geothermal energy. Agricultural products and their wastes are also sources of bioenergy (biofuels), although their use raises a conflict on whether land should be used to produce food or to produce energy; among these energy sources, second-generation biofuels are the most promising options.

Technological change in areas such as heating, lighting, and hydraulics, among others, will mobilize important changes in production; although new technologies will demand energy, they will also provide ways to use energy sustainably and profitably. In the form of biofertilizers, biopesticides, and composts, biotechnology can help to reduce the use of chemical products and their adverse effects on the environment and health. The results obtained from the co-occurrence and patent application analyses show the main topics addressed from different fields of knowledge around energy management and agriculture, as well as the main existing technological trends. However, all energy management plans will have to consider the specific context where they are applied and, based on an accurate diagnosis, they must integrate strategic actions and strive for sustainable development. In addition, the diagnosis takes special relevance in the rural environment of developing countries due to their complex problems, and it should provide adequate information to decide where government support should be used with the intention of supporting the economic and social advancement of the producers and their families, always prioritizing aspects such as culture, ethics, biosecurity, and the environment.

4 Cross-References

► Energy Conservation in Farm Operations for Climate-Smart Agriculture
► Harnessing Nanoscale Fertilizers in Attaining Sustainability Under Changing Climate

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Crop Residues Potential, Technology, Policy, and Market

Challenges and Opportunities for Sustainable Management

Sunil Dhingra and Ramakant Sarin

Contents

Abstract

Bioenergy can play a crucial role in India's quest for sustainable and affordable energy sources to bridge its supply–demand imbalance. India has 328.7 million hectares of land area, of which 139.4 million hectares is net sown area with a large diversity in the type and productivity of crops. A large amount of crop residues in forms farm residues and agro-processing waste. Agriculture residues have always played a significant role in meeting the energy requirements for many centuries. By virtue of recent policy initiatives, advances in biomass conversion technologies/processes convert these biomass resources into various end-use energy forms by providing green fuels for meeting the energy demand in industries, power generation, and transportation applications. It is playing a crucial role in bringing about a change in energy transition. In due acknowledgment of the above and from this context, the chapter reviews the existing policy regime, technology

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advancement, market development, and key challenges in scaling up of these technologies/solutions into target markets.

1 Context and Introduction

India at the COP 26 summit in Glasgow made a commitment to achieve net-zero emissions by 2070. India also made a commitment to procure 50% of its energy requirements from clean and renewable energy sources by 2030. Biomass as a renewable resource for India can play an important role in achieving a net-zero carbon emissions economy by 2070.

As per the study report, about 683 million tons (MT) of crop residue is generated per year from 11 major crops grown in India. As a source of energy for rural households and industrial use, these residues are basically used for animal feed, soil mulch, and manure. The total yearly surplus crop residues are reported to be approximately 178 million tons (MT). Additionally, agricultural waste is produced from a broad range of subsectors, including agro-processing industries (paper and pulp production, rice mills, oil mills, sugarcane processing, distilleries, and other food and food processing industries). Agricultural residues have always played a significant role in meeting the energy requirements for many centuries. It has been the source of energy for India (as per the TIFAC (Crop wise data, 2018) report).

The crop type-wise annual production and its surplus quantity are shown in Table 1.

Crop residue burning in Punjab, Haryana, and Uttar Pradesh, is practiced by farmers who alternate between long-duration rice and wheat. As per ICAR (Consortium for Research on Agroecosystem Monitoring & Modelling from Space Indian Agricultural Research Institute. Monitoring paddy residue burning in India using

Table 1 Crop total dry and surplus biomass

Crop type	Dry biomass (million tons)	Surplus biomass (million tons)
Rice	225.487	43.856
Wheat	145.449	25.07
Maize	27.88	6.036
Sugarcane	119.169	41.559
Gram	26.515	8.724
Tur	9.167	1.755
Soybean	27.779	9.95
Rapeseed and mustard	17.085	5.157
Cotton	66.583	29.74
Groundnut	12.9	3.873
Castor	4.604	3.017
All crops	682.618	178.737

Source: TIFAC report (2018)

satellite remote sensing during 2021) satellite remote sensing data available till November 30, 2021, the burning events reported are more than 100,300 in northwest states during the rice cultivation season. It is estimated that there are about 70–80 metric tons of rice residue each year in this region. The release of a high volume of particulate matter has not only serious repercussions on health and the environment but is also a major cause of loss of nutrients and energy that could be tapped for more productive use.

2 Review of National and State Government Current Policies and Initiatives

The Government of India is currently investing in a national strategy that includes many policy initiatives. The initiatives include capacity-building and public–private partnerships, which are managed by different ministries. The advantages of this strategy are to support India's sustainable development goals, providing affordable clean energy, including improving sanitation and increasing jobs in the green economy. The advantage also includes climate benefits of bioenergy development. The key programs/policies are given below.

2.1 National Government/CPSU Initiatives

National Policy for Management of Crop Residues 3 (NPMCR) – 2014: The Ministry of Agriculture, and Farmers Welfare implements national policy that envisages incorporation of technical measures, including diversified uses of crop residue, capacity building and training, along with conceptualization of suitable law/legislation. The policy also envisages using remote sensing technologies to monitor crop residue management, with active involvement of the National Remote Sensing Agency (NRSA) and the Central Pollution Control Board (CPCB). National policy for management of crop residues. Promotion of agricultural mechanization for in-situ management of crop residue in the states of Punjab, Haryana, Uttar Pradesh and NCT of Delhi (n.d.).

Under this program, the Ministry of Agriculture and Farmers Welfare in the years 2018–2019 launched the "Promotion of Agricultural Mechanization for Management of Crop Residue in the States of Punjab, Haryana, Uttar Pradesh, and NCT of Delhi" to support the initiatives of the governments of Haryana, Punjab, Uttar Pradesh, and the NCT of Delhi in addressing air pollution and subsidizing machinery required for the management of crop residue. During 2018–2019, 2019–2020, and 2020–2021, the state governments have supplied more than 1,58,135 machines to the individual farmers and the Custom Hiring Centers as subsidy for the management of crop residue. A total of 30,961 Custom Hiring Centers have been established.

National Biofuel Policy 2018: This policy traces the development of biofuels to utilize waste. Thrust is given to advanced 2G biofuel technologies, including conversion of agricultural residues/waste that can be converted to ethanol and bio-CNG. Agricultural residues (rice straw, wheat straw, energy crops, etc.) can be converted into ethanol by 2G ethanol plant. 2G ethanol plants offer a significant opportunity to utilize surplus crop residues. A 100 kl per day plant can harness 2 lakh tons per annum of agricultural residue to generate around 3 crore liters of ethanol per annum. By using different feedstocks and technology, 12 bioethanol pilot plants are being planned to be set up in the country.

Sustainable Alternative Toward Affordable Transportation (SATAT), an initiative of the Government of India with PSU Oil Marketing Companies (OMCs, i.e., IOC, BPCL, and HPCL), is aimed at providing a clean and affordable transportation fuel as a developmental effort. It would benefit both vehicle users as well as farmers and entrepreneurs. The initiative aims to set up 5000 compressed biogas plant (CBG) production plants and make available CBG in the market for use in automotive fuels by better utilization of agricultural residue, cattle dung, and municipal solid waste. In total, 2745 LoIs have been issued by OMCs, out of which about 15 projects were fully commissioned (Sustainable Alternative Towards Affordable Transportation (SATAT) 2022).

The MNRE (Ministry of New and Renewable Energy) has launched a program on energy from agricultural waste/residue in the form of biogas-bio-CNG-enriched biogas/power: The eligibility to receive Central Finance Assistance (CFA) in the form of capital subsidy and grant-in-aid under the program are projects based on biowaste from agricultural waste (paddy straw, agro-processing industry residue, green grasses, etc.). Creating conducive conditions and environment, with fiscal and financial regime, and developing, demonstrating, and disseminating utilization of agricultural waste and residue for recovery of energy are the primary objectives of this program. The focus of this program is utilizing agriculture waste materials for power projects. The Ministry of New and Renewable Energy has been promoting the Biomass Power and Bagasse Co-generation Program. The aim of this program is to recover energy from biomass, including bagasse, agricultural residues such as shells, husks, deoiled cakes, and wood from dedicated energy plantations for power generation. As per the MNRE, the potential for power generation from agricultural and agro-industrial residues is valued at about 18,000 MW. More than 550 Biomass IPP and Bagasse Co-generation-based power plants with aggregate capacity of 9373 MW have been installed primarily in the states of Maharashtra, Uttar Pradesh, Karnataka, Tamil Nadu, Andhra Pradesh, Chhattisgarh, West Bengal, and Punjab till December 2020. This includes 7547 MW from the Bagasse Co-generation Sector and 1826 MW from the Biomass IPP Sector (MNRE 2022).

The Ministry of Power, Government of India (GoI), has initiated the national mission on the use of biomass in coal-based thermal power stations (TPSs) for co-firing in pulverized coal-fired boilers and mandated all the coal-based power plants to use a 5% blend of biomass pellets along with coal effective from October 2022. This has been initiated with an objective to create a market for biomass pellets and torrefied pellets in India and achieve the national goal of reducing GHG emissions and decarbonizing the power sector in India. Around 2.5–3.0 lakh tons of biomass pellets are required for 7% blending in a thermal power plant of 1000 MW capacity.

3 Status of Biomass Energy Conversion Technologies

3.1 Biomass Densification

Utilization of agricultural and forestry residues in energy systems is generally difficult due to their low bulk density and physiochemical characteristics. The other problems of transportation, storage, and handling, and the direct burning of loose biomass in conventional grates are associated with very low thermal efficiencies and wide-scale air pollution. This shortcoming can be subdued by means of compression of the residues into high density and regular shape. The process of compression of raw material into a product of higher bulk density than the original raw material is known as densification. It has aroused a high deal of interest all over the world as a technique for beneficiation of residues for utilization as an energy source. Densification of biomass (crop residues) is performed using briquetting presses, pellet mills, and other extrusion processes. This helps in increasing the density and conquering feeding, storing, handling, and transporting problems. Though in principle a diversity of biomass residues, such as bagasse, rice straw, cotton stalk, groundnut shells, etc., are available for briquetting/pelletizing, the economics and logistics of collection, and transportation and storage of these residues can be a difficult affair. Briquettes can be used in diverse thermal applications such as industrial boilers, furnaces, as well as in power plants.

3.1.1 Types of Densification Presses

Based on the type of equipment used, densification presses can be categorized into three main types: piston press densification, screw press densification, and pelletizing. Products from the first two types of densifications are of enough large size and are normally called briquettes. Pellets are of small and uniform size, particularly suitable for automatic auger-fed combustion systems.

Piston Press

In India, predominantly ram and piston-type briquetting technology is the most common in the briquetting industry. The raw biomass is pushed into this machine through a die by a reciprocating ram with a very high pressure, thereby compressing the mass to obtain a briquette, producing cylindrical briquettes, which are a series of disks pounded together in strokes. The two essential pieces of the machine are the ram and the die. As biomass drops in from above, the ram pushes the biomass through the die at high temperature and pressure. The high temperature creates a self-binder around the briquettes, which are then cooled when it exits the machine. The majority of briquette manufacturers use piston press technology to manufacture briquettes of 65 mm and 90 mm diameter. They use a broad variety of bioresidues as raw material in different ratios in order to optimize the quality of the briquette and its cost. The raw materials are used in a particular area based on the cropping pattern and the seasonal variations in the availability of each raw material in that area. Though in principle a diversity of biomass such as sawdust, bagasse, rice husk, groundnut husk, etc., can be used in the briquetting machine, but in actual practice most of the units rely on sawdust or a mix of sawdust as the main raw material. It is notably a cost-effective technology currently offered by the Indian market. The material is pushed by the piston against the frictional force caused by die taper and is heated to 150–200°C during the process. Mechanical piston presses are normally driven by electricity that is fitted with flywheels. Piston presses with hydraulic drives is a recent development. The capacity of commercial piston presses generally ranges from 250 to 2000 kg/h. The briquettes are typically cylindrical with diameter in the broad range of 50–100 mm. It has been reported that presses fitted with flywheel generally face the problem of wear of the die and piston breakages.

Pelletizing

Biomass pellets are basically prepared from biomass. They are of pencil size of less than 25 mm diameter. The biomass after pelletizing is uniform in size, shape, moisture, density, and energy content. Pellet fuel is refined and densified biomass that allows remarkable consistency and burns efficiently. The uniform shape and size allow for a smaller and simpler feed system that reduces costs. The moisture content of pellets is significantly lower (4–8% water compared to 20–60% raw biomass). Less moisture means higher calorific value and easier handling. The density of pellet fuel is significantly higher than raw biomass (640 kg/m^3 vs. 160–400 kg/m^3 in raw material form). More amount of fuel can be transported in a given truck space, and more energy can be stored at the site. These high-density and uniform-shaped pellets can be stored in standard silos. Also, they can be transported in rail cars and delivered in truck containers at a particular location.

There are mainly two types of pellet technologies:

- Flat die pellet technology
- Ring die pellet technology

Flat Die Pellet Mill

In flat die pellet mill, the raw materials flow from the top by their own weight into the pelletizing chamber. The materials are then compressed between the rollers and die to form pellets by going through the die holes. Due to the design of portable rollers and die, flat die pellet mills are generally small in capacity, easier to be cleaned and maintained, and cheaper.

Ring Die Pellet Mill

The ring die is a simple operation where feed mass is distributed over the inner surface of a rotating, perforated die ahead of each roll, which then compresses the feed mass. The feed mass is compressed into the die holes to form pellets. Ring die pellet mills generate less wear and tear because of the inner and outer edges of the rollers traversing the same distance.

Ring die pellet mills are more energy efficient than flat die pellet mills.

The Benefits of Pellet Fuel

An enormous amount of unusable material remains on the grounds of forest, and the materials rejected by wood-based product manufacturing industries can be a perfect resource for commercial pellet manufacturers.

3.1.2 Key Challenges in Biomass Densification

The machines used for densification can process raw materials within only certain ranges of particle size and moisture content. This is the reason the two crucial steps in the preparation of the raw materials are drying and size reduction. The existing densification technologies are primarily developed for softwood materials applications and selected agro-residues-based materials. The present briquetting/pellet machines are not suitable for accepting paddy straw, bagasse, mustard stalk, etc., as the main feedstock. This may be due to less lignin content in these residues compared with sawdust. One of the major problems has been excessive wear of tooling, that is, the extrusion die, ring, piston leading to high plant downtime, high maintenance, and replacement costs.

Moisture Content

Moisture content in the raw material is a critical factor in densification process. The moisture facilitates internal heat transfer during densification. If the moisture content is too low, densification may be challenging due to nonuniform heat transfer. However, very high moisture content can cause release of steam and makes the densification process difficult. The maximum acceptable moisture content should be in the range of 10–15%.

Particle Size

Residues of small particle size such as sawdust, coffee husk, and rice husk can be used directly as feeding materials for briquetting. However, bigger size agricultural residues such as groundnut shell, cotton stalk, etc., cannot be densified directly. These must be reduced to small sizes in order to densify. This results in additional costs in preprocessing equipment and conversion. Crop residues like paddy straw have high silica content and high abrasive, which causes the wearing of the main components of the processing machines. High downtime of the briquetting machines results in higher conversion costs, making the briquettes uneconomical in end-use applications.

3.2 Biomass Gasification

Biomass gasification involves the partial combustion of biomass under calculated air supply. This leads to the generation of producer gas. It is a thermochemical process in which solid biomass materials like crop residues, wood, charcoal, rice husk, etc., are converted into a gaseous fuel with the help of a series of processes, including drying, pyrolysis, oxidation, and reduction. Normally atmospheric air is used as the gasification agent. The producer gas will consist mainly of carbon monoxide (CO), hydrogen (H_2), methane (CH_4), nitrogen (N_2), and carbon dioxide (CO_2). The first three are combustible gases. The composition of the gases obtained from wood gasification on a volumetric basis is as follows:

Carbon monoxide	:	18–22%
Hydrogen	:	13–19%
Methane	:	1–5%
Carbon dioxide	:	9–12%
Nitrogen	:	45–55%
Water vapor	:	4%

The calorific value of the producer gas is about 1000–1200 kcal/Nm^3. Natural gas or LPG has an equivalent calorific value of ~10,000 kcal/m^3, while biogas (cow dung, which roughly contains 60% methane by content) has a value of 4500–5500 kcal/m^3. Around 2.5 Nm^3 of producer gas is obtained from the gasification of 1 kilogram of biomass using atmospheric air as a gasifying agent. The producer gas can be used for heating, power generation, and motive power using gas engines. It converts the chemical energy in the gas into mechanical energy by rotating a shaft. The engine shaft is coupled to the shaft of an alternator that converts the mechanical energy into electrical energy. The producer gas can also be burnt directly in the air similar to LPG gas, and therefore is useful in cooking, water boiling, steam production, and food and materials drying in MSME units. Depending upon the positions of the air inlet and gas from the outlet, three broad types of gasifiers have been designed and operated to date (Fig. 1):

Sub-MW scale biomass gasifier systems are used for grid and non-grid applications in India. Development of poly-generation facilities the production of liquid fuels and a variety of chemicals and hydrogen. This is in addition to power

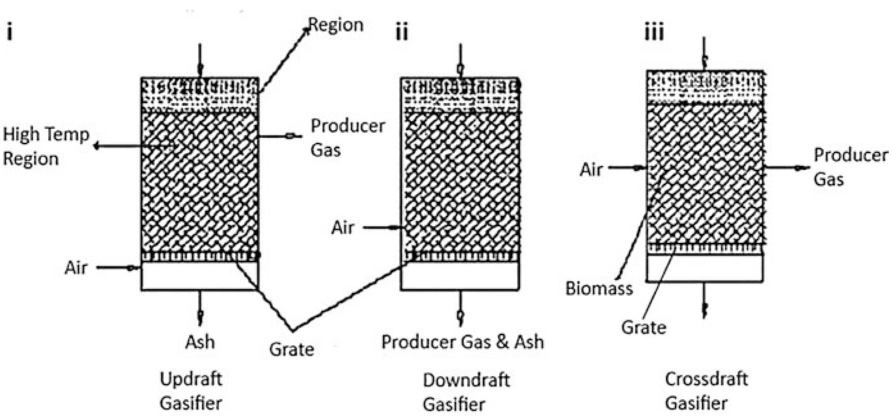

Fig. 1 (i) Updraft; (ii) downdraft; and (iii) cross-draft gasifiers

production through the IGCC route. Establishing the concept of bio-refinery is to be prioritized to increase the use of biomass resources in the country.

3.3 Biomass Combustion and Co-Generation

This is the most commonly used technology for converting biomass into thermal and electrical energy forms. The advantage of using the technology is that it is similar to a thermal power project, except for the type of boiler. The cycle used is the conventional Ranking cycle in which biomass is burnt in a high-pressure boiler to generate steam and operate a steam turbine with the generated steam. The exhaust of the steam turbine can either be fully condensed at low pressure to produce power or used for heating applications when exhausted at medium pressure in the process industry. Generating power and processing steam together is termed as co-generation. Co-generation is applicable in many industries, where biomass comes out as waste like in sugar mills, pulp and paper industries, oil mills, etc. Plant capacities are not very high due to the limitation of biomass collection economically. The investment cost for biomass combustion-based power projects or co-generation projects varies between Rs. 5 crores and Rs. 6.5 crores depending upon the project site, design, and operation-related factors. The cost of the electricity generation varies between Rs. 6 and 8/kWh depending upon the type of biomass, biomass price, specific fuel consumption, and operating pressure of the boiler and steam turbine (Biomass Combustion and Co-generation 2021).

The technology for power generation through biomass combustion is quite mature. Biomass collection and its economic transportation are the key issues. Research and development are required for

- Compacting different types of biomass for transportation
- Boiler design that can help use diversity of biomass

3.4 Biomass Torrefaction Technology

Lignocellulosic biomass (agricultural wastes) typically contains higher volatile matter and low fixed carbon compared with coal. In order to effectively utilize the crop residues as fuel in the thermal power plants for replacement of coal, it is recommended to be used in torrefied forms so that its properties are similar to coal. In the torrefaction process, solid biomass is heated in a reduced atmosphere at a temperature of 230–300°C, which results in loss of moisture and partial loss of the volatile matter in the biomass. The characteristics of the original biomass are drastically changed with the partial removal of the volatile matter (about 20%). The resultant torrefied material then becomes hydrophobic, and its heating value increases to 21–23 MJ/kg. Internationally, torrefied biomass is the preferred route due to its inherent advantages as highlighted below.

Torrefaction makes biomass more brittle, enhancing its grindability, thereby leading to a significant (85–90%) reduction in milling energy requirement for pulverization in coal-fired thermal plants.

- The hydrophobic nature of torrefied biomass increases the fuel shelf life by simultaneously minimizing the bacterial degradation and water uptake.
- A significant increase in the heating value of the torrefied fuel can be comparable with that of conventional fossil-based coal.
- Increase in energy density with a minor reduction in the mass density.
- The process is the most cost-effective energy delivery system.
- A diversified range of agricultural waste materials can be converted into torrefied form.

All agricultural waste, including RDF, can also be torrefied, with very high energy and mass recovery. After torrefaction, the agro-residues come out in the form of a black material, which can be directly used or compacted as briquettes/pellets as the case may be. The typical yield of torrefaction is between 70 and 80% depending on the biomass used and its characteristics. The torrefied bioresidue can be directly used or pulverized and fed into coal-fired boilers in thermal power stations (TPSs) or in industrial boilers as a replacement for coal. The technology provides the opportunity to torrefy the local agricultural/forestry materials into torrefied forms while optimizing the overall energy consumption of the complete plant.

3.5 Anaerobic Biodigestion

The anaerobic degradation of organic substrates is a fermentation and oxidation process that occurs under anaerobic conditions, that is, in the absence of oxygen. Several factors may affect biogas production efficiency. The most relevant ones are as follows:

- Chemical composition of residue: Easily biodegradable substances, such as carbohydrates, proteins, and lipids, propitiate a higher production of methane than the substances with difficult degradation, such as cellulose, lignin, and artificial compounds.
- Air impermeability: Methane-producing bacteria are anaerobic. The carbon dioxide (CO_2) gas is only produced in the presence of oxygen in the decomposition of organic fraction.
- Temperature: Temperature is a very important parameter for anaerobic digestion since it is within the spectrum of temperature in which the anaerobic reactor operates that the bacteria responsible for organic matter degradation are differentiated in order to interfere with enzyme stability. This takes place according to the conditions of the medium, such as viscosity, density, velocity, residue degradation, and stability. Microorganisms, especially bacteria, can be classified according to the temperature into three broad groups:

1. Thermophilic: The ones whose optimal temperature is around 60 °C.
2. Mesophilic: The ones whose optimal temperature is around 37 °C.
3. Psychrophilic: The ones whose optimal temperature is around 15 °C.

A diversity of anaerobic digestion (AD) technologies are commonly used in India. Based on input feed material characteristics such as solid content and process temperature, digester design varies. The understanding of the biogas production process is of high importance for the success of the biogas utilization process as they are complementary processes. Besides, in case proper care in the generation is not taken, the utilization processes may be highly jeopardized or even become unfeasible. To effectively and efficiently process and produce optimal quantities of biogas, understanding the above parameters is key in selecting the correct digester for biogas. Crop residues can be co-digested with cow manure using AD systems to produce biogas. Raw biogas can be used as fuel or power generation using gas engine. Raw biogas can be upgraded to bio CNG after enrichment and bottling by removing impurities such as carbon dioxide (CO_2), hydrogen sulfide (H_2S), and water so that they can be used in vehicles similar to natural gas quality. There is a need to develop CBG infrastructure and develop market, particularly in rural areas where a large amount of surplus crop residues exists.

3.6 2G Ethanol

The use of lingo-cellulosic biomass for the production of second-generation (2G) ethanol can be a potential alternative to utilizing crop residues. The process involves acid pretreatment and hydrolysis using enzymes. The Ministry of Petroleum and Natural Gas (MoPNG), Government of India, has given thrust to 2G ethanol production in the country with the objective to utilize surplus crop residues and meet Ethanol Blending Target under the National Biofuel Policy, 2018. The benefits include providing viability gap funding support for 2G ethanol refineries besides additional tax incentives and higher purchase prices. The oil marketing companies (OMCs) are in the process of setting up 12 2G biorefineries having 100 kiloliter per day (KLPD) of ligno-cellulosic 2G bioethanol plant capacity across potential states. It is said that about 500–600 tons of crop residues will be utilized on a daily basis by each plant (2G Ethanol 2021).

4 Conclusions

In India, biomass is already a significant source of energy and its dependence on energy needs is expected to rise in the future, so the contribution of biomass to the energy mix is projected to increase. As fossil-based fuel supplies dwindle, biomass will increasingly also be in demand as a substitute for fossil fuels and petrochemicals. The total demand for biomass can be expected to soar in the coming years. The issues of agri-residues include biomass collection, processing, and storage. Its transportation to the point of ultimate utilization due to the dispersed and voluminous nature of this resource and lack of robust institutional and market mechanism for efficient procurement of the required quantity of agri-residues in a short span of time add additional challenges to the management of this resource. Similarly, from the lower energy density characteristics and life cycle emission perspective, it is inevitable to use these resources at decentralized scale rather than transport them to long distances. The lack of policies and investment in crop residue collection and aggregation business is a critical missing link in value chain creation.

The key research questions that still need to be addressed are: "How much sustainable biomass can be supplied from the agriculture ecosystem considering complex interactions between its availability and human needs?" "What is the availability of biomass, and what factors does society need to consider in managing it sustainably?"

For addressing the challenge of crop residues management, it is crucial that district/block-level-specific plans be developed with an emphasis on crop residues production and surplus quantity, demand of energy (fuels, electricity, and drying/cooling applications) in agricultural industries and HH sectors, besides the use of crop residues for soil incorporation purpose. A more innovative and integrated policy approach by combining in situ and ex situ approaches is needed for a scalable and long-term solution to this problem. This can play an important role in achieving a net-zero carbon emissions economy by 2070. Also, achieving the national goal of reducing GHG emissions and decarbonizing the power sector in India.

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Part III

Ecology, Energy, and Future Agriculture Solutions/Insights in the Sustainable Energy Solutions in Agriculture

Applicability of Various Renewable Energy Sources to Agricultural Applications

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Abstract

Renewable energy sources are the best available clean energy sources. It is a feasible alternative for responding appropriately to India's energy problem. In this chapter, we will discuss the potential of renewable energy as an alternative energy source to perform different agricultural activities in the agricultural sector. By providing sources of revenue, this clean energy supports a sustainable environment while also creating employment for financial inclusion and a healthier economy for the people. It also reduces dependence on fossil fuels, minimizing the use of nonrenewable sources and fostering a strong connection between agriculture and energy. Agriculture could be reformed to utilize electric and thermal power provided by climate-smart energy sources such as biomass and solar, wind, hydro, and geothermal energy. There is a need to develop different technologies in renewable energy that can generate electricity to maximize farm production with the minimization of post-harvest losses. Therefore, it is time for agriculture to adopt sustainable sources of energy that eliminate the emission of GHGs, thereby impeding global warming and hence climate change.

Keywords

Renewable energy sources · Farm mechanization · Processing · Sustainable agriculture

1 Introduction

Sustainable agriculture is a method of resolving basic and applied food production difficulties in an environment-friendly manner (Lal, 2008). Its foundations are based on understanding both natural and environmental realities. It entails developing and implementing design and management practices that operate in tandem with natural phenomena to preserve all resources, reduce waste, and protect the environment while enhancing farm profitability. Hence, it is necessary to have a reliable energy source to accomplish a variety of agri-food chain practices, from ploughing the soil to harvesting crops and its drying (Pradhan et al., 2021). To fulfil the increasing worldwide demand for food, agricultural acreage and worker numbers must be increased. Precision agriculture (PA) has several advantages, including reducing the labor needed to meet food security, achieving sustainable management, and lowering energy consumption (Piechocki et al., 2018). To carry out field operations and enable large-scale production, farm equipment becomes essential, and it needs power inputs in terms of fossil fuels and others.

Agricultural operations are often carried out by equipment that runs on fossil fuels, potentially increasing greenhouse gas (GHG) emissions. According to the CGIAR, agri-food chains account for over 30% of world energy consumption and 19–29% of yearly greenhouse gases (Gorjian et al., 2021). Agricultural activities act as carbon source by burning of fossil fuels for operating farm machinery and other processing units and also by conventional cultivation, and soil erosion leads to breakdown of soil organic matter and emission of carbon to the atmosphere (Pretty et al., 2002). It further leads to global warming and climate change (Elum et al., 2017). The agricultural industry faces several major issues, including rising energy costs, depletion of fossil fuels, dwindling of water supplies, resistance to herbicides and pesticides, and environmental conservation (Bolyssov et al., 2019). The FAO recommends three steps to ensure that agriculture can continue to thrive in the face of climate change: increasing production and revenue, enhancing climate adaptation and flexibility, and reducing or eliminating GHG emissions (Gorjian et al., 2020; Porter et al., 2015). An increase in productivity and revenue may be achieved by improving agricultural practices, automating, mechanizing, and efficiently using resources. However, it also raises the energy needed to carry out agricultural tasks. Although mechanization has increased profitability, it has also increased energy consumption, water usage, and greenhouse gas emissions, posing a danger to long-term sustainable agriculture (Balafoutis et al., 2017; Mantoam et al., 2020). Farm machinery, such as tractors, combine harvesters, loaders, etc., play an essential part in the agricultural industry since they are used in a wide variety of farms across the globe (Malik & Kohli, 2020). Air quality and the ecosystem are constantly being harmed by rising emissions from fossil fuel-powered agricultural equipment that is poorly maintained and lacks effective pollution control legislation. According to Yousefi et al. (2017), for sunflower production alone, farm equipment accounted for 3.29% of the total CO_2 emissions of 2042.091 kg CO_2 eq/ha. Fossil fuel usage has resulted in a 13% overall carbon footprint for rice cultivation in China (Zhang et al., 2017), compared to 25% and 20% for wheat and maize cropping, respectively. To put it another way, cropping techniques, equipment type, automation degree, and production size all affect the on-farm emissions due to fossil fuel use for accomplishing different farm activities (FAO, 2017).

In view of the increasing population and high fuel cost, it's time to use alternative energy in agriculture. The application of different renewable energy sources is a long-term solution for source of power for agricultural operations by farmers as it can be harvested forever. Renewable energy sources are a possible option for farms and community buildings. Harnessing these energy sources in agriculture is termed clean energy farming. The overall quantity of carbon emitted into the atmosphere is reduced by shifting from fossil fuels for energy production to renewable energy sources (Chel & Kaushik, 2011; Waheed et al., 2018). Solar and wind energy are the most prominent renewable energy sources compared to other sources (Tyagi et al., 2012; Sibanda & Workneh, 2020).

By using different renewable energy sources, farmers can become self-sufficient by producing electrical power for lighting, heating, and fuel for different agriculture practices. It also aims to minimize the consequences of global warming and other environmental issues. Better management and the development of safe and sustainable, greener, and more efficient technology may make achieving sustainable agriculture easier. Different clean energy sources like solar, wind, biomass, hydro, and geothermal energy have greater potential to be used as power sources for agricultural machinery in farm operations. The various possible applications of renewable energy sources in agriculture are illustrated in Fig. 1.

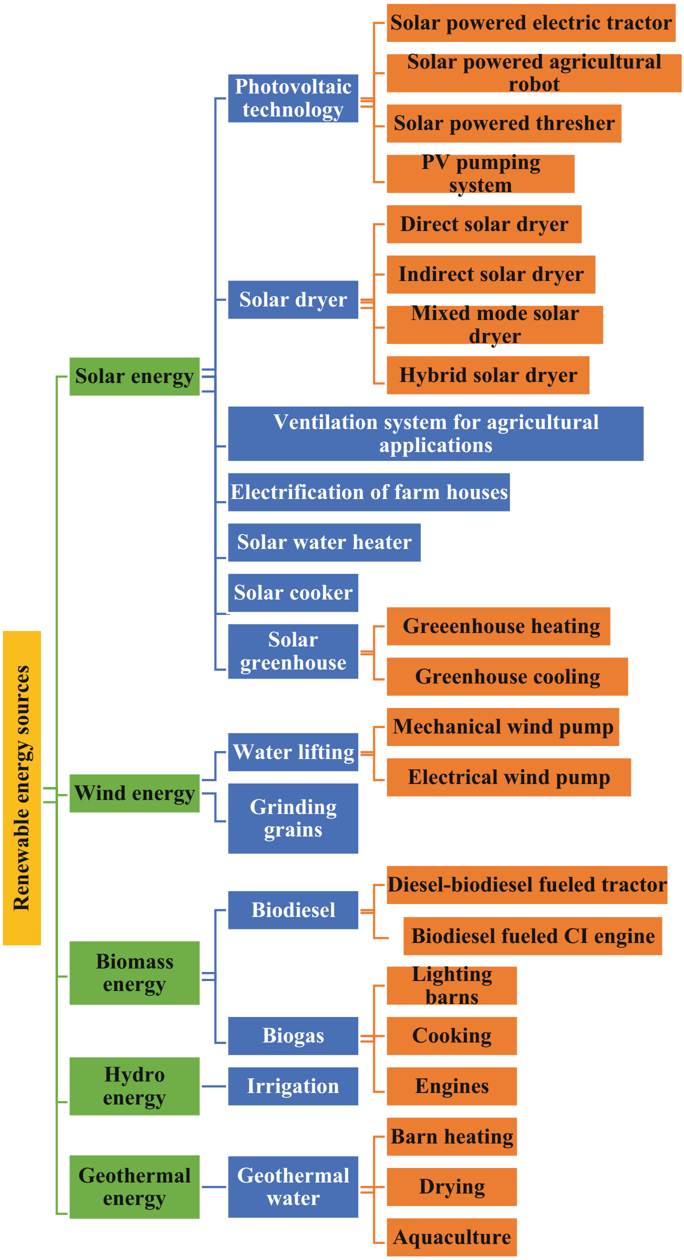

Fig. 1 Applications of renewable energy in agricultural operations

2 Application of Renewable Energy for Farm Mechanization

In its broadest sense, agricultural mechanization may be described as using tools, implements, and powered machinery and equipment to increase agricultural productivity. Human, animal, and motorized power all play a role in the production process (FAO, 2019). On the other hand, mechanization requires a substantial amount of energy because it involves a wide range of processes such as seedbed preparation, spraying, harvesting, threshing, and winnowing operation. The machines used in this process require a substantial amount of fossil fuel, which is a concern for both economic and environmental aspects. To reduce environmental pollution caused by fossil fuels, green energy (i.e., solar, wind, biomass, geothermal energy) needs to be used in agricultural field operations.

2.1 Solar Energy-Operated Electric Tractors

Several types of equipment may be attached to tractors to automate a wide range of farm operations. Additionally, tractors are also utilized for other tasks outside planting and harvesting crops and applying pesticides and fertilizers. Engine-operated machineries, which use fossil fuels and generate many pollutants into the atmosphere, are now used in most agricultural trucks. Farm equipment emission levels are substantially higher throughout tillage as it requires a significant amount of time and fuel. A hybrid electric tractor (HET) combines fossil fuels and electricity to meet the energy demands of various agriculture practices. Battery electric tractors (BETs) and fuel cell tractors (FCTs) are two types of electric tractors (ETs) that utilize just electric power (Ghobadpour et al., 2019). The electrical supply and battery storage units are the two most important components for a large-scale deployment of ETs. In this aspect, solar energy supplied by PV panels protects against power system disruptions and instabilities (Gorjian et al., 2021).

2.2 Solar-Powered Agricultural Robots

Solar-powered agricultural robots have enormous potential for performing various agricultural tasks such as ploughing, planting, food harvesting, etc. in agricultural open fields and greenhouses. At present, most agricultural robots are powered by electric engines and rechargeable batteries, making the integration of photovoltaic modules the most practicable alternative. The ecoRobotix (Gorjian et al., 2021) is a Swiss firm that manufactures autonomous solar-powered spraying robots for use in crop production, grasslands, and intercropping cultures. Weeds may be found in the field using an RTK GPS (real-time kinematic global positioning system) receiver with an onboard camera. Agrivoltaics, also known as agro-photovoltaics (APV), is a concept that involves using farmland for both agricultural output and generation of photovoltaic electricity (Dupraz et al., 2011). This method addresses the issues of restricted land areas while also increasing PV capacity and conserving fertile arable land for diverse crops. Recent advancements in PV technology have sparked widespread adoption of the APV idea globally.

2.3 Solar-Powered Harvesting System

There are several alternative ways to thresh the paddy crop, such as rubbing it against an abrasive substance or using pedal-operated paddy thresher (POPT). In most POPTs, the operator must hold the bundles of crops in place against the threshing drum's rotation so that the grains are separated from the straw by impact and rubbing against the wire loops on the spinning drum. When used for paddy threshing due to its enhanced efficiency, the pedal-operated wire-loop thresher takes more human work and time since it has a smaller threshing capacity and drudgery. These threshers may be powered by an electric motor or an integrated circuit engine. In rural and hilly areas, contemporary threshing machines driven by an engine or an electric motor are not often used. In this case, one option is a solar-powered thresher (Singh et al., 2008). The power required for threshing ranged from 130 to 160 W (Sahu & Raheman, 2020). The solar panel could not generate enough electricity for threshing during the early morning and late afternoon since the sun intensity was relatively low. During this time, the storage unit met the power requirements for the threshing process. Different parts of the solar-powered paddy thresher are shown in Fig. 2.

2.4 Wind Energy-Powered Agricultural Machinery

Wind is one of the most important, clean, renewable, and free energy sources available in the earth's surface. The bulk of present wind energy is produced as electricity, with an electrical generator converting turbine blade spinning into

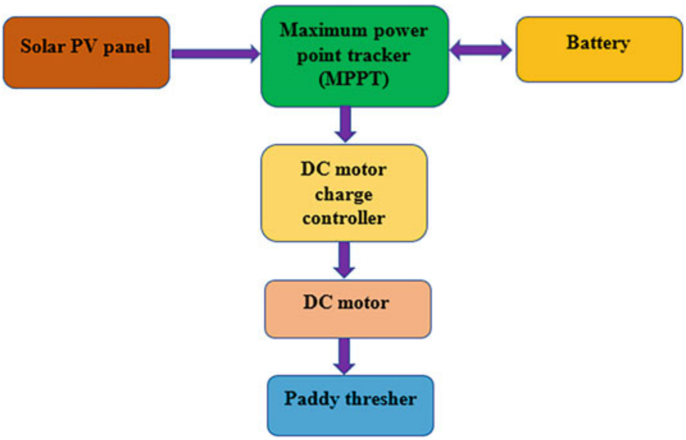

Fig. 2 Different parts of solar-powered paddy thresher

electrical current. It can be used for various purposes in agriculture, including grinding grains and water lifting (Acosta-Silva et al., 2019). Wind energy can also be used in greenhouse farming, which is hindered by rising fossil fuel prices. Due to its availability and topological superiority, wind energy is the world's foremost potential renewable energy resource (Vardar, 2003). Farmers have a unique opportunity to profit from the wind industry's advancement. Farmers may lease their farmlands to wind developers to create power for their farms or become wind power producers themselves (Chel & Kaushik, 2011). Farmers can also use wind energy to generate their power. Small wind generators, which range in size from 400 watts to 40 kilowatts or more, can provide enough power to an entire farm (Acosta-Silva et al., 2019).

Wind pumps were deployed to irrigate farms and drain the land. The regions having stable wind energy available to provide a reliable pumping solution, can use wind pump (Smith et al., 2007). When a turbine produces more energy than the farm requirement, the excess energy is fed back into the grid for others, turning the electricity meter backward. Electrical wind pumps have less efficiency than mechanical wind pumps, but they can be situated farther away from the wind turbine. When the wind turbine is rotating faster, centrifugal pumps are used, while piston and diaphragm pumps are used when the wind turbine is rotating at a slower rate. Grain and legume grinding can be done with wind energy. Early wind turbines were particularly handy for grinding even before electricity was invented. Windmills have been used to turn massive granite discs known as millstones in many parts of Europe for ages (Johnson, 1985).

2.5 Biomass Energy-Based Agricultural Machinery Operations

Bioenergy is a renewable energy source derived from biofuels or biomass-based fuels. Unlike gasoline, biodiesel is not flammable or explosive (Ramalingam et al., 2018). It is used in internal combustion engines (diesel engines) as a direct replacement for diesel fuel with minimal or little modifications to achieve the same or higher performance than conventional diesel fuel. Biodiesel is utilized in emerging and established nations such as Europe and the United States to help minimize environmental pollution and reliance on fossil diesel fuel. Biodiesel is petroleum-free and is compatible with conventional diesel fuel. Biodiesel may be mixed with diesel fuel in any proportion and form a stable mixture when used in a diesel engine. According to Buyukkaya (2010), the brake-specific fuel consumption (BSFC) of rapeseed oil was 2.5% to 7.5% greater than that of diesel fuel. Compared to diesel fuel, the smoke capacity of biodiesel diesel blends is lower, reducing 45% with B70 and 60% with pure biodiesel.

The many benefits of biodiesel are outweighed by a few disadvantages, such as increased nitrogen oxide emissions, difficulty with winter conditions, and the need to maintain engine equipment such as fuel filters, fuel tanks, and fuel lines frequently due to blockage. By using nanoparticles as fuel additives, there is even more potential for improving fuel qualities and overcoming limitations. However, extensive research on the stability, thermal conductivity, durability testing, novel models, and shelf life of NPs in relation to liquid fuels is required. Bioethanol can be used in place of or in addition to gasoline in engines. For agricultural purposes, employing bioethanol in tractors with fuel or on its own can reduce gasoline expenditures while simultaneously reducing pollutants. Bioethanol can be utilized as an energy source in generators, producing electricity for lighting barns, coops, gardens, and homes (Bayrakcı & Kocar, 2012). Our nation's domestic biogas facilities employ cattle dung mixed with an equal amount of water to keep the influent slurry at 8–9% total solids concentration (TSC). The effluent discharged from the plants is generally collected in slurry pits or scattered on the ground to dry before being transported to fields as organic manure. Biogas plants are a well-known technique for producing methane (CH_4) gas from waste like human waste and animal waste to provide clean energy (Chel & Kaushik, 2011). According to Khoiyangbam et al. (2004), methane production from an 85 m^3 biogas plant was reported to be 271.12 kg/year.

2.6 Hydro Energy-Based Agricultural Operations

Hydropower is a renewable and clean energy source. It generates no pollutants and provides low-cost electricity. Unlike fossil fuels, hydropower does not damage the environment while generating energy. Hydropower is the only renewable energy source to replace fossil fuel-based electricity production and fulfill growing energy needs. Agriculture consumes the vast majority of water on a worldwide scale. Irrigation of agricultural lands accounts for 70% of all water consumed globally (www.worldbank.org). Recycled municipal wastewater and drainage water are two alternative irrigation water sources. The use of recycled water for irrigation, on the other hand, may have some negative consequences for public and environmental health. The use of recycled water will determine soil qualities, weather conditions, and agronomic practices (Ali et al., 2012).

2.7 Geothermal Energy in Farm Operations

Geothermal energy is a type of energy in which heat energy from within the earth is captured and used for different purposes. Heat energy from the earth's interior can be used in different agricultural processes. In an open field, geothermal energy can heat the soil. Early spring and late autumn are the best times to employ this type of heating since it allows for more cost-effective production. One of the most energy-intensive aspects of agriculture is drying fruits, vegetables, cereals, and other crops. Because of its unique ability to manage drying temperature, geothermal energy can be used instead of traditional methods (Lund & Freeston, 2001).

Geothermal energy is directly used in aquaculture. The application temperature in aquaculture varies by fish type; nonetheless, geothermal resources can be employed for aquaculture activities at temperatures ranging from 21 °C to 27 °C. This temperature range enables the breeding of various fish (Ozturk et al. 2004). Creating and maintaining ideal conditions for protected plant culture is a major objective of any greenhouse construction, whether independently or with limited dependence on the outside world. Geothermal energy may be used to heat greenhouses to temperatures ranging from 20 °C to 60 °C (Babi et al., 2007). Geothermal water after producing required renewable energy may be used as a source of irrigation water after desalinizing it with the help of renewable energy, thereby reducing water scarcity in agriculture (Tomaszewska et al., 2021).

3 Application of Renewable Energy for Post-harvest Management

Post-harvest technology is a multidisciplinary method used after the product has been harvested. It involves various activities on harvested produce for conservation, handling, processing, packing, transportation, marketing, and fulfilling people's food and nutritional needs (Singhal & Thierstein, 1981). A significant amount of produce is lost during post-harvest operations due to ineffective post-harvest management practices. It includes unfavorable climatic conditions for harvesting and threshing, a lack of suitable processing technologies, a lack of basic infrastructure for drying, and improper storage handling systems (Kalaïtzis & Craita, 2016). The global agri-food value chain utilizes 30% of the world's generated power (FAO, 2021). Crop cultivation for human use necessitates the use of energy. In power cooling technologies, the accessibility of power is one of the most crucial and costlier factors as input energy (Kitinoja et al., 2011).

Due to its availability in most parts of the country, solar energy is an emerging technology used in post-harvest operations among all alternative energy sources. India's daily average solar energy incidence throughout the region ranges from 4 to 7 kWh/m^2, and most portions of the country receive 250 to 300 days of sunlight each year (Eswara & Ramakrishnarao, 2013). The International Energy Agency (SEP, 2011) states that "Solar energy offers a clean, climate-friendly, very abundant and inexhaustible energy resource to humanity, relatively well-spread over the globe". Several solar dryers, collectors, and concentrators are now being utilized for post-harvest processes such as drying, processing, storing, grinding, pressing, and value addition.

3.1 Solar Energy-Based Drying

Solar drying processes don't need an energy source or costly equipment, which makes it the most cost-effective drying technique. Natural convection drying takes longer than forced convection drying because the airflow is provided by a fan powered by an electricity/solar module, and also it is cheaper to operate (Singhal & Thierstein, 1981). Because of solar radiation's fluctuation and time dependence, energy storage is required for continuous food drying (Amer et al., 2010). Different designs of solar dryers have been adapted, keeping an eye on different climatic conditions, product types, and moisture content. Solar dryers are widely classified into two types based on how solar energy is used to remove moisture from the product, viz., direct solar drying (e.g., open-air dryer) and indirect solar drying (e.g., mixed dryer and hybrid dryer). Seaweed takes 10–14 days to dry in the open sun; however, drying using a solar dryer takes 15 h to dry with 10% ultimate moisture content from 90% moisture content (Fudholi et al., 2011). The solar cabinet dryer developed by an agency SEED with the support of Andhra Pradesh government would assist 10,000 tribal households to shorten the drying time of Gum Karaya than open sun drying from 10–15 days to 2–3 days (Ramakrishnarao, 2004). It has been made possible to shade dry leafy vegetables, spices, and vegetables, and retain their nutrient and other active components (Bamji, 2008; Eswara & Ramakrishnarao, 2013).

3.2 Renewable Energy-Based Refrigeration/Cooling

Small-scale farmers suffered postharvest losses due to physiological degradation induced by technological, biological, and environmental variables, as well as a lack of understanding about post-harvest infrastructure (Rayaguru et al., 2010). As they are produced on a small scale, modern cooling technologies are not always available to them, which are also capital intensive and require electricity. One of the most efficient methods of preserving food is to lower the temperature of the product. Because power is used across the cold chain, the refrigeration system consumes a lot of energy (Hera et al., 2007). This results in high production costs since unit energy expenses are included in the unit cost of manufacturing a specific product (Swain et al., 2009). Consequently, the enormous energy requirements on present power sources and the threat of global warming create motivation for research into innovative solutions (Hassan & Mohamad, 2012). Solar energy is the ideal among these technologies for integration with chilling methods for fresh produce because it is accessible all year (Best et al., 2013). A photovoltaic system is the heart of a solar electric refrigeration system. It drives a traditional refrigeration mechanism, which transforms solar energy into electrical energy, which is then stored in a battery and used to operate the refrigeration device's desiccating unit at night and on subsequent sunny days (Sibanda & Workneh, 2020).

Hence, evaporative cooling technology is a viable choice for marginal farmers seeking to enhance the shelf life of fresh products in hot and dry climates (Sibanda & Workneh, 2020). Zero-energy cool chamber is a simple and cheaper technology for small and marginal farmers, based on evaporative cooling technology (Dash et al., 2016). Under hot, dry, and humid circumstances with no access to electricity, a hilly remote and isolated place might benefit from a solar or wind-powered evaporative cooling system (Dash et al., 2016; Sibanda & Workneh, 2020). The evaporative cooling technique is the most effective when combined with forced air since it uses less energy to run a water pump and fans that supply cold and damp air to the storage chamber. The evaporation cooling technique is appropriate for cooling modest amounts of food for short periods, but it may extend a product's endurance by a factor of five or ten. Tomatoes, for example, with a usual shelf life of 2 days, might be preserved for 3 weeks (lal Basediya et al., 2013).

3.3 Uses of Solar Energy for Food Preparations and Processing

There are several food processing and unit activities in the food industry; therefore, various energy sources may be employed (Wang, 2013). Most electricity is utilized in heating operations and cooling activities such as freezing, chilling, and refrigeration (Drescher et al., 1997). The International Solar Energy Society has taken the initiative to develop solar food processing at the grassroot level, incorporating local groups from various African, South American, and Asian nations (Behringer, 2006). Solar energy has been effectively employed in producing numerous foods and forest products (Behringer, 2006). Some spectacular examples of daily cooking meals for a large population using solar collectors have been documented (Eswara & Ramakrishnarao, 2013).

A 10 m^2 Scheffler concentrator was recently demonstrated for bakery purposes. Each day, one concentrator could make 180 loaves of 200 g bread with uniform puffiness and color (Chandak et al., 2006). ARUN 160 is a Fresnel parabolic concentrating solar collector system used for different industrial heating and cooling applications (Eswara & Ramakrishnarao, 2013). On a commercial level, Frito-Lay's use of solar energy to manufacture sun chips in Modesto, California, exemplifies the significance of solar energy in food processing operations (Salerno, 2008). The collectors capture solar energy and generate steam, which is used to heat the frying oil used in the production of sun chips. By using sustainable energy to create steam in the production process, the company is drastically lowering its consumption of natural gas, air pollution, and greenhouse gas emissions while also generating 145,000 bags of sun chips snacks per day (Salerno, 2008). According to Frito-Lay's website (www.fritolay.com), electricity usage was decreased by 22% per bag, which was enough to power almost 15,000 houses for a year. Compared to cooking gas, the product produced by a solar concentrator was more powerful and had a less nutritional loss (Chandak et al., 2006).

3.4 Solar-Powered Milling and Pressing

Some of the most popular post-harvest tasks are milling grains and pressing oils. Since prehistoric times, water and wind power have been used in power mills and presses. Solar mills will also be used to grind essential crops like rice, corn, and cassava, which require processing after harvesting and before consumption (www.poweringag.org). The use of solar mills will help most rural villagers by increasing productivity, reducing the cost of fuel, and saving the time spent by villagers travelling to mills in remote villages, and it is also women-friendly equipment (www.poweringag.org). Integrating renewable energy generating technologies with current conventional milling and pressing machines can also generate possibilities for innovation in remote locations where grid electricity is unavailable and energy infrastructure is underdeveloped. It can also enhance energy conversion efficiency and productivity of that area and also generate income sources for villagers (www.wisions.com).

3.5 Use of Biogas in Post-Harvesting Operation

Biogas is a sustainable fuel created by the anaerobic digestion of organic materials such as food scraps and animal manure, and it may be utilized in a variety of ways as a clean energy source. Biomass power generation in India is an industry that draws investments of more than Rs. 600 crores each year, creating more than 5000 million units of energy and employing more than 10 million man-days in rural regions each year (Kumar et al., 2010). Cooking using biogas as a fuel source has emerged as a viable option for homes and communities where enclosed livestock husbandry is a common practice. It also aids in the reduction of pollutants caused by organic waste and is utilized as the best soil nutrient (www.wisions.net). Because milk is a perishable commodity that may be maintained for a longer amount of time for future use, the combustion of biogas can provide electricity that can be utilized to drive the cooling systems that store the dairy product, making the dairy value chain more efficient and sustainable. The biogas technique can chill two milk cans of up to 5 liters each in rural Tanzanian families who do not have access to electric power (FAO, 2021).

To address the domestic energy needs of developing countries, liquid biofuels such as plant oil or bioethanol can be utilized for cooking (www.wision.net). Rice milling is India's largest agro-based sector, requiring 1659 MJ of biomass energy for rice parboiling, putting it the most energy-intensive sector (Roy et al., 2006; Gupta & George, 2009; Goyal et al., 2014). As a by-product of rice milling, rice husk would generate thermal energy in furnaces for boilers and dryers, reducing fuels and electricity in the rice industry (Baqui et al., 2007). According to the literature, milling of 1 ton of rice yields around 200 kg of husk. It created 660 kg of steam, which converted into 100 kWh of power via the steam turbine (Goyal et al., 2014).

3.6 Crop Waste Used as Clean Energy in India

Every winter, pollution levels rise, and heavy haze hovers over New Delhi due to farmers in Punjab, Haryana, Rajasthan, and Uttar Pradesh burning an estimated 35 million tons of agricultural waste after harvesting (FAO, 2020). These accumulated leftovers may be processed into briquettes and pellets, which can be used to partially replace coal in thermal power plants and make compressed biogas and ethanol, which can be used to substitute natural gas in transportation fuel (FAO, 2020). According to Tuncer et al. (2019), the needed electricity in the food processing sector is fulfilled by renewable energy sources. PV units and wind turbines

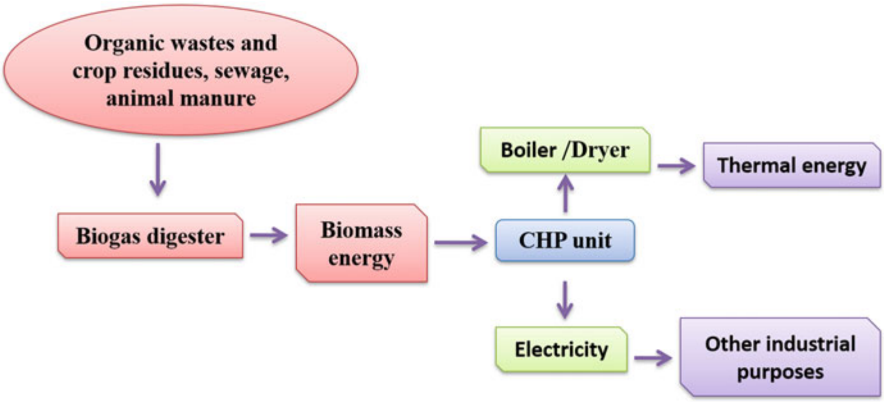

Fig. 3 Use of biomass energy sources for heat and power generation

will generate electricity, while biomass will be utilized for both combined heat and power (CHP) production (Murphy et al., 2004). PV units, made of semiconductor materials, create energy directly from solar irradiation, while wind turbine generates power stored in batteries (Tuncer et al., 2019). Biomass energy derived from burning plant waste will provide the thermal energy necessary for food preparation. The usage of fossil fuels will be significantly decreased in this approach. In undeveloped countries, proper agricultural product handling may play a critical role in ensuring food security and increasing crop economic value. Many food-processing technologies need thermal or mechanical energy, in which renewable energy sources may convert to thermal and electrical energy (Nadaleti, 2019). Flow chart showing use of biomass energy sources for heat and power generation is presented in Fig. 3.

3.7 Wind Energy Utilization for Food Processing

Wind turbines may supply a considerable portion of a farm's average power needs; nevertheless, they should be located in areas with strong winds and normally require at least 1 acre of land to generate adequate power (www.ag.umass.edu). A wind turbine is an ideal adjunct to a solar system in temperate climates. When solar energy is not available, wind energy can be used. Wind energy is also ideal for supplying enough energy to run basic, low-cost cooling equipment, which is important for the temporary storage of fruits and vegetables. As the refrigeration system is energy-intensive and consumes high electricity, for small-scale farmers, the evaporative cooling method is considered a simple and low-cost cooling option to store their fresh produce for a short-term period (Tigist et al., 2013). It is helpful in hot and dry climates. Evaporative cooling delivers cold air by pushing hot, dry air over a wetted pad, and the water in the pad evaporates, eliminating heat from the air while providing moisture (Chaudhari et al., 2015; Sibanda & Workneh, 2020). Zero energy cool chamber (ZECC) is a natural ventilated evaporative cooling system. It requires

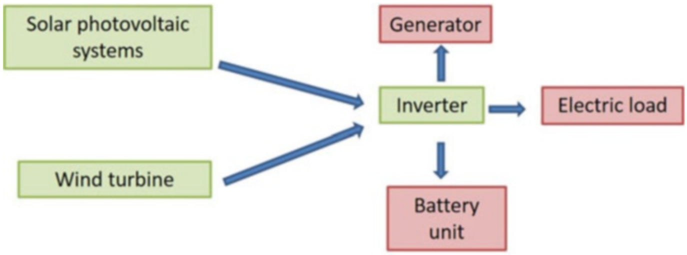

Fig. 4 Use of solar and wind energy for power generation

no electrical input in a passive system, has a modest decline in quality that is suited for rural and remote places, requires no particular expertise to run, and can be created from locally accessible materials (lal Basediya et al., 2013; Chaudhari et al., 2015; Tigist et al., 2013). ZECC is an effective and economical method for enhancing shelf life and storage of green vegetables and mushrooms so that it can reach the market without any deterioration (Chaudhari et al., 2015; Dash et al., 2016). Consequently, power-intensive refrigerating equipment was replaced with an integrated approach combining cooling technology and renewable energy as a source of power. In this approach, both solar and wind power play a vital role in supporting the farmers of developing countries. Integrated use of solar and wind energy for power generation is presented in Fig. 4.

4 Suitability, Needs, and Shortfalls of Renewable Energy

Renewable energy investments are more expensive than traditional sources. Renewable energy can enhance and alter the economy, environment, and society. Investments in biogas as a renewable resource for energy production, in particular, may be economically profitable due to revenue from power sales and the replacement of fossil fuels (Nadaleti, 2019). Solar energy can only be operable throughout the day; however, drying is discontinuous or intermittent. Solar equipment has a high initial installation cost. According to the literature, evaporative cooling is efficient in hot and dry places but has limits in hot and humid areas due to the inherent high humidity of local air (Sibanda & Workneh, 2020). It is also not suitable for large quantities of produce for a longer storage period.

5 Future Scope

In India, the utilization of rice husk for biogas to generate heat and electricity is a scope as India is a sizeable rice-producing country. Due to the absence of knowledge and awareness, solar energy is limited to micro- to small-scale processing. The high initial installation cost of solar equipment, lack of practical expertise, a lack of suitable infrastructure, and a limited number of government incentives all contribute to the industry's inability to use solar energy on a big scale. It should be researched further to make large-scale investments in renewable energy. More significant research, demonstration, and implementation efforts are required to create contemporary renewable mills and presses (www.energypedia.info). More study is required to power refrigeration cycles with solar collectors, wind energy, and biogas combustion. According to the Integrated Energy Policy Report, renewable energy is expected to provide 60,000 MW to energy production in the years 2031–2032. Renewables will be a driving factor in the social integration of the underprivileged in the development process by 2031–2032 (Kumar et al., 2010).

6 Conclusion

An agricultural industry that consumes a large percentage of its energy needs from fossil fuels threatens its long-term viability. Global food security will be threatened if agricultural equipment development does not achieve sustainability of yield. It is thus necessary to implement a revolution in technical innovation that reduces the carbon footprint while introducing renewable energy systems into agricultural operations. In addition, increasing the performance variety of agricultural operations while maintaining a better degree of accuracy has increased power consumption in this industry. Solar energy-based solutions are now employed for post-harvest operations among all renewable energy sources. Considering changing lifestyles in India, there is a tremendous scope for ready-to-eat (RET) foods, and solar food processing can play a significant role in meeting this need at a low or no cost. Solar dehydration or drying is a viable and effective alternative to mechanical drying. Despite the fact that little or no research has been conducted on the use of wind energy as an energy source for cooling technologies, there is room to develop an inclusive system including both solar and wind combined with cooling technology. It will contribute to ensuring food security by generating revenue from the sale of their produce. More research is required before designing or developing a solar- or wind-powered evaporative cooling system for usage in hot-dry and hot-humid areas. To achieve sustainable development, we must embrace innovation, make renewable energy useable, establish more efficient food value chains, and progressively migrate to energy-efficient agro-food systems. Utilizing clean energy may provide a source of revenue for farmers, minimize health risks caused by decreasing air quality, and increase soil quality and biodiversity. Therefore, renewable energy-powered machines for field operations solve productivity and the environmental issues.

7 Cross-References

► Application of Gasification Technology in Agriculture for Power Generation
► Carbon Footprint of Different Energy-Intensive Systems

▶ Efficient Management of Energy in Agriculture
▶ Energy Conservation in Farm Operations for Climate-Smart Agriculture
▶ Energy Management in Agriculture
▶ Energy Requirements for Sustainable Sugarcane Cultivation
▶ Energy Management Across the Globe and Possibilities
▶ Use of Smart Technology in Agriculture for Energy Management

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Bioenergy Crops

Challenges and Opportunities

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Abstract

Alternative sources of energy are the need of the hour since we are dependent upon traditional resources like fossil fuel for fulfilling our energy demands, but how long? The time has come when traditional sources of energy are depleting day by day and we are getting out of stock in terms of our energy. Using plants for the production of energy can be a good and efficient alternative that will be ecologically sustainable as well as financially stable for the ever-increasing population. This chapter focuses on such types of bioenergy crops, which can be the heroes of the coming generation in terms of energy production. Energy generated using bioenergy crops will be cleaner and cheaper, produce fewer greenhouses gases, and also help in carbon sequestration. Based on the roles played, the bioenergy crops can be divided into first generation, second generation, third generation, dedicated plants, and halophytes. Along with the multifaceted benefits like climate change, carbon sequestration, reduction in nitrous oxide emission and nitrate leaching, and restoration of ecological balance, there can be some challenges also in growing bioenergy crops. The challenges that we might be facing in growing bioenergy crops can be the competition for land and water with our main food crops, instability of the market for bioenergy crops, less economic incentives to produce and transport the bioenergy crops, and also the socioeconomic impacts. Despite the challenges associated, growing bioenergy crops can be beneficial in fulfilling the energy requirement of future generations.

Keywords

Ecosystem · Fossil fuels · Biofuel · Climate change · Carbon sequestration

1 Introduction

The world's energy demands are increasing along with a surge in the human population (consumption has been tripled since 1960), most of which is fulfilled by fossil fuels to date (Hein, 2005). But being nonrenewable sources of energy, there is a need of the hour to replace a part of these fossil fuels with some alternative sources of energy. Also, the burning of fossil fuels is creating a lot of pressure on the environment in terms of carbon emissions, greenhouse gases, harmful nitrogenous and sulfur gases emissions, etc. These harmful gases lead to long-term climate changes like acid rains, shift in temperatures, soil acidification contributing to the degradation of land, and also desertification of fertile soils. Hence, the fundamental reasons for alternative energy sources can be stated as climate change and the non-renewability of fossil fuels (Karp & Shield, 2008).

For ages, plants have been serving various needs of the human population, being the primary producers in the food chain, and are irreplaceable and used as fuel (wood) for cooking and heating purposes, although fossil fuels and other sources (hydropower plants, nuclear power plants) of energy have replaced their role as fuel providers up to some extent. But due to the nonrenewable nature of these other sources of energy and their harmful effects on the environment, once again, attention has shifted toward plants as a source of energy (Karp & Shield, 2008). Therefore, using bioenergy crops for energy production could be a possible alternative for fulfilling future energy needs. Energy from bioenergy crops comes from biomass of plants (Taylor, 2008). Bioenergy crops can have multifaceted uses like phytoremediation of heavy metal contaminated soils (Barbosa et al., 2015), reducing the level of carbon dioxide, decreasing the greenhouse gaseous emission, increasing soil carbon, reducing soil erosion (Wang et al., 2012; Kim et al., 2013), and also providing products like ethanol, biodiesel, biogas (Yuan et al., 2008), etc.

The renewability and eco-friendly nature are the factors responsible for so much attention given to bioenergy crops. Along with so many benefits, there come greater challenges also with the usage of bioenergy crops. Globally, the crops used as bioenergy crops are more famous for fulfilling food needs. So there is a risk for food crisis involved in the world market. Also, bioenergy plants compete with normal crop plants for their land, water, and nutrient requirements. Increased dispersion of invasive plant species and disturbance in natural wildlife habitats can be the other cons of bioenergy crops (Dipti, 2013). This chapter emphasizes on bioenergy crops, their types, and usage along with the problems and challenges associated with them.

2 Types of Bioenergy Crops

Biofuel or bioenergy crops can have multifaceted uses and contributions, although their role as bioenergy crops is still questionable due to food security, land availability, and nutritional issues. Bioenergy crops are majorly classified as per their usage like for oil production and yield, fodder production, and major ecosystem helpers to mitigate various climate change phenomena (Figs. 1 and 3 Singh, 2008). Based on their role, bioenergy crops can be classified into five different categories, viz., first generation, second generation, third generation, dedicated energy crops, and halophytes (Fig. 1).

2.1 First-Generation Bioenergy Crops

The common sources of food either locally or in the international market are included under first-generation bioenergy crops. First-generation bioenergy crops include maize, sugarcane, soybean, rapeseed, date palm, sunflower, safflower, etc. Some of which can be used to produce biofuel (Lobell et al., 2008). However, first-generation bioenergy crops are costlier than traditional sources of petroleum and fuel due to their higher cost of production (Wang & Yan, 2008), but the problems associated are counteracted by second-generation bioenergy plants due to their processing style is the use of lignocellulosic material from their residue for the extraction of oil and fuels (Eisenbies et al., 2009).

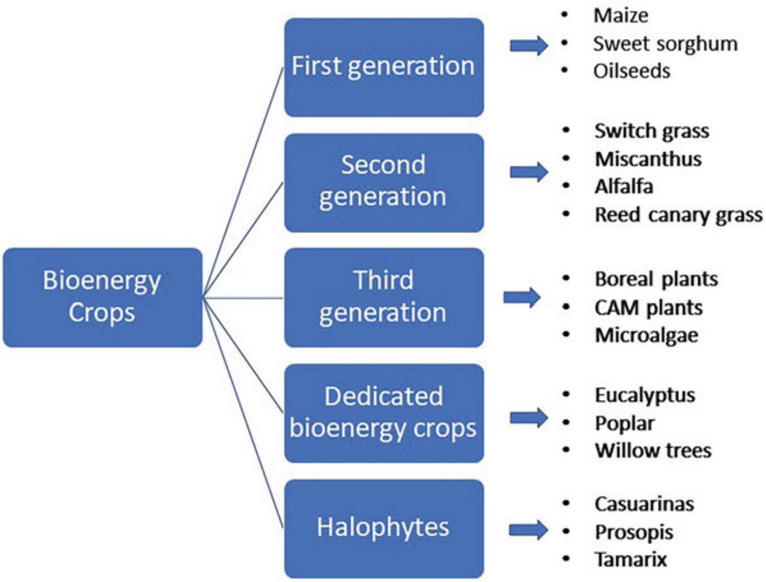
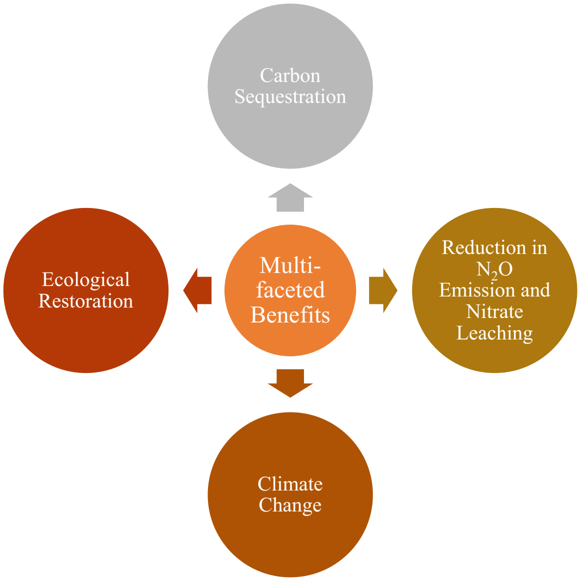


Fig. 1 Types of bio-energy crops

Fig. 2 Different bioenergy crops grown under varied agro-ecology (**a**) Maize (*Zea mays*); (**b**) Sugarcane (*Saccharum offiicinarum*); (**c**) Jatropha (*Jatropha curcas*); (**d**) Soybean (*Glycine max*) (**e**) Napier grass (*Pennisetum purpureum*); (**f**) Rapeseed (*Brassica napus*); (**g**) Datepalm (*Phoenix dactylifera*); (**h**) Switchgrass (*Penicum virgatum*); (**i**) Agave (*Agave sp.*); (**j**) Eucalyptus (*Eucalyptus globulus*); (**k**) Alfalfa (*Madicago sativa*); (**l**) Sorghum (*Sorghum bicolor*); (**m**) Sunflower (*Helianthus annuus*); (**n**) Safflower (*Carthamus tinctorius*); (**o**) Timothy grass (*Phleum pratense*); (**p**) Reed canary grass (*Phalaris arundinacea*)

Fig. 3 Multifaceted benefits of bioenergy crops



2.1.1 Maize

Zea mays has a high rate of accumulation of starch in its grains and also a high yield, proving itself as an important cereal crop (Yadav et al., 2019). The bioconversion of corn is rather easy due to the high percentage of volatile compounds present in it. Although maize is used in several Western countries for the production of ethanol, its usage as the main cereal crop in different countries poses a problem in its usage as a bioenergy crop. If we start using maize as a bioenergy crop and reduce its usage as cereal, there might be a chance of increasing the prices of maize in the world food market. Hence, different varieties of maize like sweet corn have been developed with the use of spontaneous mutations in recessive form for genes that control the conversion of sugars into starch in the endosperm of kernel. The world food supply along with energy generation can go hand in hand with the use of these dual-purpose and photosynthetically efficient hybrids of sweet corn (Takamizawa et al., 2010).

2.1.2 Sweet Sorghum

Sorghum bicolor is a C4 crop with fewer input requirements, making itself easily cultivable on marginal lands. It has a large number of grass varieties with high sugar content as its stem can store fermented sugar in higher amounts for larger biomass. Sweet sorghum can also be used as a base crop for understanding the genome complexity of other bioenergy crops like maize, sugarcane, miscanthus, etc. (Paterson et al., 2009). Even during drought stress, it can store a large amount of sugar content in its stem with high nitrogen use efficiency (Harris et al., 2007). It has a good scope in being used as a bioenergy crop by crossbreeding sorghum and sweet sorghum for gene mapping to increase crop productivity and desired characters (Okada et al., 2010; Swaminathan et al., 2010).

2.1.3 Oilseed Crops

Rapeseed, castor, sunflower, safflower, groundnut, olive, coconut field mustard, and hemp are some oilseed crops. Oils generated from these crops can be used for the transportation of biofuels and also can be utilized as fuel for heating purposes (Sims et al., 2006).

2.2 Second-Generation Bioenergy Crops

Forage crops of perennial nature like switchgrass, alfalfa, reed canary grass, Napier grass, and Bermuda grass are included in the second-generation bioenergy crops (Sanderson & Adler, 2008; Oliver et al., 2009). Second-generation bioenergy crops are more energy efficient than first generation as they are capable of generating a higher amount of biofuel from cellulosic materials. The fuel generated from second-generation bioenergy crops is in general more oxygenated and pure hydrocarbons (Oliver et al., 2009). The cost of biofuel production in second-generation bioenergy crops is comparatively less but more on environmental sustainability. Lignocellulosic crop wastes are used for biofuel production either by thermochemical process or by some biochemical process (Petersen, 2008). Growing second-generation bioenergy crops is beneficial in many ways like less cost of input, less emission of greenhouse gases, and more production of biofuel energy, and also, they need less post-harvest processing (Kotchoni & Gachomo, 2008).

Nowadays, the crop which has the most scope in bioenergy is sugarcane as the remnants of the sugarcane industry (bagasse) are generally used for heat generation in the factories which can be used on a broad scale for bioenergy production because bagasse contains a large amount of cellulosic biomass having β-1,4-glycosidic linkages, upon which on the action of cellulose, decomposing bacteria cellulose can be released that can further be used for the generation of biofuel (Waclawovsky et al., 2010). On a wide range, the use of sugarcane stalk residue is still unexplored although some developed countries are harnessing the benefits of this crop through the production of bioethanol (P Yadav et al., 2019). Some examples of second-generation bioenergy crops are discussed here.

2.2.1 Switchgrass

Switchgrass (*Panicum virgatum*) is a warm-season perennial crop grown generally on marshy areas and also erosion-prone lands. Although switchgrass (hardy, deep-rooted) does not require much attention and care to get properly established on a particular land, it can take more or less 2 years for it to grow (McLaughlin et al., 2006). Being a C4 plant and tolerant to drought and high temperature and having less requirement for care and nutrition make it a good choice for biofuel production (Vogel & Mitchell, 2008). Although the ability of switchgrass as a bioenergy crop is less explored due to its hardiness, longevity, drought and flooding tolerance, less input requirement, ease of management, wide adaptability to the environment make it efficient for bioethanol and bioenergy production (Casler et al., 2007; Rose IV et al., 2008).

2.2.2 Miscanthus

Miscanthus (commonly known as silver grass) is also a C4, high-carbon-dioxide-fixation-rate grass, with less input requirement (Villaverde et al., 2009). In European countries, it is used as feedstock in herbaceous categories due to its morphological structure and mainly used as forage crop, having about 19 to 20 species. The vegetative yield of silver grass is much higher than switchgrass due to its fast-growing nature, very low fertilizer requirement, and input requirement (i.e., cost of production is comparatively less), and it remains productive for longer periods (Heaton et al., 2010; Villaverde et al., 2009). Thus, silver grass can be used widely for biofuel production, except for difficult greenhouse production.

2.2.3 Alfalfa

Alfalfa (*Medicago sativa*) is one of the oldest cultivated forage crops, stems of which are used for the generation of electricity and leaves have high protein content (Russelle, 2001). The stem cells of alfalfa contain polysaccharides and lignin that make its vegetative biomass of high quality and quantity. Therefore, alfalfa can be used greatly as animal feedstock and also for ethanol production on a large scale (Delong et al., 1995; Lamb et al., 2007).

2.2.4 Reed Canary Grass

Reed canary grass (*Phalaris arundinacea*) is a tall, perennial bunchgrass found mainly in open wet areas with wide habitation in Europe, Asia, and North America as stated by the USDA Germplasm Resources Information Network (Abhijeet et al., 2020). Similar to switchgrass, reed canary grass has low yield and retarded growth. But it is very efficient in nitrogen assimilation and internal transfer. With riverbanks and wetland areas as habitats, it produces relatively higher vegetative biomass that rather can be used very efficiently for the production of bioenergy (Tahir et al., 2011).

2.3 Third-Generation Bioenergy Crops

Various plants like eucalyptus, crassulacean acid metabolism plants, boreal plants, etc. are included in the third generation of bioenergy crops. Third-generation bioenergy crops are majorly dominated by algae. Boreal and CAM plants have high cellulosic fiber content and hence can participate directly in contributing to bioenergy production (Patil et al., 2008; Schenk et al., 2008). Great potential exists with third-generation bioenergy crops as algae are one of its biggest components; hence it can be very cost-effective. Energy conversion of cellulosic bacteria into biofuel plays a bigger role. As in aerobic conversion, cellulose is directly converted into carbon dioxide, but in the case of anaerobic conversion, methane and hydrogen gases are produced. Third-generation bioenergy crops can emerge as newer, cheaper, greener, and renewable sources of bioenergy, ultimately helping in mitigating climate change (Bush & Leach, 2007; Rubin, 2008).

2.3.1 Boreal Plants

Ficus indica, *Opuntia*, *Agave sisalana*, and *Phleum pratense* are some of the major and famous boreal plants that can be used for bioenergy production. Boreal plants have a great potential in biofuel production as they require minimal conditions for their growth. They are resistant to diseases and pathogens, fast-growing and harvested quickly, and high methane-producing species and also have higher biomass. Boreal plants can tolerate harsh winters and rough climates and also require very less soil nutrients for their growth (Finckh, 2008). Hence, boreal plants make a good match for bioenergy production.

2.3.2 Crassulacean Acid Metabolism Plants

CAM plants are found in an arid climate with high water use efficiency and carbon dioxide assimilation. These plants help in excess carbon dioxide uptake even at night. Due to their high drought-tolerant ability and very less water requirement, they are much more efficient than C3 and C4 plants. Due to their hardy nature, they are a perfect fit for being used as biofuel crops (Borland et al., 2009; De Fraiture et al., 2008).

2.3.3 Microalgae

Microorganisms are found in seawater and freshwater and also on the terrestrial ecosystem with huge biomass, high multiplication rate, and great survival skills. Microalgae help in carbon sequestration, reducing greenhouse gases emission by absorbing most of the carbon from the atmosphere among them, thus having great potential in managing and mitigating climate change (Ahmad et al., 2011; Schenk et al., 2008). They have high photosynthetic efficiency and ability to produce large biomass than terrestrial plants due to their quick growth abilities. Due to their ability to produce huge biomass in a short period, they can be a good match for bioethanol, biofuel, and bioenergy production. Also, their use for biofuel production would not hamper world food supply and economic structure, unlike most terrestrial plants, as they can be produced and harvested throughout the year (Patil et al., 2008; Williams et al., 2007). Many industries and firms are promoting microalgae use for bioenergy as they generate biofuel with high biodegradability and conversion efficiency that will ultimately lead to ecosystem balance also.

2.4 Dedicated Bioenergy Crops

Bigger tree plants like eucalyptus, poplar, and willow tree; perennial grasses like reed canary grass and elephant grass; and oilseed crops (non-edible) like castor, jatropha, etc. are included in the dedicated energy crop plants. These are hardy, woody, and less input-demanding crop plants. Along with the generation of bioenergy, these plants can also be used for remediation purposes like alkalinity and salinity remediation, waterlogging remediation carbon sequestration, carbon farming, etc. (Lal, 2008; Peterson, 2008). Short-duration crops are also mostly included in the dedicated bioenergy crops group so that they can be harvested again and again throughout the year, providing plenty of biomass (Boe & Lee, 2007; Ranade et al., 2008). Various developed countries are promoting large-scale production of more and more dedicated bioenergy crop plants.

2.5 Halophytes

Plants like *Eucalyptus*, *Casuarina*, *Melaleuca*, *Prosopis*, *Rhizophera*, and *Tamarix* are some of the halophytes that are famously used for biofuel production. Seeds of *Kosteletzkya pentacarpos*, a perennial halophyte, are used for the production of biodiesel (Moser et al., 2013). Halophytes have a higher number of secondary metabolites and hence conversion efficiency to biofuel (Hastilestari et al., 2013). Halophytes can be grown easily on marshy lands, mangroves, swamps, and estuaries and on saline-alkaline conditions and also can be used for phytoremediation of degraded lands (Jaradat, 2010; Rockwood et al., 2008). Phytoremediation by halophytes helps in ecosystem restoration, and carbon sequestration, along with the protection of flora and faunal population of an ecosystem. Halophytes can also be used for the phytoremediation of heavy metal-polluted soils, food production, timber, and biomass, medicinal purposes, etc. (Hasanuzzaman et al., 2014). Halophytes can also be used for the conservation of wildlife (Panta et al., 2014). Hence, halophytes make a great match for large-scale use as bioenergy crops.

3 Multifaceted Benefits of Bioenergy Crops

3.1 Carbon Sequestration

Bioenergy crops, such as perennial grasses, tend to mitigate climate change by sequestering CO_2 from the atmosphere in soils and roots below ground. Degraded lands could be feasibly managed with the help of perennial plant species and hence provide an immense opportunity for land restoration (Yang & Tilman, 2020).

3.2 N_2O Emissions and Nitrate Leaching

Nitrous oxide (N_2O) contributes to global warming extensively as it is about 300 times more potent than CO_2 in terms of global warming potential. The application of nitrogenous fertilizer has the fate of nitrification and denitrification through microbial activities. Excessive nitrates in soils tend to leach, outreaching to groundwater, whereas denitrification leads to the emission of nitrous oxide. When legumes are intercropped with grasses, denitrification is checked, and similarly, the more diversification we follow, the lesser will be the wastage of resources, while biofuel production could be the spillover benefit. Many studies have been carried out suggesting the cultivation of binary crops of legumes-cereals over cereals and numerous others stress more species having complementarity to use reactive N efficiently (Hussain et al., 2019).

3.3 Climate Change

Provided that good management practices are followed and efficient systems are to be used, besides energy security, bioenergy crops can have several other potential benefits, viz., food security, climate security, and sustainable development (Souza et al., 2017). Compared to fossil fuels, biofuels have lower health toxicity and reduced GHG emissions. Achieving an aggressive goal of maintaining a rise in global temperature below 2 °C requires the substantial contribution of bioenergy on a larger scale.

3.4 Ecological Restoration

India faces two major hindrances in the way of development, viz., energy insecurity and degradation of the ecosystem, which are the major causes of perpetuating poverty. In addition to fulfilling demands of energy requirement, bioenergy crops have the potential to minimize degradation and further helps in restoring the ecosystem through their services. The positive impact of bioenergy crops is that they enhance the health and functionality of the land on which they are grown. They may even act as a substitute for the preexisting land use activity that was earlier causing degradation or posing vulnerability to future degradation. Several other benefits include the protection of soil against erosion and desertification, increased habitat for biodiversity, mitigation of soil salinity, and even improved water quality (Baumber, 2016).

4 Problems with Growing Bioenergy Crops

Can bioenergy crops play a vital role in the future of sustainable food? The answer must consider the intensive competition for resources required for food, feed, and several other activities as usage of land and other resources for bioenergy will inherently come with the drawback of diverting these from the main purpose. Hence, growing awareness of bioenergy crops has aggravated the problems of resource scarcity (Fig. 4).

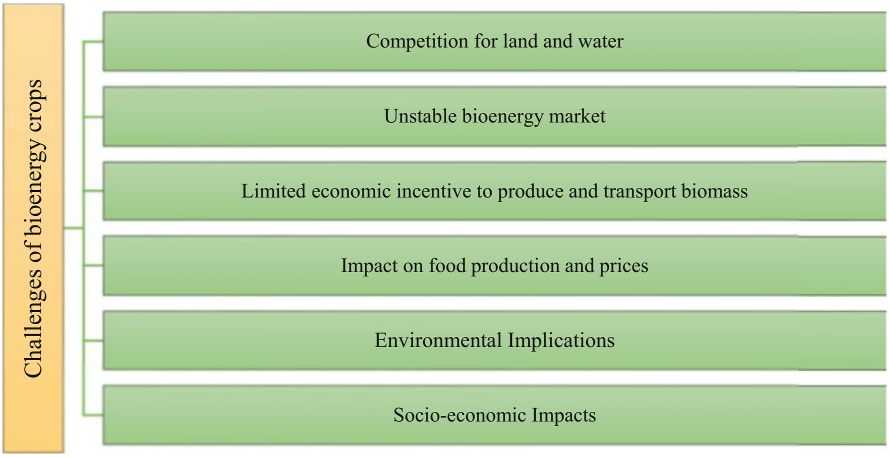


Fig. 4 Challanges associated with growing of bioenergy crops

4.1 Competition for Land and Water

Large-scale cultivation of bioenergy crops puts substantial pressure on land water resources. Usually, bioenergy crops are higher in biomass and fast-growing types which require larger land area (Boysen et al., 2016) and water requirements (Stenzel et al., 2019). These constraints could prevent targeting the achievable yield of bioenergy crops. Land constraint can be met by increasing productivity through a proper irrigation system which exerts a burden on freshwater reserves. Water, being an essential component, has a considerable contribution to the agriculture sector, i.e., 70%. For cultivating crops to meet the energy need, we would require a higher amount of water to be diverted into agriculture. Bonsch et al. in 2014 concluded that without a proper water protection policy, there is a high chance of deterioration of freshwater. Hence, focus should be shifted from higher productivity to sustainability. But prohibiting irrigation could lead to loss of an important natural resource, i.e., land. And hence, policies that balance water and land use implications of large-scale bioenergy production are of prime importance.

4.2 Unstable Bioenergy Market

Bioenergy requires feedstocks which are generally either crop or crop residue. These feedstocks are an important input for animal husbandry and horticultural purpose, and hence there is a competition. Also, insufficient market and technological development are widespread (Mouratiadou et al., 2020). In developing countries, sole dependency on financial support in bioenergy investment becomes important, which often tends to be a barrier.

4.3 Limited Economic Incentive to Produce and Transport Biomass

The potential drawback in biofuel production is that these may require subsidies and several other market strategies and interventions to compete economically with fossil fuels which again will further create deadweight losses in the economy. High costs of feedstock processing and environmental concern have been among the major issues being discussed in scientific debates and among policymakers.

4.4 Impact on Food Production and Prices

Presently, food insecurity is the most crucial problem the world is dealing with, as nearly 842 million people are estimated to be suffering from hunger and malnutrition. The idea of utilizing the land for the dedicated growth of bioenergy crops may exacerbate this problem. Subramaniam et al. (2019) reported a worsening in food security due to the use of first- and second-generation biofuels. Although there has been growing interest in biofuel production, it has also sparked debate on how the introduction of biofuels may jeopardize food security. While studying the Columbian case, Martinez-Jaramillo et al. (2019) estimated that introduction of biofuels may reduce agricultural land use by 12.4%, which will cause a rise in food prices considerably by 2030.

4.5 Environmental Implications

According to USEPA (2021), changes in land-use patterns have caused rising emissions of greenhouse gases due to the release of terrestrial carbon stocks. It was also reported that feedstocks obtained from tropical forest land after clearing have led to loss of biodiversity such as in the Amazon Forest for soybean and oil palm cultivation in Southeast Asia. An increase in fertilizer and pesticide use from increasing biomass is another burden on the environment. Indiscriminate harvest of crop residues for biofuel production could lower the soil's organic carbon stock (Cherubin et al., 2018). Forestry residue harvests have negative potential impacts on soil quality. Several trade-offs from the harvest of crop residue play an obstacle in the fast-growing biofuel industry.

4.6 Socioeconomic Impacts

This dimension is social, cultural, and behavioral, which is not the least important. The transmission of the conventional system to a sustainable one requires awareness about climate change among people. Acceptance by commoners is thus a challenge in achieving the target. Galik (2015) conducted a study where it was concluded that profit maximization is a critical motivation for bioenergy feedstock production, but constraints were infrastructural obstacles and social restrictions. To make biofuel industry successful, we should first analyze the attitude of landowners toward the adoption of new crops on their land.

5 Conclusion and Future Prospects

Restoring ecological balance, carbon sequestration, and also low cost can be some of the major characteristics of bioenergy crops. By utilizing bioenergy crops, our dependency on already existing and also depleting sources of energy will reduce to manifold. Biodiesel and biofuel are some of the major products from starches and cellulosic fiber material of bioenergy crops. Leftovers of many crops like sugarcane are being used for the production of bioenergy, which requires industrial processing only. Also, growing bioenergy crops on barren lands can help in the restoration of soil qualities and also in carbon sequestration. However, challenges associated with the production and processing of bioenergy crops like competition for land and resources, transportation costs, and also socioeconomic challenges cannot be ignored. But still, in the bigger picture, they are beneficial for the fulfillment of future energy demands and also in replacing the depleting fossil fuels. Thus, there is a need for more research in terms of which type of bioenergy crop is suitable for any particular area and also its management for biofuel production.

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Rice Straw Management

Energy Conservation and Climate Change Mitigation

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Contents

Abstract

In India, cereal crops produce the majority of crop residues (58%), followed by fiber crops (23%). In the Indo-Gangetic Plains (IGP) of India, rice–wheat is the predominant cropping system, where 81% of rice and 48% of wheat stubbles produced are burnt, whereas only 7% of rice and 45% of wheat straw are used as

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fodder. The growing use of combine harvesters in the IGP, a narrow window (2–3 weeks) for field clearance after rice harvest to prepare for the sowing of *rabi* crops, mainly wheat and potato, during October/November, and the lack of their traditional use for domestic purposes (e.g., animal feed, roof thatching, fuel, packaging, and compost making), are the major compulsions of farmers leading them to burn the crop residues. Residue burning causes a huge loss of valuable nutrients besides severely polluting the land, water, and aerial environment on local as well as regional levels. A number of alternative solutions, such as crop diversification, subsidizing happy seeders and balers for their wide-scale promotion, the use of straw as animal fodder, and in power generation, for biochar and compost making, for making building materials, and many other small-scale enterprises such as mushroom cultivation have been suggested, and policy guidelines have been framed/transformed at different fora, but the desired impact is yet to be realized because of one or other challenge. A critical analysis of the burning issue reveals that we need to ponder and arrive at a workable solution specific to region/state/locality/community. However, it is important to strike a balance between in situ and ex situ straw management so as to minimize greenhouse gas emissions in residue-loaded fields, and nutrient depletion in the fields subjected to continuous residue removal or burning.

Keywords

Air pollution · Climate change · Happy seeder · Residue management · Rice-residue burning · Soil health

1 Introduction

The use of irrigation and fertilizers pushed a large proportion of area under rice–wheat rotation, which eventually attracted mechanical harvesting, leaving more rice-stubble in the fields. As machine harvesting and threshing are more efficient and save labor, time, and money, the number of machines has increased dramatically to 26,000 in India, most of which are operational in the north-western (NW) part of the country (Singh, 2018b). But the major challenge in the use of combine harvesters is that a huge mass of residue is left in the fields after harvesting, and it is beyond the means and capacity of the farmers to manage such a huge bulk. Hence, farmers generally resort to a quick, economical, and easier way of burning the residue in their fields for timely sowing of the succeeding *rabi* crops. The world over, the annual production of rice straw is about 731 mt, of which 667.6 mt is produced in Asia alone, 37.2 mt in the USA, 20.9 mt in Africa, 3.9 mt in Europe, and 1.7 mt in Oceania (Kim & Dale, 2004; Faveri et al., 2004).

In India, standing stubble with straw (25–30 cm height) left in the fields after combine harvesting is usually burnt. Paddy generates about 22,289 Gg of straw annually, of which 13,915 Gg is burnt in the open fields, causing loss of soil nutrients to the extent of 3.85 mt of organic carbon (OC), 59,000 t of N, 20,000 t of P, and 34,000 t of K, besides causing the ambient air quality to deteriorate (Singh, 2018a). Residue burning with such a high level of emission, has been considered as a major environmental issue. This antediluvian practice of burning crop residue was banned by the National Green Tribunal (NGT, 2015) in the pollution-hit city of New Delhi, and the nearby National Capital Region (NCR) states, Punjab and Haryana, and a number of regulatory and remedial measures were suggested to ward off the ill-effects of residue burning. But, despite several strict regulatory measures and even farmer-friendly steps taken by the Government of India and the concerned state governments, the residue-burning practice continues unabated and has become a matter of serious concern for environmental safety and human health. In this chapter, we have reviewed the causes and extent of residue burning, its impact on aerial as well as soil environment, and efforts made so far in public and private sectors to mitigate the problems, including technological interventions, regulatory provisions and monitoring mechanisms, possible localized solutions, management strategies and alternate uses, and suggestions/recommendations for policy prioritization/transformation.

2 Impacts of Residue Burning

As per the report of the System of Air Quality and Weather Forecasting and Research (SAFAR), crop residue burning contributes around 10–20% of Delhi–NCR's air pollution during the winter months of October–November 2019. Air pollution in Delhi during this period was about 12–20 times higher than the WHO's safe limit for air quality.

The contribution of residue burning is estimated to be about 25% of India's total emissions of carbon-rich particles (Venkataraman et al., 2006); a serious cause of climate vulnerabilities and global warming and also a potential target for mitigation measures. The second-largest contributor to global warming black carbon (next to CO_2) is produced because of the partial burning of biomass such as agricultural residues (UNEP, 2009). It implies that burning crop residue in open fields or places is the most undesirable practice, leading to environmental degradation and further intensifying the problem of global warming.

In addition to higher levels of smog and particulate matter (PM) that cause health hazards, burning of crop residues leads to biodiversity loss of farm lands, and deterioration of soil health. Further, frequent residue burning leads to huge losses of soil nutrients as well as microbial population and reduces the levels of nitrogen (N) and soil organic carbon (SOC) in the top soil profile, which is essential for root development of crops. It causes a huge monetary loss in terms of health impacts on people and soil. The temperature of the top soil layer (10 mm) increases up to 33.8–42.2 °C by residue burning (Gupta et al., 2004), and persistent burning effects can even reach up to 15 cm of the top soil.

3 Management of Rice Residue

Crop residues should not be considered as waste, but as a source for the provision of essential environmental services, assuring the perpetuity and sustainability of productive agroecosystems. Rice residue is a benevolent and bountiful natural resource, and its recycling helps to improve the health of soil with regard to physical, chemical, and biological aspects. According to Singh et al. (2019), crop residues need to be managed on-farm and post-harvest by modifying machinery, sensitizing farmers, adjusting the cropping system, or utilizing them in industry and for power generation. Among several options of residue management (open burning, removal, surface-retention, soil-incorporation, and mulching), the majority of the farmers opt for burning to get rid of any interference in the smooth running of farm machinery while preparing and planting the succeeding crop (Ramteke et al., 2018). As crop residues are highly rich in essential plant nutrients, their continuous use will positively impact the nutrient management in the rice–wheat cropping system. Crop residues need to be aptly managed in the field, including their retention on the soil surface, incorporation into the soil, adoption of suitable crop rotation, promotion of alternative competitive methods of their utilization in small-scale industries and biomass power plant establishment in public-private partnership mode for sustaining soil fertility and ensuring an improved farm income.

3.1 In Situ Residue Management

In situ crop residue management involves its incorporation into soil, surface retention, or mulching without burning within its natural environment. Better crop residue management improves soil carbon sequestration leading to minimization of agriculture's impact on the environment in a cost-effective way (Singh et al., 2019). Various technologies and management practices have been identified to deal with the issue of managing crop residue. Paddy residue can be utilized to a very small extent for ex situ purposes; some important reasons are low-calorific value and high silica content. In situ rice residue can be managed broadly in two ways: (i) retaining the stubble on the soil surface for using as manure, and (ii) soil incorporation.

3.1.1 Surface Retention of Stubbles

Surface retention of residue is one of the important substitutes of burning. Two major benefits of retaining residues on the soil surface are: (i) enhanced organic matter content near/on the soil surface and (ii) increased cycling and retention of nutrients. As evidenced from five seasons of continuous experimentation under rice–wheat rotation, SOC was higher in zero-tillage (ZT) plots with surface-retained residues than in the conventionally tilled plots from where residue was removed (Paudel et al., 2014). Rice residue retained on the soil surface as a mulch, especially with no-tillage, is a promising option for managing rice residues in wheat crops for improving yield, water-use efficiency, and profitability while alleviating the burden of weeds. ZT technology (with residue retention/anchored stubble), now covering around one million hectares, was found to increase productivity (1–3 q/ha) and economic returns in wheat within a range Rs. 3000/- to Rs. 6600/- ha from Punjab to Bihar besides savings of fuel (on an average 60 l of diesel/ha) resulting into economic gains of approximately Rs. 1200 million and a reduction of 0.20 t/ha of CO_2 emissions into the atmosphere. Improved water productivity (0.4 kg/m^3) and reduced *Phalaris minor* population to the extent of 30–40% in ZT wheat over conventional tillage wheat are other significant impacts (Malik et al., 2014). Studies from long-term (>20 years) ZT sites in Haryana indicated improved grain and soil quality, soil temperature moderation (1–3 °C; avoiding terminal heat stress during the grain-filling period), and increased population of microbes, favorable insects/ predators, and nematodes across different cropping systems (Malik & Yadav, 2019; Yadav et al., 2020).

But the major limitation is the availability of suitable machinery that can directly drill the seed through a heavy load of combine-harvested rice residues in the presence of loose and tough straw left after harvesting. Presently, the most beneficial and cost-effective way of managing paddy straw is to use a happy seeder (turbo happy seeder), which cuts, picks up, and unrolls on soil surface as mulch ahead of the sowing tines. It is a mechanical device for ZT sowing in lines, that simultaneously places required fertilizers directly in the silt with surface-retained residues (Sidhu et al., 2007). The machine drills wheat into soil in the presence of standing rice stubble, thus getting rid of air pollution, and avoiding loss of soil nutrients and SOC, simultaneously maintaining or increasing yield, which helps farmers to save about INR 2300–2750/- per ha in field preparation, and nutrients worth INR 2779/- per ha, offering farmers an economically viable alternative to burning (Sidhu et al., 2007; Gupta, 2019). Moreover, it also allows farmers more time for the rice–wheat interphase, as the machine can operate in the field shortly after harvesting of the rice crop. The long-term use of the happy seeder for managing paddy straw in situ reduces the fertilizer requirement and reduces the emission of CO_2 by an average of 13.0 t/ha (Singh et al., 2013). In field demonstrations at Ambala, Haryana, wheat sown with a happy seeder with surface-maintained rice residue recorded a reduction in weed population by 24.5%, whereas the average wheat yield increased by 9.22% compared with the conventional sowing after burning rice residue. Besides multiple benefits, including lower weed population, greater root length, and dry weight of the wheat, less proneness to lodging under adverse conditions, and 5–7 days' delay in maturity due to presence of more soil moisture, reduced bulk density of the soil due to the presence of straw, fuel saving (16.03 l of diesel/ha), time saving (5.38 h/ha), and monetary saving (INR 3250/- per ha) over the farmer's practice have also been realized (Singh et al., 2013). The reduction in cost and increase in wheat yield, when sown with the happy seeder, resulted in an increased saving by INR 2920/- per ha over the farmer's practice (Guru et al., 2017).

However, the availability of a sufficient number of happy seeders is a big issue for timely sowing of wheat following in situ rice straw management. The Government of Punjab had distributed 200 happy seeders to Primary Agriculture Cooperative Societies in 2013 (Roy, 2013). Prior to 2017, around 1000 happy seeders were made available to farmers in Punjab and Haryana. It is estimated that considering a machine operational efficiency of 2.5–3 ha per day during a window of 25 days after rice harvest, the total number of happy seeders (12,694) given by the Punjab Government to the farmers in the years 2018–2019 (9758) and 2019–2020 (2936) are sufficient to manage straw and sow wheat in only one third (10 lakh ha) of the total paddy cultivated area (30 lakh ha) in the state (Nirmal, 2019). Currently, in Punjab, residue of about 5.68 million acres of land is burnt per annum. Based on the availability and capacity of machinery, to cover the whole area in Punjab, around 35,000 happy seeders would be required. The present limited availability of machines in custom hiring centers (CHCs) is not accessible to the farmers of the 12,000 villages in Punjab with 3200 farmer cooperative societies that charge INR 500/- per acre, whereas others charge as much as INR 1500/- per acre (Gupta, 2019). It is estimated that to bring the residue burning to a halt within 5 years, there is a need to continue purchasing 12,000 happy seeders every year (Singh, 2018b).

In Haryana, the area managed by happy seeders during 2018–2019 was 53,883 ha, and 12,456 farmers benefitted from the technology. Besides the issue of availability, the cost of a happy seeder (~INR 1.5 lakh/unit) is another major constraint in its scalability. Although the Governments of Punjab and Haryana have extended a 50% subsidy to the individual farmers who buy happy seeders, and an 80% subsidy to the cooperatives, the machine is still unaffordable. An individual farmer getting a 50% subsidy, still has to pay INR 75,000/- per unit from his pocket (Kumar, 2019). Besides the high cost of happy seeders, its rental cost also restricted its use by some farmers, especially the small landholders (constituting 68% in Punjab and Haryana), as experienced from a case study in Punjab. To run a happy seeder in the fields with a full residue load demands tractors with higher hp and combine harvesters attached to a straw spreading mechanism. Poor germination of crop and a decline in wheat yields under a full rice residue load has also been realized (Malik & Yadav, 2019). Alternatively, ZT seed-cum-fertilizer drills also provide ample opportunities for the establishment of wheat and other *rabi* season crops in sequence with rice, particularly in those fields that have anchored stubble and/or that are harvested manually (60% in Haryana and 25% in Punjab of scented rice is hand harvested). Mechanized direct seeding of rice (DSR) and machine transplanting of rice in puddled and nonpuddled situations sequenced with ZT wheat have revealed significant and sustainable outcomes on resource (land, water, energy) conservation, improved system productivity and profitability, water productivity, improved soil quality, herbicide resistance, and residue management in northwestern India (Kamboj et al., 2013; Yadav et al., 2021). Pairing hybrids, high yielding short/medium duration rice varieties, and/or stress-tolerant rice varieties with suitably long-duration wheat varieties or other crops (pulses, oilseeds) during *rabi* season further layered with Sustainable Intensification (SI) technologies (DSR, Mechanical Transplanted Rice (MTNPR), ZT etc.) will help to realize a more sustainable production system in the different ecologies of India.

3.1.2 Soil Incorporation of Rice Residue

Crop residue incorporation into the soil increases OC stocks, improves structure, and substantially contributes to maintaining the appropriate level of macro-nutrients (nitrogen, phosphorus, potassium), micro-nutrients and microbes in the soil. However, soil incorporation may lead to a decrease in grain yields as a result of possible incidence of diseases, and enhance GHG (methane) emissions from anaerobic decomposition of straw in the soil.

The possible consequences of remnant crop residues are primarily inflicted on the succeeding crop, depending on seedbed conditions, disease incidence, and nitrogen immobilization. However, surplus residue produced from the preceding wheat crop can safely be incorporated into the soil to raise the paddy crop without any negative effect on rice yield, but anaerobic decomposition of residue in flooded rice paddies considerably enhances methane emission compared with off-field residue removal (Jiang et al., 2019). Ploughing is considered one of the most effective residue incorporation methods. Surface spreading of the loose straw is quite simple and costs less, but its incorporation into the soil involves a high cost. For the proper incorporation of paddy straw, it needs to be ploughed into soil to a depth of at least 30 cm. If not done properly, it negatively impacts the productivity of the succeeding crop and increases GHG emissions. Even from paddy fields in which straw is properly incorporated, the GHG emission is about 1.5 times higher than the fields from which paddy straw had been removed (http://www.knowledgebank.irri.org/step-by-step-production/postharvest/rice-byproducts/rice-straw/in-field-rice-straw-management) The recent Iowa research revealed no variation in residue decomposition, with variable rates of added nitrogen (Al-Kaisi, 2014). Ideal soil moisture status for decomposition is field capacity, but decomposition is inhibited when soil is saturated owing to the absence of oxygen for decomposing microbes (Vigil, 1995). These results reveal that the tillage practice and use of nitrogen fertilizer do not affect the process and rate of decomposition, but rather are economically and environmentally counter-productive. Therefore, the cultivation of cover crops and following crop rotation may help to improve soil health and microbial populations that accelerate residue decomposition. Recent research at the International Rice Research Institute revealed that soil incorporation of rice straw resulted in emission of about 3500 to 4500 kg CO_2eq/ha converted from CH_4 and N_2O (Romasanta et al., 2017), an amount around 1.5–2.0 times more than rice straw removal.

On the other hand, residue incorporation caused a favorable and significant improvement in the soil chemical properties viz. organic carbon, available nitrogen, phosphorus, potassium, and improved thermal and hydraulic conditions of soil leading to improved microbial activity and residue decomposition, stimulating production of organic binding substances and excretory products of microorganisms that improve soil aggregation (Ramteke et al., 2018). The SOC in the top soil layer (0–20 cm) and cation exchange capacity (CEC) increased by 22 and 8% for straw incorporation over straw removal respectively, with a significant increase in soil aggregates $>$2 mm when straw was returned to the soil (Zhao et al., 2019). The type of soil in which paddy straw is incorporated affects the yield of wheat as well; for clay-loam soil the yield increases significantly, whereas sandy-loam soil yield decreases in the short term as well as the long term. Compared with removal, the incorporation of straw significantly (58%) increased the wheat yield. In contrast, rice straw incorporation into soil has been found to decrease the wheat yield for the following 2 or 3 years because of immobilization of soil nitrogen due to wide a carbon:nitrogen ratio (ideal carbon:nitrogen ratio in soil for microbial activity is around 10:1 (Hoeft et al., 2000)), although the impact may differ in the long term. Residue incorporation led to an increase in the activities of enzymes such as urease, catalase, and invertase in the top 0–15 cm soil layer by 11.4, 12.9, and 41.0% respectively, whereas the soil-microbial carbon and nitrogen content in the 0–20 cm soil layer increased by 59 and 54% respectively (Zhao et al., 2019). Paddy straw contains high amounts of cellulose and lignin, which interfere with decomposition when incorporated. Inoculation of paddy straw with a blend of lignocellulolytic fungi culture (*Rhizopus oryzae* + *Aspergillus fumigatus* + *Aspergillus oryzae*) accelerated the process of paddy straw decomposition, causing a significant reduction in lignin and cellulose, and produced a good-quality compost with higher amounts of macro-nutrients (Viji & Neelanarayanan, 2015).

In situ rice residue incorporation improved the microbial balance in the soil, enhanced the activity of the enzymes dehydrogenase and phosphatase, and enhanced the grain yields of paddy as well as wheat crops in the rice–wheat system compared with residue removal or burning practices (Singh et al., 2019a). Crop residue incorporation in soil resulted in a dramatic multiplication of the microbial population, probably because of the increased activity of the enzymes phosphatase and dehydrogenase, improved granulation and soil aggregation, and thus increased the infiltration rate (Singh et al., 2019a). For rapid degradation of straw, a nano-biosystem to load a mixture of bacteria in nanostructured attapulgite (ATP) has been evolved as a straw-returning agent, in which ATP could bind bacteria efficiently to the straw surface and substantially help with the growth of bacteria and adhesion that potentially hasten the process of degrading and transforming straw into nutrients, including nitrogen, phosphorus, potassium, and organic matter. The meta-analysis of 68 experiments conducted under different soil and climatic conditions and farming regimes revealed that straw incorporation sequestered significantly more SOC in the top-soil layer (0–20 cm) at the rate of 0.35 Mg C/ha/year, enhanced the grain yield by 13.4% with a conversion efficiency $16 \pm 2\%$ of the incorporated straw compared with straw removal (Han et al., 2018). A soil-nutrient balance study in Vietnam on 12 rice paddies across variable crop-residue management practices showed that direct soil incorporation and in situ burning of rice residues had a positive nutrient balance. In contrast, removal of rice residues as livestock fodder had a negative impact on soil nutrient balance, underlining the significance of returning residue in enriching soil to maintain and sustain soil fertility (Hung et al., 2019).

3.2 Ex Situ (Off-Field) Utilization of Rice Residue

This is the management of crop residues outside their natural environment. Continuous removal of residues negatively impacts the soil health, leading to poor fertility and reduced crop yields. Residue removal affects aggregate stability owing to a lack of organic binding agents. By residue removal, its beneficial effects such as reduced raindrop impact, increased water infiltration rate, air permeability, and hydraulic conductivity, etc., vanish, thus resulting in increased runoff/soil erosion and transport of nonpoint source pollutants (e.g., sediments and chemicals). Residue removal accelerates evaporation from bare soil, increases diurnal fluctuations in soil temperature, and reduces the input of organic matter necessary to improve the soil's water retention capacity (Ramteke et al., 2018).

Crop residues can be used as fuel-source-producing biogas, compost making, power generation, thermal combustion, bedding material for cattle, etc. Most of these options need to be tested on the ground, and subsequently, they need to be adapted and scaled up depending on their success in a specific location, the availability of residue and the market for it, and the transportation of bales. Ex situ utilization of crop residues including rice straw has increasingly become a point of attraction owing to growing environmental concerns arising from residue burning in open fields for ready disposal. Different countries use and manage the crop residues in different ways, such as animal feed, compost making, bio-energy production, and other agricultural activities viz. mushroom cultivation. Wheat, rice, and sugarcane as three main crops in northwestern India (Haryana, Punjab, Uttar Pradesh) are subjected to residue burning to the extent of 22, 40, and 20% respectively (Jain et al., 2014), and this calls for alternative and cost-effective management option(s). Lohan et al. (2018) suggested the promotion of ex situ management of straw such as assortment, fuel for boilers, converting into briquettes, and developing suitable harvesters for better straw management. They added that crop residue is also utilized for generating bioenergy and compost making in countries such as China, Indonesia, Thailand, Nepal, Japan, Malaysia, Philippines, and Nigeria. In India, paddy straw has multifarious uses such as fodder and bedding material for livestock (nearly 50%), domestic purposes, energy, and material (nearly 30%).

In the Philippines, the partial or complete removal of rice straw from the fields reduced GHG emissions by 30 and 40% in comparison with its complete retention and incorporation respectively (Nguyen et al., 2019). Straw removal impacts the potassium balance in the soil, and complete removal of straw consistently for several cropping seasons without replenishing soil potassium by mineral fertilizer is bound to lead to incidences of increasing potassium deficiency. South Asia, a vast region with varying landscapes, has diverse agricultural practices and technologies, and the farmers have different levels of awareness. A study conducted across South Asia revealed that the cost of the subsidy for returning the residue back into the soil is USD 20–27/ha, which, however, depends on the base costs involved in the different interventions, instead of the absolute profit of the farmer (Ahmed & Ahmad, 2013), whereas in southwest Bangladesh where the happy seeder use is also yet to find a place, the farmers' profit with residue burning is higher by USD 111/ha over residue removed. This is possible because of the higher productivity of fields where residue was burnt (although the long-term impacts may be different), whereas the rice-harvesting costs are lower. To abstain from residue burning, the Bangladesh Government would have to pay farmers an amount of USD 2.1 million per annum, which equates to the current 4% subsidies paid to farmers for inputs such as fertilizers (Haider, 2012). The following are a few ex situ rice residue management options.

3.3 As Animal Fodder

Rice straw serving as one of the major foods for ruminants, is the most abundant, practical, and cost-effective agricultural by-product worldwide. The problem in collection, hauling, and storage of rice straw is a major limitation of its utilization as livestock feed. According to the Indian Council of Agricultural Research (ICAR)-National Institute of Animal Nutrition and Physiology, Bengaluru, Karnataka, the requirement for dry fodder, green fodder, and concentrates was short by 26 mt (21%), 21 mt (26%), and 34 mt (34%) respectively during 2015, and the corresponding deficits are likely to rise to the extent of 40 mt (23%), 21 mt (40%), and 38 mt (38%) respectively by 2025. In northwestern Indian states including Punjab, the straw of rice is not used as animal fodder owing to the high silica and low calcium levels in it, besides the abundant availability of wheat straw. Owing to low nutritional value (low protein and poor digestibility) in comparison with grasses, rice straw is a poor-quality livestock feed and cannot support the nutrient requirement of high-yielding milk animals. Urea treatment of rice straw can help to improve digestibility and consumption. There is no dearth of technologies generated for enhancing nutrient digestibility, nutritive value, and utilization of rice straw, such as physical processing, chemical blending, or biological treatment, but their adoption is still low. To maximize the utilization of rice straw as a fodder for ruminants, it is important to give pace to the processes of collection, hauling, and stacking through mechanization (Aquino et al., 2019). It is reported that nitrogen fertilizer reduces neutral detergent fiber and acid detergent fiber content and increases crude protein content in the rice straw (of varieties PR 111, Pusa 44, and PR 122), thereby feeding nutrition-enriched rice straw to ruminants by adding value to the rice crop along with beneficial impacts to the environment (Dhillon et al., 2018). Lignin and silica, the two important structural components of rice plants during the growth and fruiting stages, are indigestible when ingested by animals. Silicon is an element absorbed by rice in huge amounts, i.e., several times that of other macro-nutrients. It is estimated that, on average, a rice crop yielding about 5 t of grain/ha normally removes from the soil about 230–470 kg Si/ha (500–1000 SiO_2 kg/ha) (Savant et al., 1997). The silica content of rice straw collected from the rice-growing area of the middle Gujarat region of India ranged between 3.52 and 9.80%, with an overall average of 6.30% in various districts. The silica buildup in rice straw (Table 1) was higher than nitrogen, phosphorus, potassium, sulfur, and sodium by almost 2, 47, 20, 14, and 30 times respectively (Patel et al., 2017). It is reported that if rice straw is used as fodder, it decreases calcium in milk by at least 2%, impacting the quality of the milk (The Citizen, 2017).

Therefore, there is a need to improve the quality of straw so that it can be included in the animal diet. In principle, two approaches to straw delignification treatment and nutrient supplementation should be taken in combination, considering local physical and socio-economic conditions. Crop residue can be nutritionally enriched by supplementing with fodder-tree lopping and concentrated feeds (compounded cereal grains, legumes, and their by-products). Studies elsewhere have revealed that supplementing 30% rice straw with 50% *Leucaena* leaves and 20% rice bran can

Table 1 Nutrient, micro-nutrient, Si, Na content, and the Si:nutrient ratio in rice straw

	Nutrient content					
	N, P, K, S, Si (%), Fe, Mn, Zn, Cu (mg/kg)			Si: Nutrient ratio		
Element	Range		Average	Range		Average
N	1.82–3.58		2.64	1.06–4.32	4.32	2.35
P	0.05–0.29		0.14	15.6	4.32	2.35
K	0.19	0.49	0.34	8.7	46.2	19.7
S	0.10	1.01	0.56	4.3	61.6	14.0
Na	0.13	0.44	0.25	13.9	90.2	29.9
Fe	33	869	401	41	989	242
Mn	22	684	238	66	1595	498
Zn	4	66	30	640	9477	2451
Cu	1	18	8	1780	23,183	9530
Si	352	980	630	–	–	–

Source: Patel et al. (2017)

help in maintaining daily weight gain by 68.6 g/day (Rasjit & Perez, 1980). In urea-treated rice straw, when supplemented with ad lib feeding of 20% Ipil-Ipil (*Leucaena leucocephala*) green foliage, an Average Daily Weight Gain (ADG) of 41.11 may be obtained in stall-feed management systems (Upreti, 2004). A higher rate of dry matter digestibility (DMD) of rice straw was reported in goats (Devendra, 1988) indicating the opportunity to combine 20% rice straw in the total dry matter requirement of goat diet without any adverse effect on growth (Upreti & Orden, 2010).

There is regional disparity in the methods of straw management in India. West Bengal produces 35.9 mt straw (Anonymous, 2009), which is twice as much as Punjab (17 mt), but it is largely consumed as cattle feed (Roy & Kaur, 2015). It was found that paddy residue management by its off-field removal was practiced most in the farming systems that included a livestock component. The straw of basmati/scented paddy is also used as an animal fodder in Haryana. Therefore, against the present backdrop, when there is no demand or market for straw, it is quite challenging to switch over to this option. However, it can be made possible if it is promptly baled and hauled by public or private entrepreneurs at their own cost from the farmer's point to their destination. Second, the government should develop fodder banks locally to stock straw and distribute to the landless livestock owners at subsidized rates in the locality, and also sensitize farmers to the nutrient enrichment of rice straw.

3.3.1 Power Generation

According to Gadde et al. (2009), the quantity of rice straw produced in India, Philippines, and Thailand has an annual energy potential as renewable fuel to the extent of 312, 142 and 238 petajoule (PJ) respectively, as estimated at 100% collection efficiency, considering that all straw harvested was utilized in energy production. Moreover, this alternative option of electricity generation is environmentally safe, economically viable, and sustainable as it requires no additional land, and thus has no competition with commercial, food, fodder, or fiber crops. Electricity generation from crop residues as potential fuel is regarded as a sustainable solution with low environmental footprints and reduced net emissions of GHGs (CO_2, SO_2, and NO_x) in comparison with thermal power plants in which lignite is used as a major source of fuel (Ergudenler & Isigigur, 1994).

According to Purohit and Chaturvedi (2018), the surplus biomass available from the farm sector in India alone can substitute 25% of current coal consumption through the co-firing of coal with biomass pellets in the power sector, which can generate 244 TWh electricity per annum out of a total production of 4000 TWh, in addition to direct biomass co-firing for power generation. The main reasons why the energy and heat should be produced from straw are (i) a market demand, (ii) abundant availability of agricultural waste that could be transformed into energy, and (iii) reducing environmental footprints by avoiding burning of residues, particularly rice straw (TERI, 2018). It is an established fact that more than 80% of the current world demand for energy is met through nonrenewable resources, which is a serious concern for the sustainability of our energy supply (NL Agency, 2013). In the ten potential districts of Haryana, producing a total rice residue of 18,75,000 t, the surplus of 10,28,500 t has a potential of generating 102.9 MW power, whereas the surplus rice residue produced in the top four districts comprising Karnal, Kurukshetra, Kaithal, and Fatehabad (with 26.2–35.1% of the area subjected to rice-residue burning) can meet the 82.6% of the fuel needs of the total power generation potential (Yadav et al., 2015).

A small fraction of rice straw is utilized in the brick kiln industry, paper making, and for packaging. Utilization of rice residue for power production can hopefully fulfill a part of the ever increasing energy demand. Unlike forest or woody biomass, herbaceous or agricultural biomass contains a higher amount of ash, chlorine, nitrogen, and sulfur and more abrasive particles. The agricultural residues have a lower ash-fusion temperature, leading to higher slagging and fouling with faster corrosion of boilers, resulting in increased emissions of atmospheric pollutants (IRENA, 2017). Recently, the Central Electricity Authority, Government of India, planned and directed the thermal power plants to replace 10% of the total raw material with stubble, and the National Thermal Power Corporation (NTPC) has granted permission to utilize stubble in briquette form, as an alternative fuel source to thermal plants. This initiative may result in the commercialization of agricultural residue in a sustainable way and help to increase farm income (NTPC, 2018).

The Rajiv Gandhi Thermal Power Station (RGTPS), Khedar, Hisar, Haryana endorsed the directions of NTPC to help farmers to provide USD 77 per ton of crop residue. Once these farmer-friendly measures come in action, they can be profitably exploited by the farmers. When this is realized, the RGTPS alone will require 2000 t of stubble briquettes daily. Furthermore, the residue in briquette form is also needed in the boilers of industries, which would make this model more diversified and commercially viable. It is, therefore, sought that the Government of Haryana compulsorily permits usage of stubble briquettes in thermal power generation. The Indian Renewable Energy Development Agency has introduced new

Table 2 Element composition, volume of rice straw and torrefied products

	Composition of elements (wt %)		Change in volume (cm^3)		
Element (wt %)	Rice straw	Torrefied product	Sample	As such	After grinding
C	23.23	48.52	Rice straw	7426	909
Si	33.03	15.32	Chopped rice T_1 (0°C)	3408	909
O	43.18	34.25	T_2 (250°C)	3905	505
K	0.56	1.56	T_3 (300°C)	2919	375
Mg	0.0	0.34	T_4 (350°C)	2885	355
			T_5 (400°C)	2768	340

Source: Dhakate et al. (2019)

schemes for the financing of "biomass projects for heating application for commercial use" and "manufacturing of biomass pellets/briquettes/torrefied pellets/refuse-derived fuels" for the processing of agriculture crop residues in an economical way, and support a sustainable environment. Torrefaction, a process of mild pyrolysis (temperature remains between 200 °C and 350 °C) of biomass in a shielding atmosphere, helps to alter the physical form (reduce volume, and increase density, brittleness, and ease of grinding) and chemical composition (increase in hydrophobic effect, carbon content, and energy density) of rice straw. Dhakate et al., (2019) reported that paddy straw containing 23.23 wt% carbon, 33.03 wt% silicon, 43.18 wt % dioxygen, and 0.56% potassium, after torrefaction at 350 °C, owing to the degradation of lignocellulose's structure and volatilization, increases carbon content to 48.52%, whereas silicon and dioxygen contents decrease to 15.32 wt% and 34.25 wt% respectively, whereas potassium content rises to 1.56% with an increment of magnesium. Moreover, rice straw with a huge volume (7426 cm^3) is the major hurdle in the transport of rice straw to the thermal power plants. By chopping the rice straw into 2-cm-long pieces, the volume can be brought down to 3408 cm^3, and torrefaction further decreases the volume by between 66 and 75%. At 350 °C, the volume of torrefied biomass reduces to 2885 cm^3. Moreover, there is a significant reduction in torrefied product volume after grinding (Table 2).

Establishing sufficient biomass power plants locally will help to provide an additional source of farmer's income, besides saving the environment from the menace of residue burning. Punjab Biomass Power Limited is a pioneer amongst the nine power plants that use rice straw for power generation. Such a power plant of 12 MW capacity utilizing rice straw consumes 0.12 mt of residue, gathered from around 15,000 farmers. Company agents help farmers with harvesting, baling, and transporting to depots for storage (Verma, 2014). The Power Development Plan of Vietnam is mobilizing the highest potential of the domestic resource, i.e., rice residue (straw and husks) to reduce annual emissions by 28 Mt CO_2 eq/year by 2030. At this level, biomass co-firing of the thermal (coal) power sector leads to a reduction in emissions of 8% reducing the cost by USD 137 million (Truong et al., 2018).

3.3.2 Biochar Production

Biochar is generated by the combustion of biomass waste at 300–600 °C under partial or complete anoxia; the process is called pyrolysis. It is a relatively biologically stable product, and when applied in the soil, the carbon from this waste biomass is switched from a speedy to a steady carbon-cycling reserve in the soil. This requires the evaluation and maximization of the advantages of applying biochar on soil health, carbon sequestration, and nutrient use efficiency in various soils across different cropping systems in India. Results of limited research elsewhere in the world indicate that the use of synthetic biochar can potentially resolve these issues. In recent times, application of synthetic biochar has opened up new vistas of soil management practice to improve fertility and SOC content, mitigation of GHG emissions, retention of soil nutrients, and increased efficiency of nutrient use and agricultural productivity (Lehmann et al., 2006). To reduce carbon levels in the atmosphere, its diversion to a passive pool containing stable or inert carbon is essentially required. Incorporation of biochar in the soil triggers a facile flow of carbon from the active to the passive pool (Kwapinski et al., 2010). Zahida et al. (2017) reported a breakthrough in mitigating the GHG (CO_2, CH_4, and N_2O) emissions into the atmosphere. It not only sequesters carbon into the soil, but also alleviates methane production under anaerobic conditions such as submerged paddy fields, and stimulates sorption of N_2O, restricting its release into the atmosphere.

In addition, biochar is known to enhance crop productivity and decrease water stress, thereby helping to adapt to climate change. Haefele et al., 2011 reported that biochar produced from rice residues could be advantageous in rice-based systems, but its real impact on fertility, SOC status and crop yield will vary according to different specific sites. Owing to reactive surfaces and the recalcitrant aromatic structure of biochar, its application to soil can impact a series of bio-geochemical processes serving as a sink for atmospheric CO_2. Lehmann et al. (2006) revealed that half of carbon in biomass is released immediately upon the pyrolysis process, which can be utilized for production of energy as a substitute for fossil fuel, leaving biochemically recalcitrant biochar as residue. The small-scale biochar production system from paddy straw may be encouraged for its production and utilization as soil amendments on a trial basis for proving its economics and acceptability.

Biochar can increase inherent microbial activity in the soil, provide a congenial environment for soil microbes, and stimulate colonization of mycorrhiza fungi to improve plant water status and nutrient supply (Warnock et al., 2007), and may stimulate N_2 fixation in leguminous plants through *Rhizobium* bacteria. Biochar can also control nitrogen cycling in soil; in particular, a reduction in N_2O emissions from soil is reported to the extent of 54% and 28% in laboratory and field studies respectively (Cayuela et al., 2014). Biochar, often being alkaline, increases the pH of soil when applied (Jemal & Yakob, 2021). Bacteria responsible for denitrification in soil are capable of enhancing their N_2O-reducing activity with the rising pH, leading to reduction in N_2O emissions from soils. Spokas and Reicosky (2009) also reported that soil application of biochar can mitigate net emission of methane from the forest nursery. Biochar as liming material can help to improve acidic soils. The biochar produced from rice straw possesses the highest concentrations of calcium

(10.44 mg/kg), magnesium (1.61 mg/kg), and silicon (170.8 mg/kg), and also a high pH (10.5) both in water and in KCl. Considering the abundant availability of rice straw and using some cheap improvised local methods for biochar production, the rice straw biochar may be the best remedy for ameliorating the acidity problems of highly weathered tropical soils (University of Ghana http://ugspace.ug.edu.gh).

Deka et al. (2018) evaluated physicochemical properties (ash content, moisture content, bulk density, particle density, porosity, pore-volume, particle size, and specific surface area) of biochar produced from locally available bio-waste such as straw and husk of rice in Jorhat, Assam, under a slow pyrolysis (300–400 °C) process and found that rice-straw-derived biochar had high alkalinity and high levels of available phosphorus compared with biochar derived from rice husk, implying that biochar produced from rice straw can be successfully used as a fertilizer and amendment in the acidic soils of Assam extending over 51% of the total geographical area and impregnating 98% of the net sown area with a soil pH < 6.7, of which 2.33 m ha are under strong soil acidity, having a soil pH <5.5. Experiments conducted in Indonesia revealed that the rice-husk-derived biochar possessing 4.96% water, 18.72% carbon, 0.12% phosphorus, 0.20% potassium, 0.41% calcium, 0.62% magnesium, 1.40% sodium, 8.70 pH, and 17.57cmol/kg CEC, when applied as a soil amendment in acid soils, led to a decrease in bulk density, soil strength, exchangeable Al and soluble Fe, and an increase in porosity, available soil water content, SOC, pH, available phosphorus, CEC, exchangeable potassium, and calcium (Masulili et al., 2010). In China, biochar applied to cold waterlogged paddy fields significantly increased the soil pH, but caused a significant reduction in exchangeable soil cations Ca, Mg, Al, and base cations, owing to its liming effect (Si et al., 2018).

Results of the studies revealed that biochar application to soil increased pH, CEC, available phosphorus, and organic carbon content of soil, and significantly enhanced the crop yield (Jemal & Yakob, 2021). Incorporation of biochar into soil can change its physical properties, influencing aeration, water-holding capacity, and workability of the soil, which is generally desirable for most plant growth. At several locations in Laos, Asai et al. (2009) found improvement in surface infiltration of water in upland rice. Gaskin et al. (2007) reported 18% more water retention in biochar-treated loamy-sand soil than in highly weathered tropical soil. The International Biochar Initiative (IBI) recommends the blanket use of biochar for amending soil, and promotes its inclusion in national and global climate mitigation programs, and its commercial production and marketing, galvanizing a global system that sequesters 2.2 Gt carbon/year by 2050 (Yadav et al., 2018). However, Rittl (2015) challenged the dictum that all biochar persists in all soils for thousands of years. He reported that when applied to sandy savannah soils, the biochar decomposed at the same rate or even faster than native SOC; the prevailing warm and dry conditions probably stimulated the decomposition of unprotected biochar in soils, and the intrinsic chemical recalcitrance of charcoal is not the vital phenomenon accountable for its build up in the Amazonian Dark Earths soils.

The abiotic or biotic processes and interactions of this are responsible for biochar decomposition. One of the possible abiotic mechanisms is the chemisorption of oxygen at unsaturated carbon rings, which brings about the formation of carboxylic groups, which was reported to be higher at elevated temperatures and under drier conditions. Some organisms may also be involved in biochar decomposition. Reports in the literature substantiate the role of fungal growth on the biochar surface, although it is unclear whether biochar is utilized for its major carbon and energy needs. Some microorganisms also possessed the capability of readily decomposing polyaromatic structures of biochar. Seemingly, the chemical–physical protection of biochar is crucial for its residence time in the soil. It is evidenced that the stability of biochar can be enhanced and it can be protected from degradation when stabilized within micro-aggregates (<250 μm), and/or bound in organomineral complexes and clay minerals in soils. These mechanisms may cause a substantial reduction in the availability of biochar to decomposers, increasing the fraction of biochar sequestered in soil. Results of laboratory studies corroborated that the presence of calcium and phosphorus in soils prevents the decomposition of biochar (Clough & Skjemstad, 2000). Gurwick et al. (2012) reviewed the work on biochar and reported that out of the 56 original research papers, only 25% presented pragmatic data regarding the residence time of biochar in the soil and/or related to the impact of the soil environment on biochar decomposition. While summarizing the key results of six experiments, the mean residence time (MRT) or turnover time across different locations of study, the experimental approach followed, and the source of biochar derivation, it was deduced that the MRT ranged from a mere 8 years to more than 3000 years. The authors opined that as far as this variation remains inexplicable, it can hardly be assumed that all biochar applied to soil would persist for a longer period of time.

3.3.3 Biogas Energy Generation

According to the estimates of the Ministry of New and Renewable Energy, Government of India, the photosynthesis activities store as much energy as 17 times that consumed by all nations of the world annually. Considering the energy needed in collecting, processing, and conversion into other useful forms, biomass is still sufficient to fulfill the total energy demands of the world, if managed properly, and used effectively and sustainably (https://biomasspower.gov.in/biomass-info.php). Biogas plant installation is a reformative move of the Government of India toward the curbing of residue burning and prevention of air pollution. This technology has been in use since the 1970s and several off-grid biogas power productions for cooking and lighting purposes under the aegis of “waste to energy mission” were run by the National Biogas and Manure Management Program. Currently, 56 biogas-based power plants are operational in India, mostly in the states of Maharashtra, Kerala, and Karnataka (CPCB, 2013). In a novel green energy drive making use of bio-methanation technology by utilizing rice straw, a biogas plant was set up in conjunction with commercial farms and processing units in Fazilka, Punjab, with the certification of the premier academic institutes such as the Indian Institute of Technology, Delhi, and Punjab Agricultural University, Ludhiana, which produces around 4000 m^3 of biogas by utilizing 10 t of agricultural residue (Akshay-Urja, 2016). The private enterprises have generated about 7,00,000 jobs for rural people, and the secondary user farmers were offered USD 8–22 per ton of straw (Sood, 2015). According to Manas Puri, an expert in Sustainable Energy in Agriculture, the FAO's Bioenergy and Food Security, a rapid appraisal approach comprising a set of functional, practicable, and user-friendly tools allows countries to evaluate their sustainable bioenergy potential and the associated opportunities, risks, and trade-offs. This tool can be customized and adapted according to country-specific needs, e.g., residue burning in India. Residue burning leads to strong air pollution, and puts an embargo on opportunities to diversify income-generating activities.

In Punjab, the total biomass production was estimated to be 48.26 mt in 2009–2010. The surplus biomass after farmers' home consumption was estimated to be 35.96 mt. At 30% combustion efficiency, the energy equivalent of this biomass surplus has the potential to run 904 power plants of 5 MW capacity for a year while working 20 h/day. It shows that more than 4852 MW of electricity can be generated through these plants. If the biomass potential of many other crops is harnessed as fuel to run biomass plants for generating electricity, a huge amount of coal used in the thermal plants throughout the state can be saved.

Nettenergy B.V., a Dutch company, has been granted a license in India to partner Shirke Energy (India) in producing biochar for fuel/soil amendment (Elbersen & Keijsers, 2019). Assessing various supply options of rice straw for Nettenergy, a requirement of 3650 t of rice straw pellets per annum at an cost of €136/t was estimated. Nettenergy is devoted to developing technology and manufactures mobile installations (2 t/day, and 10 t/day capacity) to convert biomass into energy and valuable products. The firm is focused on the local market in which raw materials (wood, grass, crop residue) for the pyrolysis process are already present. The unit needs to be placed outside the container for operation (BRB, 2018). The unit can be made self-supporting in its energy usage (wood gas), and no diesel or connection to the electricity grid is required. Second, the Advanced Environmental Composite Panel (ECOR) + Internationaal Maatschappelijk Verantwoord Ondernemen (IMVO) venture for market development of the straw pellet in India, as well as abroad, in place of forest wood and contributing to a reduction in emission, and projects on residue valorization for the development of technological solutions in India (Gujarat, Haryana). ECOR, an Advanced Environmental Composite Panel, is formed from the conversion of cellulose fiber under pressure and heat. Fibers are sourced from different sources such as old corrugated cardboard, old news print, agricultural fiber, and even bovine process fiber. ECOR was developed to tackle the most challenging global environmental problem of waste disposal and diversion. It is entirely bio-based and recyclable, comprising recycled residual materials, and is cradle-to-cradle compliant. The estimated capacity of the ECOR board production facility requires 10,000 t/year, whereas Nettenergy requires 3650 t/year (Elbersen & Keijsers, 2019).

All the aforesaid measures adopted by the public and private sectors have achieved partial success in mitigating residue burning, but much more is yet to be done.

4 Way Forward

To have a check on prevailing rice-residue burning, the following suggestions and recommendations can serve as useful tools in policy formulations and for devising future strategies:

(i) Incentivize farmers or provide higher subsidies to farmers who abstain from burning rice residues in the open and retain them in the field (maintain on the surface or incorporate) as a measure of long-term improvement in soil health. On 25 November 2019, the Governments of Punjab and Haryana, in line with Supreme Court guidelines, took the initiative in this regard, to incentivize farmers to desist from rice-residue burning to check air pollution, and announced a money bonus of INR 2500/- per acre for small and marginal farmers who abstain from residue burning. In addition, the Government of Haryana announced an additional INR 1000/- per acre as an incentive for CHCs and straw baler units to support their operational costs.

(ii) Diverting the surplus crop residue to viable and sustainable alternative uses such as the generation of energy, biochar making, animal feed supplements, and other location-specific enterprises for the improvement of air quality, soil fertility, and human health.

(iii) Promotion of early-maturing varieties: the Punjab Agricultural University has developed short-duration rice varieties such as PR 126 (123–125 days) and PR 127 (137 days), yielding around 7.5 t/ha and consuming less water than late-maturing traditional cultivars with a greater need for water and a heavy stubble load. Switching over to the cultivation of short-duration varieties will help farmers to avail themselves of sufficient time to clear their fields in preparation for establishing the succeeding crops. Another short-duration (120 days), short-statured Basmati variety Pusa 1509, generated by the ICAR-Indian Agricultural Research Institute, New Delhi, produces almost half the straw-mass compared with the prevailing Basmati rice variety, Pusa Basmati 1121.

(iv) Currently, a subsidy is provided to CHCs and individuals for purchasing happy seeders, but for its accelerated adoption, the government should make provision for a double subsidy, both to the purchaser entrepreneur/service provider/CHC as well as the user-farmers for wheat sowing.

(v) Awareness programs should focus on the potential benefits and operational proficiency of agricultural machinery such as happy seeders or in situ straw management, which saves the cost of inputs because of reduced use of fertilizer and water, and imparts a beneficial effect to soil health. There is a need to ensure the straw-spreading mechanism with combine harvesters to avoid gluts and glitches while operating happy seeders. Any misperceptions regarding practices or of the cost of alternative management of the technological option(s) of removing residue and other practices may seriously jeopardize the uptake of technology. Evaluation of any farming practice by farmers usually entails consideration of the total yield only, and not the input cost or benefit:cost ratio.

(vi) The policies and directives are in place highlighting the management and utilization of bio-waste, in addition to its multifarious uses. It is essential to analyze, review, and evaluate the existing options of managing crop residue, taking into consideration the technical, financial, and socio-economic aspects of selected options (e.g., the use of 100% paddy straw in power generation, partial co-firing with rice straw in existing thermal plants, using rice residue as fuel in brick-kiln industries) in the light of environmental and health benefits.

(vii) Supplementary policies on the collection, aggregation, and hauling of crop residue are required to promote investment in the private sector for the business of collecting crop residues, and further offer farmers the opportunity to dispose of their residue and build viable business models to establish a residue supply-chain mechanism that allows the private sector to invest in processes for residue valorizations through the production of bio-compressed natural gas, bioethanol, bio-pellets, bio-power, paper, tableware, fabric production, etc. Tractor operators may be allowed to run their tractors loaded systematically with rice residues freely across different states (to transport rice residues from surplus to deficit states).

(viii) Educate and incentivize farmers, and promote the use of chemical or biological means for the faster decomposition of straw in situ as well as off farms.

(ix) Research and development should focus attention on designing and developing harvesting machines able to cut paddy at a lower stubble height from the ground, reducing residue load and eliminating any interference in wheat sowing.

(x) Promotion of crop diversification in favor of crops other than paddy (maize, pulses, horticultural, and vegetable crops), their remunerative minimum support price, and assured procurement for efficient resource use and long-term sustainability.

(xi) To run decentralized cold storage of horticulture products and chilling of milk at the village level, utilization of paddy straw as fuel can be a viable solution. This will help farmers to provide alternative options to diversify the cropping system and integrate the farming systems. Presently, farmers in rural India are reluctant to part with their traditional farming practices owing to a lack of cold storage facilities at the local level.

(xii) Rigorous application of advanced technologies and remote sensing data through the National Remote Sensing Agency, the Central Pollution Control Board, the Haryana Space Applications Center, etc., and to strengthen more localized monitoring mechanisms. Mobile-based applications are useful in raising farmers' awareness and detecting burning events in the fields.

(xiii) It is recommended to shift from the current short-term, fragmented, administrative, prohibitive policies and penal provisions to the long-term, cohesive, stable, economically effective, socially acceptable, and results-oriented policies that are supported by the legal systems. Of course, our approach must be strictly prohibitive, but our actions should be a conglomeration, more curative and less punitive.

(xiv) The government, along with research and development institutes should present an alternative that is more attractive, lucrative, remunerative, native, and socially receptive, relative to the burning objective.

(xv) The Government of India, in a departure from sectoral thinking revolving solely around agriculture and energy, must devote themselves to the concept of "nexus thinking," which encourages integration and involvement of multi-stakeholders, to provide a common supporting platform in managing environmental resources, to resolve the issue of burning residues.

(xvi) Animal husbandry, an integral part of farming in India, is facing a fodder-deficit problem, which affects productivity. Therefore, rice-straw utilization for animal fodder needs a special focus through nitrogen enrichment to enhance the protein content. Moreover, this is a viable system for long-term sustainability, as straw removed for feeding livestock is recycled in the soil in the form of manure to maintain soil health.

(xvii) As an alternative to rice-straw burning, farmers should be trained to use other viable options such as soil mulch or a substrate for mushroom cultivation.

(xviii) To avoid burning, rice straw should be used as an industrial material or energy source, taking into consideration its optimal benefits.

5 Conclusion

Mechanized harvesting leaving a huge bulk of stubble in the field poses a major challenge to rice-straw management, as its consumption for animal feed is restricted owing to its high silica content, and the availability of more preferable and relatively superior quality wheat straw. As a result, the farmers adopt the cheapest, quickest, and easiest route of residue burning to clear their combine-harvested field in the process of field preparation for succeeding crops. The present regulatory provisions and penal impositions prohibiting rice-residue burning have not worked, and the burning goes on unabated, particularly in Punjab and Haryana. A number of alternative technical solutions, such as crop diversification, subsidizing happy seeders and balers for their large-scale promotion, and use of straw as animal fodder, and in power generation, for biochar and compost making, and many other small-scale enterprises, have been suggested, and policy guidelines have been framed and implemented, but the desirable impact is yet to be realized. A critical analysis of the issue reveals that we need a workable solution specific to agro-ecologies and landscapes. The use of happy seeders is an apt resource-conservation technique in view of dwindling soil and water resources of the IGP under the continuous rice-wheat system. However, the affordability and operational feasibility are the main issues in its scalability and faster adoption, depending on the size of the landholding. Mechanization use holds great promise and can be successfully operated as a custom hiring or service provision approach in public–private partnership mode. There is a stringent need to handle the complex issue of rice-residue management/burning with a holistic and system approach by linking and combining all the fragmented and improved pieces of technological interventions together.

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Biotechnology and Genomics-Based Strategies for Enhancing Photosynthetic Capacity and Nutrient-Use Efficiency of Crops

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Contents

Abstract

Advances in biotechnology and genomics have empowered researchers to manipulate the molecular networks involved in various plant processes enabling plants to exploit resources efficiently. For photosynthetic capacity (PC), several approaches are followed to improve the PC involving conventional and molecular genetic improvement such as breeding for favorable traits, engineering the genes

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of more efficient C_4 into C_3 system or genes related to leaf architecture, and improving canopy photosynthetic nitrogen-use efficiency, etc., to increase net photosynthesis. Nutrient-use efficiency (NUE) comprises components like nutrient acquisition and utilization efficiency. Understanding the molecular as well as the physiological level in determining how to enhance efficiencies in plants has been well developed in the recent past, which would be crucial to devise the approaches to addressing the involved constraints. This chapter covers the updated knowledge and information on photosynthetic capacity, nutrient acquisition and utilization, and their molecular regulators in plants for researchers and academicians working on crop improvement for better crops.

Keywords

Photosynthetic capacity · Nutrient-use efficiency · Biotechnology · Genomics

1 Introduction

Agriculture today encounters multiple issues such as climate change, burgeoning population pressure, and higher cost of inputs; more importantly, among others, in such scenarios, the strategies based on climate resilience, lesser input driven, and high PC and NUE of crops would be appropriate to ensure high crop production. Advances in biotechnology and genomics have empowered researchers to manipulate the molecular networks involved in various plant processes enabling plants to exploit resources efficiently. For photosynthetic capacity, several approaches are followed to improve the PC involving conventional and molecular genetic improvement such as breeding for favorable traits, engineering the genes of more efficient C_4 into C_3 system or genes related to leaf architecture, and improving canopy photosynthetic nitrogen-use efficiency, etc., to increase net photosynthesis (Wang et al., 2016; Guo et al., 2019). NUE depends on two major components: nutrient acquisition and utilization efficiency. Understanding the molecular as well as the physiological level in determining how to enhance efficiencies in plants has been well developed in the recent past, which would be crucial to devise the approaches to addressing the involved constraints.

The advent of molecular and transformation technologies has led to the manipulation of plant genomes in a way conventional hybridization approaches may never imagine. Advances in genomics have augmented crop breeding in accelerated delivery of high-performing and resilient crops. In addition, intervention of high-throughput phenomics has complemented genomics substantially in exploring genetic regions and diversity at nucleotide-scale precision. The identification of genomic regions of desirable traits, coupled with advanced molecular breeding strategies like marker-assisted breeding, genomic selection, etc., has accelerated breeding accuracy and gain. Furthermore, spatial and temporal regulation of engineered genes and pathways through targeted editing in genome hasten breeding accuracy. Understanding plant mechanisms of sustainability traits in variable environments is imperative to harness substantial gains in crop, which can be fueled by genetic diversity and implemented by genome-scale breeding, finely tuned gene engineering, and more precise agronomic management practices.

Moving ahead with an increased production of cereals, oilseeds, pulses, vegetables, fruits, etc., is necessary to achieve food and nutritional security for the burgeoning human population. This chapter covers the updated knowledge and information on the role that biotechnology and genomics could play in enhancing PC and NUE of better crops for the benefit of researchers and academicians working on similar aspects.

2 Enhancing Photosynthetic Capacity (PC) and Nutrient-Use Efficiency (NUE) in Plants

Better yields in crop plants need better nutrition (in particular, nitrogen, phosphorus, and potash) that is met mainly through inorganic fertilizers. In order to enhance nutrient sufficiency and judicious use, understanding the mechanisms of its uptake, transport, and use is very crucial in plants. Plant mechanisms balancing photo-assimilate uses and nutrient uptake are very critical for optimizing yields. The natural mutations conferred plant height shortening in cereals, revolutionized world agriculture, and brought unintended efficiencies in nitrogen use that compensated with other transcription factors controlling growth and nutrient use. In this context, breeding plays a crucial role in reducing nutrient imbalances through root systems optimization, nutrient uptake and transport activities, and partitioning. In nature, plant system creates specific biomes along with beneficial microorganisms that facilitate judicious uptake of nutrients, thus nutrient-use efficiency. In modern agriculture, these natural associations are often dampened by excess use of fertilizers as they conquer plants–symbionts interaction. Many plant species have symbiont association with arbuscular mycorrhizal fungi that encourage root growth and expand root area for nutrient uptake, which mine immobilized phosphates of the soil. The strategies to enhance PC and NUE in plants are outlined in Fig. 1.

2.1 Enhancing Photosynthetic Capacity (PC)

Modern-day crops are very quick in spreading their canopies, and efficient in photo harvesting, assimilates, and nutrient partitioning into the seeds. However, inefficient conversion of harvested photons assimilates through photosynthesis. This might be due to inefficient photosynthesis machineries in crops that evolved in a low-light marine and are very less adaptive to modern agronomic and environmental conditions. Conservation of transmembrane protein along with enzymes that are involved in photo harvesting in chloroplast and carbon fixation across the crop species have aided the modeling of photosynthesis and identification of targets enhancing photosynthesis efficiency in plants. In this context, theoretical targets include optimizing light capture in leaf, rapid letup of non-photochemical quenching at photosystem II,

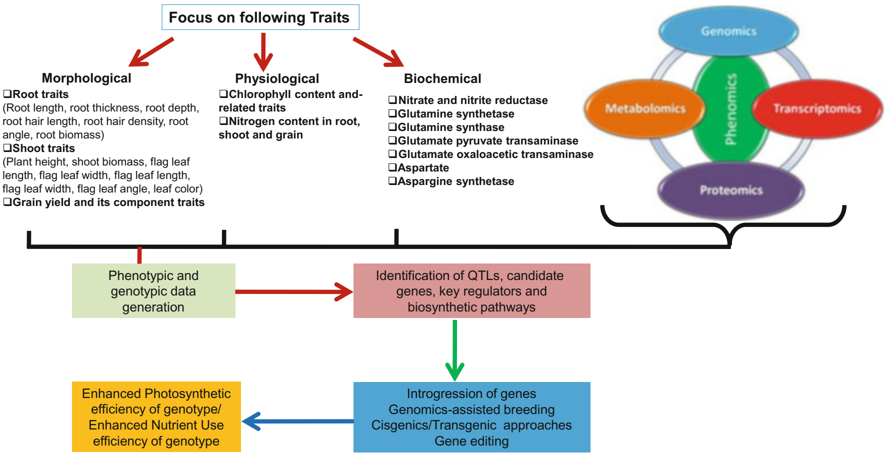


Fig. 1 Ways for enhanced PC and NUE in plants

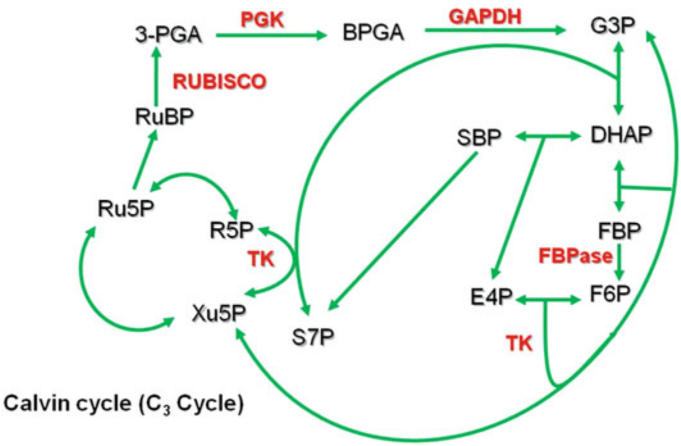


Fig. 2 Schematic overview of the Calvin cycle (C_3 cycle): RuBP: ribulose1,5-bisphosphate; G3P: glyceraldehyde3-phosphate; PGK:3-phosphoglycerate kinase; GAPDH:glyceraldehyde-3-phosphate dehydrogenase; BPGA:1,3-bisphosphoglycerate; 3-PGA: 3-phosphoglycerate; DHAP: dihydroxyacetone phosphate; E4P: erythrose 4-phosphate; Xu5P: xylulose 5-phosphate; S7P: sedoheptulose 7-phosphate; SBP: sedoheptulose1,7-bisphosphate; FBP: fructose 1,6-bisphosphate; F6P: fructose 6-phosphate; R5P: ribose5-phosphate, Ru5P: ribulose5-phosphate; RUBISCO: RuBP carboxylase/oxygenase; FBPase: fructose1,6-bisphosphatase; PRK: phosphoribulokinase; TK: transketolase

improving the capacity of RUBISCO enzyme for their carboxylation ability, minimizing oxygenation and photorespiration, improving regenerative capacity of carbon reduction cycle, optimizing electron transport reactions, C_3 to C_4 conversion

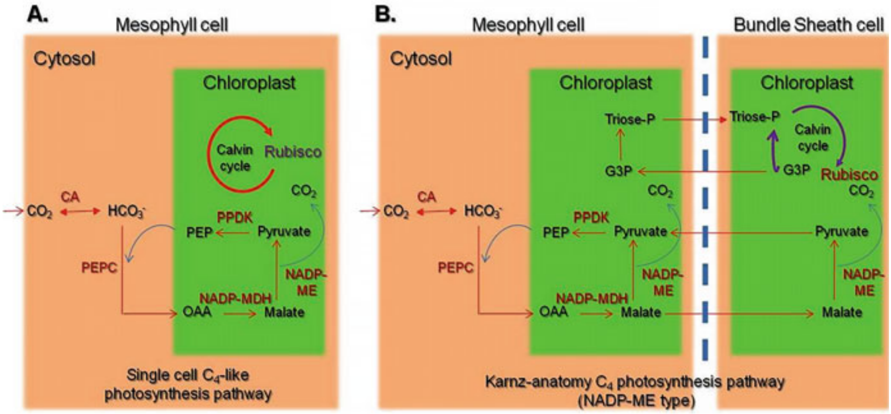


Fig. 3 Schematic diagram of C_4 photosynthesis pathway. (a) Single-cell C_4 photosynthesis pathway. (b) Karnz anatomy C_4 photosynthesis pathway (NADP-ME type). NADP-ME: NADP-dependent malic enzyme; NADP-MDH: NADP-dependent malate dehydrogenase; *CA:* carbonic anhydrases; *OAA:* oxaloacetic acid; *G3P:* glycerol-3-phosphate; PPDK: pyruvate/orthophosphate dikinase; PEPC: PEP carboxylase

Table 1 Genomic resources related to PC in plants

Name of gene	Function/role	Plant	References
PEPC	Overexpression of C_4 PEPC in C_3 plants enhances photosynthesis and drought tolerance	C_3 plants	Zhou et al. (2011a)
PPDK	Enhances photosynthesis	Rice	Gu et al. (2013)
C_4-*PPDK*	Overexpression of C_4-*PPDK* encourage photosynthesis rate	*Arabidopsis thaliana*	Wang et al. (2012)
ZmNADP-ME	Overexpression of *ZmNADP-ME improves* net carbon assimilation, total biomass, and WUE, shortening life cycle	Tobacco	Müller et al. (2018)
GOLDEN2-LIKE	Improves mitochondrial and chloroplast development in vascular sheath cells in rice	Maize	Wang et al. (2017)

(Figs. 2 and 3), and harnessing cyanobacterial or algal systems to pump up CO_2 or compartmentalize RUBISCO.

Successful engineering in photosynthetic enzymes and introducing efficient pathways in chloroplasts anticipating substantial improvement in crop performance are shown in Table 1. Maize is a cereal system having C_4 photosynthesis with enhanced ability to assimilate and metabolize carbon and nitrogen. In maize, photosynthesis and fresh weight respond with overexpression of small and large subunits of RUBISCO and assembly of chaperone protein, RAF1 (Salesse-Smith et al., 2018). In wheat, it is *sedo-heptulose-1,7-biphosphatase* (*SBP*) whose overexpression-enhancing rate of photosynthesis results in increased plant growth (Driever et al., 2017). Similarly, in *Chlamydomonas reinhardtii,* overexpression of

SBP1 enhances the rate of photosynthesis without affecting other enzymes involved in the Calvin–Benson cycle (Hammel et al., 2020). These technological innovations are key to enhance photosynthetic potential in elite crop varieties. In transgenic tobacco, photosynthetic manipulations with altered combinations of sedoheptulose-1,7-bisphosphatase, fructose-1, 6-bisphosphate aldolase, and putative-inorganic carbon transporter B (ictB) led to substantial improvements in photosynthesis and ultimately increase in leaf area and total biomass (Andrew et al., 2015). These findings are the major breakthroughs in understanding photosynthesis systems and help in engineering, which may be deciphered into technology from the proof-of-concept stage.

Comparatively, C_4 photosystem is more efficient than the C_3 as it has enhanced concentration of Co_2 around RUBSICO and reduced photorespiration activity. Transforming rice photosystem into C_4 through genetic engineering via "proto-Kranz" anatomy is quite feasible with enhanced organelle volume in sheath cells in leaf. Induction of maize constitutive genes, GOLDEN2-LIKE in rice, led to mitochondrial and chloroplast development in the vascular sheath cells (Wang et al., 2017). The role of leaf morphogenesis in the photosynthetic activity is well established and has positive associations in photosynthesis as it is the main site of CO_2 fixation; hence, it is directly plant biomass and yield (Guo et al., 2019), and leaf area also affects grain and other panicle traits (Fu et al., 2019). Zhang et al. (2017) studied the importance of leaf morphology in rice plant development and found a strong correlation between spatial arrangement of leaf with yield. It is evident that the photosynthetic activity in plants leads to substantial changes in canopy structure (Monneveux et al., 2005).

In plants, source and sink capacity are usually enhanced by nitrogen uptake and utilization, which leads to plant dry matter accumulation and crop yield. Morphological parameters like spike shape and size, canopy stature, and total biomass accumulation are the primary traits having a strong association with nitrogen uptake and utilization (Xu et al., 2019). In plants, RUBISCO is the enzyme that regulates energy conversion from inorganic to organic through C_3 pathway, and high RUBISCO activity encourages more nitrogen accumulation (Wang et al., 2017). In plants, post-anthesis active remobilization of nitrogen to the grains is ensured by RUBISCO degradation, stem nitrogen assimilation and stay-green phenotypes. The frequency with which plants evolved C_4 photosynthesis is challenging for researchers to decipher the genetic mechanisms underneath this convergent evolutionary switch (Schuler et al., 2016).

The genes encoding enzymes PEPC, PPDK, or NADP-ME specific to C4 photosynthetic are reported in several plants, potato, tobacco, wheat, rice, *Arabidopsis,* etc. (Häusler et al., 2001; Shen et al., 2015; Kandoi et al., 2016; Peng et al., 2018; Müller et al., 2018). Overexpression of C4-specific phosphoenolpyruvate carboxylase (PEPC: EC 4.1.1.31) gene in C_3 plants catalyzes primary CO_2 fixation of C_4. The PEPC gene is reported to be upregulated under drought and salinity conditions in both C_3 and C_4 plants (Zhou et al., 2011a; Kandoi et al., 2016). Overexpression of C_4 PEPC in C_3 plants improves photosynthesis and drought stress tolerance (Zhou et al., 2011a). Overexpression of chloroplastic-specific *PPDK* gene in maize enhances internal CO_2 concentration and stomatal conductance, resulting in a higher rate of photosynthesis (Gu et al., 2013). Overexpression of C_4-*PPDK* gene in *Arabidopsis thaliana* is also reported to have high photosynthesis (Wang et al., 2012). Similarly, overexpression of *ZmNADP-ME* in the guard and vascular companion cells of tobacco leads to enhanced net carbon assimilation, high biomass, water-use efficiency, early flowering, and reduced life cycle (Müller et al., 2018).

Active NAD-malic enzymes (NADP-ME) enhance nitrogen assimilation in C_4 plants than in C_3 plants. In barley, dose effects of the *HvGS1-1* gene enhancing GS1 enzyme activity in turn enhance NUE and grain yield (Gao et al., 2018). The impact of overexpression of two isoforms of enzymes (GS1), that is, *Gln1-3* and *Gln1-4* in the maize, has been demonstrated and leads to increases in the number of kernels (Martin et al., 2006); hence, the role of genes in nitrogen assimilation is important in kernel yield.

The stay-green trait is an important plant feature and encourages assimilate partitioning at grain-filling stage as retained photosynthetic activity while plants start to age (Thomas & Smart, 1993). Stay-green trait in plant is encoded by *STAY-GREEN* (*SGR*) genes, encodes highly conserved chloroplast proteins, and disrupts chlorophyll–protein complexes responsible for the degradation of chlorophyll and apoprotein in plants (Hörtensteiner, 2009). *SGR* homologs are also important for plant growth and development like fruit maturation and nodule formation (Jiao et al., 2020). In alfalfa (*Medicago sativa*), RNAi-led downregulation of *SGR* (*MsSGR*) produces stay-green transgenic plants (Zhou et al., 2011b). The RNAi-positive alfalfa lines, along with the greenish appearance, retain >50% chlorophyll and increased level of crude protein content during senescence, thus improving forage quality. The functional stay-green trait causes delayed chlorophyll degradation with extended photosynthesis in the leaves (Thomas & Ougham, 2014).

2.2 Enhancing NUE of Crops

NUE is the relative difference in nutrient uptake under fertilized and unfertilized crop in relation to the quantity of the used nutrients. In a better way, it can be defined as unit biomass accumulation of biomass per unit use of input. The NUE in the plants depends on nutrient uptake, transport, assimilation, storage, remobilization, etc., during plant growth. Understanding the processes and mechanism regulating nutrient dynamics in plants can be obtained through genomics and expression analysis. In soil, nutrient availability is often influenced by several interrelated factors like soil texture and structure, humus and moisture content, aeration, pH, temperature, surface area of root, rhizoflora, and other mycorrhizal growth. Mainly, NUE depends on genetic architecture and root structure of plants to take nutrients from the soil. However, plant system is responsible for nutrient transport, and its storage and remobilization are also equally important. Soil microbes play an important role in nutrient mobilization; conversion of NH_4^+/ NH_3 (an immobile form) into nitrate (NO_3^-) (mobile form) via nitrite (NO_2^-) is done through a microbe-driven process called nitrification. Though nitrification pertains to few negative aspects, it encourages pollution and deterioration in soil quality. Nitrification leads to nitrogen loss in the form of NO_3^- leaching into groundwater and source of water pollution. Besides, nitrification enhances acidification in the soil that promotes leaching important cations like K^+, Ca^{2+}, and Mg^{2+}. Whereas the other important nitrogen cycling process is called denitrification that causes air pollution.

Besides, for judicious management of nitrogen in the soil, understanding NUE in terms of total nitrogen input and nitrogen output is imperative. In estimating the NUE, nitrogen uptake efficiency (NUpE) and nitrogen utilization efficiency (NUtE) are considered to be important parameters. NUpE is the total amount of aboveground nitrogen content during harvest by available nitrogen in the soil. Whereas NUtE is the proportion of the nitrogen present in grain tissues and above-the-ground plant biomass. Generally, in plants, yields and protein content in grains represent NUE, but are inversely related, hence, while making breeding strategies for high NUE, breeder must consider these points to make higher genetic gain (Oury & Godin, 2007).

In plants, root growth and root architecture are highly responsive plant parameters to the availability of nutrients, and thus are considered an important trait for NUE improvement. In addition, important microbes like endophytic bacteria present in the root zone directly influence the nutrient uptake. Under symbiotic association, soil microbes establish nutrient exchanges for mutual benefits.

In this context, breeding plays a paramount role in making nutrient balances in the soil through optimizing rooting, internal transport activity, and partitioning. In nature, plants have several beneficial associations with microorganisms that convert immobile nutrients like nitrogen and phosphate into mobile form and make them available to the plants. In this area, genomics has made substantial improvements.

Several potential candidate genes in plants have been identified responding to NUE. The genes encoding transcription factors, transporters, sensors, and metabolic enzymes are identified to have substantial association with NUE (Table 2; as reviewed by López-Arredondo et al., 2013).

The genes/enzymes involved in nutrient uptake, transport, and use in plants are discussed next.

2.2.1 Glutamate Synthase (GOGAT)/Glutamine Synthase (GS)

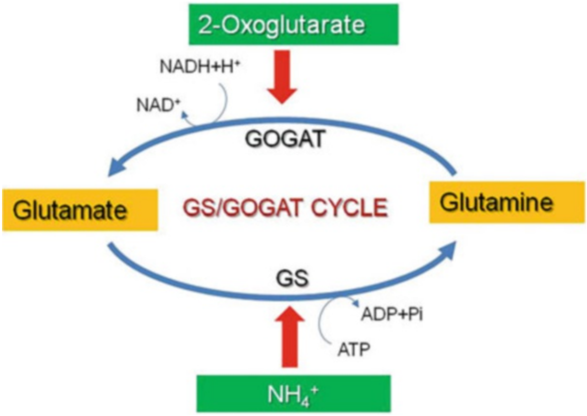
In plants, GOGAT is present in two isoforms in the leaves and has a vital role in nitrogen assimilation. A ferredoxin-dependent GOGAT (Fd-GOGAT) is solely present in chloroplasts, whereas NAD-dependent GOGAT (NADH-GOGAT) is especially found in the vascular bundles of unexpanded leaves (López-Arredondo et al., 2013). The GOGAT/GS-dependent pathway of nitrogen assimilation is presented in Fig. 4.

The NAD (P)H-dependent nitrate reductase (NR) (NR; EC 1.7.1.1) catalyzes rate-limiting step of NO_3^- reduction. NR activity in plant is dependent on molybdenum (Mo) co-factor and plays a role in NO_2^- abundancy, growing tissue, phosphorylation, and hormonal induction (Garg, 2013; Nemie-Feyissa et al., 2013). The enzymes, NR, NiR, GS, GOGAT, involved in nitrogen assimilation in plant are very sensitive to Mo co-factor ((Imran et al., 2019). The Mo deficiency in plants led

Table 2 Genomic resources associated with NUE in plants

Name of gene	Function/role	Plant	References
NADH-dependent nitrate reductase	Catalyze rate-limiting step of nitrate reduction	Wheat	Boisson et al. (2005)
NIN-LIKE PROTEIN (NLP) genes	NLP family proteins bind the promoter region and activate nitrate-responsive *cis*-element	*Arabidopsis*	Konishi and Yanagisawa (2013)
SlNLPs, SlNLP1, SlNLP2, SlNLP4, SlNLP5, SlNLP6,	Regulation of nitrate uptake	Tomato	Liu et al. (2021)
DOF1 gene	Increases N assimilation and plant growth under low-N conditions	Rice	Kurai et al. (2011)
VfAAP1	Overexpression of VfAAP1- encourage higher N, globulin, and weight, respectively, accumulation in plants	Pea	Rolletschek et al. (2005)
IRON-REGULATED TRANSPORTER1 (IRT1)	Act as major transporter for Fe, expressed in epidermal cells of Fe-starved roots	*Arabidopsis*	Vert et al. (2002)
YELLOW STRIPE1 (YS1) and YS1-like (YSL) transporters	Activate Fe3+ -DMA complexes transport from rhizosphere in rice		Inoue et al. (2009)
IRON DEFICIENCYRESPONSIVE ELEMENT-BINDING FACTORS1 (IDEF1)	Activate transcription of Fe-responsive genes		Kobayashi et al. (2007)
OsIRO2 (bHLH protein gene)	Transcription factor involved in the regulation of Fe uptake during Fe deficiency	Rice	Ogo et al. (2007)

Fig. 4 GS/GOGAT pathway of nitrogen assimilation



to poor nitrogen assimilation, which results in nitrogen deficiency symptoms (Kaiser et al., 2005). In hexaploid wheat, two genes responding to NADH-dependent nitrate reductase are reported (Boisson et al., 2005). In rice, functions of three iso-enzymes of cytosolic glutamine synthetase (GS1.1, GS1.2, and GS1.3) and two NADH-glutamate synthases (NADH-GOGAT1 and NADH-GOGAT2) are elucidated through reverse genetic and spatial expression analysis approach (Yamaya & Kusano, 2014). The genes OsGS1.2 and OsNADH-GOGAT1 are found to be expressed in the root surface cells in the presence of NH_4^+. It is reported that transposon-mediated disruption of these genes results in reduced tillering and panicle number that were found to be normal in case it (OsGS1.2 Cdna) is reintroduced in the mutant.

2.2.2 Transcription Factors

Transcription factors (TFs) are the major switches in the regulatory networks of plants. TF modulates expression of genes/biological processes under varying spatiotemporal and environmental shocks. The TF and NLP have affinity to bind with nitrate-responsive *cis*-element, which in turn activate NO_3^--responsive *cis*-element and transcription. The activity of NLPs is post-translationally modulated by nitrate signaling (Konishi & Yanagisawa, 2013). In tomato, genome-wide survey and expression analysis of NLP explained their potential in nitrogen signaling (Liu et al., 2021). Nitrogen starvation upregulates SlNLP1, SlNLP2, SlNLP4, and SlNLP6 in tomato (Liu et al., 2021).

Plant-specific TF in maize Dof1 (ZmDof1) induces the expression of phosphoenolpyruvate carboxylase (PEPC) through trans-activation of PEPC promoters in protoplast and enhances nitrogen assimilation in *Arabidopsis thaliana* even under N-deficient conditions. Similar results are also reported in rice where ZmDof1 gene enhances carbon and nitrogen assimilation (Kurai et al., 2011). Other TF, ZmDOF1, AP37, and OsNAC5 also induce nitrogen-use efficiency and ultimately yield in the crop plants (Li et al., 2020).

2.2.3 Transporters

The N accumulation in the root is an active process, mediated by specific transport protein that enhances nitrogen uptake. In soil, nitrogen is present in inorganic forms like NO_3^- and NH_4^+ (Nieder et al., 2011). In the uptake of N forms like NO_3^-, NH_4^+, amino acids or peptides, and urea, mainly, substrate-specific transporters are involved in N uptake (Crawford and Glass, 1998; Kant, 2018). There are five transporter families – the nitrate transporter 2, nitrate transporter 1/peptide transporter, chloride channel, slow anion-associated channel homolog, and aluminum-activated malate transporters – involved in the uptake and transport of NO_3 (Léran et al., 2014; Li et al., 2017).

Fe and Zn are important micronutrients for plant development regulated by zinc-regulated and Fe-regulated transporter-like protein (ZIP) (Li et al., 2013). In maize, several ZIPs are reported, for example, ZmIRT1 is specific to silk and embryo, whereas ZmZIP3 is leaf-specific, both being located in plasma membrane and ER

(Li et al., 2016). In *Arabidopsis,* overexpression of ZmIRT1 or ZmZIP3 showed enhancing Fe and Zn concentration in roots and seeds (Li et al., 2015).

Besides, signaling cascade, that is, NAC42-NPF6.1, is discovered to improve nitrogen-use efficiency and yield in rice, a potential breeding target (Tang et al., 2019). OsNPF6.1^{HapB} is a haplotype of nitrate transporter and confers high nitrogen-use efficiency under low nitrogen supply. Though OsNPF6.1^{HapB} has natural variations in protein and promoter element and is differentially trans-activated by TF, OsNAC42.

2.3 Phosphorus-Use Efficiency (PUE)

Phosphorus (P) is a requisite nutrient for plant growth and development and is involved in many vital biochemical processes related to gene expression, energy generation and transfer, and protein metabolism (Fageria et al., 1997). P is an essential part of cell membranes (phospholipids, lecithin, and cephalin) and is involved in various metabolic functions. In soil, it is found in two forms, organic and inorganic, which are the least accessible to plants as they exist in the form of compounds of metals, such as Fe, Al, and Ca. P deficiency in soil causes severe yield loss and necessitates its judicious management to prevent soil degradation. In plants, root makes several modulations in cellular processes to sustain P starvation. P encourages plant growth and development, particularly helping profuse tillering and fruiting (Fageria & dos Santos, 2008). Under P deficiency, plants show growth retardation with thin stems, and smaller and dark colored leaves. In plants, P deficiency encourages excessive accrual of anthocyanin in leaf, which appears as a reddish or purple tint. P deficiency results in reduced cell and leaf area expansion and enhances chlorophyll formation, which leads to more chlorophyll accumulation with less photosynthesis. However, P is not a constituent of chlorophyll, and its increased accretion in deficient leaf causes the dark green color of leaf than normal plants. Phosphorus is an important constituent of cell membranes (phospholipids like cephalin and lecithin) and protects cells against diseases. P deficiency in rice encourages brown spot (*Bipolaris oryzae*) occurrence and severity. The current demographic scenario demands more P fertilizers to produce sufficient food, and the demand is steadily increasing. Given the high costs of fertilizers, enhancing P fertilizer use efficiency in agriculture is imperative for its judicious exploitation.

2.3.1 P Mobilization and Acquisition in Plants

Plants' ability to uptake P from the soil differs from case to case. In soil, P is available in various complexion; in plants, its availability depends upon the root architecture and their ability to compete with microbial and soil constituents. Plants are able to uptake only ~20–30% of the total applied P (Richardson & Simpson, 2011). In plants, P acquisition efficiency depends on root and microbiomes that are able to mobilize insoluble P from the soil. Plants adapt several modulations/mechanisms to increase their P acquisition/uptake/absorption efficiency. Root modification through its absorptive area expansion, better symbiosis with soil microbes, release of biomolecules capable of freeing P from metallic-P compounds or organic P complexes, increased production of phosphatases that enhances the rate of P uptake, and P acquisition efficiency (PAE)-the ability of plant to take P from soil are the determinant of PUE in the plants (Dissanayaka et al., 2018), which reduces loss of P from soil due to runoff. Besides, high PAE results in depletion of P in the soil and also encourages P accumulation in the seeds in phytate form that cause environmental problems like eutrophication in water reserve and ultimately water pollution. Plant physiological improvements to enhance PUE are thus desirable to secure food production and protection of water bodies (Hammond et al., 2009). Recently, considerable research advances have been made toward understanding the adaptive and efficient utilization of P.

2.3.2 Redistribution of Pi Between Tissues

Under Pi shortage in the system, plants mobilize it from older leaves and maintain resource acquisition through photosynthesis in young leaves and nutrient uptake by roots (Hammond et al., 2003). Plant systems catabolize a variety of organic P compounds in non-senescent as well as senescent tissues and maintain photosynthesis and proper growth (Veneklaas et al., 2012). In addition, in the reproductive stage, Pi is transported to seed and stored in the form of phytate. Pi transporters coordinate Pi fluxes in leaves from older to young leaves during the vegetative stage and leaves to grains at the reproductive stage. The molecular mechanism of Pi transport in plants is unraveled; details are given in Table 3.

2.3.3 Vegetative Stage Pi Transport

A lot of Pi transporters belong to the Pht1 family, which are specifically expressed in root and shoot (Nagarajan et al., 2011). Usually, Pi transporters are induced under P-deficient conditions, and catalyze Pi transportation to sink from the sources (Table 3). It is reported that Pi transporters like AtPht1;5 (*Arabidopsis*) and HvPht1;6 (Barley) are low-affinity transporters, getting activated in case of Pi deficiency in leaves (Nagarajan et al., 2011). Similarly, in soybean, GmPT1 transcripts that are Pi remobilization factors are reported in young, mature leaves and roots during long P deficiency (Song et al., 2014). Overexpression of another Pi transporter, GmPT1, enhances total dry weight, PUE, and per se grain yield in plants (Song et al., 2014). OsPht1;8 is a high-affinity Pi transporter reported to catalyze transportation of Pi from old leaves in rice (Li et al., 2015). Moreover, OsPht1;4 is activated under Pi-deficient condition, and downregulation of OsPht1;4 and OsPht1;3 causes reduced Pi concentration in flag leaves and xylem sap of rice (Chang et al., 2019). Besides, ZmPT7, a close OsPht1;8, are bundle sheath cell-specific transporter and get phosphorylated in old leaves under Pi-deficient conditions, which enhances Pi transport in old leaves (Wang et al., 2020).

2.3.4 Pi Allocation of Leaf Cells

Leaf cells have differential physiological responses; nutrients partitioning in the leaf are highly specific to the genotype of the plant, life stage, and surroundings (Conn & Gilliham, 2010). P allocations in the leaf cells inhibit the formation of insoluble P

Table 3 P transporter in plants transports Pi at the vegetative and reproductive stages

	Gene	Species	Expression site	Mechanism	References
At vegetative phase	*Pht1;1*	*Glycine max* L. Merr.	Root, leaf, stem, and flower	P remobilization from source to sink, > PUE and yield	Song et al. (2014)
	Pht1;3	*Oryza sativa* L.	Phloem tissue of both RVB and EVB	Source to sink leaves P remobilization	Chang et al. (2019)
	Pht1;4	*Oryza sativa* L.	Flag leaf, ligule, nodes, internodes	P remobilization in flag leaf and panicles	Ye et al. (2015), Zhang et al. (2015)
	Pht1;5	*Arabidopsis thaliana*	Root, leaf	Source to sink leaves P remobilization	Nagarajan et al. (2011)
	Pht1;6	*Hordeum vulgare* L.	Flag leaf, old leaf	Remobilization of stored P in leaf	Rae et al. (2003)
	Pht1;7	*Zea mays* L.	Root, leaf	P remobilization from source to sink leaves	Wang et al. (2020)
	Pht1;8	*Oryza sativa* L., *Triticum aestivum* L.	Root, leaf, stems, seeds	P mobilization from source to sink and seeds	Li et al. (2015)
Reproductive phase	*SPDT*	*Oryza sativa* L.	Xylem tissue	Enhancing distribution of P from leaves to grain	Yamaji et al. (2017)
	Pho1;1	*Oryza sativa* L.	Phloem of DVBs of node I	Loading P into the phloem of DVBs and allocating to grains	Che et al. (2020)
	Pho1;2	*Oryza sativa* L., *Zea mays* L.	Xylem of EVBs of node I	Unloading P from the xylem of EVBs	Che et al. (2020); Ma et al. (2021)

Pht, phosphate transporter; *SPDT*, SULTR-like phosphorus distribution transporter; Pho, phosphate; *EVBs*, enlarged vascular bundles; *DVBs*, diffuse vascular bundle; *RVBs*, regular vascular bundles; *PUE*, phosphorus-use efficiency

compounds. Mesophyll cells contain chloroplasts and are the main site for photosynthesis in the plants (Braun & Slewinski, 2009). P is the major element of ATPase activities that catalyze ATP formation in thylakoids. In order, phosphorylated intermediates get into the Calvin cycle pathway and are released again with CO_2 reduction and revert back to the chloroplast (Stitt et al., 2010). In dicot plants, P is especially distributed in epidermal cells, whereas it is allocated preferentially in the mesophyll of monocots (Hayes et al., 2018). The preferential distribution of P element in photosynthetic tissues modulates photosynthetic efficiency in plants under deficient habitats (Hayes et al., 2018;). It is reported that a substantial amount of P is needed for photosynthesis, the formation of phospholipids (PLs), and other metabolic pathways of carbon metabolism (Veneklaas et al., 2012). Proteaceae family are adapted to low P and has slow photosynthetic apparatus development that contributes to PUE in plants (Sulpice et al., 2014). In Proteaceae plants, younger leaves contain a very low amount of plastid rRNA and cause a delay in chloroplast genesis. Delayed chloroplast biogenesis facilitates sequential use of P in the ribosomes. Generally, in plants, P distribution follows preferential allocation for leaf growth, photosynthetic machinery development, and thereby PUE (Kuppusamy et al., 2020).

2.3.5 P Transport Reduction During the Reproductive Stage

In cereal plants, ~60–85% of P during the reproductive stage allocated to the grains led to large P offtake from soil to grain (Che et al., 2020). In wheat, it is quantified that 65% of grain P is a part of remobilized P from vegetative tissue (El Mazlouzi et al., 2020). A certain amount of P in the seed is required for the germination and seedling establishment, but it becomes high in case plants receive a high P supply (Wang et al., 2021). Hence, identifying crop breed with minimal seed P content without any germination and crop establishment harm is easy to improve PUE in a given agro-environment. In seeds, P delivery is determined by its concentration and rate of transportation in the phloem (White, 2012). A gene SPDT (SULTR-like phosphorus distribution transporter) whose expression is induced under low P in the node of rice is reported (Yamaji et al., 2017). Knocking out SPDT is reported to change the distribution of P among plant leaves and grain. Transporter, OsPHO1;2 (PHO1-type), plays a very decisive role in Pi reallocation throughout grain-filling stage (Ma et al., 2021). Mutation in Ospho1;2 leads to excess P accumulation in the seeds and inhibits the activity of ADP-glucosepyrophosphorylase (AGPase). Overexpression of OsPHO1;2 leads to reduced P accumulation in the seeds and enhances AGPase activity as well as grain yield (Ma et al., 2021). Recent technological developments, particularly omics tools, provide more insight into the regulatory networks of P distribution to grain.

2.3.6 Remobilization of Phosphorus in Cellular Pools

In plant tissue, P is present in the form of Pi or organic (Veneklaas et al., 2012). In case of plants' inability to acquire requisite P, plant tissue releases its vacuolar Pi and maintains its concentration in cytoplasm and facilitates normal cellular activities (Pratt et al., 2009). Replacement of PLs (plant membrane) with non-PLs, phosphorylated with non-phosphorylated metabolites, needs minimal P, reduces ribosomes, and optimizes protein synthesis; it can be a strategy to improve PUE (Prodhan et al., 2019).

2.3.7 Phosphate Recycling from Vacuoles

Cellular P is present mainly in the vacuole; under optimum P conditions, it contributes to ~85% P in vegetative tissues (Veneklaas et al., 2012). Cellular Pi homeostasis is determined by its transportation between vacuoles and cytosol (Veneklaas et al., 2012). In case of Pi sufficiency, excess Pi is stored in the vacuoles, which is remoblized upon deficiency. It is an imperative modulation in plants to sporadic low P stress (Liu et al., 2015). In model plants like rice and *Arabidopsis*, substantial research progress has been made toward Pi transporters in tonoplast that are responding to carrying Pi between the vacuoles and the cytosol (Xu et al., 2019).

Vascular Pi transporter (VPTs), a Pi type 5 transporter (PHT5), is responsible for Pi transportation from cytosol to vacuolar lumen in *Arabidopsis* (Srivastava et al., 2018). Mutant transporter, VPT1 (Pht5;1), in *Arabidopsis* reduces Pi concentration in vacuolar section and low vacuole/cytoplasmic Pi quotient (Liu et al., 2015). On the other hand, the double mutants, vpt1/vpt3, respond to excess Pi allocation in the floral tissue than storing it in vacuoles of leaf that impairs siliques development in P-sufficiency (Luan et al., 2019). It was further suggested that VPTs regulates Pi balance during the reproductive phase through Pi sequestration (Luan et al., 2019). Rice homolog, PHT5, OsSPX-MFS1, OsSPX-MFS2, and OsSPX-MFS3, are located on tonoplast. Overexpression of OsSPX-MFS3 causes reduced Pi concentration in vacuoles, suggesting its involvement in the Pi efflux (Wang et al., 2015). Whereas OsSPXMFS1 works as a vacuolar Pi influx transporter (Liu et al., 2015).

2.3.8 Foraging Pi from Organic P Fractions to Improve PU

Under extended P deficiency, vacuolar Pi gets depleted, which leads to a severe decline in the cytoplasmic Pi. Re apportionment in Pi fractions is imperative to support growth and development in plants under minimal vacuolar Pi conditions. In plants, four types of organic P compound exist: (1) lipid-P; (2) low-weighted Pi esters (ester-P); (3) nucleic acid-P; and (4) residual-P (phosphorylated proteins and other residues serve regulatory role) (Veneklaas et al., 2012). Organic P size is usually found in decreasing order in RNA-P > lipid-P > ester-P > DNA-P (Veneklaas et al., 2012). P distribution among the main organic pool differs from species to species, and is greatly influenced by P availability in the plants (Yan et al., 2019). In barley, it is reported that under P sufficiency (100 μmol L^{-1}), Pi accounts for ~79% of the total P and is mainly stored in vacuoles. Nucleic acid-P, lipid-P, and ester-P account for ~13%, 4%, and 4% of the total P, respectively. However, under low P condition (1 μmol L^{-1}), nucleic acid-P, lipid-P, and ester-P account for comparatively high amount, 42%, 14%, and 23% of the total P.

Lipid is the main constituent of cell membrane and comprises PLs, glycolipids, and sulfolipids. Reports indicate that PLs comprise ~30% of the total organic P pool that is diluted under low vacuolar Pi condition and meets the demand of the plants (Lambers et al., 2012; Veneklaas et al., 2012). In general, PLs are dominant phospholipids; however, in case of thylakoid membranes, galactolipids (monogalactosyldiacylglycerol [MGDG]; digalactosyldiacylglycerol [DGDG]) and sulfolipids (sulphoquinovosyldiacylglycerol [SQDG]) are dominant (Narayanan et al., 2018). Hydrolysis in PLs and its substitution through galactolipids and sulfolipids were found to be an imperative strategy for PUE enhancement in plants. In other cell membranes, PLs were found to be substituted with galactolipids, sulfolipids, etc., though it is very poorly known (Veneklaas et al., 2012). In contrast, Proteaceae species are adapted to very extreme

P-impoverished habitats, where PLs are highly substituted by galactolipids and sulfolipids but plants do not lose photosynthetic rate. PL replacement with galactolipids and sulfolipids looks to be a pervasive response in plants under deprived P supply. Replacement of PLs with DGDG is reported in *Arabidopsis*, soybean, oat, and bean. In plants, young leaves maintain a high PL to protect the cell integrity during cell division. In the membrane remodeling process, phospholipase C catalyzes PL decomposition, resulting in diacylglycerol (DAG) and polar group phosphocholine that is further hydrolyzed with acid phosphatase (APase) and release Pi. Phospholipase D catalyzes PL hydrolysis and produces choline and phosphatidic acid, which is further hydrolyzed to DAG and releases Pi (Dissanayaka et al., 2018). Moreover, PLs are deacylated by phospholipase A and lysophospholipase into glycerol-phosphocholine and glycerol-phosphoinositol that is further hydrolyzed to glycerol-3-phosphate (G3P) and choline or inositol; G3P is then hydrolyzed by APase to release Pi and glycerol (Dissanayaka et al., 2018). Anon-specific phospholipase C5 (NPC5) in *Arabidopsis* degrades PLs under P deficiency and promotes DGDG synthesis as well as Pi release. Another enzyme, NCP4, was found to be involved in PL hydrolysis and remodeling is induced under P starvation and hydrolyzes glycosyl inositol phosphoryl ceramide to release Pi (Yang et al., 2021). Overexpression of OsGDPD2 in rice enhances tillering, shoot biomass, and Pi under deprived P condition. Monogalactosyldiacylglycerol and DGDG contents of OsGDPD2-overexpressing lines were 2.2- and 2-fold higher than in wild-type plants, respectively (Mehra et al., 2019).

3 Prospects of Advanced Biotechnological Tools in the Manipulation of PC and NUE of Plants

Research advances in biotechnology and genomics provide better opportunities and technologies that can help in the modulation of PC and NUE of crops. Better crops in the wake of climate change and other challenges have become a necessity for future food security. Recent success in the genetic engineering of photosynthesis, nutrient use, and beneficial plant–microorganism interactions is remarkable and gives hope for better crops in the future. The vigorous assessment of varieties for the interaction with the environment (GXE) is important to address the farmer's acceptance or adoption of that variety. An in-depth understanding of the basis of genetic variation empowers the plants to respond to and interact with the surrounding environment and pathogens while maintaining the well-being of plants is essential. Gene editing has recently been adopted as a method of choice to generate changes in DNA sequences at precise genomic locations, leading to the knockout or knockdown of one or multiple genes without the stable insertion of any foreign segment of DNA. Unlike cisgenic or transgenic, which uses genes from within the organism's gene pool (cisgene) or from other organisms (transgene), it can be inserted into precise locations within the genome to knock-in a new trait. Several gene-editing methods are reported such as Transcription Activator-Like Effector Nucleases (TALENs), Zinc Finger Nucleases (ZFNs), and CRISPR/Cas systems that have been utilized to achieve precise gene edits (Singh et al., 2017). The precision and efficiency of generating edits with the introduction of CRISPR/Cas systems have been reported, yet offtarget editing and gene flow to wild relatives are of major concern in the adoption of gene-edited crops. Realizing the potential role "gene editing" may play in bringing better crops in the future, it should be accepted for the larger interest of the humanity but with proper safety guidelines.

The role of noncoding RNAs such as microRNA (miRNA) and long noncoding RNAs (lnc-RNAs) is also needed to be explored intensively in the PC and NUE as their role in gene regulation is widely being reported in plants. The miRNAs are small single-stranded noncoding RNA molecules (containing about 22 nucleotides) that play important roles in regulating gene expression by repressing translation and/or by promoting decay of mRNA having a sequence complementary to the miRNAs. For example, the miRNA169 family is reported to regulate the expression of genes for nitrogen transport under low nitrogen conditions, and in maize, miR169 expression decreases in N-deficient plants (Zhao et al., 2011). Efforts are being made to engineer the N_2 fixation using the genes involved in nitrogen fixation from the nitrogen-fixing bacteria such as gene encoding enzyme nitrogenase. In the future, the results of engineered *Synechocystis* 6803 strains that showed remarkably more than 30% of the N_2 fixation activity of diazotrophic cyanobacterium *Cyanothece* 51142 (Liu et al., 2018) are awaited. This effort has significance as it will boost the prospect of engineering nitrogen fixation ability in crop plants.

4 Concluding Remarks

Improving PC and NUE is very important for profitable crop production by enhancing crop production and productivity. The collaborative research on genomics, marker-assisted breeding, biotechnology (transgenic and gene editing), agronomy, soil science, and plant physiology will help in this direction. This chapter covered the updated knowledge and information on the role that biotechnology and genomics could play in enhancing PC and NUE of better crops for the benefit of researchers and academicians working on similar aspects.

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Energy-Efficient Tillage System for Crop Production

A Review

Fiaz Ahmad, Aftab Khaliq, Ding Qishuo, Farman Ali Chandio, Muhammad Sultan, and Muhammad Awais

Contents

Abstract

Agriculture tillage system is one of the most significant operations in crop production. Land preparation for crop cultivation is an expensive and laborious practice. The conventional tillage system is used for the field preparation process since decades. The conventional tillage systems cosume more than 50% of fuel for arable farming. This review aimed to identify the energy-efficient tillage system for crop production while considering the soil properties, crop residual management, and environmental aspects. Furthermore, this review discussed the studies about tool geometry and simulation model selection for the

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energy-efficient tillage system for crop yield. The extensive review of the literature revealed that the conservational tillage system is more energy efficient than other tillage systems. This chapter will provide the guidelines for future practices and research-related activities.

Keywords

Tillage system · Conventional · Laborious · Conservational · Energy efficient

1 Introduction

The tillage system is one of the most significant operations in terms of energy and cost consumption during crop production (Singh et al., 2008). Tillage is the mechanical manipulation of the soil layers and used to create desired soil physical, chemical, and biological conditions concerning plant growth since decades (Zhang & Peng, 2021). However, it is an energy-expensive, time-consuming, and laborious operation. Due to such limitations, farmers could not improve conventional cropping orders (Barzegar et al., 2016). Tillage practices can enhance crop productivity potential up to certain limits. However, in the longer period, they have negative consequences that can reduce soil productivity by increasing soil erosion and decay of soil organic matter (Reicosky, 2015). Soil quality is one of the most important parameters to agricultural production and supplies fundamental ecological services for human beings, such as carbon sequestration, and maintenance of biodiversity (Greiner et al., 2017).

For researchers and farmers energy consumption is one of the most concerning issue in the tillage system. The energy consumption in tillage practices contributes a significant amount to the total on-farms energy use. Conventional tillage machinery is not only energy extensive but also badly affects the soil productivity due to compaction by intensive traffic of machinery (Hensh et al., 2021). The movement of heavy machinery in the conventional tillage system usually compacts the subsoil which reduced the aeration, soil fertility, and organic matter in the soil. The conventional tillage systems used more than 50% of fuel for arable farming (Moitzi et al., 2021). In this regard, the geometry of the tillage implement is selected based on the draft and downward vertical forces using software simulations. The main purpose of the simulation model is to identify the impact assessment of implement design and geometry on soil disturbance (Rogovskii et al., 2020). The draft force of tillage implement depends on the operational factors (i.e., depth and speed) and soil conditions. The moldboard (MB) plough is one of the main implement in the conventional tillage system that completely buries the crop residue during soil pulverization (Hoseinian et al., 2022). The implements used in the conventional tillage system like MB plow, chisel plow, and rotavator consume 29–59% diesel fuel and need more energy input during field operations (Šarauskis et al., 2018). In addition, the consumption of fossil fuel for land preparation contributes 30–40% to the total carbon dioxide (CO_2) emissions from the agriculture sector (Martin-Gorriz et al., 2020). Many researchers performed experimental and analytical studies to identify the long-time impact of the conventional tillage systems on soil cutting forces, draft forces, energy consumption, and crop yield (Askari & Abbaspour-Gilandeh, 2019; Ani et al., 2018; Liu et al., 2021). All the studies agreed on the adaptation of a suitable tillage system that must be energy efficient and protect soil health, such a system is termed as the conservational tillage system (Zhang & Peng, 2021).

Conservation tillage is a noninversion tillage system with a broad spectrum of practices, in which no-tillage, direct sowing, reduced tillage, ridge tillage, and disc plow implements intend to retain crop residue on the soil surface to conserve soil from erosion and save energy in the form of fuel, draft force requirement, and mitigate the GHG emissions (Jug et al., 2019). Moreover, conservation tillage is a sustainable approach to enhance crop production while improving soil quality and crop yield (Jug et al., 2019). Comparative analyses showed that the conventional tillage system disturbs the soil more than 20 cm while the conservational tillage system disturbs soil not more than 10 cm (Morris et al., 2010). The conservational tillage methods have the potential to enhance farm economic performance by reducing fuel and labor costs (Hensh et al., 2021). In recent years, noninversion tillage has earned more importance to fulfill the needs of farmers at low cultivation costs, as a major portion of 25–30% of energy is utilized for field preparation and crop production. This amount of energy can be saved by reducing the intensity of tillage operations (Sharma et al., 2002). Some researchers compared the conventional and conservational tillage systems from the viewpoints of crop yields and environmental degradation under different agroecological conditions (Schwab et al., 2002). It was found that the use of the conservation tillage system utilized the crop residue along with controlling the CO_2 emissions from the soil, reducing nutrients' leaching, and energy consumption while maintaining the soil health (Cooper et al., 2017). As a matter of fact, the CO_2 emissions enhance up to 13% with an increase of plow depth from 100 mm to 200 mm (Šarauskis et al., 2018). The amount of postharvest residues that remain on the soil depends on the tillage system. The burial of crop residues largely affects tillage energy consumption. According to the research (Celik & Altikat, 2022), crop residues buried with the moldboard plough need more force as compared to conservation tillage. It is evident that there is a need to identify an energy-efficient, cost-effective, and environmental friendly tillage system that could enhance crop productivity while maintaining the soil health.

The review aimed to identify the impacts of energy-efficient tillage systems on crop production while considering soil health, residue management, and environmental threats. This study also discussed the tillage draft force and power prediction models to identify energy-efficient tillage implements. This study is essential for selecting energy-efficient tillage implements for better crop yield and soil health.

2 Efficient Tillage Systems for Crops

The tillage practices are considered as one of the most important factors for crop production in the agriculture sector to alleviate the food requirement. Gupta et al. (Gupta et al., 2021) compared the effects of crop residue mulching with the conventional tillage (CT) and zero-tillage (ZT) practices on the soil evaporation (Es) in wheat cropping seasons. The authors concluded that zero tillage (ZT) reduces less major Es loss (55–66%) during rice cropping and (12–22%) wheat cropping, but also improves soil health and crop productivity. Vizioli et al. (Vizioli et al., 2021) evaluated the impact of the long-term adoption of the conventional tillage (CT), strategic tillage (ST), and no-tillage (NT) systems on the crop yield related to soil physical qualities, and energy requirement for maize and soybean crop. The study concluded the relational impact of tillage practices on soil parameters, i.e., pore tortuosity (τ) and degree of compactness (DC); no tillage improves 1211 kg h^{-1} higher maize yield and 381 kg ha^{-1} soybean yield with efficient soil quality in comparison with conventional and strategic tillage as shown in Fig. 1. Kar et al. (Kar et al., 2021) evaluated the effect of intensive conventional tillage practices on natural resources degradation for rice-based cropping sequence. Zero tillage, reduced tillage (RT), and conventional tillage (CT) levels were selected for the wheat-rice-green gram cropping order. This study reported that RT was the best practice for the rice-based cropping system concerning crop productivity, recovery of nutrients, and less energy consumption.

Furthermore, Acharya et al. (Acharya et al., 2019) evaluated the impact of winter cover crop and different tillage systems on hydrological and agronomic conditions for the soybean crop in a humid region. Conventional tillage and no-tillage practices were adopted to investigate crop growth, crop height, and crop yield. The study

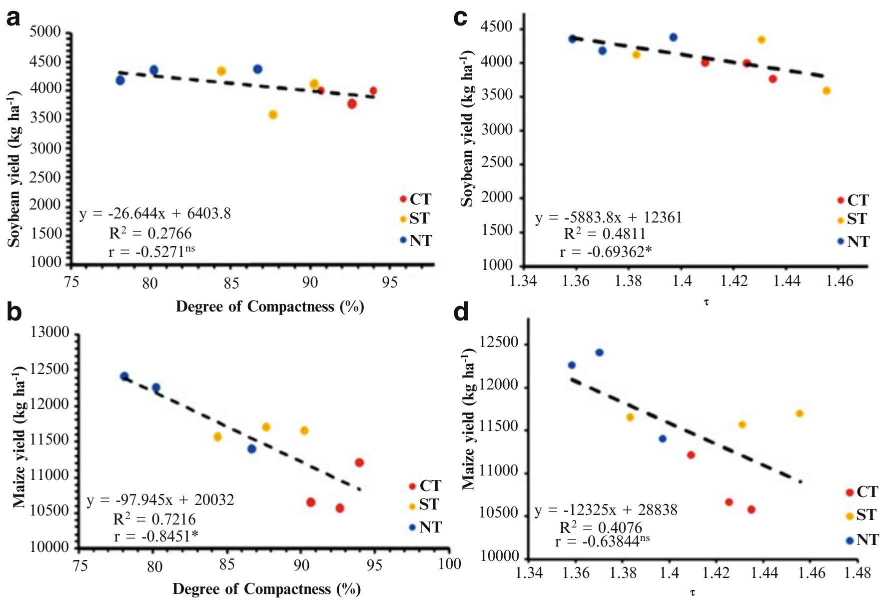

Fig. 1 Tillage practices impact on soil parameters (DC), and (τ) related to yield: (**a**) soybean yield; (**b**) maize yield, and the relationship between pore tortuosity (τ) and yield; (**c**) soybean; and (**d**) maize under conventional tillage (CT), strategic tillage (ST), and no tillage (NT) (Vizioli et al., 2021)

reported that conventional tillage maintains soil moister from 0–15 cm depth soil, while no tillage and cover crop increase crop by maintaining the soil moister 0–30 cm of soil depth for long time and conserves more energy by improving 20–30% biomass which was more than conventional tillage (Acharya et al., 2019). Latifmanesh et al. (Latifmanesh et al., 2018) compared annual rotational tillage impact of crop residue mulching on wheat crop yield in the corn-wheat cropping season. The authors used multiple-year data of annually rotatory tillage system (N-SR: no tillage without subsoiling; and SR: subsoiling with rotary tillage) used to identify the impact on crop productivity and soil health for wheat growth and energy consumption. The study concluded that SR subsoil with rotatory tillage in wheat cropping significantly creates adverse effect on the crop yield. While, rotatory tillage without subsoiling (N-SR) in corn season stimulates biomass production for wheat to promote the dry matter accumulation, nutrient uptake, and reduce energy consumption with minimum tillage passes to improve the wheat yield (Latifmanesh et al., 2018). Comparison of conventional and conservational tillage system is shown in Fig. 2. Nyakudy and Stroosnijder (Nyakudya & Stroosnijder, 2015) studied the conservation tillage system for the maize crop in rainfed areas. Maize crop requires high amount of water for maxium production. The conservation tillage, i.e., tied ridging, mulch ripping, and clean ripping system, suggested to identify the effects of that practices on maize yield. The study evaluated that conservation tillage increase

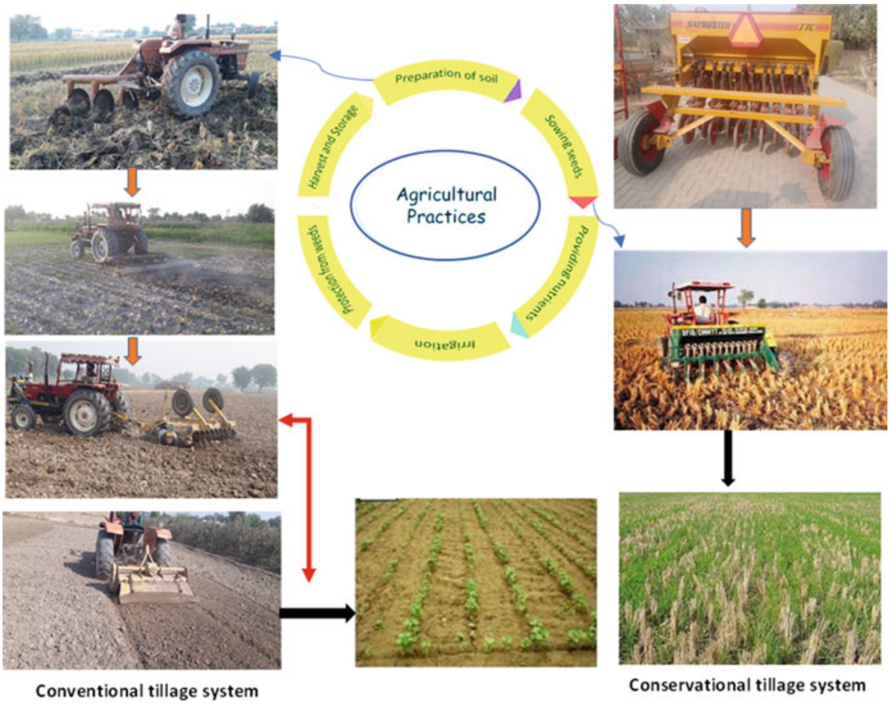

Fig. 2 Various land prepration pratices under conservation and conventional tillage system

Table 1 Studies about tillage system for crop yield enhancement

References	Year	Tillage system	crop	Growth
Liu et al. (2021)	2021	CT, ST, and NT	Maize	NT – 8740.9 kg ha^{-1} ST- 8512.6 kg ha^{-1}
Sun et al. (2018)	2018	DP, SP, and NT	Winter wheat	241.1 kg ha^{-1}
Anup Das et al. (2018)	2018	CT and CST	Rice and maize	CST 4–70%
Calonego et al. (2017)	2017	NT and chisel plow	Soybean	225.7 kg ha^{-1}
Erenstein and Laxmi (2008)	2008	Zero tillage	Rice-wheat	ZT-US$97 ha^{-1}

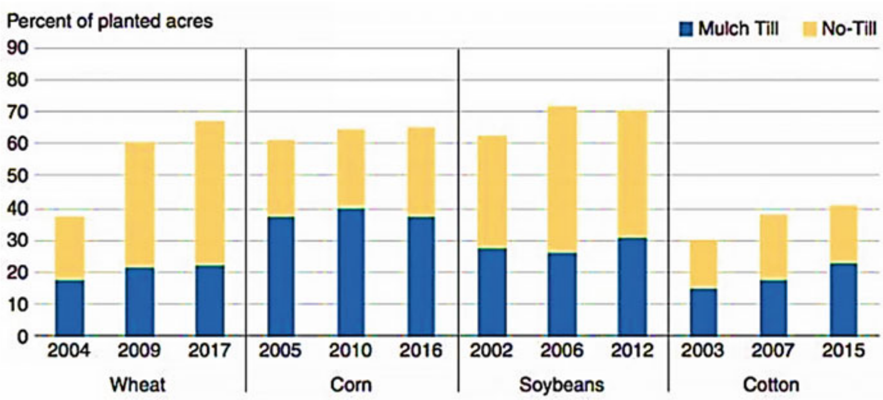

Fig. 3 Percentage enhancement in the adoption of conservation tillage for crop cultivation (Good, 2018)

$\leq$2.5th^{-1} in maize crop yield, tide ridging produces 144 kgh^{-1} increment and mulch ripping 344 kgh^{-1} that is more than conventional tillage which is $\geq$640 kg ha^{-1}. Furthermore, studies about the efficient tillage system for crop management are discussed in Table 1 below. The table shows the effect of various tillage practices effect on the crop growth.

The above studies about the different tillage systems for various crops revealed that conservation tillage options, i.e., reduced tillage, no tillage, and zero tillage, are more feasible solutions for energy-efficient and sustainable agriculture for crop yield. Keith Good (Good, 2018) finds out from the effort reporting system (ERS) about the effect of percentage enhancement of crop cultivation area with conservation tillage system as shown in Fig. 3. This figure shows years-wise enhancement in conservation tillage practices adoption for crop cultivation in the USA.

3 Efficient Tillage System for Soil

Agricultural intensification and crop productivity is limited by poor soil quality and low fertility. The tillage practices are widely used across the world to increase crop output by optimizing soil temperature and moisture, lowering seedbed penetration resistance, and controlling weeds. For better crop production, soil physical, chemical, and biological conditions are improved by the tillage practices. Çelik et al. (Çelik et al., 2021) compared conventional tillage (CT), reduced tillage (RT), and no-tillage (NT) systems to assess their effect on the soil quality using soil management assessment framework (SMAF) on clay soil. The authors have selected fourteen soil indicators including soil physical, chemical, and biological properties, and used three different depths (0–10 cm, 10–20 cm, and 20–30 cm) for a sample collection from disturbed and undisturbed soil samples. The study concluded that soil resistance and resilience (RR) and physical stability of soil (PSS) were higher in conservation tillage (NT and RT) at 0–10 cm depth. While strategic tillage (ST) gives better soil resistance and resilience (RR) and showed physical stability of soil (PSS) at the depth 10–30 cm as compared to long-term conservation tillage. Liu et al. (2021) reported the effect of tillage systems on the soil properties and conditions on crop yield. Three tillage systems discussed continuous moldboard (MB) plough or CT, subsoiler /MBP/subsoiler or strip tillage (ST), and no-tillage/subsoiler/no tillage (NT) or conservation tillage for soil quality. The authors concluded that conventional tillage reduced soil moister retention and organic matter in the soil (3.68 g kg^{-1}), and consumes more energy during field operation. Moreover, no tillage provides more soil moisture (20.42%), and stable the soil physical, chemical, biological health with less energy and fuel consumption and gives maize crop yield increment from 12.9–14.9% as compared to conventional tillage as shown in Fig. 4. Behera et al. (2021) compared the designed rota-cultivator with the conventional rotavator on the

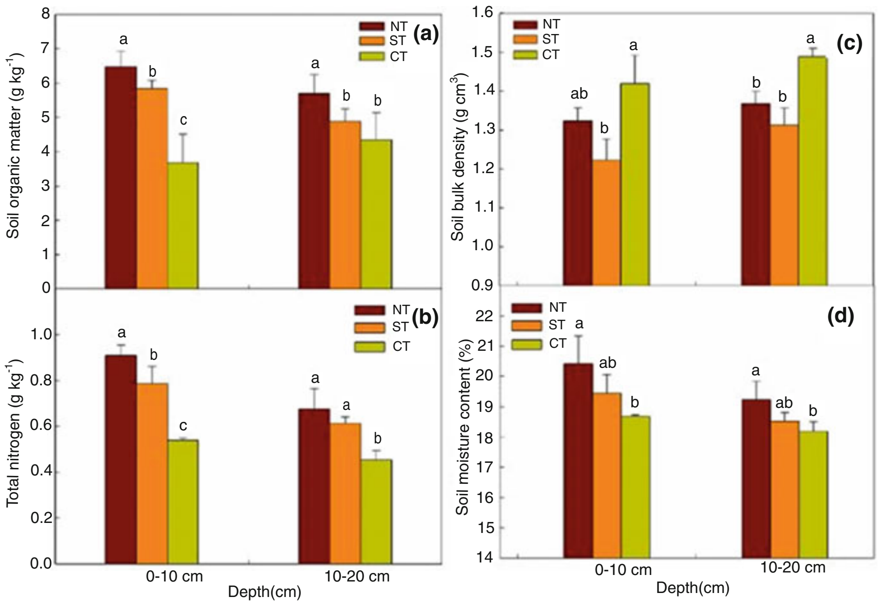

Fig. 4 Comparison of tillage treatments impact on soil parameters at different soil depth: (**a**) soil organic matter; (**b**) bulk density; (**c**) total nitrogen; and (**d**) soil moisture content (Liu et al., 2021)

sandy clay loam soil with 11 + 0.89% moister content to investigate its soil compaction under tillage power and fuel consumption. The study reported that the rota-cultivator required 28% less PTO power, less fuel consumption, and 27% less soil compaction as compared to the rotavator, and it could be operated with a 34 kW wheel drive tractor for 120 mm operational depth.

Cooper et al. (2020) compared conservation and conventional tillage practices based on five-year data to access the impact of a specific tillage system on soil health. The authors selected 143 ha area cultivated with the conservation tillage and 324 samples were collected to investigate the soil physical, chemical, and biological conditions. The study concluded that conservation tillage gives 13% more margin than conventional tillage in crop yield improvement with effective soil health. Moreover, conservation tillage is benificial for the environment with low energy and fuel consumption. Mairghany et al. (2019) used rotatory tillage on clay loam soil to identify the tillage impact on soil condition. This study focused on the bulk density, soil penetration resistance, porosity, and moister content measured at four tillage levels, i.e., no tillage, first tillage (FT), second tillage (ST), and third tillage (TT). Authors concluded that soil bulk density decreases with soil disturbance in the order NT > FT > ST > TT (Mairghany et al., 2019). Damanauskas et al. (2019) discussed the disc harrow tillage fuel consumption on the clay soil and clay loam soil at different adjustments of tillage and operating speed. The study investigated that fuel consumption varies from 2.6 to 5.9 Lha^{-1} at different speeds. Efficient fuel consumption was 2.85Lha^{-1} at 10^0 disc harrow adjustment at 3.5 ms^{-1} speed and the depth of cutting was 8 cm in loam soil and 5 cm in clay loam soil (Damanauskas et al., 2019). Sağlam et al. (2015) conducted the study to find out the efficient tillage combination to improve the soil quality index. Moreover, the finding of the study recommended that reduced and soil mulch tillages had the long-term effectivity for the soil health of clay soil conditions, while reduced tillage practices are proficient with plowing for better soil quality. Furthermore, some more studies about the efficient tillage system for soil quality improvement are discussed in below Table 2. The table shows year-wise studies about the effect of the tillage system on soils and their remarks.

Table 2 Studies about tillage system for soil quality improvement

References	Year	Tillage system	Soil type	Remarks
Burgos Hernández et al. (2019)	2019	NT, MT, PT	Silty clay loam soil	NT
Deiss et al. (2021)	2019	NT, no tillage, chisel plow, and MB plow	Silt-loam versus clay-loam	NT
Obalum et al. (2019)	2019	Reduced tillage	Silt-loam luvisol	Remarkable
Alam et al. (2014)	2014	ZT, MT, DT, and CT	Grey terrace soil	ZT
Busari et al. (2015)	2015	Conservation tillage (ZT, MT) and CT	General	Conservation tillage (ZT, MT)

4 Efficient Tillage for Residue Management

Crop residue incorporation and retention on the soil is highly significant for soil fertility, crop yield, and environmental aspects. Tillage practices play a vital role in crop residue management for the improvement of soil physical, chemical, and biological properties, also saving energy and fuel consumption with reducing the tillage practices. Torotwa et al. (2021) compared the designed biomimetic disc with the conventional disc (i.e. plan disc and notch disc) for crop residue mulching (conservation tillage) in the soil and less fuel consumption using soil bin at three different depths (i.e. 40, 70, and 100 cm) to increase the crop production. The authors concluded that biomimetic disc achieves 8.5%, 23.9%, and 12.0% efficient percentage of straw mulching which was higher than plan disc, and 4.9%, 11.7%, and 10.2% more efficient than notch disc and requires 28.5% less draft force as shown in Fig. 5. Celik and Altikat (2022) investigated the impact of two power harrow (heavy and light) type rulers on crop residue mulching into soil and fuel consumption at two operating speeds of peripheral blades and three working speeds (0.56, 0.92, and 1.26 ms^{-1}) of the tractor. That study concluded the maximum crop residual incorporation and fuel consumption with heavy roller and no significant impact on the soil properties as shown in Fig. 6.

Ahmed et al. (2017) studied the various types of the disc (notch, toothed, smooth-edge single disc, and double disc) furrow openers for rice residue management for wheat crop direct seedling, based on draft force requirement at three different depths (30 cm, 60 cm, and 90 cm) and working speeds (0.1 ms^{-1}, 0.2 ms^{-1}, and 0.3 ms^{-1}). The study evaluated that straw cutting efficiency was higher at various depths and operational speeds in order double disc>tooth type>smooth type>notch types as shown in Fig. 7(a, b). Qin et al. (2018) designed a set of the sliding knife-notch disc (SKO), modified notch-type disc (MNO), and smooth disc openers (SDO) to identify

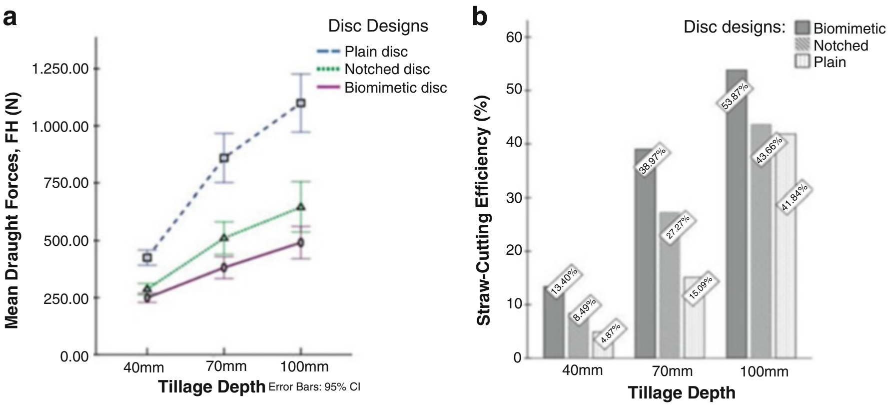

Fig. 5 (**a**) Draught force at different depth with biomimetic disc, plain disc, and notch disc (**b**) Straw cutting efficiency at different depth with biomimetic disc, plain disc, and notch disc (Torotwa et al., 2021)

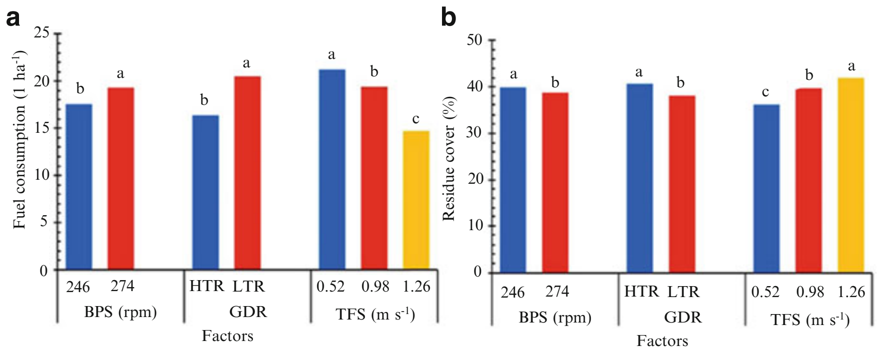

Fig. 6 (**a**) Fuel consumption of heavy and light rollers at different rpm, and total forward speed. (**b**) Residue cover efficiency of heavy and light rollers at different rpm, and total forward speed (Celik & Altikat, 2022)

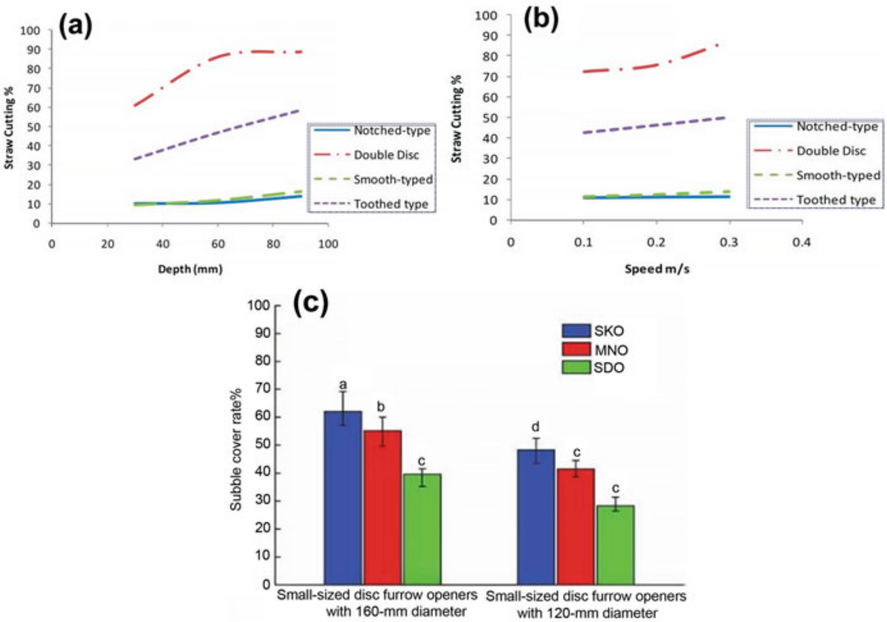

Fig. 7 Straw cutting efficiency with different furrow openers. (**a**) Various operational depths. (**b**) Various working speed (Ahmad et al., 2017). (**c**) Various disc diameters (Qin et al., 2018)

their performance for crop residue mulching for the no-till seedling in the soil. The study concluded that sliding knife-notch disc furrow opener provides better residue cutting efficiency with 3.52 cm depth of cut and 3.5 cm width of cut with 60 mm diameter that provides 62.5% efficiency which is efficient for seed drilling. Moreover, the authors recommended SKO which was 61.7% more efficient than another type of disc and consume less fuel as shown in Fig. 7(c). Raper (2002) investigated the effect of tillage depth, type, and timing on crop residue management by using chisel plow and disc plow implements. The study reported that disc-type implements were best to bury crop residues as compared to deep tillage operation and consume less fuel.

Xiao et al. (2019) investigated the impact of conventional and conservational tillage (i.e., NT and RT) systems with and without straw mulching on crop yield and soil properties (i.e., dissolve organic matter, aggregates, and biological factors). The conventional tillage with straw mulching (CT + S) and conservation tillage with mulching (NT + S, RT + S). Both studies concluded that crop yield and soil quality decline without mulching tillage operations in the soil while improved with mulching tillage (NT + S, and RT + S) as shown in Fig. 8. Cherubin et al. (2018) and Stavi et al. (2016) studied the impact of crop residue mulching on bioenergy production and its adoption for efficient soil quality. These studies concluded that high crop residual harvesting had high pest management. Moreover, there are less soil erosion control, less crop growth, and high greenhouse gas emissions, while at moderate crop residual harvesting moderate change in soil health and crop yield, no harvest of crop residues from the soil gives high crop yield, efficient soil health, and no GHG emission as shown in Fig. 9. From the all above studies it is concluded that the conservation tillage systems (i.e., no tillage, reduced tillage, biometrical disc, sliding notch furrow openers, and double-disc furrow openers) are best practices for the crop residues management for the enhancement of crop yield and soil health and low fuel consumption and energy management. Furthermore, more studies discussed in the table are given below (Table 3). This table shows the studies about the effect of various tillage operations that impact crop residue management.

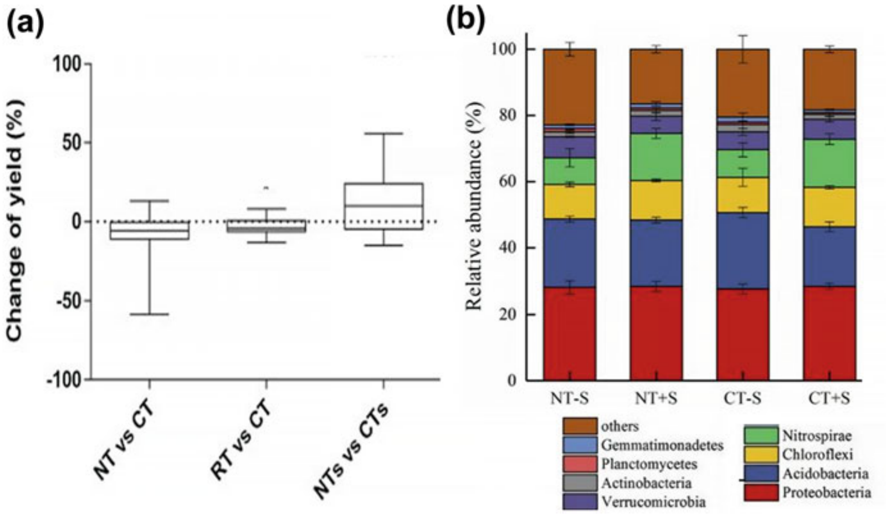

Fig. 8 Effect of tillage system without straw mulching and with straw mulching (**a**) on crop yield (Xiao et al., 2019) and (**b**) on soil properties (Bu et al., 2020)

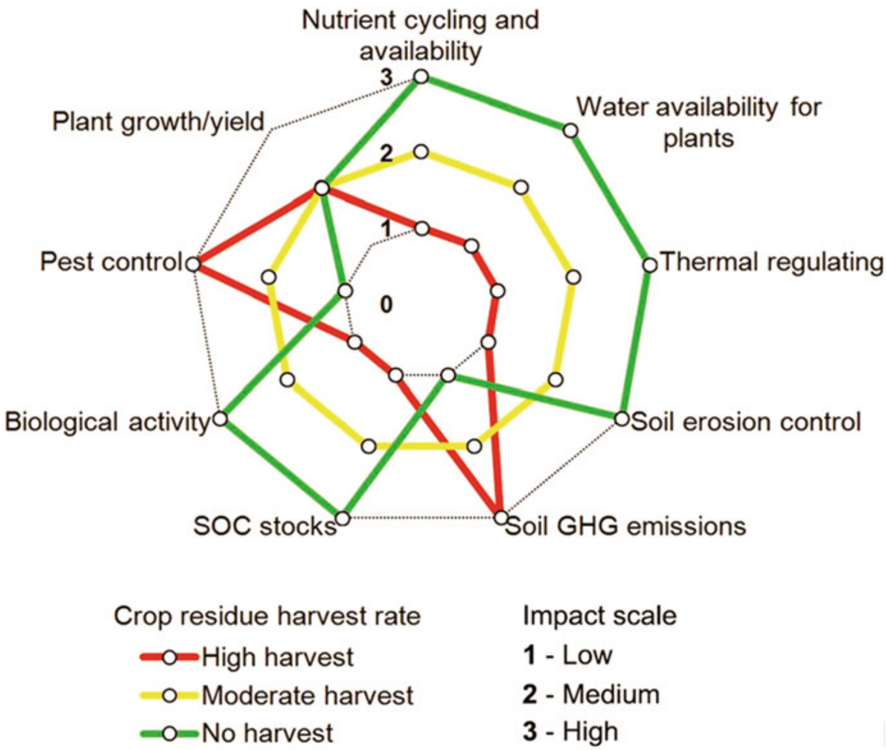

Fig. 9 Spider chart of crop residue management's impact on soil functions and ecosystem services (Stavi et al., 2016)

Table 3 Studies about tillage system for crop yield enhancement

References	Year	Study	Tillage system	Remarks
Li et al. (2021)	2021	The effect of various tillage practices on straw mulching alters the soil organic carbon composition and microbial community	NT, DT-S, DT + S, and shallow tillage	Support SOC, and C stock enlargement
Wang et al. (2019)	2019	Soil aggregates and carbon storage affected by residual management with various tillage operations in a double paddy cropping system	NT, strategic tillage, and rotatory tillage	Strategic tillage
Singh et al. (2018)	2018	Soil biological and physical health affected by crop rotation and residue management	Zero tillage	Significant impact on soil
Nouri et al. (2019)	2019	Crop species affect soil quality and yield in summer crop rotations in an Alfisol with conservation tillage	NT	Improved soil hydrophysical quality and/or yield
Sarauskis, et al. (2013)	2013	Disc coulters in NT forms and speed ratios effected on cutting of crop residues	–	–

5 Efficient Tillage System to Control the GHGs Emission

Greenhouse gases are essential for boosting the agriculture sector and leading a human intervention in the environment. The tillage practices are highly significant for GHGs maintained in the soil and controlling the global warming potential (GWP). It is related to soil diversification with the adoption of tillage implement. Many studies identify the impact various tillage practices on GHGs management. Martin-Gorriz et al. (2020) studied the impact of various soil management strategies on carbon emission footprint, and economic assessment on two different farms using conventional tillage (CT), reduced tillage (RT), reduced tillage with green manure (RTG), and no-tillage levels. The study investigated that GHGs emission in conventional tillage system was 134 and 106 CO_2 eq/ha which was 19% more than reduced tillage. The no-tillage strategy reduces the carbon emission footprint 33% from other strategies. Along with this, the reduced tillage reduces carbon emission and improves the ratio of profit while reduced tillage with green manure (RTG) increases GHGs and reduces the ratio of profit. Moreover, this study recommended that the carbon emission footprint could be reduced with a reduction in tillage passes (Martin-Gorriz et al., 2020). The effect of the conventional tillage and conservational tillage on the soil profile is shown in Fig. 11. Ashraf et al. (2021) investigated the input and output energy consumption and carbon emission footprint in rice and wheat crops. Data envelopment analysis (DEA) of that study examined that the highest reduction in energy consumption potential was –42.97% in rice crop and –17.49% in wheat crop, while the highest carbon emission footprint found during rice crop production was 1762.5 kg CO eq/ha. The authors concluded that carbon emission reduced by minimizing the energy input as shown in Fig. 10. Lal et al. (2019) investigated the impact of zero tillage and conventional tillage practices on rice-maize crop residue management on the carbon emission for environmental cleaning and soil health. The study reported that zero tillage practices reduced 56% energy consumption and 39% in carbon emission, as well as 20% less NO_2 emission as compared to conventional tillage.

Rutkowska et al. (2018) compared conventional and conservational tillage with 2-year maize crop data to investigate their impact on carbon emission. The study concluded that conservational tillage improves maize yield and reduces CO_2 emission from 7–35% which was lower than conventional tillage systems. Huang et al. (2018) provided a meta-analysis on GHGs emission control and crop yield with conservation tillage practices. The authors were collected the 740 paired measures from 90 articles. That study concluded conservation tillage practices control the GHGs emission in the dry field but not in humid and climatic conditions. The conservational tillage decreases 22% of GWP by mitigation of both CO_2 and CH_4 (Sørensen et al., 2014). The framework of the tillage practices on GHGs emissions is shown in Fig. 12. From the above studies, it is clear that conservational tillage practices are very brilliant for controlling GHGs emissions from agricultural soil and crop. Furthermore, studies about the tillage effect on GHGs control are listed in below Table 4. This table shows literature about the effect of tillage practices on GHGs emission control.

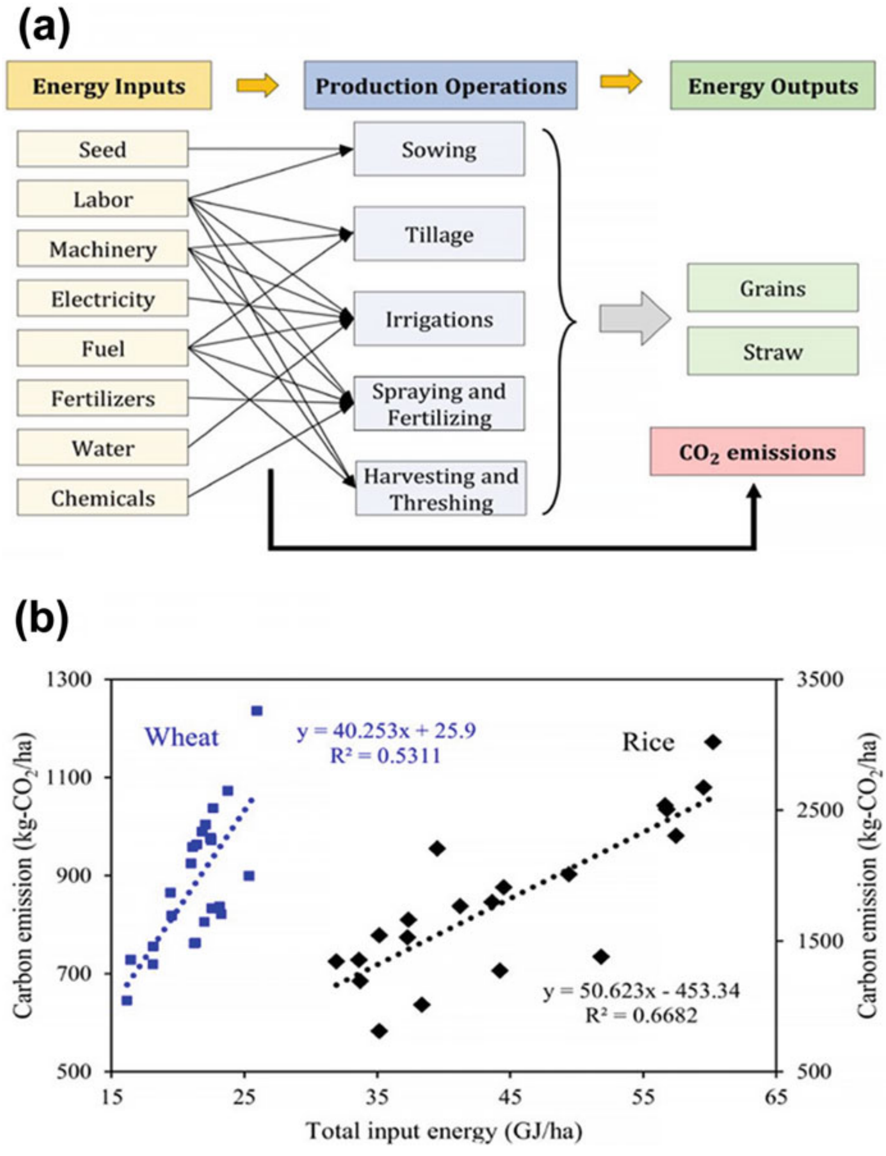

Fig. 10 (**a**) System boundaries and energy flow pattern for input-output energy analyses in crop rotation system. (**b**) Relationship between total input energy (GJ/ha) and carbon emissions (kg-CO_2/ha) in wheat and rice production (Ashraf et al., 2021)

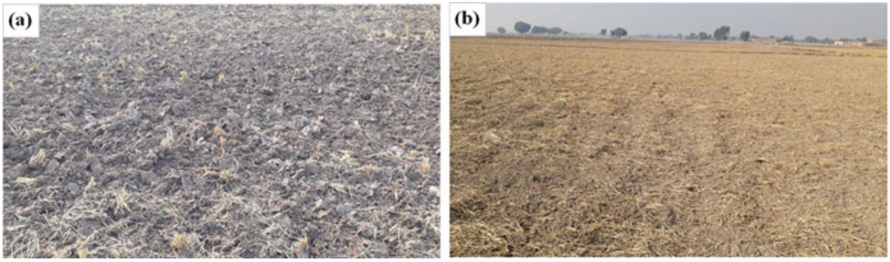

Fig. 11 Comparison of tillage system on soil profile. (**a**) Conventional till soil and (**b**) conservational till soil

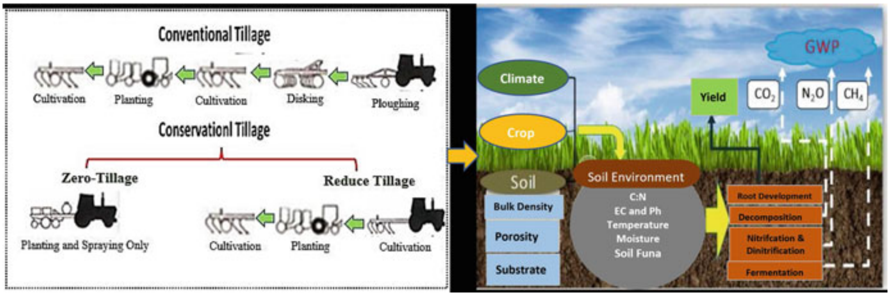

Fig. 12 Cycle of the various tillage practices impact on soil processes (biophysical, physiological, and biogeochemical), greenhouse gas (GHG) emissions, and crop yields (Sørensen et al., 2014)

Table 4 Studies about efficient tillage system to control GHGs emissions

References	Year	Study	Tillage system	Remarks
Guo et al. (2021)	2021	Enhancement of water harvesting and depletion in soil CO_2 emissions of wheat in dry regions using conservational tillage with previous plastic covering	NT+ residual cover	Improve water harvesting, reduce CE, and enhance soil carbon sequestration
Maucieri et al. (2021)	2021	A meta-analysis for methane emission from soil conservational tillage	CT vs NT	NT was a better solution
Volter et al. (2021)	2021	Soil compaction and GHG emissions effected by tillage system	Reduced tillage	6% reductions in carbon emission
O'Brien & Daigh (2019)	2019	A review about surface energy alters by tillage operations	Conservational tillage	Total available energy is increased
Lekavičienė et al. (2019)	2019	Effect of fuel consumption on carbon emission in conservational tillage machinery	Strip tillage	Reduce diesel consumption and CO_2 emissions

6 Effect of Tool Geometry on Energy Requirement

The tillage tools geometry is the key point for the draft force and power consumption during field operations. Therefore, the engineering knowledge of draft force prediction and energy consumption count is very important for designing the tool geometry. However, for profitable and sustainable crop production, tool geometry is the main concern during tillage practices, but it is a difficult task due to alternation in soil conditions and mechanics (Godwin & O'Dogherty, 2007). The tillage tools are designed on the basis of various parameters, including cutting angle (rake angle), lifting angle, operational depth, and speed. These parameters are highly effective for the fuel consumption in operating machinery (Ibrahmi et al., 2015). The alternation in the tillage tool geometry is directly related to the field capacity and fuel consumption index (Jafari et al., 2011). Ahmad et al. (2020a) designed a cotton stalk puller shredder to control the pink ball warm. The authors tested the machine at four blade attachment angles (30°, 45°, 60°, and 75°). The statistical analysis of the study reported that maximum equal stress, total deformation, and directional deformation at 75° angle give better straw cutting efficiency. Sahu et al. (Kumar Sahu et al., 2018) investigated the effect of rotator blades geometry on fuel consumption. The authors were selected the L-shaped and J-shaped blades for residue management. The study reported that L shaped gives 86.8% finer soil aggregation and 19.53% more fuel consumption than J-shaped blades. Owsiak et al. (2018) identify the vertical forces on cultivator tines in sandy soil which influenced by flexibility and shearing in the field. The cultivator was operated at two depth 9 cm and 13 cm at 3 ms^{-1} operating speed. This study revealed that the highest vertical forces at tine flexibility reduce with decreasing shearing depth.

Furthermore, Askari et al. (2019) studied the effect of wing angle on the tine performance on the bases of draft force and soil disturbance area. The authors adopted the conventional wing without bent, in addition to forward and backward bent wings with 10° and 20° bend angles. The bent wings were attached with the subsoiler and paraplow tines with 15° rake angle. Both implements operated at 40 cm depth and 1.6 kmh^{-1} speed. The study investigated the bent wing required more draft forces, high soil disturbance, and lower specific draft than conventional tines without bent. Moreover, the forward bent wing with 10° bend angle attached with paraplow tines was the best solution for the deep soil operations. Ibrahim et al. (2015) identify the impact depth, operational speed cutting angle, and lifting angle of the moldboard plow using finite element analysis. The study revealed that draft force increases with increasing plowing depth, while vertical and lateral forces were linearly related with depth, as well as cutting and lifting angles. Besides, the lateral force decreases with cutting angle and increases with lifting angle. Furthermore, the minimal energy requirement was found at 150 cm depth, 25° lifting angle, and 30°, 45° cutting angle. In Table 5, discus some studies about the tool geometry effected on energy requirement.

Table 5 Studies about the effect of tool geometry on energy consumption

References	Year	Study	Parameters
Jiang et al. (2020)	2020	Investigation of curved subsoiler for the specific resistant in field	Draft force
Azimi-Nejadian et al. (2019)	2019	Cylindrical moldboard plow performance evaluation using FEM and statistical model	Depth, draft force
Barr et al. (2018)	2018	Effect of rake angle of narrow furrow openers in field operation	Soil disturbance, draft force
Ucgul et al. (2015)	2015	Investigation of sweep tool cutting edge geometry effect on forces requirement during filed operation	Draft force, upward vertical force
Badegaonkar et al. (2010)	2010	Effect of shank angle of cultivator on the power requirement in the field	Draft fore requirement

7 Simulation Studies for Design of Efficient Tillage Tool

Draft force requirement for whole agriculture machinery is a very serious issue. Especially, tillage machinery needs a minimum draft force for efficient field operations. The predicting of draft requirements for tillage implements is essential from the viewpoint of proper tractor implement matching and machinery design. The required draft force and power are among the most important engineering specifications for efficient tillage machinery. However, with the decreasing draft force, vertical and horizontal forces fuel the consumption and power requirement of machinery would be reduced (Ucgul et al., 2015). Moreover, the actual use of applicable material, interface models, and mathematical simulation models depends on accurate modeling based on correct assumptions for efficient design of implementation (Ibrahmi et al., 2015). The main focus of the simulation models is to provide less soil disturbance with accurate modification for less energy consumption (Forgó et al., 2021). So, many models were used for the prediction of the forces during the soil texture disturbance like discrete element (DEM) analysis, finite element analysis (FEM), ANIFIS and RSM, draft force calculator, fuzzy logic, computational fluid dynamic, and load cell used for the estimation of energy and power for good machine performance. Figure 13 represents the comparative graph of various models and experimental results for draft force analysis. Many studies represent the soil-tool interaction, and draft force prediction models. Table 6 shows the different model studies for the tillage implement draft force prediction.

8 Conclusion

This review aimed to identify the energy-efficient tillage system for crop production while considering the soil properties, i.e., physical, chemical, and biological conditions. Furthermore, this study also discussed the impact of residue management

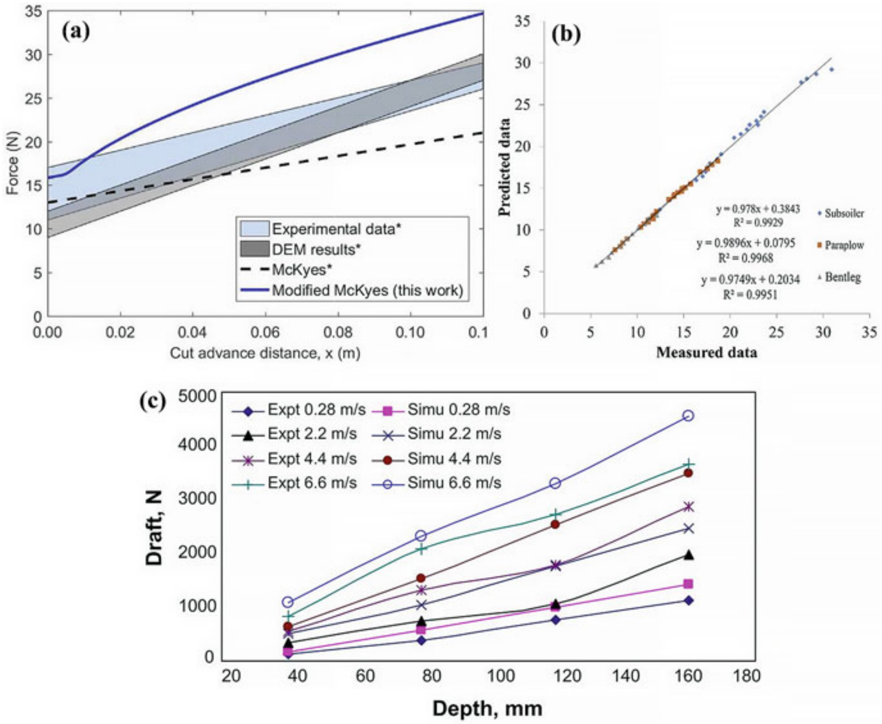

Fig. 13 Comparison of various model study and experimental results. (**a**) DEM model (Skonieczny, 2018); (**b**) fuzzy logic model (Askari & Abbaspour-Gilandeh, 2019); and (**c**) CFD model (Karmakar et al., 2009)

practices on the environment, crop yield, and soil health. In all the studies which we reviewed conservational tillage system, i.e., no tillage and zero tillage, are best for the soil health, crop residue management, and environmental aspects as compared to conventional tillage. Moreover, the extensive literature survey revealed that the long-time use of no-tillage and minimum tillage practices should be harmful to the soil health by affecting the soil organic matter, increasing soil compaction, and reducing water holding capacity. While it plays a vital role in crop residual management, crop yield enhancement, and mitigation of environmental threats by reducing greenhouse gas emissions. The authors also studied the tool geometry and model used for the selection of energy-efficient tillage system. Discrete element and finite element models are mostly used for the design of efficient agricultural machinery. It is also concluded that the efforts should be continued to design the efficient tillage tools in various working and crop conditions.

Table 6 Studies about the model for selection of energy-efficient tillage implements

References	Year	Study	Models
Aikins et al. (2021)	2021	Analysis of narrow point opener for its validation on cohesive soil	DEM
Ahmad et al. (2020b)	2020	Simulation disc–type furrow opener performance evaluation in paddy soil for residue management	DEM
Ucgul and Saunders (2020)	2020	Moldboard plough simulation to investigate its interaction with tillage forces and furrow profile in the soil	DEM
Barr et al. (2020)	2020	Analysis Bentleg furrow opener to investigate its performance in the field	DEM
Bo et al. (2016)	2016	Identification of draft force at different subsoiler points in soil	DEM
Hang et al. (2018)	2018	Subsoiler tine spacing simulations and experiments of soil disturbance	DEM
Milkevych et al. (2018)	2018	Modeling approach for soil displacement in tillage	DEM
Obermayr et al. (2011)	2011	Prediction of draft forces in cohesionless soil	DEM
Askari and Abbaspour-Gilandeh (2019)	2019	Assessment of approaches in draft force prediction of subsoiling tines	ANFIS and RSM
Alimardani et al. (2009)	2009	Prediction of draft force and energy of subsoiling operation	ANN
Mohammadi (2012)	2012	Modeling of draft force variation in a winged share tillage tool	Fuzzy logic
Ahmadi (2016)	2016	Development and assessment of a draft force for disk plow using the laws of classical mechanics	Draft force calculator

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Harnessing Nanoscale Fertilizers in Attaining Sustainability Under Changing Climate

Retrospective and Outlook

Nandini Roy and Prithusayak Mondal

Contents

Abstract

The escalating human population and the need for acceleration of food production have led to the intensive exploitation of our land and water resources. It has become indispensable to reconsider the existing farming practices and make way for sustainable use of natural resources while aiming at optimizing the yield. Intensive use of chemical fertilizers to meet the demand for superior quantity of

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yield is gradually destroying the soil health resulting in widespread economic losses of farmers. Leaching of chemical fertilizers into the groundwater and runoff into various water bodies are also major factors affecting human health and can be associated with various environmental hazards also. Nanofertilizers can be a promising substitute, as not only it provides sustained and effective nutrient absorption but also it is less hazardous to the environment. Nanoparticles of the fertilizers are microscopic particles ranging from 1 to 100 nm in size, and they vary in their physical and chemical properties as compared to their bulky variants. Their salient properties allow them to act as smart delivery system having controlled-release mechanism. Economically, it can provide considerable benefits to the farmers, as there is almost no wastage. Application of nanofertilizers can result in curtailed application frequency and effective uptake of the nutrients. The impact of climate change on the physiology and yield of crops is very prominent nowadays. Nanofertilizers can be helpful in mitigating the effects of climate change by enhancing nutrient uptake and preserving soil health. They also release less greenhouse gases as compared to conventional fertilizers, thereby paving the path for eco-friendly approach in agriculture.

Keywords

Nanofertilizers · Sustainability · Nutrients · Crop · Climate change · Energy management

1 Introduction

In this era, it has become very crucial to draw our focus on availing maximum crop production and productivity to meet the exponential demand for food. The world overall needs 50% increase in production by 2050 to fulfill the nutritional demand of 9 billion people (Cackler, 2015). The rising population and the burden on our land and water resources have made it necessary to look for suitable interventions that can tackle the existing problems while optimizing the yield in changing climatic conditions. In the mid-1960 “Green Revolution,” bulky chemical fertilizers and other agro-chemicals had resulted in significant increase in the productivity of crops. From that point of time, the farmers had been practicing intensive application of chemical fertilizers, but the fertilizer utilization efficiency remained below 30% (Albanese et al., 2012). Low utilization of fertilizers by plant can be attributed to low uptake efficiency (for instance, 20–50% for nitrogen and 0–25% for phosphorus), imbalanced use of chemical fertilizers, higher rate of leaching of minerals, low assimilation potential of plants, less amount of micronutrients in soil, and low soil organic matter content (Chinnamuthu & Boopathi, 2009). These chemicals tend to have an adverse effect on our ecosystems, when these are released into the environment due to the various processes, like polluting the groundwater and other water bodies, decomposition, degradation, leaching, and hydrolysis. Therefore, cutting down the quantity of chemical fertilizers used in agriculture is a pre-requisite to achieve a balance between agriculture and natural ecosystems.

Agriculture today is facing a two-way challenge, which includes diverting our focus to incorporate suitable and smart scientific innovations in the current agricultural practices and disseminating the innovations to the farmer's field. One such aspect of scientific innovation is the "nanoparticle." When the technology was harnessed to produce target-oriented nanofertilizers, they addressed many existing difficulties like less productivity, nutrient deficiency, loss of nutrients, environmental hazards, health hazards, and economic loss. The great physicist Richard Feynman in his lecture "There's plenty of room at the bottom" emphasized on the manipulation of targeted atoms and molecules to get some customized advantages (Feynman, 1961). The term "nanotechnology" was proposed by Prof. Norio Taniguchi in 1974, which was then used to define semiconductor processes like iron beam milling. This term was later popularized in almost every major field of studies (Mondal et al., 2017). "Nanotechnology" in agriculture for the production of nanofertilizers can channelize the modern-day agriculture in such a way, so that a number of burning issues can be addressed. Nanofertilizers can also prevent the widespread problem of eutrophication, which is mainly caused due to runoff of overdoses of nitrogen and phosphorus fertilizers resulting in the destruction of the entire faunal population in the water body. Slow-release fertilizers have less solubility in water or solvents and are supposed to get broken down by microbes. Coating them with nanoparticles can significantly reduce nitrogen loss causing through denitrification and leaching. Crops can also be fed in a controlled manner by the proper application of nanofertilizers.

The salient features of nanofertilizers are price effectiveness, requirement in small quantities, target orientation, enhancements of nutrient use efficiency, eco-friendliness, easy transportability, and slow/controlled fertilization. Mass production can also be possible within a short span of time. Inclusion of nanofertilizers as an integral part of agricultural practices can help in coping up with growing food demand along with maintaining sustainability in changing climatic conditions. Therefore, it is the need of the hour to develop a deeper and detailed insight on the functioning of nanofertilizers, their associated benefits, and other significances in modern agriculture and the way forward.

2 Nanofertilizers as Tools of Smart Agriculture

2.1 Major Drawbacks of Traditional Agriculture

Fertilizers serve as food elements to the plants, and they provide the plants with nutrients that are essential for their growth. Therefore, optimization of fertilizer dose is a pre-requisite for the proper growth and development of plants. Balanced application of macronutrients like nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S) and micronutrients like iron (Fe), manganese (Mn), copper (Cu), zinc (Zn), boron (B), molybdenum (Mo), and chlorine (Cl) are essential in order to maximize yield. A huge portion of the current agriculture scenario is about the use of fertilizers for the minimization of yield gap. The estimated worldwide consumption of the three main fertilizers (N, P, and K) in 2016 was 186.67 million tons, which was 1.4% higher than the amount consumed in 2015 (Bernela et al., 2021). Traditional agricultural practices have wretched havoc on the current nutrient status and health of the soil. Conventional agriculture practices often include the uncontrolled use of chemical fertilizers, which results in net negative soil nutrient balance and adverse effects on soil health. Moreover, there are evidences that improper use of chemical fertilizer led to negative consequences like soil quality degradation, chemical burn, air pollution, and water pollution (Rahman & Zhang, 2018). Bioavailability of nutrients to crops is suppressed as a result of high nutrient release rates of conventional fertilizers. As a consequence, the rate of transformation of nutrients in soil surpasses the absorption rate of crops. Synthetic fertilizers are less soluble due to their bigger size and are readily fixed or adsorbed into the soil particles. To increase the nutrient use efficiency, various alternative methods are undertaken, such as precise fertilization, limited application, fertigation, and use of nanofertilizers in the replacement of conventional fertilizers. Yield enhancement while improving the nutrient use efficiency can act as the foundation of sustainable agriculture and a step toward maintaining environmental health and soil quality.

Healthy soil is the residence of a multitude of beneficial microorganisms which assists in controlling pests and diseases and recycling plant essential nutrients. It also helps in improving the physical and chemical properties of soil, like improving soil structure and higher retention of soil water and nutrients. It also plays a crucial role in the symbiotic association of plant roots and microorganisms. Therefore, healthy soil is a foremost requirement in order to increase the crop productivity. Some of the basic soil functions are maintained by the interaction of a number of biotic factors along with different abiotic components. In the absence of optimum microbial population in soil, soil physical properties (e.g., soil texture, aggregate, porosity, bulk density), biological properties (e.g., microbial biomass C and N, soil respiration, enzymes), and chemical parameters (e.g., cation exchange capacity, total C and N, available nutrients, soil organic matter) are affected adversely. This results in the reduction in yield and degradation of soil health. Modern agricultural practices like intensive tillage and uncontrolled use of chemical fertilizers can reduce the microbial population in soil, thereby interfering with the plant-microbe relationship and eventually hampering the essential soil functions. The trend of inorganic fertilizer (NPK) in agriculture over the period of several years and their fates are illustrated in Figs. 1 and 2.

2.2 Rationales of Applying Nanotechnology to Fertilizers

Owing to the small size of the nanoparticles (below 100 nm in at least one direction), specific atomic orientation, and structural arrangement, they undergo complex interactions with ion particles, colloids, and biomolecules (Liscano et al., 2000).

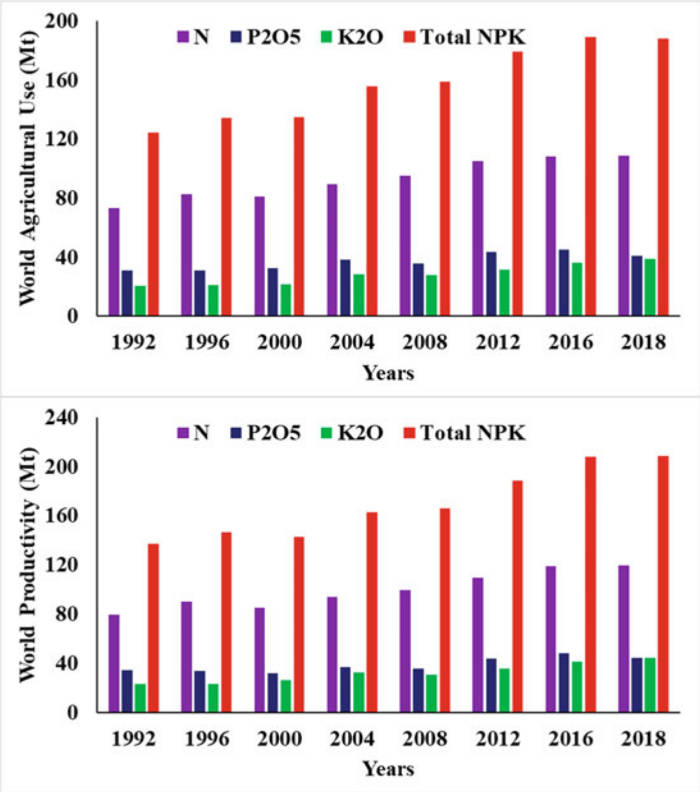

Fig. 1 Total productivity and use of nitrogen (N), phosphorus (P), and potassium (K) fertilizers worldwide. (Bernela et al., 2021)

Due to their high reactivity, they readily react with fertilizers increasing the nutrient uptake and absorption efficiency of plants. The small size helps in increasing the specific surface area, thereby enhancing their bioavailability (Mondal et al., 2017). Use of nanofertilizers in proper and controlled way can feed the plants slowly for a longer period in a way that prevents loss of nutrients, increases the uptake, and diminishes any adverse effects toward the environment. Moreover, their high solubility rate is a boon for further increasing the nutrient dispersion in soil, as a result, further increasing their availability (Bernela et al., 2021). Overall, nanofertilizers have a significant role to play in enhancing the productivity and quality of agricultural products and improving soil fertility. Figure 3 depicts the main advantages of nanofertilizers over the conventional ones.

In the case of controlled-release nanofertilizers, nutrients are released over a considerably longer period than conventional ones. Zeolite-based nanofertilizers ensure the availability of nutrients to plants throughout the growth period, which not only plays a major role in preventing nutrient loss but also minimizes the accumulation of salt in soil (Zulfiqar et al., 2019). In the case of urea, loss of 70%

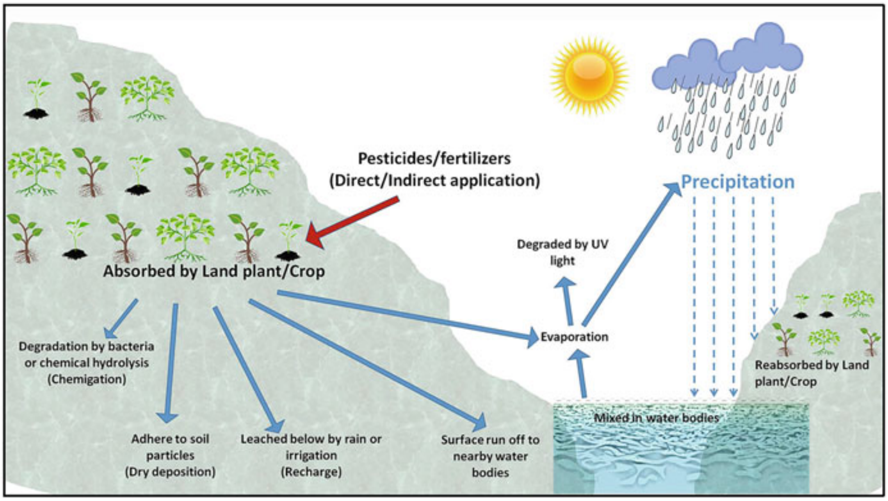

Fig. 2 Pathway of agro-chemicals in environment. (Reprinted with permission from Baweja et al., 2020. Copyright © 2020, Springer Nature Switzerland AG)

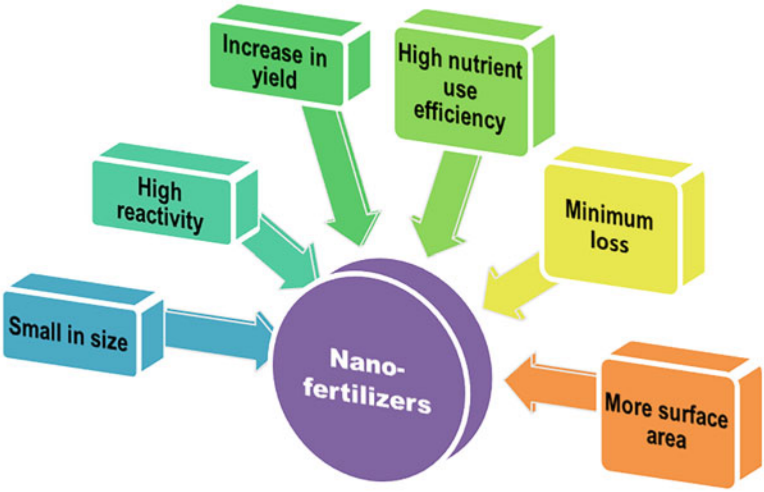

Fig. 3 Main highlights of the advantages of nanofertilizers

of the nitrogen can occur, as soon as it is applied to the fields through leaching and volatilization. The remaining less than 20% is absorbed by plants (Roshanravan et al., 2015). Nano-hybrid of urea (i.e., modified form of hydroxyapatite) has the potential of increasing the yield of paddy, at half the rate of the application of urea. Chitosan and zeolites, which are porous nanomaterials, help in improving the uptake by ensuring the controlled release of nutrients. The use of porous nanomaterials, such as chitosan and zeolites, has been found to considerably improve uptake

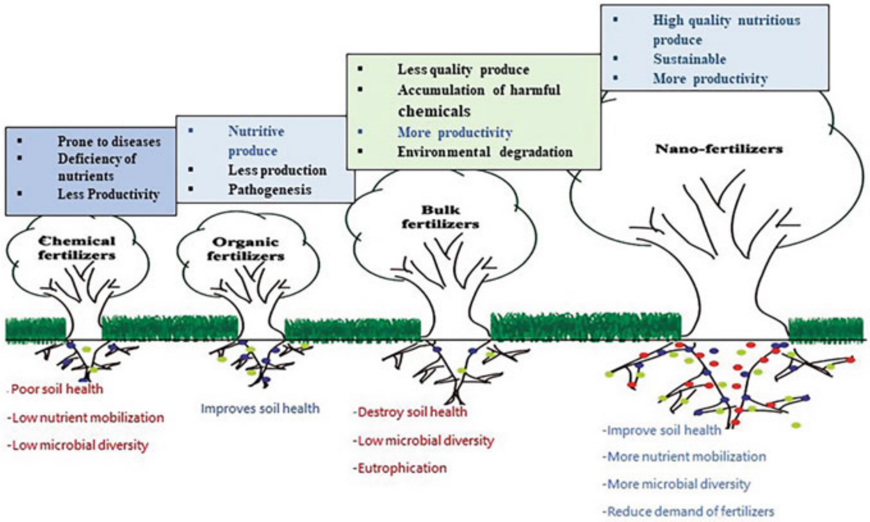

Fig. 4 Comparison between chemical, organic, bulky, and nanofertilizers in relation to yield and soil health (Bernela et al., 2021)

efficiency by controlling demand-based release and decreasing the loss of N (Rastogi et al., 2019). Increases in grain yield, shoot growth, and plant height were observed in soybean (*Glycine max* L.) as a result of the application of the hydroxyapatite nanoparticles compared to the synthetic phosphorus fertilizers (Sotelo-Boyás et al., 2017). Therefore, it can be concluded that nanoparticles may be helpful in coordinating some of the plant's metabolic functions due to the potential of mobilizing phosphorus and other nutrients. As these are required in very small quantities, these are also cost-effective and beneficial to the farmers in the long run. Figure 4 provides us a notion in a nutshell of how nanofertilizers are comparatively superior in maintaining the soil as well as plant health than chemical, organic, or bulky fertilizers.

2.3 Types of Nanofertilizers

There are three broad categories in which nanofertilizers are classified: (i) nano-formulated macrofertilizers, (ii) nano-formulated microfertilizers, and (iii) nutrients loaded with nanofertilizers (Kumar et al., 2013). Nanonutrients are more popular, as these are easy to handle in terms of safety and sustainability. Nanofertilizers are capable of controlled release due to their encapsulation with various particles such as nano-clays, carbon-based nanomaterials, mesoporous silica, carbon-based nano-materials, polymeric nanoparticles, and other nanomaterials (Singh & Rattanpal, 2014). Plants consume primary nutrients in much higher quantities, but secondary nutrients and micronutrients are also vital for the growth and physiological development of plants.

2.3.1 Macronutrient-Based Nanofertilizers

These elements are extremely important for the functioning and development of crop and are required in higher quantities. These include carbon, hydrogen, oxygen, nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur. Among these elements, some structural elements like carbon, hydrogen, and oxygen either are taken from the atmosphere or are absorbed by roots through roots. Others are made available to crops as a natural source from soil or as fertilizers in required doses. Nitrogen, phosphorus, and potassium are primary macronutrients, which are involved in the growth and functioning of crops, whereas calcium, magnesium, and sulfur are mostly involved in maintaining the structural integrity of crops.

Nitrogen (N) Nanofertilizers

Nitrogen is essential for metabolism and protein synthesis in plants and is usually applied in quite large quantities. Overuse of nitrogenous fertilizers has resulted in several environmental concerns, for instance, pollution of the atmosphere through the release of nitrogenous oxides during the process of denitrification and volatilization and contamination of groundwater through leaching causing eutrophication. But optimum use of nitrogen fertilizers is also essential as it increases the yield. Therefore, the use of nanofertilizers can diminish the harm caused by conventional ones and can supply the nutrients effectively to the plant system. For achieving maximum plant uptake, nitrogen can be applied judiciously through the use of nanocarriers like clay, chitosan, or zeolites (El-Ghamry et al., 2018). Recent researches have suggested that zeolite-based nanofertilizers have shown considerable accumulation of N in plants along with better post-application effects in soil like better pH, available N, and moisture, compared to conventional fertilizers (Milani et al., 2012).

Phosphorus (P) Nanofertilizers

Along with root growth and development, phosphorus is essential for carrying out a significant number of physiological activities in plant system, such as photosynthesis, formation of organic compounds, and storage and transportation of energy. It helps in enhancing plant's resistance to adverse climatic conditions. Apart from the fact that P is present in soil in considerable amounts, only 10–20% is taken up by the plants because of the several limiting factors (Sohrt et al., 2017). It forms complexes with iron and aluminum hydroxides and calcium or is immobilized in clay particles, which are the major factors for its less availability to plants. Nanoparticles may appear as a potent solution in making phosphorus more available to plants. Use of nano-hydroxide-based fertilizers has shown 32.6% increase in the growth rate and yield of soybean as compared to regular P fertilizers (Fan et al., 2018). Hydroxyapatite nanoparticle P has also resulted in enhancement in growth parameters, chemicals, and anti-cancer agents in the leaves of *Adansonia digitata* (Soliman et al., 2016). Some Danish scientists in their attempt of encapsulating nanophosphorus in biodegradable formulations discovered that P could be absorbed directly through leaves that might eliminate the chance of P binding in soils (Husted, 2018).

Potassium (K) Nanofertilizers

Potassium assists in carrying out vital functions such as transportation of plant reserves and water, improving photosynthetic capacity, synthesis of carbohydrates, strengthening of the cell tissues, and absorption of nitrates. Nano-K was reported to increase the chlorophyll content, potassium percentage, leaf area, harvest index, grain yield, and biological yield, when applied at a concentration of 0.006 nano-K in *Ocimum basilicum* (Ghahremani et al., 2014). Experiments showed that potassium nanofertilizers at the rate of 150 ppm (applied twice) have resulted in a notable increase in nutrient content in shoots and seeds of peanut plants (Afify et al., 2019).

Calcium (Ca) Nanofertilizers

Calcium plays the major role of cell wall stabilization and formation of seed. It also assists in neutralizing the toxic effects and storing mineral in soil. Studies revealed that calcium nanofertilizers significantly reduced fruit cracking and yield was increased considerably as compared to foliar spray of calcium chloride, which did not show any significant effect on average fruit weight and fruit per tree (Davarpanah et al., 2018). In the post-harvest stage of apple, nano-calcium has shown significant improvement in crop quality and quantity, when applied at a concentration of 2% (Ranjbar et al., 2020). Spraying of nano-$CaCO_3$ on lisianthus, at a concentration of 500 mg/L, has resulted in flowering almost 15 days earlier with an increase of 56.3% in the number of flowers (Seydmohammadi et al., 2020).

Magnesium (Mg) Nanofertilizers

Magnesium is the core-composing element of chlorophyll molecule and thus is inevitable for photosynthesis. It also plays a vital role in enzyme activation. Presence of other cations like NH_4, Ca, and K affects the uptake of magnesium (Gransee & Führs, 2013). Magnesium hydroxide nanoparticles in the concentration of 500 ppm have been effective in exhibiting 100% seed germination in both in vitro and in vivo conditions in *Zea mays*. The magnesium contents found in leaves and roots for in vitro plants were 131.45 and 103.52 mg/kg, respectively, and for in vivo grown plants, these are 132.58 and 114.58 mg/kg, respectively (Shinde et al., 2020).

Sulfur (S) Nanofertilizers

Sulfur helps in the formation of chlorophyll and increases nitrogen efficiency. The most prevalent sources of sulfur are sulfate and elemental sulfur. Sulfates are readily taken up by the plants, but due to low concentration in soil, these cannot meet up with the plant's requirements (Bernela et al., 2021). Elemental sulfur contains the highest concentration (>90% S in products) of S, but it can only be made available to plants after its biological oxidation by soil microbes, which is largely influenced by the particle size of the fertilizers (Valle et al., 2019). Therefore, reduction in particle size can have a significant impact on oxidation rate as the surface area increased. Therefore, development of suitable nanofertilizer is necessary. A pot study was done with green nanoparticles synthesized from *Ocimum basilicum* leaves extract in various concentrations (12.5, 25, 50, 100, and 200 μM) to *Helianthus annuus* seeds, and 100 mM $MnSO_4$ was added. Results showed that application of sulfur nanoparticles resulted in the elevation of water content of seedlings and elimination of physiological drought. Therefore, it can be concluded that sulfur nanofertilizers are effective in eliminating the harmful effects of Mn stress.

2.3.2 Micronutrient-Based Nanofertilizers

Fe, Zn, Mn, Cu, B, Mo, and Ni are required in minute quantities, but are important for maintaining the physiological cycle, flower setting, and activating enzymes.

Iron (Fe) Nanofertilizers

Iron serves as a cofactor for a number of enzymes in plants. As iron is present in soil in insoluble forms, it becomes less available to plants. To address this problem and to make iron available to plants, nanofertilizers like iron chelate, which are slow-release and highly stable, can be considered as a good option as they are effective in a wide range of pH. A study suggested that foliar application of iron nanoparticles (500 mg/L) on black-eyed peas could improve the weight of 1000 seeds by 7%, Fe content in leaves by 34%, and chlorophyll content by 10%, the number of pods per plant by 47% in comparison with control (Delfani et al., 2014). Application of nanoscale zero-valent iron (nZVI) on *Medicago sativa* (alfalfa) showed increase in chlorophyll content in 20-day-old seedling and slight decrease in carbohydrate and lignin contents (Kim et al., 2019).

Zinc (Zn) Nanofertilizers

Zinc assists in catalytic activity for several enzymes like transphosphorylases, dehydrogenases, isomerases, and RNA and DNA polymerases. The Zn fertilizers applied in field mostly remain fixed in soil, rendering it unavailable to plants. Zinc nanofertilizers can stand as a potent solution to solve this problem. The various methods in which zinc nanofertilizers can be applied to plants are seed priming, foliar spray, and mixing in soil, out of which seed priming stays the most efficient and cost-effective method. When ZnO nanoparticles were applied in low concentrations ($\leq$100 mg/Kg) to the soil, the uptake of zinc by cucumber plants was increased (Moghaddasi et al., 2017).

Manganese (Mn) Nanofertilizers

Experiments yielded the fact that Mn nanoparticles enhanced the growth and photosynthetic rate of mung bean (*Vigna radiata*). When applied at a dose of 0.05 mg/L, it increased the shoot length by 10%, root length by 2%, and dry biomass by almost 100% (Pradhan et al., 2013). Mn nanoparticle also acted as a nano-priming agent and showed improvement in salinity stress and root formation, when applied at the doses of 0.1, 0.5, and 1 mg/L in *Capsicum annuum* L. (Ye et al., 2020).

Copper (Cu) Nanofertilizers

Copper plays a significant role in coordinating several physiological functions, like hormone signaling, cellular and protein transportation, and mitochondrial respiration. The yield and growth of finger millet plants were boosted as a result of applying foliar spray of Cu-chitosan nanoparticles in combination with seed coating. This combination also showed an enhanced defense system against the blast disease (Sathiyabama & Manikandan, 2018). Mitotic index improved in *Allium cepa*, when sprayed with Cu nanoparticles at the rate of from 20 μg/mL, biosynthesized from *Citrus medica* L. fruit extract (Nagaonkar et al., 2015). When pigeon pea (*Cajanus cajan* L.) seedlings were treated with 20-nm-sized Cu nanoparticles, a substantial improvement in height, fresh weight, dry weight, and root length was noticed (Shende et al., 2017).

Boron (B) Nanofertilizers

Boron is required in minute quantities by crop, and it assists in the transportation of photosynthates and germination, flowering, and formation of cell wall. As it is very important for flowering stage, it should be present in optimum amount in the soil throughout the stage. Application of boron nanoparticles can increase the availability of boron to plants, thereby increasing the efficiency of the fertilizer. Under calcareous conditions, when boron nanofertilizers were used, it resulted in the large-scale production of alfalfa with suitable forage quality (Taherian et al., 2019). Boron nanoparticles showed beneficial effects on plant characteristics like plant height, seed yield, and number of pods when sprayed at a concentration of 90 mg/L (Ibrahim & Al Farttoosi, 2019).

Molybdenum (Mo) Nanofertilizers

Mostly required in very small amounts (between 0.01 and 0.20 ppm for a growing medium, between 0.3 and 1.5 ppm for plant tissue), deficiency or toxicity of molybdenum is generally rare (Thomas et al., 2017). Molybdenum serves as the activator for enzymes that convert nitrate to nitrite and then eventually to ammonia that is the building unit for amino acids within the plant. It is also essential for the atmospheric fixation of N as molybdenum is required by symbiotic nitrogen-fixing bacteria. Legumes showed notable increase in yield and disease resistance with the application of Mo nanoparticles alone or in combination with microbial treatment (Taran et al., 2014). Mo nanoparticles (2–7 nm) biosynthesized from *Aspergillus tubingensis* TFR29 have shown improvement in microbial activities in the rhizosphere along with root length, root area, and root diameter, when applied at the rate of 4 ppm (Thomas et al., 2017).

Nickel (Ni) Nanofertilizers

Nickel is involved in several functions like physiological, biochemical, and growth responses as well as in maintaining the redox condition of cell. Application of nickel NPs showed a little stimulation in the content of chlorophyll-a and chlorophyll-b, when applied at the rate of 0.01 mg/L (Zotikova et al., 2018).

2.3.3 Biofertilizer-Based Nanofertilizers

Biofertilizers comprise beneficial microorganisms, like phosphorus-solubilizing bacteria, *Pseudomonas* and *Bacillus* species, blue-green algae, *Rhizobium* species, mycorrhizae, and *Azotobacter* species. These microorganisms play an active role in solubilizing insoluble complex organic matter and converting them into simpler bioavailable forms that can easily be taken up by the plants. It augments certain physical and chemical properties of soil like soil structure, soil aeration, water retention capacity, and microbial population. Although it seems rewarding to the soil, plant, and environment, it comes with certain drawbacks. Biofertilizer formulations are susceptible to environmental fluctuations like temperature, pH, and radiation. Shortage of beneficial microbes, requirement in bulk for larger areas, poor stability, and vulnerability to desiccation are major limiting factors related to biofertilizers (Mishra et al., 2017). These problems were resolved by nano-encapsulation through the coating of nanoscale polymers, conferring protection to the nutrient content and the growth-promoting microorganisms (Golbashy et al., 2017).

Nano-biofertilizers generally involve the presence of a biologically derived organic fertilizer and a biocompatible nanomaterial, which facilitates the gradual availability of nutrients to plant, over a long span of time, encouraging improved nutrient use efficiency leading to high yield and productivity. Nano-encapsulation not only helps in strengthening the structure of the biofertilizers and increasing their shelf life but also confers better nutrient release capacity and disease resistance and resulted in the improved uptake of inorganic fertilizers. It also stands as an economically viable solution to many of the problems faced beforehand.

Nanomaterials like chitosan, zeolites, and polymers are used for the nano-encapsulation phenomenon, which facilitated the absorption of nutrients, rendering them available to plants. The increased surface area and high reactivity of the new formulations can substantially lead to better interaction of nutrients with soil and roots. Treatment of *Zea mays* with nano-biofertilizer for 7 days resulted in significant increase in grain yield (Farnia & Omidi, 2015). Application of nano-biofertilizers on sugar beet reported the optimization of certain morphological and physiological parameters, like root biomass, leaf area, net photosynthetic production, and sucrose content (Jakiene et al., 2015).

2.4 Brief Synthesis of Nanofertilizers

There are mainly two approaches for synthesizing nanoparticles or nanofertilizers – top-down and bottom-up (Zulfiqar et al., 2019). Top-down approach is basically a physical method that involves reduction to well-organized nano-sized particles from the bulk materials using machines. The drawback includes the presence of a greater number of impurities and less control over the size of nanoparticles. Bottom-up approach involves the fabrication of nanoparticles using chemical reactions, initiating from atomic or molecular scales. This process is more chemically controlled and therefore contains less impurities and better particle sizes (Pradhan & Mailapalli, 2017). Biosynthesis of nanofertilizers is also a trending approach utilizing natural sources such as plants, fungi, bacteria, etc. Greater control in particle size and reduction in toxicity are the two main advantages of biosynthesis process. This process is also advantageous to chemical routes of synthesis of nanoparticles, which consumes more energy and generates hazardous byproducts (Pantidos & Horsfall, 2014). The existing physical or chemical methods are comparable with biological methods. The microorganisms, used for the remediation of heavy metal due to their capability of reduction with the help of several reductase enzymes, have the potential to act as nano-biofactories in the synthesis of metallic bio-NPs (Singh et al., 2016).

The synthesis can broadly be classified into intracellular and extracellular. Intracellular processes occur within the cells of the microbes, such as plants, bacteria, and fungi, whereas extracellular processes, happening outside the cell of the organism, are assisted by extracellular enzymes and biomolecules (Hulkoti & Taranath, 2014). Thus, the efficacy of nanoparticles is enhanced by additional biological capping agents that help in imparting stability to the particles. In a study, it was concluded that hydroxyapatite nanoparticles stabilized by carboxymethyl cellulose led to the increase in seed yield and growth rate of soybean by 33% and 18%, respectively (Liu & Lal, 2014).

Bottom-up approach, being considered as the more effective one, is the most widely used technique for nanoparticle development (Raliya et al., 2017). Extensive researches are being carried out for the development of target-specific nanoparticles that will serve the dual purpose of being economically sustainable for manufacturers and meeting the market demand. The synthesis of nanoparticles varies with the physical or chemical parameters undertaken for production. The organic nanoparticles comprise lipids, polymers, graphenes, and carbon nanotubes, whereas the inorganic nanoparticles include metallic (silver, gold, etc.), bimetallic alloy (silver-gold, silver-platinum, etc.), metal oxides (AgO, ZnO, TiO_2, MgO, etc.), and magnetic (magnetite and maghemite). Preparation of nano-oxide fertilizers was done by green microwave-assisted hydrothermal method using analytical-grade salts like zinc, ferric, and manganese nitrate as precursors (Shebl et al., 2019). Figure 5 provides a flowchart regarding the synthesis of various types of nanofertilizers.

2.5 Nanonutrient Uptake and Regulation in Plants

The rate of absorption of nutrients by plants mainly depends on their bioavailability and their amount, nature, and interaction with other nutrients present in soil. Several other edaphic factors, like cation exchange capacity (CEC), pH, texture, water holding capacity (WHC), redox potential, and microbial population present in the soil, are also responsible for their transformation from solid to available solution form, translocation from soil to the root of the plants, and assimilation in plant's body. Contact of root with soil is crucial for the absorption of nutrients and their transport to the plant parts, and soil acts as a habitant for beneficial associations (like ecto- and endomycorrhiza, *Rhizobium* species). Development of roots is proportional to several physical and chemical properties of soil, such as pH, aeration,

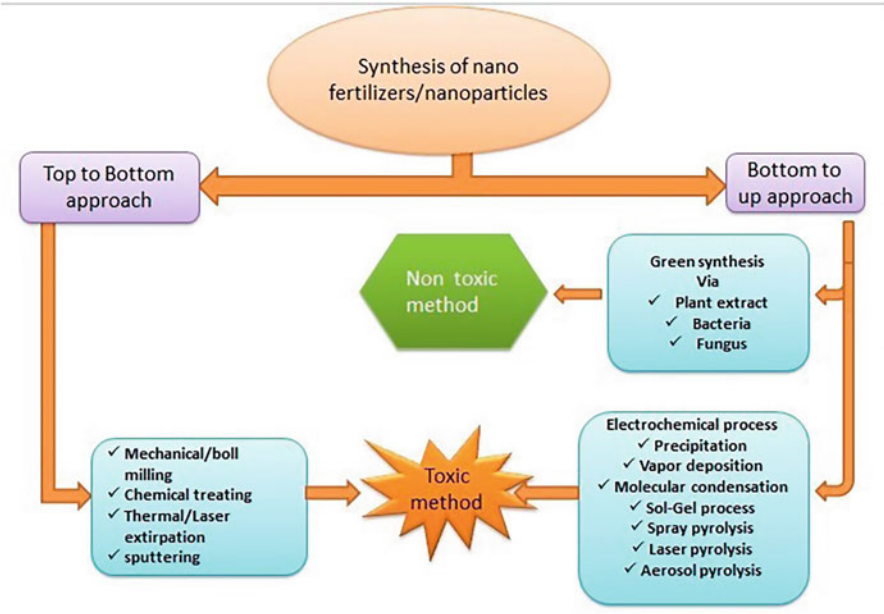

Fig. 5 Approaches for the synthesis of nanoparticles (Seleiman et al., 2021)

texture, and nutrient availability (Taiz & Zeiger, 2010). The movement of nutrients from soil to the vicinity of roots takes place with the help of three processes: mass flow, diffusion, and root interception. It is quite hard to predict the uptake of nanoparticles, and it is a result of multiple factors interacting together like characteristics of nanoparticles (surface area, net charge, size, and stability), mode of application, soil properties, and physiology of plants. When the external defensive layer is penetrated, nanoparticles are mobilized by two pathways: symplast and apoplast. In apoplastic transport, the movement is generally toward radial direction, which results in the movement of nanoparticles toward the center of the root cylinder and vascular tissues. It also follows an upward movement in aerial parts. For the systemic delivery of nanoparticles, apoplastic translocation is essential. In root endodermis, the Casparian strip blocks the way of radial movement. This can be subdued by switching over to symplastic pathway, which is a more regulated pathway in the case of the transportation of nanoparticles in plant system (Zhang et al., 2017). Furthermore, there are several other processes by which nanoparticles can enter in a cell, such as phagocytosis, pinocytosis, and endocytosis. Accumulation of the particles can occur inside lysosomes, vacuoles, or cytoplasm. Receptor-dependent endocytosis is a phenomenon in which nanoparticle-bound proteins or ligands are exposed to the integral receptors within the cell and engulfment occurs at specific sites of adhesion (Decuzzi & Ferrari, 2007). Integrity of the cell is not hampered by the direct passage of nanoparticles, which is mediated by amphipathic cell-penetrating peptides. In this phenomenon, the cationic groups of cell-penetrating peptides communicate with anionic groups present in the membrane to leave their hydrophobic surface for reaching the interior of the film, therefore penetrating the hydrophobic barrier of the cell membrane (Verma et al., 2008). Plasmodesmata assist in the cell-to-cell translocation of nanoparticles in the cytoplasm (Zhai et al., 2014).

3 Current Scenario of Nanofertilizers in Research and Development

3.1 International Status

Intense researches are being conducted all over the world on the developmental aspects of nanofertilizers and to harness their potential in agriculture. Nevertheless, there is a need of conducting advanced studies in order to design suitable target-oriented forms for increasing agricultural productivity in farmer's field. The two main goals of global sustainability are to achieve remarkable social and economic development while having minimum negative impacts on the environment and ecosystems. An argument by Wiek et al. (2012) highlighted that nanotechnology is used very narrowly, by focusing only on the end of a pipe application. Therefore, research and development of nanoparticles are required in agriculture to meet the sustainability goals.

The study of grain yield of *Zea mays* with 7-day treatment of nano-biofertilizer revealed an increase in grain yield (Farnia & Omidi, 2015). Research conducted by Abbasifar et al. (2020) disclosed that 4000 ppm Zn nanoparticles combined with 2000 ppm Cu nanoparticles resulted in a significant variation in morphological parameters. It also resulted in a significant increase in yield and altered the concentrations of chlorophyll and carotenoid in the leaves of basil plants (Abbasifar et al., 2020).

3.2 In India

The researches on nanofertilizers in India are mainly based on formulations that are non-toxic and highly efficient, but there is substantial lack in strategies related to the commercialization of the innovation. Experiment with biogenically synthesized silver nanoparticle in legume crop *Vigna radiata* showed a significant increase in yield. It was also reported that silver nanoparticles could be used as nanoparticles as such or for nano-encapsulation in combination with other nanofertilizers (Kumari et al., 2017). The study of the biogenic synthesis of zinc nanoparticles by the use of microorganism *Pseudomonas aeruginosa*, conducted by Barsainya and Singh (2018), reported its broad-spectrum antimicrobial properties that could impart resistance to the plants. The technical report submitted to the Ministry of Agriculture on prospects of nano-biofertilizer in horticultural crops of Fabaceae family by Allahabad University reported enhanced yield and nutrient content in crops. They also reported that, in country like India where there is a scarcity of land and water resources, use of silver and gold nanoparticles can prove to be effective in nanofertilizer development (Shukla et al., 2013). Nanostructured NPK fertilizer system was fabricated by Celsia and Mala (2014) along with neem cake and plant growth-promoting rhizobacteria (PGPR). Application of this formulation of nanofertilizer and PGPR assisted in increasing seed germination in *Vigna radiata* plant. An experiment was conducted on *Cajanus cajan* by Rajak et al. (2017) with a combination of biofertilizer, plant growth-promoting fungus, and copper nanoparticle which showed enhanced vitality and growth. When zeolites were used as carrier, the solubility and availability of phosphorus were increased (Dwivedi et al., 2016). The application of zeolite-based nanofertilizers ensured higher accumulation of nitrogen in plants as well as better soil properties like available N, moisture, and pH (Rajonee et al., 2016).

4 Climate Change and Environmental Sustainability

4.1 Impacts of Climate Change on the Morphophysiology of Plants

Increase of greenhouse gases in the atmosphere and its subsequent effects like climate change are a matter of major concern worldwide. Developing countries like China, Bangladesh, India, the Philippines, Thailand, and Sri Lanka are major rice-growing countries (Ane & Hussain, 2016). Around 89% of the total area is accounted for rice cultivation in Asia (Roy et al., 2021). Paddy fields emit about 20% of the total greenhouse gas emission in the world (Adhya et al., 2000). Paddy fields account for a significant emission of methane and nitrous oxide. It was estimated by the Intergovernmental Panel on Climate Change (IPCC) (Watson et al., 1996) that global rate of emission of methane from paddy fields is 60 Tg/yr. and lies between the range of 20 and 100 Tg/yr. with 5–20% of the total emission from all human sources. Emission of nitrous oxide mainly occurs due to the degradation of nitrogenous fertilizers applied to the soil. Nitrogenous fertilizers are prone to volatilization, denitrification, and leaching losses. About 0.3% of nitrous oxide emission is due to nitrogenous fertilizers and mid-season drainage which mainly occurs during the heavy application of nitrogenous fertilizers in paddy fields (Roy et al., 2021).

In a long run, the changing climatic conditions can adversely affect crop's morphophysiological characteristics. Due to the availability of CO_2, radiation, and longer growing seasons, there may be an increase in yield of plants having C3 photosynthetic pathway (Roy et al., 2021). This mainly occurs due to enhanced growth as the availability of light and CO_2 levels increases, resulting in the formation of more structural components. A greater quantity of photosynthetic assimilates are transferred to vegetative structures to support the leaves, which are light-harvesting structures, whereas in C4 plants, there can be a drastic reduction in harvest index (Roy et al., 2021). Climate change is also responsible for the aberrant rainfall pattern and unpredictable incidence of monsoon. Unavailability of sufficient moisture during sowing and throughout the growth period can adversely affect the crop's yield and productivity. Heavy rainfall and occurrence of flood can result in crop failure incurring huge losses to the farmers. Climate change can also lead to the frequent incidence of pest and diseases. Nanofertilizers are promising alternative to conventional fertilizers to reduce nitrogen loss and improve the nitrogen use efficiency. About 95% of the Indian soils are deficient in N (Tarafdar et al., 2013) and low in nitrogen use efficiency 30–35% (Olk et al., 1999). Nanofertilizers might be a potential solution to these existing problems.

4.2 Energy Reckoning of Nanofertilizer Treatment in Precision Agriculture

Fertilizers are characterized as an indirect energy consumer on the farm. Fertilizers are widely used in agriculture to maintain soil fertility and to increase crop yields. In spite of their benefits, fertilizers are associated with high-energy consumption. In particular, they are very dependent on natural gas for production. Energy constraints and high fuel costs necessitate the implementation of energy efficiency measures in the production and use of fertilizers. From Fig. 6, we can easily conclude that numerous inputs and outputs are associated with the fertilizer production operation. The energy resources utilized are either manual or mechanical. Benefits of nanofertilizers are gained only when the synthesis portion is managed through energy-saving approaches. The targeted delivery of fertilizers is another crucial issue. Nutrient use efficiency of normal synthetic fertilizers is very low as a maximum portion of the applied fertilizers go to the non-targeted matrices increasing environmental load, which requires more energy for environmental clean-up, whereas nanofertilizers, if formulated as controlled release and target specific, can definitely save the energy required for environmental decontamination in the case of commercially available synthetic fertilizers. Thus, nanofertilizers, if fabricated via low-energy strategies and applied judiciously, can not only increase crop production but also save a huge amount of energy that can be applied for some other operations, and thereby, the application of nanofertilizers can significantly maintain the sustainability of the surrounding environment.

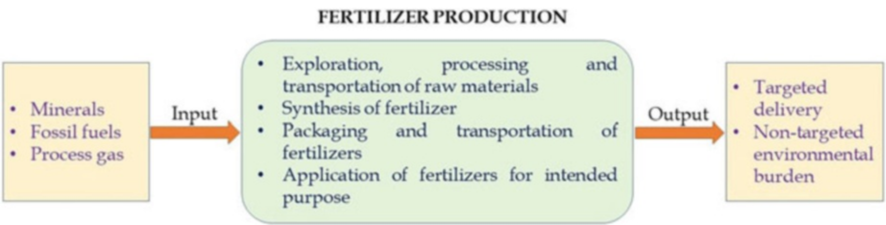

Fig. 6 Fertilizer production using various resources and their fates

5 Counter-Angles: Ethical, Safety, and Policy Matters

Baseline for the successful development of safe nanoparticles and its commercialization should depend on risk assessment and nano-toxicological studies. The general perception of nano-form being more toxic than the bulk forms must be analyzed from toxicological point of view. Environmental fate of the compound needs to be considered in various risk assessment studies. Safety and ethical issues are major concerns for the agronomic use of nanoparticles and should be evaluated closely. Agribusiness and food manufacturing sectors are concerned about the fact that sparse information is available on the regulations related to the safety standards of nanoparticle usage. Appropriate dose of nanofertilizers and their suitable designing are only possible, when there is an extensive life cycle assessment (LCA) (Hasler et al., 2015). Risk assessment studies are necessary for identifying the bioaccumulation of nanofertilizers in the food chain and its accumulation in various plant parts. This will provide a clear view regarding the fate of nanoparticles in the food chain while standardizing policies for commercial production. Biocompatibility of the protein surrounding the nanoparticle with the cellular components and functioning of the test organism is of primary concern. Nanoparticles can show considerable influence on uptake and limit the intracellular functions. Deposition of nanoparticles can result in structural differences in proteins and alter the surface area available for protein absorption and cellular interactions. Curbing the agglomeration of nanoparticles is the foremost requirement to improve the bioavailability, limit its accumulation in subsequent trophic levels, and ensure its safe use (Nel et al., 2009). Preferential uptake of active nanoparticles depends on the protein coating, surface area, and net charge on the residues of amino acids (Fröhlich, 2012). The degree of toxicity of the nanoparticles depends on various factors involving protein component, such as type of protein, charge associated, and hydrodynamic size (Walkey et al., 2014). Oxidative damage due to the phytotoxic effects of some nanoparticles can be evident on various morphophysiological characteristics of plants, like injury to root tips, decrease in root length, reduced biomass, and degeneration of chlorophyll. Evidences of reduction in chlorophyll content were visible with Ag nanoparticles in *Solanum lycopersicum* (tomato) and ZnO nanoparticles in *Pisum sativum* (sweet pea) (Mukherjee et al., 2014). Nanoparticles are capable of producing reactive oxygen species (ROS) in biological systems and can combat the genes associated with stress-related functions leading to genotoxic effects, which can seriously disrupt the abiotic stress-related functions in plants' body (Radhakrishnan et al., 2018). The generation of ROS can induce cell death, ion leakage, oxidative stress, and abnormalities in cell membranes mainly due to lipid degeneration. In maize, CeO_2 nanoparticles resulted in the peroxidation of lipid and ionic leakage in cells (Rico et al., 2013). Interactions of plant physiological functions with nanoparticles can cause a significant impact on hormonal regulation, growth, and secondary metabolism of plant. A recent study on the analysis of transcriptomes in *Arabidopsis thaliana* revealed that nanoparticle exposure can suppress the expression of specific genes responsible for the management of stress response, phosphate loss, and pathogens. This mechanism can result in negative impacts on defense mechanisms of plant and limits the development of roots (Sanzari et al., 2019). Another impactful consequence of nanoparticle toxicity is the disruption of nutrient distribution, limiting growth and development. The N_2-fixing ability of rhizobacteria was hindered by CeO_2 nanoparticles, reducing the nitrogen availability in soybean (Schwabe et al., 2013). Moreover, if no toxicity effects are visible at phenotypical level, there is a need for thorough and close examinations at genetical and metabolic aspects. No documentation is available on how nano-toxicity is dependent on its interaction and type. Proper knowledge is also required on whether the activation of detoxifying mechanism is enough to balance out the stress at biomolecular level. It is essential to consider the risks it possesses to living beings and environment before it enters the plant system. Toxicity induced by nanoparticles at proteomic level can be investigated with the help of protein markers. Before the commercialization of any agro-products, its thorough in vitro and in vivo phytological testing should be done to harness its maximum benefits with negligible associated toxicity. Soil can act as a significant sink for nanoparticles in comparison to air, water, and living communities, Therefore, proper validation and evaluation of its ecological impact are necessary for the commercialization and dissemination of nanofertilizers into Indian agricultural practices.

An integrated approach should be taken to increase its public and consumer acceptance. Setting up of a legal framework along with scientific research, industrial interventions, regulatory measures, and social development is key to a full-fledged approach to turn the technology into a wide success.

6 Future Roadmap

The application of nanobiotechnology in agriculture is at its infant stage. The low profit margins of farmers in agriculture and the absence of sound researches have resulted in the staggered growth of the nanotechnology in this sector. The successful incorporation of nanotechnology in the production of fertilizers and agro-chemicals will add value to the already existing product. However, there is still a long way left in its way of successful implementation. The results of the researches conducted on its uptake, its mobilization in plant's body, and its relation with various biological and ecological systems have been inconsistent, which is creating a hindrance in designing effective formulations. Both opportunities and limitations should be kept in view while searching for logical solutions to the current problems. Figure 7 depicts the opportunities and limitations that should be kept in mind while planning for the future strategies of commercializing nanofertilizers. There is a necessity to fill up the knowledge gap between fate and impact of nanoparticles on various living systems for the sustainable development of nanofertilizers, through research and mass awareness.

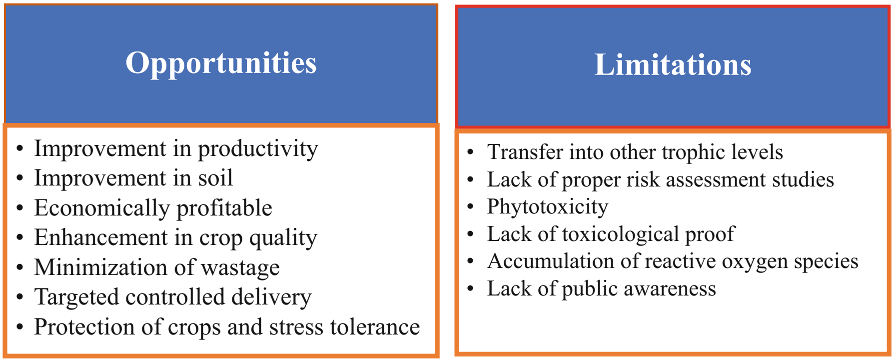

Fig. 7 Opportunities and limitations of nanofertilizers

7 Conclusion

The role that nanofertilizers play in enhancing productivity and resistance to abiotic stresses cannot be overlooked. Therefore, proper application of nanofertilizers in biotechnology, agriculture, and horticulture sectors can efficiently boost the production, even under changing climatic conditions. It can also be of tremendous importance to our farming community, as it can prevent the loss of conventional fertilizers through leaching and volatilization. This technology can maximize the profit margin of the farmers by a two-way approach of increasing productivity and restricting the loss of resources. In spite of so many positive sides of this technology, there is a great obstacle in its marketability and acceptance. The further arena of its interaction with various biotic components in environment and the extent of toxicity in living creatures are still in its initial phase of exploration. Therefore, to incorporate nanomaterials into the sphere of sustainable agriculture, effective and detailed researches should be conducted on their fate as well as on their suitability according to various physicochemical properties in soil. Then only suitable nanofertilizers can be recommended for a specific soil and crop type.

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Part IV

Country Experiences and Challenges

Energy Management Across the Globe and Possibilities

Overview

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Contents

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Abstract

The basic goal for agriculture is to provide energy (food) for the people. Reaping what nature could provide developed into goal-oriented agriculture, amazingly at around the same time about 8000 years ago in different independent parts of the world, The development was slow until the scientific base was discovered about 1850. Then also the emerging fossil era opened up new possibilities: energy for mechanization and plant nutrient regulation. "Auxiliary energy" became important. The concept "energy in agriculture" now directs the mind to the use of input energy. But the definitions of both "agriculture" and "energy" in popular and often also in scientific work and statistics are unclear.

Still, the most important influence of agriculture is the provision of energy (as food and products) for the society. A field of cereals multiplies the input energy more than fivefolds, by capturing solar energy.

However, the global challenges (climate, environment, and resources) demand action, and several programs have been initiated. Also, the beginning end of the fossil era both demands and promotes new possibilities: improved crops and agricultural systems, technical developments, and circular economy, including energy production from agriculture, enabling high production from local resources.

Further, the whole food chain needs consideration, all the way to dishes served and eaten. Recently an European Union (EU) program called "From Farm to Fork" has been launched.

These issues are discussed, with emphasis on:

The complexity of agriculture: crop production, animal production, and the food chain.

Energy relations in cereal production, based on the practical interpretation for Swedish conditions.

The interplay between energy, nitrogen, and climate. Improvement possibilities.

The two faces of agricultural bioenergy – competes with food production or promotes it.

Can agriculture become both high producing and self-reliant?

1 The Total Energy Picture

To gather, put together, and discuss energy data is not a straightforward issue. Here data from the website Ourworld in Data are used (Ourworld in data). The unit is Twh according to the substitution method, meaning that the primary figure for, for instance, bioenergy is expressed as the amount of fossil energy it can replace. This is of importance especially for nuclear and renewable sources.

The total world consumption was 171000 Twh in 2019. Until then, it has steadily increased; the figure for 2015 is 162000. For 2020, preliminary figures show a decline, but that is a special year because of the Covid-19 pandemic. 76% was supplied by fossil sources, hydro 6%, nuclear 4%, wind 3%, solar and modern renewables each 1%, and traditional renewables 11% (Ourworld in data).

We certainly have a long way to go to reach a fossil-free society.

2 The Agricultural Sector

Some figures:

In fact it is hard to find sector-wise figures for agriculture from the energy statistics.

EU specifies the energy use by agriculture, forestry, and fishery: 2017 together 2% of total consumption (Eurostat, 2019).

Maybe this figure explains the difficulty. Agriculture is normally not significant enough to earn a place in the statistics. Now, for instance, fertilizer production belongs to the sector industry, but, in fact, this does not influence much.

However, there are other voices (Hans-Erik, 1995). A press release:

> 29 November 2011, Durban, South Africa/Rome - The global food system needs to reduce its dependence on fossil fuels to succeed in feeding a growing world population, FAO said today.
>
> The food sector (including input manufacturing, production, processing, transportation marketing and consumption) accounts for around 95 exa-Joules (10^{18} J), according to the report – approximately 30 percent of global energy consumption – and produces over 20 percent of global greenhouse gas emissions.

Now, this is another matter – the whole food chain.

3 What Is Agriculture? What Can We Do?

For meaningful actions and programs, we need to better specify what is important and what is possible.

An old Swedish report (1995, Royal Swedish Academy for Agriculture and Forestry: H-E Uhlin. Energy balance of Agriculture) (FAO, 2011) gives a good description of the system. The figures may be outdated but their relations are not.

The energy flows of Swedish agriculture in 1993 are quantified in energy terms. Also agricultural products are given energy values (Table 1).

Table 1 Energy flows in Twh

Input	Output
Crop production Fuel + fertilizer. 12.6 Animal production “Housing,” import feed 6.9 From crop 38	Biological production 88 Residues returned 35 to animal (feed) 38. To consumers 11.5 To crop (manure) 3.5 to consumers 5.2

Swedish farms engage in crop production and animal production. Often this is integrated on the same farm and anyhow, there is interaction via the market. Total arable are about three million hectares.

3.1 Summing Up

Different components of agriculture must be analyzed for energy values. The values for crops, animals, and total agriculture are presented in Table 2.

For perspective: the input of solar energy to the Swedish cropland in 1993 is estimated to be 23300 Twh. That is the driving force.

Uhlin, the author of the report, made a note that the crop residues returned to soil contain several times more energy than the external input. A potential resource.

This report leaves the system at farm gate. Then there is the rest of the food chain. But so far we see that the crop sector works fairly well and multiplies the input energy about fourfold. The animal sector has a different role: to use energy for producing high-value food products. In addition, the ruminants in the animal sector can utilize grassland and roughage which without them would be of no use for human nutrition. And this is no small thing; globally, "grassland" occupies 3600 million hectares while "arable" is 1400.

It seems necessary to consider each production separately for an improvement discussion. Then there is the overriding process of integrating everything including landscape, environment, and society.

But let us learn more about what happens in the agricultural system of the world.

The Swedish agricultural consultant Gunnar Rundgren in his book "Den stora ätstörningen" (The great eating disorder) has compiled the following summary from FAO databases (Rundgren, 2016).

The end sum corresponds well with the normal need of about 2500 kcal/capita and day (Table 3). Losses at farm and industry level amount to about 20% of the production. But losses at household level are not included.

Table 2 A comparison between crops and animals in energy flows

Crops	Input 12.6	Output from crops	49.5	Output/input	4.0
Animals	input 6.9 + 38	Output farm gate	5.2	Output/input	0.12
Sum agricult.	19.5	To consumers	16.7	Output/input	0.85

Table 3 Global agricultural production, kcal per capita and day

Total gross production	+5600
Used for seed	−130
On farm losses	−560
Food from animal sector	+510
Biofuels	−480
Other industrial use	−200
Losses in food industry	−400
Food from sea and forest	+50
Sum, available for food	2847

The fertilizer input to the system is 110,000 thousand tons of nitrogen (FAO Fertilizer Trends). To make 1 kg of fertilizer N, about 10 kwh are needed in modern factories. The fertilizer input means about 350 kcal per person and day, roughly 10% of the food energy.

4 Sweden as an Example from an Industrialized Country Within EU

The total energy consumption was 645 Twh in 2019, ten million inhabitants.

Sweden exports surplus of cereals but imports animal products (about half of the market share).

Agriculture consumed 182 thousand tons of nitrogen in fertilizers (70 kg N/hectare), and the use of fossil fuels can be estimated to about 250 thousand tons of diesel (100 l/hectare).

Wheat yields are in average 7–8 tons per hectare; around 10 tons is currently quite common.

Summing up the agricultural use of fossil energy sources: nitrogen, 10 kwh/kg N in modern factories means 1.8 Twh, and diesel 2.5, together 4.3 Twh, which means 0.7% of the Swedish energy consumption. In addition, energy is used for manufacturing machinery, buildings, and for soil maintenance of phosphorus and lime.

This small influence of agricultural input energy is at odds with the general view in the society. However, it does not mean that the issue is unimportant. It affects the most fundamental process in our society; it has improved a lot in recent years, and we must continue to improve and work on it. We will come back to this issue, but first take a wider look at the food chain.

5 The Food Chain

The important issue is not agricultural production, it is the total resources needed to get food for nourishment.

An FAO statement was briefly mentioned above. Behind it is an ambitious investigation and a summary of ways of improvement, “Energy-smart food for people and climate.”

The relations for “Direct and indirect energy inputs” to the food chain are also estimated as per the country income categories (Table 4).

Table 4 Percent of total energy input

	Global total	High GDP	Low GDP
Cropping	12	11	14
Livestock	6	9	24
Fish	3	3	2
Processing and distribution	43	48	23
Retail, preparation, and cooking	37	29	13

There is a waste category, which is probably not included here: waste in connection with eating, i.e., food spoilt or left for different reasons.

It is clear that "cropping" is not the major issue as far as energy is concerned. But cropping, together with livestock, is a major caretaker (or destroyer) of our soils and resources and deserves special attention. The final end of the food chain includes cooking and takes about one-third of the total, at first sight an unexpectedly high proportion.

5.1 On Scientific Cooking

People have been made aware of energy use in our "industrial and intensive agriculture." Therefore, the following comparison is of interest.

We have 1 kg potatoes to cook for dinner. According to SIK report: to cook 550 g potatoes (20 min) costs 1.1 MJ, 2 MJ per kilo, and 0.6 kwh per kilo.

How much is spent on the field? According to the field manual for potato growing in Sweden (Produktions grenskalkyler för växtodling, 2019): yield 44 tons per hectare, input nitrogen 125 kg (1250 kwh), and use of fuel 154 l (1540 kwh). So far 2790 kwh. If we say 4000 kwh to also cover plant protection, etc., we have spent 0.09 kwh in input energy for 1 kg potatoes. The cooking (simple boiling) took seven times more energy than the production in the field.

Cooking spaghetti gives about the same result. The kitchen uses much more input energy than the field.

5.2 The Crucial Question: To Toast or Not to Toast

Or about the difficulty of keeping focus and perspective.

One slice of bread for breakfast weight 50 g. It originates from wheat grown in the field (and everyone knows about the energy-gobbling fertilizer being used) and then comes the milling, baking, packaging, and transport to the supermarket. That is too much to think about so we forget it. Anyhow, may be 80 g of wheat is the base for the slice. The fossil input of fertilizers and diesel is 0.3 kwh per kilo (see below), so 0.024 kwh have been used in the wheat field. The toasting takes 2 min, 1000 w, and 0.033 kwh. So toasting took more energy than the wheat production. "But, never mind, it is less than 100 m driving with my car and it is worth it" (own calculations and considerations).

It seems that the energy issues should be worth considering in the kitchen art and science and practice.

6 Energy Use Improvement in Crop Production

We go from broad statistics and kitchen issues to practical crop production. Which factors can be improved? Knowledge and research data are digested into practical recommendations, and "field manuals" maybe the best and most important "peer review" available (Produktionsgrenskalkyler för växtodling 2019). It means that there is a check on the general practicability of the figures; it is not just measurements limited in space and time. The important energy inputs to crop production are fuels and nitrogen fertilizers. Crop protection (chemicals) is not very important as concerns energy for common crops. Irrigation, however, is an important factor, but we consider rainfed agriculture in these examples.

Data from Swedish "Field manuals" issued by advisory organizations (Jordbruksverket (Board of Agriculture, Sweden) 2020; Bidragskalkyler för ekologisk produktion 2020). Figures in kg or kwh/hectare (Table 5).

Table 5 Fossil energy inputs to important crops and nitrogen balance (input fertilizer – output grain/tubers)

	Barley			Wheat		
Yield, kg/ha	5000	6000	7500	6500	8000	9000
N (kg, kwh)	85 850	100 1000	125 1250	156 1560	180 1800	220 2200
Diesel (l, kwh)	69 690	69 690	69 690	74 740	74 740	74 740
Sum (kwh)	1540	1690	1940	2300	2540	2940
Kwh/kg	0.31	0.28	0.26	0.35	0.32	0.33
N in – out	85–90	100–108	125–135	156–130	180–160	220–180

	Potato			Potato, organic	
Yield, tons	40	46	50	18	25
N (kg, kwh)	115 1150	124 1240	135 1350		
Diesel (l, kwh)	167 1670	172 1720	178 1780	222 2220	232 2320
Sum (kwh)	2820	2960	3160	2220	2320
Kwh/kg	0.07	0.06	0.06	0.12	0.09
N in – out	115–140	124–161	135–175		

	Barley, organic		Wheat, organic	
Yield, kg	2500	3000	3000	4000
N (kg, kwh)				
Diesel (l, kwh)	101 1010	101 1010	96 960	96 960
Sum, kwh	1010	1010	960	960
Kwh/kg	0.40	0.33	0.32	0.24
N in – out				

About energy (fossil) figures: Nitrogen fertilizer. Modern factories use about 10 kwh per kg nitrogen in fertilizers. This is on the frontline but dominant in Sweden. We are aiming at the future, are we not? Diesel: 10kwh/l.

About nitrogen use and recommendations: general recommendations issued by the Board of Agriculture (Jordbruksverket (Board of Agriculture, Sweden) 2020) are based on the economics of field trials in farmers' fields. These are adapted locally. They should be adjusted according to cropping history, analyses, etc.

Sweden is fairly representative for "western agriculture."

Organic cropping uses no nitrogen based directly on fossil energy but have nitrogen inputs from manure, green manuring, and some accepted organic fertilizers. This is difficult to specify and is not included (Bidragskalkyler för ekologisk produktion 2020).

What can we learn from the tables?

1. The fossil energy input for cereals is about 0.3 kwh per kg (whereas the energy value for the harvest is about 3.5 kwh/kg).
2. Higher yields need more nitrogen but are, in general, more energy efficient. To reduce intensity does not save energy. Unless, of course, in the case of overdoses.
3. Applied nitrogen is used well and corresponds to the offtake by the harvested products.
4. Organic cropping according to the rules of today does not save energy. Low yields and higher use of diesel give drawbacks.

The nitrogen data for winter wheat points at an interesting possibility with some general importance. The input figures are higher than the offtake. For bread wheat, the protein content is an important quality factor, which means a higher nitrogen requirement. However, two developments might change this old truth: the baking technology is developing techniques with less need for high protein, and, further, the cereal industry is developing methods to sort out quality fractions needed. That might reduce the nitrogen requirement for bread wheat in general. Adaptation of quality specifications may increase the total efficiency.

Irrigation costs energy but is not very much used in Swedish conditions. But where it is used anywhere in the world, it increases the need for efficient nutrient management. Irrigated land as well as water are precious resources which should not be wasted by nutrient deficiencies.

7 Challenges and Opportunities

7.1 Nitrogen Management

We see in the tables above that when we know the yield and act accordingly, all is well with high efficiency of nitrogen and, consequently, of energy. But in practice, the farmer in the planning stage does not know the yield. It depends very much on the weather. He must guess and hope, but increasingly science and technology comes to help. The yield figure of importance is the estimated yield on the specific field the actual season. General average figures are not sufficient. Weather and pests have great influence and are hard to predict.

For nitrogen and energy efficiency, there are two critical points.

1. Do not apply surplus nitrogen which the crop cannot use. And use efficient products and application methods.
2. Reduce leaching after harvest. This might require an explanation. A normal soil contains about 5000 kg nitrogen per hectare in the form of organic matter (humus). Microbial activity liberates 1–2% per year, let us say about 10 kg nitrogen per month. This is consumed by the crop during growth. But when the crop ripens in the autumn, this uptake stops and reactive nitrogen (nitrate) accumulates in the soil and it is subjected to leaching. This is the most important source of nitrogen leaching from crop production.

Soils, precrops, and manure have always been important factors to consider for fertilizer planning. Subsequently, soil and plant analysis began being used. Techniques for split application of fertilizers were developed, which means that the fertilizer could be better adapted according to the actual development of crop growth. Electronic devices for field use provided direct data concerning the crop status. This was developed further to remote sensing. Precision agriculture was born. Now measurements from satellites provide maps for adaptation of measures according to local variations within the field. So, the critical point 1 is site-specific management which should be taken due care during the process.

It should be mentioned that high technology helps but is not necessary. By using zero plots with no fertilizer and pilot plots with higher rate small and middle-sized farms can go a long way in field-specific adaptation.

Point 2, leaching after harvest is governed by the type of agricultural system. Late growing or perennial crops reduce this leaching component. Cover crops are important, and soil till age plays a role.

A recent development is conservation agriculture. It is a combination of several measures: no till or reduced till age, protection of the soil surface with residues or a growing crop, variation in the cropping sequence, as well as cover crops or bottom crops. This is a system gaining pace in several countries and shows great promise. Local adaptation is essential. Probable effects: protection of soils, building soil carbon, biological diversity, reduced erosion and nitrogen leaching, less need for fuels, and full production is expected. The practical on farm development is ahead of research, a development which gives hope in the world of today. To sum up: Conservation Agriculture is good for soil protection, will reduce use of fuel (about 50%), will probably reduce leaching, increases biodiversity on land and in the soil, and all this without compromising production.

The measures mentioned can be seen as a part of the program "Sustainable Intensification," with the aim of providing food for a growing global population combined with reduced resource use and environmental impact.

Site-specific background for measures as fertilizer use is necessary for energy and nutrient efficiency. This is emphasized by Poore and Nemecek (2018) who made a comprehensive investigation of details of the global food chain. They found a very large variation between individual enterprises, which means that there is a great scope for improvement.

“Reduced inputs” are often proposed as necessary for environmental improvement. However, this works only in case of overdoses or as a consequence of better management or recycling measures. In this context, it is necessary to discuss the purpose of agricultural production. We can eliminate the need for inputs by closing down production. We can reduce input and reduce production. But the need for production is the driving force. Reduced inputs must be critically considered at system level.

Biological nitrogen fixation is an important resource. It is very powerful and should be used where possible. It has some limitations: few food crops are nitrogen fixers, leguminous crops need space in the rotation because of risk for disease buildup, and they cannot be planted too often. The nitrogen they leave in the soil is hard to conserve between seasons. Organic agriculture relies on biological fixation but has a yield penalty of 40–50% in crop production, around 20% for livestock production where leys are important. These figures are for Scandinavian/European conditions. With lower yield levels, the yield penalties are somewhat lower. Nevertheless, probably leguminous cover crops will be more important in the future.

There is work going on to develop perennial and may be nitrogen-fixing cereal crops. It would be an advantage in several regions of the world, but the probable yield penalty should be considered. The yield penalty is not only economic but it is also straining limited resources, including land and water.

8 Animal Production

Animal production is not very energy efficient as was mentioned in the introductory system descriptions. Only about 10% of the input energy becomes food products. This is a natural consequence of the ecological hierarchy. We can work for marginal improvements of the efficiency, and we can decide what proportion of animal products to consume. These relations are about the same for nitrogen. From a technical lifecycle viewpoint, we should abandon animal food. And now the climate issue sharpens the situation. Livestock production is in focus. There are many aspects to consider: The present global trend towards increased share of animal foods in the diet is not sustainable. There are considerable losses of nitrogen caused by animal production, and the climate issue is pressing, especially for the methane emissions from ruminants. Biological methane gives no long-term accumulation but the short-term effect (10–20 years) of methane can be important. Somewhat larger methane emissions come from the fossil industry whose products also directly emit carbon dioxide to the atmosphere.

There are several factors favoring ruminants. The use of 70% of global agricultural land, billions of people, and great cultures are dependent on them. Also in

Europe, for instance, they improve the landscape for everybody and provide work and a living for people in the countryside. Moving the production of high-value protein from the countryside to industrial and urbanized areas has wide consequences for the environment and society which should be more discussed.

However, it is important to promote an animal production in harmony with environment, landscape, society, and animal welfare. May be mixed systems type agroforestry can play a larger role.

9 Recycling

Recycling should be necessary for a long-term function, and this concerns both energy and nutrient resources. The problem is that the waste systems in our societies are built for removal, not recycling. The waste is either very diluted or mixed with all kinds of materials. But a positive development has started. A few examples:

Sewage sludge (bio solids) is used as soil amendment to some extent. If phosphorus precipitation is used in the treatment plant, it contains the main part of the phosphorus from the sewage system and some nitrogen. But there are question marks: heavy metals, sanitary safety, unclear phosphorus effect, and low nitrogen efficiency.

Clean phosphorus from sludge. A Swedish product (www.easymining.se) under development. Could technically solve the P recycling problem? Unclear: how to compete on the phosphorus market? The phosphorus issue is also worked on at several other angles. However, important breakthrough at the practical level has yet to come.

Nitrogen recycling in general is a more difficult issue. Reactive nitrogen is easily lost. For human waste in the sewage system, there are two small pathways for recovery: catch the ammonia in acids or as struvite. But development efforts continue.

Another approach is to catch the urine in a separating toilet in an absorbing material. In this way, the main part of nitrogen and phosphorus can be taken care of (Sinha et al. 2020).

Theoretical calculation: If all toilet waste from a village of 1000 people could be collected and efficiently used, it would provide nutrients for about 40 hectares of cereals and give food energy sufficient for the village. Consequently, 4000 hectares are needed for 100,000 people.

Animal manure belongs to agriculture and farms, still the nitrogen losses are a problem. The production manual (Jordbruksverket (Board of Agriculture, Sweden) 2020) for the most efficient handling chain for cattle, slurry stored for using as efficiently as possible, gives the following nitrogen figures (kg N per year) for a dairy cow producing 10,000 kg milk/year: excreted by cow 142, after storage 124, effect compared to fertilizer nitrogen 44. There may be an additional long term effect. But at least 50% of the original nitrogen is lost according to these figures, and this is currently the best possible case with good management and timing. Manure may be good for the soil but is problematic for the environment.

There are some improvements worked on:

Acidification reduces ammonia losses both during storage and spreading. But then input of some acid is needed.
Anaerobic digestion for biogas improves the nitrogen function.

There have been many efforts to develop an efficient transportable product from manure, but there has been no breakthrough for ordinary agriculture.

10 Local Energy Production from Agricultural Land

Bioenergy production from agriculture has two faces: If land is scarce, it competes with food production, which is a negative factor, unless local "surplus" land is used. It might be a driver for deforestation. However, if manure or harvest residues are used, there is no such competition, On the contrary, there can be favorable combinations which also promote the crop production. Some examples:

Manure goes to biogas, and the resulting slurry, where all nutrients have been conserved, is used as fertilizer. Straw is used for biogas, resulting slurry used as fertilizer. A cover crop grows enough in the autumn to be harvested and used for biogas, which improves both the agricultural system and soils, reduces leaching, saves energy use in the field and produces local energy, and recycles nutrients more efficiently.

10.1 Some Figures from Sweden

Biogas use is 4 Twh of which two currently are produced in Sweden. 10% from manure, 30% from household food waste and food industry, and the rest from sewage sludge (www.energigas.se/fakta).

Potential resource, Twh: three from manure and five from straw (www.energigas.se/fakta, Lantz et al. 2018). In addition, harvest of cover crop scan be developed. The fossil fuel today needed for fuel and fertilizer for Swedish agriculture is about 4 Twh. So we see that Swedish agriculture can replace the fossil use with "homegrown" energy without using more land or extra inputs – on the contrary, with improved efficiency and environmental performance. What is needed is investing in knowledge and technology already available, together with organizational skill and foresight. In addition, the cultivation of energy crops on suitable land can be expanded.

However, we have here discussed energy flows of a few Twh in the agricultural sector. Sweden uses over 600 Twh of which about 100 is for the transport sector. These relations show that, however, beneficial bioenergy from side products is for the agriculture they have a minor importance for the total energy sector. It is important that the society understands the total picture of local energy from agricultural side products: improved system in general with recycling, strengthening of agricultural systems for soil protection and resilience, and reduced losses of especially nitrogen. And maybe most important: strengthening the countryside in general and more local self-sufficiency.

Energy from our ecological and natural systems needs area. Here are some estimates (own calculations based on general and available figures. Unit: hectares for producing 1 Twh.

Embedded Electricity or (Heat) fuel.

Bioenergy. Crops (10 tons dry matter per hectare and year) 3000090000

Solar panels, 160 kwh/m^2 and year (Swedish conditions 2020) 625

Wind, today's technology, land based (https://hpklima.blogspot.com/2019/08/arealbehov.html. Petter Jacobsen) 3000

Per unit land area solar panels are more than hundred times more efficient than bioenergy from crops. Under North European conditions.

Arithmetic exercise 1: We have one hectare of wheat, using 150 kg nitrogen and 70 l fuel. Together the energy needs are 2200 kwh. This energy can be produced by 14 m^2 solar panels, about 3 by 4 m in a corner of the field. And then the wheat (8 tons) multiplies the input and gives 30,000 kwh in grain and 15,000 (embedded) in straw.

Arithmetic exercise 2. A good wheat crop gives 10 ton dry matter per hectare, including straw, 1 kg per square meter. If used to biogas, it gives at least 1 kwh per square meter, 10,000 kwh and nitrogen, and fuel costs 2500. So we need about one-fourth of the field to compensate for all the input energy. Or better: We need straw from about half of the field for compensation. And technology is available.

11 Local Fossil-Free Energy and Small-Scale Ammonia

Biogas energy is local. All you need is water, organic materials (manure, wastes, and straw), plus equipment more or less advanced. Biogas develops rapidly in many parts of the world, from Sweden to Africa (https://snv.org/project/africa-biogas-partnership-programme-abpp). It is an established technology available in different scales.

Ammonia is the first step in nitrogen fertilizer production, The factories of today are huge establishments producing several thousand tons of ammonia per day and serving millions of hectares. The process of today is efficient with an energy use close to chemical limitations. The environmental function has continuously been improved. Now, fossil-free alternatives are being worked on. Nevertheless, alternatives emerge.

Several alternative processes for small-scale ammonia are worked on, from modified Haber-Bosch to radically different electrochemical processes. There are also complete factories being marketed, in sizes from 1000 tons ammonia per year (Blackwell et al. n.d..; Tallaksen et al. 2015).

What is important is that this development has started. It opens the gate for local agricultural development and security. For instance, Sweden – we are now completely dependent on imported nitrogen and international trade. Local fossil-free production would give control and security. For areas in Africa, local nitrogen (and recycling) could greatly advance agricultural development. The biogas is rapidly developing. Wind is also a possible energy source (Tallaksen et al. 2015).

With biogas, there is the possibility of a "nitrogen loop," if nitrogen is the limiting factor for yield development: Use some manure or straw for biogas, some of the biogas is converted to ammonia fertilizer which gives higher yields, which also gives more residues, which gives more biogas and more ammonia, which. . . .

Now, there are hurdles. How use ammonia efficiently as fertilizer? For Sweden, there is available machinery, but for Africa, it is not so easy. Maybe small-scale applicators can be developed. And there is the very important issue of other nutrients. The increased recycling of biogas residue will help somewhat, but it cannot solve the problem.

Biogas gives the opportunity to also improve recycling. But any energy source can be used for ammonia production, for instance, wind (Tallaksen et al. 2015). Only energy, water and air are needed as raw materials.

Another type of development efforts could be worked on: exchange with the established markets and organizations for agricultural products and fertilizer. Exchange energy for easily handled fossil-free, efficient fertilizers? And there is another issue to consider about yield development: lime. Increased yield is a goal. This means an acidification, which some soils can handle, others cannot. This issue is important to consider for sustainable yield development. Local basic soils or lime could be a resource.

12 The Food Chain

An experience a few years ago:

Our neighbor had invested in 5 hectares of lettuce. Planted, hired workforce for weeding, etc., had started harvesting but stopped very soon and nothing further was done until all was plowed down. What happened? The Netherlands had surplus of lettuce and prices plummeted. Not even harvesting the good crop was worthwhile.

The market is efficient only as concerns economy. This may result in inefficiency concerning products and, for instance, transports. There is probably much to do about organization of markets, rules about quality, etc., which also consider resources and environment. Work in this direction is going on and much has happened in the last decade, for instance, work on innovative systems for product identification and branding.

Waste is another issue. Sorting the waste in categories for recycling is now the rule in Sweden and other countries.

13 Diversity

Diversity is important in several dimensions.

Landscape. For the well-being of people, for nature, ecological function, resilience, and more.

Agricultural systems. Our workhorse, "Conventional," organic, permaculture, tower gardens in big cities, polyculture, conservation agriculture, regenerative, and more. All have a contribution to offer. Why not favor establishment of permaculture units in an agricultural landscape? Good for people, good for environment and landscape. New technology for sanitation, etc., may allow dispersed housing.

Crops and fields. Diversity in the crop rotation. Flowering field margins. Cover crops with several species. All this is an ongoing development.

Research and development is required for development of agricultural systems. Institutional research is a necessary base, but practical development at farm level plays an increasing role. For example, for conservation agriculture, several factors are important. Soil, climate, crop, companion crops, timing, nutrients, soil till age, machinery are just some of them. This cannot be handled by conventional institutions. Development in practice is important, and Facebook groups for exchange of experience and ideas have been formed. May be something to encourage for other topics. And flexible help from scientific institutions should be important. More flexibility and freedom could play a great role. A small sector of resources for ad hoc research ideas?

Local awareness and perspective. Rather a consequence of diversity: know your local opportunities. For example, Sweden: zero plots and pilot plots. A few square meters in area: one plot without nitrogen fertilizer (or other inputs), the other with an extra dose. Even with sensors and satellite maps, etc., available, these hands on visible demonstrations give an extra feeling and perspective on how your fieldworks.

Other examples (based on impressions long ago):

1. Driving along the western side of Thar desert in Pakistan. A barren landscape. Suddenly a plot with high grass. My Pakistani colleague explained: that is a fenced off plot with no grazing.
2. Driving in Masai land towards the national park Masai Mara. Again it looked like a barren landscape and I wondered how the Masai herds could find some grazing. Then we passed the fenced border to the national park and the landscape was covered by lush grass.
3. A recent TV program about horses in Lesotho. Not a green plot in view. Is this consequence of climate and soils? What could nature do if we give it a chance?

What can be done? May be fencing off for a demonstration. Bur fencing is difficult in many places. Mark out a plot and guard it. Day and night, local watch people could do it and they should be paid for the work. May be a push for the community. Other factors could be added, for instance, recycling.

14 What Has Happened the Last Decade?

Some basic data:

World population has increased from 6.92 billion in 2010 to 7.75 in 2020. An increase by 12%.

World energy use has increased from 145 in 2010 to 173 in 2020. An increase by 19%.

But also: Babies per woman goes down, figures from 2009 to 2019, examples: Tanzania 5.3 (2009) – 4.8 (2019); Congo Dem. Rep. 4.8–4.5; Ethiopia 5.1–3.9; Ghana 4.5–3.8; and Kenya 4.2–3.7. There is a difference of about 0.5 births in 10 years. Stability demands around 2.5 per woman. If the trend continues, we have 20–50 years of growth before stability. A challenge to handle.

The countries are arbitrarily chosen among countries south of Sahara. A change is coming but slowly (Data based on Gapminder Tools).

The FAO paper from 2011 on "Energy smart agriculture" has been referred to (FAO 2011). Agricultural policies were recommended. Now 10 years have gone. What has happened? We take point for point.

14.1 Promote Conservation Agriculture

This is gaining in importance, both in area in several countries and in knowledge and interest. Machine development for no till, knowledge, and seeds for companion crops favor development.

Can be a game-changer.

14.2 Maintenance of Soil Health

On the rise in awareness in general and especially together with conservation agriculture.

14.3 Integrated Food-Energy Systems

Using food waste for energy and recycling is becoming the norm. More general, the concept circular economy is becoming well-known and worked on.

Local farmers' markets have been established.

14.4 Cultivation of Drought-Tolerant Crop Varieties

CRISPR has certainly opened some possibilities.

14.5 Precision Farming

Precision farming is a dynamic field with progress in many dimensions: concepts, sensors, satellites, drones, and much more.

14.6 Improved Management of Fertilizers and Chemicals

To a great extent, this is covered by precision agriculture. This started with fertilizers, but applications for chemicals are emerging. The concept integrated pest management is important. There is improved caution about this issue.

15 Possible Game-Changers

Conservation agriculture. Protect soils, diversity, save energy, and reduce nutrient losses.

Crispr. Opens a wide range of possibilities for crop developments. Also, widening knowledge about biological relations and possibilities.

Local energy and local ammonia. Forget that fossil inputs are needed for feeding the world; a way to more local resilience.

16 Discussion

Our topic is energy, but let us widen to “resources.” It is necessary to improve the ecological function and food availability. Population growth rate is declining, but we face a population increase during several decades. It takes time to flatten out. Absolute food requirements will continue to increase and strain all sectors of society. In addition, we have the climate issue.

For crop production, we have a good base as concerns technique and agronomy. Nitrogen fertilizers are sometimes criticized for poor utilization and environmental effects. In principle, this critique is misleading, but in the practical field, there may occur shortcomings. Used according to good practice and adapted to the site, the nitrogen is fully used by the crop. By providing the needed element for growth, it increases the yield, multiplies the energy from the input, and saves land and water. Even without fossil energy, we have this function, so fossil-free production is important. In general, there is a greening trend in the world with more consideration of diversity in cropping, soil protection, and minimizing chemical crop protection. But to be effective, this trend needs more support from the society and market, and this is under discussion in EU. Maybe it should not be called support. In fact, it is a help to overcome the ecological malfunction of the free market economy. There are especially two things to hope for in this context. One is that science and balance will be guideline, not dogma or “popular views,” and the other is that the farmers are allowed enough freedom to drive the development we need.

17 Conclusions

If "Agriculture" is defined as the production on the farms, then the agricultural share is a few percent of the total energy consumption in the society. But if "Agriculture" means the whole food chain from land to fork, the energy share is more than 30%. This ambiguity presents a difficulty for meaningful information.

The production can save energy, for instance, by reducing soil tillage and streamlining transports. Biofuels are increasingly used. But because of the small share of the total the impact will be small.

The food chain has a larger impact, and there are many steps and procedures: transport, storage, processing, and cooking. One thing needs to be stressed: food waste. About a third of the production is lost as waste in various ways. Improvements must be possible.

Another waste is the toilet waste, which contains all the nutrients we eat (almost). Most of it is wasted in sewage works. This is the driving force for the need for fertilizers, but this fundamental issue is seldom discussed. There is work on recycling going on, but it is a difficult issue and progress is slow.

Agriculture can grow energy crops, but these should not compete with ordinary production or drive deforestation. So, marginal lands should be used and their contribution to the energy supply will be fairly marginal. Present law-making in EU goes in that direction.

However, side products as straw and manure from agricultural production is another matter. They do not compete with ordinary production; they strengthen it by promoting efficient recycling and improving crop systems as well as fossil-free energy for fuel.

If we take one step more and produce local ammonia from local energy sources (biogas, wind, and solar), we open up for a self-reliant and high-producing, fossil-free agriculture anywhere in the world where climate and water permit.

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Conservation Agriculture in Energy Management

Social and Ecological Dimensions

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Abstract

Agriculture manipulates natural ecosystems for crop production. However, in the initial times of civilization, humans were an integral part of the wild ecosystem as were other animals and were dependent on the natural energy flow in these systems. When the human population started growing above the carrying capacity, they initiated modification of the ecosystem and energy hunting for more food. Because of this continuous harvesting of energy in growing more and more food following conventional agricultural systems, natural resources are being overexploited and ecosystem services are being hampered. Hence, conservation agriculture-based energy-efficient zero-tillage technology can be a potential solution. From the case study included in the present chapter it has also been found that farmers' age, their perception, ground water depletion, crop residue management, farm size, and cropping intensity play a critical role in making a farm energy efficient. Thus, a proper action plan, management, and awareness can only make the world energy productive.

Keywords

Agro-ecosystem · Conservation · Energy prodigality · No-tillage · Perception

1 Introduction

From the onset of the Green Revolution, energy consumption has increased to a great extent in agriculture and made this sector more energy intensive. Farmers have started using high energy to enhance production and some mismanagement on using inputs is increasing. However, energy consumption status in agriculture is directly associated with the technology involved and the level of mechanization. In addition to these, entropy in farm-energy dynamics is increasing because heavy depletion of groundwater, high-intensity mechanization, and use of nitrogenous fertilizer beyond proportions are making our farm increasingly energy prodigal (Mondal et al., 2017). Perception of groundwater depletion has become reasonably significant as groundwater depletion is closely associated with chaos in hydrothermal mobility and cycling. An experienced farmer, through his deeper learning and intuition, can guess the reasons for weather aberration adhered to the high-intensity groundwater depletion. Is it that high-intensity groundwater depletion is associated with a higher perturbation in climatic behavior? Hence, farm energy metabolism needs to be scrutinized in terms of both productivity and its ethos relating to an estimated aberration of ecological services. The energy flows in and out has rightly been associated with a new genre of energy research, social metabolism. The upscaling mechanization vis-a-vis modernization in Indian farms has accentuated a kind of proportionate and abrupt change in character of the farm family life cycle. Higher income, fragmentation of holdings, organically linked to disintegration of the pristine rural joint family system, and a high mobility trajectory, are all fueling the disruption of the energy recycling process and potential.

There are many studies delineating the energy consumption patterns in various crops and cropping systems in different locations throughout the world. It has been found that per hectare usage of operational energy and size of holdings are inversely related to each other. Seed and fertilizer have been found to be the two major sources of on-farm input energy. In the Indian context, most of the studies have been conducted on the pattern of energy consumption in irrigated and dry areas with traditional methods of sowing; however, very little information is available on the pattern of energy consumption of direct seed sowing in Indo-Gangetic plains. However, the alternative techniques of the conventional methods of agriculture viz. conservation tillage or zero tillage, happy seeders and rotavators, along with the three principles of conservation agriculture (CA) technology for the planting of rice, wheat, maize, and other crops have been recently introduced. Many studies have found that these technologies have benefits such as saving on fuel consumption, irrigation water, time, and farm laborers in comparison with the conventional methods and proved to be efficient in energy conservation. As we know that efficient use of energies helps to gain increased production, productivity, and sustains the economy, profitability, and livelihood. Here, CA technology also claims the same including proper energy management.

2 Energy Management and Energy Conservation: Opportunities

Energy management can be simply defined as the management of various energy consumption points to produce greater output for the same input or the same output for a lesser input, i.e., making the system efficient. Energy management is the process that should be taken into account during system design, using energy in a skilled and planned way to meet maximum possible efficiency with a lesser impact on the environment (Saharan, 2018) and society.

Energy management not only manages the energy generated from various sources viz. fossil fuel, nuclear, solar, wind, biomass, etc. but also optimizes the use of energy in energy-consuming operations. Therefore, energy management is defined as “the judicious and effective use of energy to maximize profits at minimum cost and enhance competitive positions” (Kumar et al., 2020).

2.1 Techniques of Energy Management

2.1.1 Self-Information and Building Awareness Amongst the People

The process of energy management will be successful only when the concept is implemented with proper information on the process. The operational process of the introduced technology is very important for the operators. Otherwise, the use can be reluctant to adopt the new concept or technology (here, adoption of CA technology by the farmers). This is because of the users' own perception of energy consumption and management. It is necessary for the stakeholder to understand the cost and benefit of the energy conservation practices. Hence, awareness on the part of the practitioner leads to up to 5% of total energy saving (Kumar et al., 2020).

Example:

1. Promotion of the concept, i.e.,
   "Zero Production = Zero Power Consumption."

We should save electricity (i.e., energy) during unused time. In agriculture, this is an indifferent practice of discharging water through flood irrigation in the crop fields (mainly rice) for an unaccountable time period. This expends both energy imbibed in the form of water resource and fuel.

2. Use of a microprocessor-based timer where appropriate or feasible; it helps with auto switch off during idling times, resulting in huge energy savings.

2.1.2 Re-engineering and Assessment of the Whole Process

Sometimes, we are handicapped by our ability and capacity of the system in the matter of energy saving. However, it is not always necessary to complete the work on time, it depends on the situation, as the energy optimization will occur when it is to be done. First, we need to start assessing and re-engineering the whole process and its unnecessary energy-consuming steps (Kumar et al., 2020).

2.2 Energy Conservation

Energy is an indispensable need of an established economy and social configuration. One of the major problems associated with its supply side is the exhausting nature of the withdrawal of fossil fuel, its contribution toward greenhouse gas emissions, the relentless input expenditure combined with the introduction to renewable energy resources and resource-use efficiency. However, it is contingent on a number of scientific and technological innovations, and energy conservation has the ability to bridge the gap between supply and demand. Various steps for energy conservation are essential for consideration. In Newtonian physics, there is a universal law of conservation of energy, which says that energy can neither be created nor destroyed, it can only change from one form to another (Acharya et al., 2019). Hence, the conservation of energy will opt for less energy consumption with more judicious use than before. The supply of an energy unit is certainly always costlier than saving a unit. However, the idea and perspective of energy conservation has changed dynamically over the years. Presently, the fuel cost has increased and waste has become expensive, although it is more expensive to recover the already wasted energy. Thus, the meaning of energy conservation is inhibition from wasting energy (Kumar et al., 2020).

Conservation of energy can be achieved through the following actions:

- *Reduction in the use of energy*: energy use optimization can be attained by reducing the consumption of energy, water, and other natural resources, for example, turning off pumps in an agricultural field, judicious application of agrochemicals and seeds, reduced tillage, and an optimal number of irrigations.
- Use of energy-efficient technology: agriculture must be energy efficient. Energy-efficient technologies causing minimum disturbances to soil like no/reduced tillage, mulching/permanent soil cover make conservation agriculture a sustainable and energy efficient technology.

Energy conservation in the agricultural sector consists of the following:

- Use of renewable energy resources in various agricultural activities, e.g., solar pumps or wind-driven pumps, solar drying, and biogas-powered dual fuel engine or biodiesel. These will help with the switching of the cultivation system toward lower-carbon energy sources.
- Introduction of energy-efficient pump sets and water-saving irrigation methods such as drips, sprinklers, etc., that conserve a huge amount of energy.
- Reduction in energy use by using energy-efficient equipment or by lessening the number of tractions through low-tillage agriculture.
- Agro-chemicals are energy-intensive products. Thus, there is a need for a reduction in the use of herbicides, pesticides, and chemical fertilizers. It can be achieved by either effective plus calibrated application or promoting organic/microbial substances. Reduction in the demand for chemical substances will reduce energy use in the chemical industry.
- Adoption of conservation tillage systems. It cuts the amount of labor number and time; in the case of equipment, the number of passes and the wear and tear. Apart from these, conservation agriculture improves soil structure for root establishment, makes water availability better, sequesters carbon through crop residue incorporation, and saves fuel consumption. Finally, conservation agriculture practices as a whole curb the total energy required to produce a handful of grains.
- Enhancement of the post-harvest drying and storage efficiency through the use of better equipment and appropriate maintenance.
- Reduction in post-harvest food grain losses that will ensure food safety and reduce food wastage. Hence, saved energy can be used in fresh production.

3 Energy Input Sources in Agriculture and Their Prodigality

The foundation of the life system on Earth depends upon the capacity of plants to convert solar energy into stored chemical energy. Then, the captured energy is used by consumers including humans and their livestock. In the agricultural production system, energy is captured in the form of biomass, as food crops, manipulating plants, land, and water resources while using humans, animal power, and fossil energy power to re-arrange the agro-ecosystem (Pimentel, 1992).

Energy inputs are classified into two main groups, i.e., direct-use energy and indirect-use energy. Direct and indirect energy inputs can be calculated considering biological energy (human labor, seed), chemical energy (fertilizer, toxins, and other agrochemicals), and field operational energy. Energy equivalents for all inputs are to be summed to provide an estimate for total on-farm energy input (Tabatabaeefar et al., 2009).

3.1 Types of Energy Engaged in Agriculture

3.1.1 Biological Energy

Energy analysis of farming systems implies an assessment of the energy embodied within human labor (Mario & Pimentel, 1990, 1991). The biological energy for tractor and combine operators as well as for the farm labor can be calculated as below: Biological Energy = Labor × Hours of work/ha × Energy Equivalent (energy-equivalent values are shown in Table 1).

3.1.2 Chemical Energy

Individual fertilizer materials and other agrochemicals were estimated from available sources (Tabatabaeefar et al., 2009). The total energy input from fertilizer was calculated by summing the energy amounts of individual fertilizer nutrients. The total energy input from agrochemicals can be estimated as follows:

Chemical Energy = (Amount of fertilizer ingredients × Energy Equivalent) + (Amount of pesticides × Energy Equivalent) + (Amount of herbicide × Energy Equivalent) + (Amount of x × Energy Equivalent) + (Amount of y × Energy Equivalent) + ...; where ‘x’ and ‘y’ stand for any other agrochemicals.

3.1.3 Field Operation Energy

This type of energy input is mainly specified for transportation and farm machinery operations viz. tillage, planting, plant protection, and harvesting. Energy in transport is generally estimated as energy intensity, the energy required per unit of weight and per unit of distance travelled (MJ/t/km).

Then, transportation energy was established by taking the energy equivalent of 1.16–4.6 MJ/t/km. For each and every machine in a particular farm operation, transportation energy is estimated by fuel tank and mass method; fuel energy is measured by the quantity of fuel multiplied by the energy equivalent. Energy related

Table 1 Energy values in agricultural input

System input	Energy equivalent	References
Human labor	1.95 MJ/h	NAAS (2017), Tabatabaeefar et al. (2009), Mittal and Dhawan (1988), Olsen et al. (1954), Parihar et al. (2013)
Operator	1.05 MJ/h	
Diesel fuel	56.31 MJ/l	
Oil	50.23 MJ/l	
Water	1.03 MJ/m^3	
Fertilizer		
(a) Nitrogen (N)	60.60 MJ/kg	
(b) Phosphate (P_2O_5)	11.10 MJ/kg	
(c) Potash (K_2O)	6.7 MJ/kg	
(d) Zinc (Zn)	8.4 MJ/kg	
(e) Nitrous oxide (N_2O)	74.78 MJ/kg	
Herbicide		
(a) 2,4-D	84.91 MJ/kg	
(b) Topik	271.38 MJ/kg	
Pesticide	280.44 MJ/kg	
Fungicide	181.9 MJ/kg	
Agricultural machinery production	138 MJ/kg	
Transportation	357.2 MJ/h	
	4.5 MJ/km/ton	
Seed (rice, maize, wheat, and mung bean)	14.7 MJ/kg	

to tractor or machinery operations can be calculated by (Mass × Yearly energy for equipment) × (Operational work capacity per year/work hours per year); where, yearly energy for tractor 9.5 MJ/(kg year) and machines 7 MJ/(kg year). Hence, field operation energy is considered to be fuel energy plus transportation energy plus energy of machinery operations (Tabatabaeefar et al., 2009).

3.1.4 Social Energy

In sociological thermodynamics, social energy is a general term referring to any of a number of types of energy in a social system modeled as a thermodynamic system, connecting or driving people. A famous demarcation on the topic of social energy is the 1910 argument by American historian Henry Adams on the applicability of the second law to human history, who commented on the lack of physical rigor in the thermodynamically understanding of social energy in contrast to the adamant adherence to entropy in the social context (e.g., psychic entropy or social entropy). In a noted humorous statement Adams tells us: ‘Although the physicists are far from clear in defining the term vital energy, and are exceedingly timid in treating of social energy they are positive that the law of entropy applies to all vital processes even more than to mechanical’ (Acharya et al., 2019).

3.2 Energy Status of Conservation Agriculture Farms

The conventional agriculture system of growing crops is found to be input (nutrients, energy, and water) intensive (Chaudhary et al., 2006). Here, intensive tillage and crop management practices contribute major shares to the costs of high energy and labor, resulting in lower economic returns in the rice–wheat and maize–wheat cropping systems (Aryal et al., 2015; Parihar et al., 2017). Hence, intense efforts are made to find out more efficient alternatives to the current agricultural practices in rice–wheat and maize–wheat cropping systems (Choudhary et al., 2018; Gathala et al., 2013).

Conservation agriculture-based crop production systems embrace three core principles of minimum tillage, crop residue incorporation, and crop diversifications or rotations. Practicing CA technology on farms can reduce energy and labor costs, and at the same time enhance crop productivity (crop, water, and energy) (Choudhary et al., 2018; Parihar et al., 2017) and improve the soil (Jat et al., 2018) and the environment (Kumar et al., 2018). Jat et al. (2013) found in their study that maize planted on permanent beds with residue mulch saved 11–29% of the total irrigation water applied and enhanced the water productivity by 16–25% compared with the conventional tillage-based system (Jat et al., 2015). Apart from this, the introduction of short-duration mung bean into rice–wheat and maize–wheat cropping systems assisted farmers to increase farm profits (Gathala et al., 2013; Kumar et al., 2018) as well as soil quality (Jat et al., 2018).

From a 5-year study, it has been elucidated that the crop residue retention and incorporation led to the maximum energy consumption in CA-based rice–wheat and maize–wheat cropping systems compared with the conventional tillage-based systems because of the crop residue retention (Choudhary et al., 2017; Parihar et al. 2018). Parihar et al. (2018) also found that crop residue consumes a significant amount (approximately 76–79%) of input energy on CA farms. Zero tillage reduces the energy requirement by saving energy in some management practices such as land preparation and weeding (Jain et al., 2007). The seed bed preparation and sowing of wheat consumes about 61% of the total operational energy. However, irrigation and harvesting account for 15.7% and 11.9% energy consumption respectively in Sari regions of Iran (Yadi et al., 2014). Pratibha et al. (2015) found conventional tillage-based management practices to be more energy intensive because of poor resource utilization. In these conventional tillage systems, maximum energy is consumed in indirect sources of renewable energy for crop production inputs, viz. fertilizers, other agrochemicals, and farm machineries (Choudhary et al., 2017; Parihar et al. 2018). In both the rice–wheat and maize–wheat cropping systems, 25–30% of the total energy is consumed in tillage operations and crop establishment (Tomar et al., 2006).

In CA-based systems, crop residues are retained on the soil surface and sometimes incorporated, and the sowing is done in one operation. Hence, no extra input energy is involved in managing the crop residues in CA-based systems. However, fertilizer applications contributed the maximum operation-wise input energy use under both the systems. Parihar et al. (2018), also state that higher operation-wise input energy consumption is related to the use of fertilizers after crop residues compared with the conventional tillage-based systems.

Higher net returns are recorded in CA-based crop management systems because of the lower costs associated with tillage, crop establishment, and irrigation, along with higher crop yields. In comparison with those of the conventional tillage-based system, it has been found that the tillage and crop establishment costs are reduced by 79–85% in zero tillage along with residue retention (CA-based) practices (Gathala et al. 2011). Some other researchers also reported similar experiences when they compared the CA system with the conventional one (Choudhary et al., 2017, 2018; Gathala et al., 2013; Sharma et al., 2015).

4 Farm Labor: Energy Source to Sink

Agriculture has provided food and fuel to mankind throughout history and to a large extent this process is backed up by human muscle. However, energy expense in labor conflicts with another very basic and perhaps insufficiently recognized human drive, i.e., the desire to avoid work (Zipf, 1965).

4.1 Accounting for Agricultural Labor

The generalized anthropocentric view of agriculture as a human-directed activity opposes the approach of equating agricultural to an agrochemical, cow, or a tractor. Norman (1978) suggested a logical refinement of this approach by subtracting basic metabolic rate (the rate of energy metabolized during rest) from the quantity metabolized during work. Therefore, the difference represents the net energy cost of farm labor. However, in the absence of any commonly accepted calculation procedure, it is not surprising that very few analysts have been reluctant to assign any energy measure to labor (deWit, 1979). Actually, in some situations, this type of measure is almost essential, e.g., in the study of non-industrial agricultural systems where human labor acts as an important, often limiting, and sometimes the only energy input. Besides, when the production system is autarkic or nonmonetary, energy accounting seems to be the only logical method of accounting.

4.2 Indirect Energy Costs of Reducing Farm Labor

The difference between on-farm energy expenditure per person and alternative urban employment should be considered while assessing the total energy cost before adopting any agricultural production system with reduced labor requirements, e.g., in US maize production, energy expenditure per person is equal to that of the most energy-intensive industries and this is also true for the UK agricultural system as a whole (Leach, 1975).

In developing economies, the situation is quite different. One example can be found in China, in the case of agriculture, fossil fuel use per worker was 24 GJ per year and in urban areas, it was 32 GJ per year. However, when a family migrated to the city energy expenditure increased to 14 GJ per year per person (Kalma & Newcombe, 1976). From this revelation, it is clear that the proportion of energy expenditure in employment, which revolves around urban-based agricultural support, i.e., fertilizer and tractor manufacture and marketing industries, must be reduced. Another most important indirect energy cost of urbanization is related to the nonproduction sectors of the food cycle. Transport, storage, processing, marketing, and preparation of food and waste disposal account for prodigious amounts of fossil fuel energy, about five times as much as that used in their production (Deleage et al., 1979; Leach, 1975).

5 Energy Inside Farm Produce (Table 2)

Table 2 Energy equivalent of farm produce

System input	Energy equivalent (MJ/kg)	References
Grain (rice, maize, wheat, and mung bean)	14.70	NAAS (2017), Olsen et al. (1954), Parihar et al. (2013)
Straw/stover (rice, maize, wheat, and mung bean)	12.50	
Barley grain	19.21–22.26	
Skim milk	15.39	
Clover, red, hay	18.61	
Corn cobs	18.51	
Corn grain	18.43–23.24	
Oat grain	19.69–23.24	
Orchard grass	19.24	
Rice, ground rough	14.42	
Rice, white, polished	16.95	
Sorghum, milo, grain	18.37	
Soybean meal	19.75–20.15	
Sugarcane molasses	13.44–17.22	
Wheat grain	18.82–20.09	

5.1 Energy Input–Output Relationship

Energy concentration is the quality that helps to characterize much agricultural produce, and there are several means of measuring energy concentrations. The value of the agriculture and forestry products can be determined by the heat of the combustion method. In the case of carbohydrates and other organic compounds, caloric energy determines their eligibility for conversion to or use as fuels. These useful measures of energy concentration are based upon the energy contained within the individual component of the products.

Hence, any of these measures of energy concentration of agricultural products can be useful for carrying out energy analyses of agricultural production systems by comparing the energy concentration of the output product with that of the production system or input energy. On the contrary, for the organic produce, e.g., plant and animal fibers, flowers, and other ornamental horticultural products, few agricultural products are used as feedstock in industrial processes, and certain other agricultural products such as tobacco and drugs, although they contain energy, energy concentrations do not determine their usefulness.

5.2 Source of the Energy in Agricultural Produce

The energy packed in agricultural produce is derived from electromagnetic radiation in the visible spectrum of sunlight. Then, this radiation energy is converted through photosynthesis to chemical energy of constituent compounds within plant tissues of the agricultural products, e.g., carbohydrates, proteins, and fats in plant produce.

5.3 Energy Input–Output Status of Conservation Agriculture-Based Farms in Comparison with Conventional Farms

It has been found from study that rice-based cropping systems consume more energy than maize-based systems depending on management practices. The greater amount of energy utilization occurs under CA-based systems in comparison with the conventional tillage-based management cropping systems. In rice-based cropping systems, input energy and energy intensiveness seem to increase by 229% and 275% respectively in conservation agriculture-based management systems, if compared with the conventional tillage-based systems, when the system does not integrate legumes. However, the net energy and energy use efficiency under CA-based management are 30% are 66% respectively, in the conventional tillage-based rice–wheat system when the system does not integrate legumes (Jat et al., 2020).

6 Energy in the Transportation of Agricultural Machinery

Energy is indispensable for farm-level transportation and for the sustenance of the food chain. Energy is also needed for the transfer of farm inputs to the farm from their points of origin, for movement of laborers to and on the farm, and for taking farm produce from the farm to the market. Additionally, farm managers have to transport, and consumers have to travel, to the market, to purchase food and other farm products.

In the case of industrialized agriculture, sometimes there is commodity- and geography-based agricultural production, where farmers are dispersed and distanced from their markets, leading to further agricultural transportation. However, modern and industrialized agriculture involves nonrenewable energy-based transportation, specifically liquid fossil fuels. Thor and Kirkendall (1982) studied energy conservation regarding transportation in industrialized agriculture. Anderson et al. (1979) provided a glossary related to agricultural transportation and energy conservation literature. Although conventional cultivation systems also need energy for transportation, they depend, at least in some part, on renewable energy sources in the form of feed for draft animals and food for humans. Here, also, the total transportation of agricultural materials is considerable (Table 3).

7 Social Dimension of Energy Management

To understand the role of energy in farming, more and more studies are required from different corners (Connor, 1977). However, much work has been carried out in piecemeal fashion to analyze energy use by the farm sector during the past decades (Lockeretz, 1977); very few focused on the social dimensions of energy use (Koppel & Schlegel, 1981).

The energy management in agriculture has many social consequences. This affects society as a whole; affects farm operators and their families; affects farm workers. The maximum impact on society comes not directly from the use of energy on agricultural farms but indirectly from the specific use toward which that energy is directed, e.g., the energy consumed in irrigation leads to depletion of groundwater resources. Similarly, the energy used for agro-chemical inputs may pollute both

Table 3 Energy requirements for trucks (Fluck & Shaw, 1976)

Item	kJ per t km	Percent total
Fuel	1227	76
Taxes and licenses	120	7
Depreciation	100	6
Tires and tubes	50	3
Repairs and services	60	4
Insurance and safety	30	2
Other	40	2
Total	1627	100

surface and sub-surface waters. Both of them have serious consequences for society, but they have only a minor direct relationship to energy use per capita. However, attention must be given to the aftermath of energy use in agriculture on the farms and on the activities of farm personnel.

7.1 Social Entropy and Thermodynamics

The social entropy theory illuminates the fundamental problems of societal analysis with a no equilibrium approach, a new frame of reference built upon contemporary macro logical principles, including general systems theory and information theory.

In sociological thermodynamics, social entropy is a manifestation of entropy, defined as the amount of energy unavailable for doing work in a given process, in a given social system, distinguished by modes of negative behavior, especially alienation, anomie, and deviance, that function to have a disordering effect on a given social structure or order. This anomalous behavior is seen as withholdings or cross uses of the deviant manifestation of the human energies that normally go into support or fulfilment of the norms, roles, and statuses that make up a social order. The maximum of the energy consumed by social organization is generally the spirit to maintain its structure, counteracting social entropy through legal institutions, and education where the normative consequences of 'anomie' is the maximum state of social entropy (Acharya et al., 2019).

7.2 Energy and the Social Structure of Farming

The social structure of agriculture can be characterized in many different ways. A few of the most common ways involve the categorization of farms by the form of organization under which the farm is being operated, which type of commodities are produced on the farm, the size of the farm, and the inter-sector relationship.

7.2.1 Form of Organization

Two forms of organization characterize the operation of most farms worldwide. The first is the family-labor farm. On these types of farms, entire or all of the labor input is supplied by members of the respective farm family. Land resources and capital equipment are owned by the family itself, or sometimes may be rented in. Farm decisions are made by the farm family, and the net farm income is used for the benefit of the whole family. This type of farm is most common in developing countries.

The second type of farm is the corporate farm, which is seen mostly in developed countries. On these farms, the family is not able to solely supply the required farm labor; hence, outside laborers are hired to continue the farm operations. Changes in the pattern of energy usage in agriculture affect these two types of farms differently. The substitution of energy sources for human labor can be taken as a response to labor supply problems (Perelman, 1975). During periods of non-activity on the farm, there is basically no fuel consumption for the tractors or harvesters.

The use of a tractor, labor time savings, and optimizing the number of laborers can be understood as the attempts by farm operators in both forms of organizations to utilize the available resources most efficiently. However, the rationale behind the mechanization and the impacts on labor are different (Berardi, 1981). For a family-labor-intensive farm, mechanization denotes the most effective use of family resources to produce family benefits, and it also increases family income. For the corporate farm, mechanization would eliminate some part of the wage labor actually hired by the unit. In the latter situation, a tractor can replace worker benefits; however, in the former, the tractor costs a livelihood.

Hence, in the early years, the introduction of mechanical energy benefitted family farms (Friedmann, 1978); eventually, mechanization also led to differentiation between the family farms and corporate farms (Buttel, 1981). Additionally, the adoption of technologies using biochemical energy enabled family-labor-based farms to increase the intensity of production; in the case of corporate farms, labor requirements decreased to increase profits. Thus, high-energy intensive farms started to associate with external capital control (Buttel et al., 1980).

7.2.2 Energy and Commodity Groups

The second dimension of the structure of agriculture depends on the commodities produced by the farm. Most of the farms produce more than one commodity for sale; however, they are increasingly going to concentrate on a single crop or agricultural enterprise. If one studies the differences in farm energy usage, it can be found that a good portion of total farm expenditure goes on energy products such as electricity, petroleum, natural gas, and other types of fuels. Besides, the input index ratio of cash grain farms indicates them to be more energy-intensive (Macheski, 1986).

7.2.3 Energy and Size of the Farm

The third dimension of the social structure of agriculture is the size of the farm. One of the most frequent questions related to farm size is whether small farms are more or less energy-intensive than larger farms. Hence, if small farms are less energy intensive (Buttel, 1978), and if the government has a policy in favor of energy conservation, then the government must also have a policy in favor of small farms. However, Gilles (1980) stated that the relationship between the size of the farm and energy intensity is largely because of the use of irrigation, whereas Larson and Buttel (1980) reported that the relationship is not affected by aridity and hence the need for irrigation is highly solicited.

7.2.4 Energy and Inter-Sector Relationships

The last and final dimension of the social structure of agriculture is the relationships between farmers and other related agricultural business. The adoption of mechanical energy-based technologies means that farmers will not produce the "fuel" for their farm power. The adoption of bio-chemical energy technologies creates the meaning that farmers are less interested in producing fertilizers from their livestock and work-stock, i.e., out-of-the-farm inputs. Farmers now tend to purchase fuel and fertilizer from petrochemical companies. Thus, in this process of inter-woven market inter-relations within farm production, both the source and the composition of farm inputs have undergone a dramatic transformation. The cost of these production inputs and the kind of inputs available are affected by the present market structure, e.g., in a market with limited competition, the cost of farm input products rises, or the oligopolistic conditions affect the availability of the product mix (Martinson & Campbell, 1980).

Hence, on the occasion of adopting external input, after considering both of the above facets, it can be easily found that they limit the scope of decisions a farmer makes in the area of production inputs. Under this condition, farmers will not find self-esteem within their occupation or the situation to realize self-actualization. Instead, farmers must feel alienated from their occupation that was the source of their strong sense of identity (Blauner, 1964).

8 Farm Level Energy Metabolism in the Conservation Agriculture System: A Case Study from West Bengal, India

The success of CA is dependent on the enhancement of soil foundation and water use efficiency combined with some other on-farm factors such as labor efficiency and environmental sustainability (Binns, 2017), adopting less soil disturbance through no or reduced tillage, permanent soil cover, and crop rotations. These three principles combine to make the farm energy efficient as well. Although a good number of farmers are becoming aware and developing a perception of CA, and are willing to mitigate the effects of climate change, they hardly have a perception of energy. It is true that farmers have been made sufficiently input literate over the years, but they remain unaware about the energy imbalances prevailing in the agro-ecosystem. They do not always apply fertilizers, herbicides, insecticides in a calibrated manner; flood irrigation is still in practice. However, the mind-set for leaving tillage operations is said to be a pre-requisite before adopting CA and zero tillage. Changes are required in tillage practices, weed control mechanisms, in the date of sowing, crop residue management, crop rotations and diversifications, harvesting, and many other aspects of the production system (Wall, 2007). McRoberts and Rickards (2010) found that community perceptions are at the center of the adoption of conservation agriculture technologies. Thus, in the New Alluvial zone of West Bengal, a perception study has been carried out, taking some factors operating in farmers' fields into account, viz. the age of the farmer, formal education, farm size, cropping intensity, number of fragments, irrigated area, ground water depletion, weight of residue, etc. A total of 65 farm households were selected from the 13 villages (i.e., five households from each village) for personal interviews using a questionnaire. Participants were practicing farmers, who unknowingly, partially or fully adopted CA technologies.

8.1 Variables Studied

8.1.1 Independent Variables

Age of the farmer (×1), family size (×2), formal education (×3), functional education (×4), farm size (×5), cropping intensity (×6), numbers of fragments (×7), total holding (×8), irrigated area (×9), annual income (×10), access to information (×11), number of ploughings (×12), perception on soil erosion (×13), perception on ground water depletion (×14), perception on bio-diversity erosion (×15), perception on agricultural pollution (×16), weight of rice residue (×17), cost of fuel consumption (×18), amount of nitrogen fertilizer applied (×19), amount of phosphorus fertilizer applied (×20), amount of potassium fertilizer applied (×21), total number of laborers engaged (×22).

8.1.2 Dependent Variables

Energy perception (y) of the farmers.

8.2 Statistical Analysis

Statistical Packages for Social Sciences (SPSS) software was used for analysis of the data. Descriptive statistics was employed to summarize the data. Then, stepwise regression was used to identify determining factors of the farmers' perception regarding energy conservation and management on their CA farms.

8.3 Results

Based on the statistical analysis performed as mentioned earlier, relationships amongst the respondents in terms of responses toward the main influencing traits, which are of utmost importance, have been depicted here in the descriptions of results compiled as follows (Fig. 1):

In this study on the energy perception of CA farmers, results derived from the analysis of data collected using an interview schedule have been put under step-down regression analysis, which has revealed some interesting results for discussion.

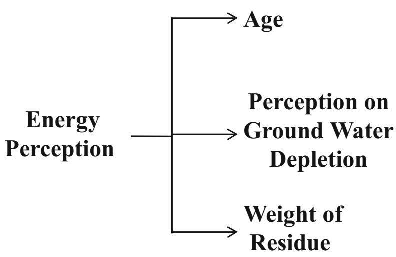

Fig. 1 Stepwise regression among ten independent variables (x_s) versus energy perception (y)

Taking energy perception (y) as a dependent variable, three parameters viz. age ($\times 1$), perception on ground water depletion ($\times 14$) and weight of rice residue ($\times 17$) have been taken as predictor variables to have influenced energy perception (y) the most, which is evident from the regression coefficient value from the model.

Farmers' age is a good predictor of their energy perception, as experience can make a person knowledgeable enough to understand the sustainability of their farm. Apart from this, if a farmer is aware of ground water depletion, then he/she will go for micro irrigation, viz. drip, sprinkler, etc., instead of flood irrigation. Crop residue also helps to maintain soil health by protecting it from the impacts of rain or wind, or mechanical erosion, adds organic nutrients, and maintains soil microbiological activity making the agro-ecosystem energy efficient as a whole.

9 Energy Action Plan and Policy

The energy action plan (EAP) is the outline used by governments and authorities to manage their current energy consumption and to frame policies. There are four key points for an effective energy management policy viz. technical ability, monitoring system, strategy plan, and top management support. Any effective energy management program should have enough support from its higher authority. Besides, the energy efficiency must have equal priority to raw materials, manpower, production, and marketing in any system. There must be a sound plan, a sustainable strategy, an efficient monitoring system, and the technical stability for evaluating and implementing energy conservation and management practices.

9.1 Energy Management System

A perfect energy management system is a pre-requisite for figuring out and executing energy conservation choices, to maintain the flow and for regular and effective monitoring and improvements.

9.1.1 Appointment of an Energy Manager

The duties of an energy manager are to set the location-specific plans and programs, to monitor and evaluate the progress of energy conservation activity, and to promote the energy efficiency program. The energy manager need not always be a technical expert in the energy conservation process; he or she just has to be knowledgeable enough to understand energy efficiency to achieve its goals both environmentally and financially. Energy managers (here, farmers) only have understand how to choose energy-efficient crops and management practices. In the case of agricultural farms, farmers have to be appointed or self-appointed as the farm managers of their own farms.

9.1.2 Formation of an Energy Team

Development of a team for energy conservation and management will make the management more compact for better use of energy on the particular farm. An energy team will have the responsibility for computing and monitoring on-farm energy performance, and providing feedback to top management and other shareholders. The energy team members must come from each and every operational unit that has an influence on energy use, such as farm laborers, engineering personnel, operations and maintenance section, infrastructure management, purchasing, environmental health and safety segments, input suppliers, and many more.

9.1.3 Establishment of Energy Policy

An energy policy is to be established to form the basis of the energy management team, to set the energy conservation goals and location-specific targets in the operations considering the values of energy management. It should offer a strong foundation for efficient and effective energy management implementation at the farm. It legalizes the support of top management for the shareholders and the community. An official energy policy must be (i) a clear statement considering energy conservation and environmental protection, and (ii) valid documentation to guide the perception and practice of energy management and conservation consistently (Kumar et al., 2020).

9.2 National Action Plan on Climate Change: Missions Including Energy Efficiency

India's National Action Plan on Climate Change (NAPCC) comprises a range of measures, which are as follows (Pandve, 2009):

- *National Solar Mission*: the action plan is aimed at promoting the development and use of solar energy for power generation and other uses, with the objective of making it an alternative to fossil-based energy. It also embraces the establishment of a solar research center, greater international collaboration on technology development, facilitating domestic manufacturing.
- *National Mission for Enhanced Energy Efficiency*: the NAPCC intends to mandate a decrease in specific energy consumption in large energy-consuming sectors, trade energy-saving certificates, public–private partnerships to cut down energy consumption through energy management and conservation programs on the demand side, e.g., in municipalities, buildings, and agricultural sectors, and providing energy incentives, including reduced taxes on energy-efficient appliances.
- *National Mission on Sustainable Habitat*: this action plan also has the aim of promoting energy efficiency as a core component of urban planning, greater enforcing of automotive fuel economy standards, and encouraging the purchase of efficient vehicles and giving incentives for the use of public transportation. It also emphasizes waste management and recycling.

- *National Water Mission*: the NAPCC sets a goal for a 20% improvement in water use efficiency by adopting pricing and other measures that will deal with water scarcity caused by climate change.
- *National Mission for Sustaining the Himalayan Ecosystem*: this mission has the goal of combating melting of the Himalayan glaciers and protecting Himalayan biodiversity.
- *Green India Mission*: afforestation of 6 million hectares of degraded forest lands to expand the forest area from 23% to 33% of India's territory.
- *National Mission for Sustainable Agriculture*: this mission also embraces climate adaptation in the agriculture sector through the introduction of climate-resilient crops, expanding weather insurance, natural resource conservation, and sustaining agricultural practices.
- *National Mission on Strategic Knowledge for Climate Change*: to get a better understanding of climate change impacts, and to make a plan with the help of the Climate Science Research Fund, climate modeling, and greater international collaboration.

The NAPCC also describes some other ongoing initiatives (Pandve, 2009):

- *Power generation*: retirement of inefficient coal-fired power plants and providing support to the research and development of an integrated gasification combined cycle and supercritical technologies.
- *Renewable energy*: setting the central and state electricity regulatory commissions under the Electricity Act 2003 and the National Tariff Policy 2006.
- *Energy efficiency*: undertaking energy audits for large energy-consuming industries under the Energy Conservation Act 2001.

10 Conclusion

The significance of agriculture and energy lies in the inter-relationships between energy and other agricultural production inputs. In addition to direct farm usage of energy as fuels, however, fossil-fuel energy inputs to agricultural production systems can also be presented as indirect energy needs for land, labor, water, machinery, or knowledge. Throughout the present chapter, the significant role that energy inputs play in the enhancement of global agricultural productivity has been discussed. It was likely thought that the food security of the growing population could only be met by increasing the energy inputs into agricultural production systems. However, it is at present being claimed that increasing energy inputs into an agricultural production system do harm by lowering energy productivity, whereas the total production as well as the productivities of other inputs are simultaneously increased. Thus, the alternative to this conventional agricultural system must be found out. Apart from this, there are the quadruple challenges of eroding soil health, depleting groundwater, energy shortages, and decreasing farm profitability that threaten the sustainability of traditional tillage-based cereal production systems. Here, CA-based cereal (rice/maize/wheat) systems recorded greater net energy and were found to be energy intensive; similarly, this system enhances crop productivity, water productivity, and profitability while saving irrigation water. However, the majority of studies delineate the ecological study of energy in relation to agricultural systems; social dimensions are hardly discussed. In the present work, a case study on CA has been incorporated. Farmers' perception and on-farm practices related to energy management have also been elucidated. Hence, in this chapter, an overall view has been presented, from what energy is to how to improve energy productivity in world agriculture.

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Food Security and Carbon Footprint

Lessons from COVID-19 in the Indian Subcontinent

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Abstract

India is dealing with the most diverse, vast landholding where rural agriculture practice plays a key role to manage hunger, poverty, health, nutrition, and overall quality of life in a sustainable manner. Constraints, challenges, and regional inequality for food production, distribution, and nutrition program persist in different spatiotemporal frameworks here; their analyses under COVID-19 catastrophe may spot out the key determinants and linkages in solution finding, monitoring, and implementation for local conditions. Availability, access, and stability for complex food chains have been discussed where coexistences of economic breakdown, hidden hunger, inequality, and malnutrition are further threatening to aggravate rural distress, denials, and disease potential. This chapter intends to appraise multifaceted trends, consequences, and vulnerabilities in agri-food ecology, and requisite policy interventions and regional planning in pandemic response toward economic resilience and nationwide sustainable nutritional nourishment and food security have been suggested.

Keywords

Agriculture · COVID-19 · Food security · Pandemic · Climate change · Nutrition

1 Introduction

The United Nations Sustainable Development Goals (SDGs) launched in late 2015 are a compendium of 17 goals to upgrade the existence of human beings throughout the globe by 2030. The second goal, SDG 2, urges "to end hunger, achieve food security, improve nutrition and promote sustainable agriculture" (UN General Assembly, 2015). Current decades have experienced significant treads against hunger and malnutrition, although the challenges are stiffer ahead for 8.5 billion people estimated globally in 2030. India, the second-most populous country and fifth-largest economy by nominal GDP (2019) in the world, faced a remarkable incremental change in the last 50 years from 108.4 million tonnes of food-grain production in 1970–1971 to 284.8 million tonnes in 2017–2018 (GoI, 2018). Despite changing climate, finite natural resources, lack of farm mechanization and marketing infrastructure, etc., 44.2% workforce in the country depends on agriculture for their livelihood (National Statistical Office, 2019), and it still sustains almost 60% of the population.

India's achievement in self-sufficiency for staple grains often overlooks the sluggish growth rate and lower farm productivity leading to reduced farm profitability. It gradually shifts toward intensified, input-oriented extensive agricultural production, which negatively impacts soil fertility, lowers groundwater table, and accelerates agricultural pollution. Meanwhile, the complex, diverse socioeconomic issues, demographic, climatic, ecological, and landholding variations on a sub-national scale, are also the basis for widespread regional inequality from production and distribution to the consumer's end. This substantial spatial and temporal variability and fluctuating trends of potential productivity are more relevant for determining direct physical and economic access to food. Also, it reveals other qualitative social indexes, e.g., rural poverty, employment, and undernutrition.

COVID-19, caused by a novel coronavirus (SARS-CoV-2), is a rapidly transmissible disease identified in December 2019 and declared a pandemic by WHO. Food and nutritional security have marked serious concerns worldwide due to threatening health crises from this pandemic and history's biggest post-lockdown phase. The pandemic may also seriously impact labor-intensive crop production and processing due to labor shortages (ILO Monitor, 2020). Farmers with perishable commodities have faced severe adversities due to disrupting the supply chain and cold storage facilities. The worker's migration from different states to their native homes has also triggered inconvenience in the processes of harvesting onward.

The agri-food sector is the most vulnerable part of society, usually affected by broad natural external factors, and this type of recent incidence exaggerates the situation. It is crucial to reassess the ongoing and possible impact of pandemonium with its consequences on food systems on a regional scale to implement suggestive mitigation measures.

Here we analyze availability, access, and stability, three backbones for food security in the spatiotemporal context under the COVID-19 pandemic situation, for regional planning and policy innovations in the postcrisis period.

2 Food Security Issues in COVID-19

Food security is the critical component of the United Nations 2030 Agenda to achieve Sustainable Development Goals (SDG) (UN, 2019). Food security links with a nation's socioeconomic and environmental dimension, which is often underestimated by biological context. Theoretically, Food and Agricultural Organization (FAO) defines this term as "exists when all people at all times have physical and economic access to sufficient, safe, and nutritious food that meets their dietary and food preferences for an active life" (FAO, 2018).

Ensuring a robust food security system is very challenging but imperative in times of pandemic crisis. The far-reaching ramifications of this pandemic will resonate with all the dimensions of food security – availability (whether or not the supply of food is adequate), access (acquiring food at need), utilization (intake of enough nutrients), and stability (accessing food at all times), but in the short term, its most intense effect will be on food availability and access (Adhikari et al., 2021). The number of people facing acute food insecurity skyrocketed in 2019–2021. Persons who already are or are at risk of becoming acutely food insecure are globally 272 million (WFP 2021). A study in an informal settlement in Kenya reported 88% of the households to be food insecure between December 2019 and April 2020 (Shupler et al., 2021). Food security remains highly demanding in developing countries like India, where three out of four poor people are from rural regions and predominantly rely on agri-livelihoods.

After the Green Revolution, there was rapid growth in production to be habitually self- sufficient despite India's steady population growth rate (Gadgil et al., 1999). By introducing a national agriculture development program (NADP) with high-yielding varieties (HYV), fertilizer technology, and modern irrigation infrastructure, accelerating supplies and access rates of staple grains have been marked gradually as major policy concerns. Thereof, intensive cereal production over the past 50 years has tripled, with rice and wheat contributing 44% and 30% of total cereal production in India, respectively (ICRISAT, 2015). In the last 20 years, the country's total food and grain production steadily proliferated from 198 to 284.8 million tonnes (MT) (GoI, 2018). Consequently, the country has topped to be the highest producer of jute, tea spices, milk, cashew, and pulses and has achieved the second highest position of global vegetables, oilseeds, and fruits production. Agricultural goods account for the country's 10% of exports, the fourth largest principal commodity (APEDA, 2016).

Nutrition can be linked with agriculture with either generic or specific effects (Gillespie & Haddad, 2001). Generic effect emphasizes income, employment generation, and "women's role" by categorizing their social status and decision-making power in agri-sector and rural households (Bhavani & Rampal, 2018). Whereas specific effect relies on food access and availability, consumption, and allocation behavior (Gulati et al., 2012). Overall, comprehensive food policy should focus on diet diversity with minerals, micronutrients, and vitamin-rich diets, which ultimately positively impact national nutritional status (Bhavani & Rampal, 2018).

Although, with the squeezing of available resources and extreme weather event scenarios, a large section of agrarian communities across the country today is in a position of disaster, the rest of the population is still making a profit from it (Narayanan, 2015). In the face of increasingly scarce fertile land and water resources, India's cereal productivity is far below the national target of 5018 kg. ha^{-1} by 2030 with the current 2509 kg.ha^{-1} (GoI, 2019). Production of maize which dominates the Indian coarse cereal scenario has improved in the last decade. However, only 9% of it is used as food, leaving major parts as poultry feed and for the brewery industry. Estimated pulse demand accounts for 29–30 MT, where production attained 23 MT in 2016–2017, out of which only 8–10 MT of pulses are consumed directly as a food item (Dal) (GoI, 2017a). The remaining pulse food is imported due to lower productivity and cultivable area. Laterally, distribution and outreach are the ruling problem sustained in the nation's food system. With India's population continuing to expand, the persistent issue of food losses and wastage, coupled with substantial food exports, severely restricts the achievement of optimal per capita net food availability (GoI, 2019). These trends ultimately emulate pressure on the demand side for feeding overpopulating nations.

For the last few decades, per capita, food grains production has been impeded from 186.2 kg/year in 1991–1992 to 180.3 kg/year in 2018–2019. This declined cereal production in India has raised a fair chance of other options like dairy, eggs, pulses, edible oil, and sugar, which skewed scenarios toward high-value horticultural and animal products (Kumar et al., 2007). Now noncereal items share significant contributions for proteins and calories in rural and urban areas. The household expenditure on cereals was reduced from 18 and 10.1% in 2004–2005 to 10.7 and

6.6% in 2011–2012 for rural and urban India, respectively (NSSO, 2004–2005 and 2011–2012).

2.1 Hampered Food Production Systems

In developed countries, agricultural production systems of staple crops are being mechanized, and workers needed for operations are less, inherently following social distancing. These farms are somewhat resilient to disruptions emanating from strict COVID protocol. Complete farm mechanization is tougher in vegetable or fruit production systems wherein weeding and other intercultural operations, as well as manual harvesting, are heavily damaged even in developed countries. Travel bans and inter-country border closure have created an acute shortage of the labor force available for harvesting, which has heavily affected globalized food systems (Petetin, 2020). In countries like India (Rabi harvesting), where the lockdown has coincided with harvesting time staple crops, vegetables, and fruits, the non-availability of the migratory labor force has resulted in colossal food loss and economic loss of the farmers (FAO, 2020a, b, c; Ceballos et al., 2020). In India, vegetable harvesting is the hardest hit crop by COVID-19 and it is the most wasted crop due to a lack of harvest and marketing (Jaacks et al., 2021; Harris et al., 2020). Higher labor and machinery costs have made the labor and harvesting costs go higher in India (Jaacks et al., 2021; Ceballos et al., 2020). Lack of migratory labors, if it happens in the long run, in the twin Indian breadbasket states of Punjab and Haryana may delay rice transplanting, which will also defer subsequent wheat seeding (turnaround time between rice harvest and following wheat planting is typically only 2–3 weeks) exacerbating national food insecurity issues through attenuating yields of two major staple crops (Singh et al., 2020).

Seasonal labors in France, Germany, the United States, Canada, Australia, and Italy either faced a travel ban due to visa restrictions or border closure, creating labor shortages (ILO, 2020; Torero, 2020). In parts of Europe, restrictions imposed on the mobility of seasonal farmworkers have unfortunately left agricultural produce not harvested and rotting in the field (Torero, 2020; Laborde et al., 2020). These restrictions on farm labors can exacerbate food insecurity and may threaten their lives (IOM, 2020). Besides, the travel ban had heavy reverberations on procuring agricultural inputs like pesticides, fertilizers, and seeds for producers and increasing their costs (Rivera-Ferre et al., 2021). The massive lockdowns have exacerbated the peril of rural farmers even more. A survey conducted by Ceballos et al., 2020, reported that 74% of pulse farmers in the Indian state of Odisha, where subsistence farming is widespread and agricultural operations are poorly mechanized, suffered income loss due to delays in the purchase of products by the traders until travel restrictions were eased. Farmers could not place their produce in urban markets, schools, leisure establishments, sweet shops, hotels, and restaurant chains that are closed following safety protocol and the closure of public transport systems. The closure of mandis or licensed marketplaces (the bulk of the agricultural products are sold here) in India created a massive surplus of marketable commodities.

There are also reports of the culling of animals due to a fall in demand in hotels and restaurants (Barling, 2020). Fishery production systems are also hit at large due to reduced demands (Rivera-Ferre et al., 2021). Farmers' dependence on other players in food production and delivery systems has made them vulnerable to damage. A study in 200 Indian districts by Jaacks et al., 2021, reported that landless farmers are ten times and small or marginal farmers three times more likely to miss out on meals or starve the entire day – the nadir of food insecurity. Many rural farmers in India fed strawberries to cows because they could not mobilize the produce to urban marketplaces (Torero, 2020). In Peru, the United States, and Canada, farmers had to throw away their cocoa to landfills and milk inroads either due to a lack of transport or the closure of business operators who would buy the produce regularly (Torero, 2020). East African high-value flower export systems were suspended due to the closure of international passenger aviation systems compelling farmers from Ethiopia and Kenya to dump tonnes of high-quality flowers (Bhalla & Wuilbercq, 2020).

2.2 Consequences for Food Supply Chain

Guaranteed supply of raw materials from suppliers and smooth flow of food products from manufacturers to consumers are two critical components of the food supply chain (Alonso et al., 2007) which is mainly offtrack during the pandemic. Most farm production activities and food supply are intricately connected; even a small delay can significantly create a butterfly effect, ultimately declining yield (FAO, 2020b) and affecting food availability. Food delivery chains in high-income countries are more resilient because they are knowledge and capital-dependent. In contrast, small and informal food sector operations in poor and developing countries are highly manual labor oriented and severely wrecked due to social distancing guidelines (Swinnen & Vos, 2021). In parts or whole of Australia, Madagascar, Colombia, India, Kenya, and Ethiopia, high-value perishables, like milk, fruit, egg, tea, vegetable, and fish production, and the supply chain were hampered due to the unavailability of agricultural inputs like seeds and fertilizers, shoddy transport system, night curfew, or restricted market trade (ILO, 2020; FAO, 2020a). Compared to high-value produces, staple food items require less labor but are more capital and knowledge-intensive. In the staple food product supply chains, travel restrictions and social distancing guidelines also created a negative impact (FAO, 2020c). Almost every stage of the food supply chain of China was either dismantled or severely affected (Kim et al., 2020). An estimate by Laborde and coworkers, 2020, estimated as high as 5% postharvest produce loss in agricultural production.

The bounty of COVID-19 is heavy on the Indian food supply chain putting food security in danger. Colossal production of export-quality Darjeeling tea in India had gone wasted in the first lockdown, and there are fears for the second (BBC, 2020). Total 92% of food consumption in India is purchased, a majority from by private sector (Reardon et al., 2020). Indian farmers faced the most difficulty in procuring seeds, fertilizers, and labor, as reported by Jaacks et al., 2021. These problems have created a significant impasse in supplying food to markets. Logistic hindrance has reduced the supply of high-value goods for their shorter shelf life (FAO, 2020b). Grape and onion in Maharashtra (the largest onion trade market in Asia) and biscuits, noodles, and other snack production in India were wrecked (Kim et al., 2020). The impasse in logistics has forced the farmers to sell their produce at a much lower price.

Not only poor or developing countries, but the food supply of the rich ones, who have highly developed and modern systems, are also hit. More than 30,000 workers in meat processing plants in the entire USA and Europe have been affected by the disease, resulting in closure or reduced production (Laborde et al., 2020). In the USA, there are reports of nearly 75,000 unhatched eggs per week and onions rotting due to disruptions in the supply chain (BBC, 2020). Nearly 5 million liters of milk per week are threatened by wastage in England (Aday & Aday, 2020). These accounts suggest the importance of smooth logistic systems to cope with global pandemic events.

Public food distribution is also affected, which further adds to the number of food- insecure people. More than 160 countries have enacted school shutdowns covering 87% of the world's student mass, which have often dented the only source of food and nutrition in many families (FAO, 2020c). The nationwide shutdown of schools in India had impacted millions of children due to the suspension of the midday meal program, which caters to nearly 110 million children nationally at school, and about 100 million pregnant and lactating mothers, as well as children below the age of 6 depending on Anganwadi centers (village child care centers) under the aegis of Integrated Child Development Services Scheme, are affected (Alvi & Gupta, 2020). School closure has also affected poor children in the USA who rely on meals provided thereat (Laborde et al., 2020). The suspension of school feeding programs has cut the jobs of meal suppliers and caterers (FAO, 2020c). Restrictions in movement and quarantine protocols cause vessels to remain on shores for an extended period causing owners and workers to incur substantial losses and delays in the supply of raw materials (Havice et al., 2020).

2.3 Fallouts in Food Access

COVID-19 has hampered access to food and increased food insecurity through reduced household income and assets and the imposition of physical constraints like reduction or closure in mass transportation facilities. Lack of income for covering fuel charges of personal vehicles culminated in a significant barrier to food access.

Many poor households had to travel long distances or to several food stores to find affordable food items in the USA (Kinsey et al., 2020). Households already suffering from food insecurity are more vulnerable to limited food access (Niles et al., 2020). Access to food is also hampered due to food market closure. In some areas of Nepal, people could not procure food because shops were closed (Shahi & Gautam, 2020). Shop closure also affected people who solely rely on supermarkets for food. Food prices in New Zealand skyrocketed due to their only being available in supermarkets in crisis times (New Zealand Herald, 2020). In many cases, food retailers where they are the only food source during the pandemic looted customers or suppliers by increasing prices or reducing the cost of raw materials.

Worldwide, 1.5 billion people already cannot access healthy diets based on diverse plant- based foods (Hirvonen et al., 2020). At the time of writing this report, there are mounting apprehensions of a third wave (could be several waiting!) to hit India and other countries; It is foreseeable that the magnitude of the impact will remain substantial even after this crisis subsides. The downscaling of income arose due to a reduction in agriculture and nonagriculture income. As high as 70% of the income in poor households is spent on buying food compared to 15% in affluent families (Laborde et al., 2020). It is not wondrous that the poor and downtrodden people will be badly hit by the price rise of foods as they do not have savings or food reserves. A very recent forecast for average household income decline predicts a 9.3% fall in European Union countries due to the crisis (Almeida et al., 2021). India suffered a significant per capita income drop (Deaton, 2021). There are forecasts that the number of poor people in South Asia will increase by 15% or 42 million people (Laborde et al., 2020). Although governments in almost every country substantially provided relief measures, there are concerns about food access arising from those. Lack of communication with many vulnerable populations has deprived them of free-of-cost food (Adhikari et al., 2021). In developing countries like India, Indonesia, Ethiopia, Kenya, Mozambique, Rwanda, and Tanzania, food price increments were 3.8, 2.5, 3.4, 4.2, 10.5, 19.5, and 12.3%, respectively (Global Alliance for Improved Nutrition, 2020). Prices of meats, fruits, and vegetables in Algeria, fruits and vegetables in Tunisia, rice and pasta in Egypt, and milk in Albania increased, as reported by CIHEAM (2020), rendering those unaffordable for the weaker sections of the society.

Food prices in Southeast Asia spiked during the pandemic (Kim et al., 2020). Apart from food scarcity at the national level, food access issues are at the household level. Nearly 380 million Indians are employed in informal sectors, unprotected by labor laws, and lack secure job contracts (Summerton, 2020). The prolonged lockdown measures have downscaled casual labor employment due to the halt of business and farm activities. For many labors, lockdown is “an order to starve” (Abi-Habib & Yasir, 2020). Lack of savings and a poor social security net of the labor depended on households taking fewer, lesser, and cheaper meals. Even in the prosperous economies, people’s dependence on food relief spiraled, which is evident from budget allocations of the countries like the USA ($25 billion in food assistance), Catalan countries (4 million € to buy fresh food from marginal farmers), and UK (Rivera-Ferre et al., 2021).

There will be far-reaching reverberations, especially for young children, due to malnutrition arising out of the inaccessibility of food for their cognitive development, and delayed educational attainment might be hampered, notwithstanding the recession is short- lived.

3 Spatial and Temporal Food Security: Explaining Scale-Dependent Diversity

Regional divergence and inequality are two inherent parallel stories of Indian food policy. So far, food security is highly concerned with the synergism of policies on various scales that may be temporal and spatial for the underprivileged, which is an utmost need for adequate consideration and planning. The normative concerns include agricultural sustainability's economic, social, and environmental impacts. Historical growth series indicate that superior technology and institutional reforms moved a step forward, with the growth rates ranging from 2.2 to 2.7%, higher during 1988–1996 and highest during 2004–2014, 3.72%. This may be due to more public and private investment and a trade boost which declined to 2.55% during 2014–2017. The area dedicated to fruits and vegetables has witnessed a significant twofold increase, expanding from 3.0% during 1975–1989 to 6.5%. Meanwhile, the allocation for pulses and cereal crops such as rice and wheat has experienced a relatively stable distribution, with pulses accounting for 13.3% to 12.2%, while cereals' share has remained largely unchanged, comprising 36.0% initially to 37.3%.

It occurred due to much acceleration in yield compared to the growth area. In parallel, prices determine the prime role in raising farmers' incomes. Shares of all cereals and pulses declined while fruits and vegetables, condiments and spices, livestock, and fisheries increased in total price over periods (GoI, 2017b). Surprisingly, the surging of consumer food prices did not correlate strongly with the rising agricultural growth (Mahendra Dev, 2018). The reason may be that price control plays a significant role in rising output growth with a strong association wherever output growth fails to control the price, which is the primary cause of agrarian misery. India has various seasons throughout the year, influencing the agriculture output; therefore, it is necessary to analyze data on various timescales.

India's total or agricultural growth rate becomes futile except due to consideration of inter-state variance and their spatial scale assessment. The country has 20 agro-ecological zones, with 46 out of 60 soil types in the world. Different states' primary investments in food production and parallel goal toward nonagricultural sectors, along with resource availability, influence production growth rate. Few states experience less economic growth due to low crop yield or cereal-focused strategy compared to others where higher productivity benefits from technology or infrastructure buildup (Pingali et al., 2019).

The impact of regional diversity is accelerated due to extreme weather events frequently. Northwest states like Punjab and Uttar Pradesh lead in wheat, whereas West Bengal is the "rice bowl" of the country. Pulse has markedly switched into central and southern from the north, which accounts for >90% of total production (GoI, 2017a).

Production environment and food choice play a pivotal role in determining demand and price extensively with regions, household patterns, and income levels. Inequalities of reasonable prices of produce are very often spatial, increasing class conflicts. Lower access to institutional credit, investments, insurance, and poor technology dissemination in many states are the ground reality for regional growth differences and may be measured by other indicators such as poverty and malnutrition. Agricultural foods are primarily perishable, and the situation has become more threatening during the crisis of COVID-19. Huge income loss among the working poor adversely strikes food demand-price-supply channels. The situation will be more complex if the pandemic sustains.

4 Climate Change and Population Pressure on Nutrition: Agricultural Impacts and Adaptation

One of the largest concerns facing the globe today is climate change, which is defined as significant changes in the average values of meteorological components, such as precipitation and temperature, for which means have been estimated over a long period of time. The progress accomplished in the fight against hunger and malnutrition so far is in danger of being undone by climate change. Additionally, it could present health risks for people and have a considerable impact on price stability, food markets, and exchange flow. According to a recent assessment report from the Intergovernmental Panel on Climate Change (IPCC), food security concerns are growing and becoming more severe for the most vulnerable populations and countries. Out of the eight important risks brought on by climate change, the IPCC AR5 highlighted four that have immediate implications for food security:

- Rural livelihoods and income loss
- Marine, coastal ecosystems, and livelihoods loss
- Terrestrial, inland water ecosystems, and livelihoods loss
- Food systems breakdown and food insecurity

The effects of climate change on precipitation, runoff, snowmelt, hydrological systems, water quality, water temperature, and groundwater recharge will be felt. Increased water scarcity brought on by climate change will be a substantial obstacle for climatic adaptation in many parts of the world. Surface salinity and groundwater conditions in coastal locations will change as a result of rising sea levels. The frequency and severity of outrageous incidents will change as a result. According to a recent FAO analysis of 78 postdisaster needs assessments conducted in 48 developing countries between 2003 and 2013, the agriculture sectors in developing countries are responsible for 25% of all economic losses and damages brought on by medium- and large-scale climatic hazards like droughts, floods, and storms.

It indirectly has an impact on agricultural production systems. A change in physical characteristics, such as temperature and precipitation distribution, can have direct implications on certain agricultural production systems. Through changes in other species like pollinators, pests, disease vectors, and invasive species, indirect effects have an impact on productivity. Given the numerous interacting elements and relationships that need to be defined, these indirect effects can be quite important even though they are much harder to analyze and estimate.

Results from significant agrarian model inter-comparison projects show that, despite ongoing weaknesses in how models depict the portrayal of combined carbon dioxide fertilization, ozone stress, and high-temperature effects, there is agreement on the direction of yield changes in many major agricultural regions at both low and high latitudes, with clear adverse effects occurring most often at lower latitudes and higher levels of warming. The IPCC has expressed high confidence that crop output in low-latitude nations will be regularly and negatively impacted by climate change in the future. In northern latitudes, however, it can have either favorable or unfavorable effects.

In a recent multimodel study, the most extreme warming scenario used by the IPCC was found to have a mean global effect of minus 17% by 2050 on the yields of four crop categories (coarse grains, oil seeds, wheat, and rice, which account for around 70% of the world's harvested crop land). The most extreme radiative forcing scenario and the assumption of limited CO_2 fertilization impacts in 2050 were combined in the hypothesis for this multimodel evaluation, but the harmful effects of elevated ozone concentrations, biotic stresses from a variety of pests and diseases, and the likelihood of an increase in the frequency of outlandish events were excluded.

Climate change effects on farms and households could decrease income and stability by influencing production costs and productivity. Such changes may result in the sale of productive capital, such as cattle, which lowers the long-term potential for household productivity. Threat exposure reduces the incentives to invest in production systems, which frequently has negative effects on sustainability, returns, and long-term productivity. It has also been demonstrated that household ability and desire to spend on health and education are impacted by reductions and risks to agricultural revenue. The accessibility and stability of food supplies for the entire population can be affected by shocks to crop production and food availability, with risks of market disruptions, effects on supply and storage systems, and spikes in agricultural commodity prices. By deterring investments, climatic concerns might also impede agricultural development.

People whose livelihoods depend heavily on agriculture and natural resources are those most at risk from the effects of climate change. Droughts will notably affect poorer households and may affect women disproportionately due to their vulnerability and limited access to resources, according to recent trends in food insecurity and inequality. Indigenous peoples are particularly at risk in places like the Arctic, mountainous regions, Pacific islands, coastal areas, and other low-lying locations because they depend on the ecosystem and its biodiversity for food security and nourishment (FAO, 2015b).

5 Malnutrition Paradox: Reality Check Under Pandemonium

"Let food be thy medicine and medicine be thy food," a famous quote by Hippocrates, and what to eat and what not to is relevant during the recent COVID-19 scenario. COVID-19 is affecting the poor and the vulnerable heavily, which is a significant concern (Mardones et al., 2020). Headey and Ruel (2020) argued that the COVID-19 pandemic has all the makings of a perfect storm for global malnutrition.

Unhealthy diets and nutritional immunity are the main preconditions for a viral disease, e.g., COVID-19. Therefore, dietary assessment and nutritional strategies are the best way for precautions or treatments when any pharmaceutical approach is still unknown. The result from a review of previous clinical trials with nutrition- based interventions for viral diseases has positively correlated with vitamin-A, C, and D along with zinc, and selenium, which favors modulatory effects (Jayawardene et al., 2020), which is critical for India, where one in five persons suffers from non-communicable diseases (Hindu Business Line, 2018). Micronutrients, tea bioactive, garlic, fruits, vegetables, and various probiotics can also shield the elderly and new age population against any viral infection like COVID-19 (Rodriguez-Leyva & Pierce, 2021). Persons with obesity, malnutrition, high use of saturated fat in the diet, etc., are vulnerable to this pandemic (Rodriguez-Leyva & Pierce, 2021). Vitamin D deficiency and malnutrition are widespread in COVID-19-infected patients admitted to an intensive care unit (ICU) (Goncalves et al., 2020). Analysis of COVID-19 deaths among African Americans revealed that vitamin D deficiency adds to greater morbidity risk (Kohlmeier, 2020). A study by Allard and coworkers (2020) reported that 39% of COVID-19-infected patients had a malnutrition prevalence. A very close result found by another study was that 42% of infected patients and 67% of ICU patients of COVID-19 were suffering from malnutrition. As reported by Rodriguez-Leyva and coworkers in 2021, 24% and 18% of COVID-19-infected patients exhibited moderate and extreme malnutrition, respectively. The world is lagging in achieving its 2030 SDG targets of hunger and malnutrition, further exacerbated by the pandemic (FAO et al., 2020).

Disruptions in the rice-wheat production systems may trigger significant ramifications in Indian food and nutritional security because these two crops provide 60–70% calories and 50–55% protein intake in India (Singh et al., 2020). Perishable farm produces like vegetables and fruits are often the most nutritious (Beal et al., 2017). Therefore, a deadlock in transport facilities has hindered these crops' harvest and marketing, negatively hampering diet quality. A survey done by Harris et al. in 2020 in India reported pulse, dairy, and vegetable consumption sank in 20–30% of surveyed households, which may magnify malnutrition.

The healthy dietary concept is still a way for India, where the principal portion of the population struggles against poverty and hunger. In contrast with remarkable economic growth in recent years, India is encountering the so-called "triple burden of malnutrition" – the widespread coexistence of inadequate calorie intake, undernutrition, and excess dietary energy intake among most of the population (Narayanan, 2015). India ranked 102 out of 119 countries as per Global Hunger Index in 2019, mainly due to "hidden hunger." Nearly 50% of Indian children are malnourished, anemic, or starved, and roughly 10 lakh newborn die before 1 month of age (IFPRI 2016).

At the onset of the corona pandemic, followed by a massive lockdown, an additional 130 million people (with the previous 135 million) are estimated to be forced to the verge of starvation of which the majority is from India. The economic impact could potentially devastate even more than the virus itself (WFP 2020).

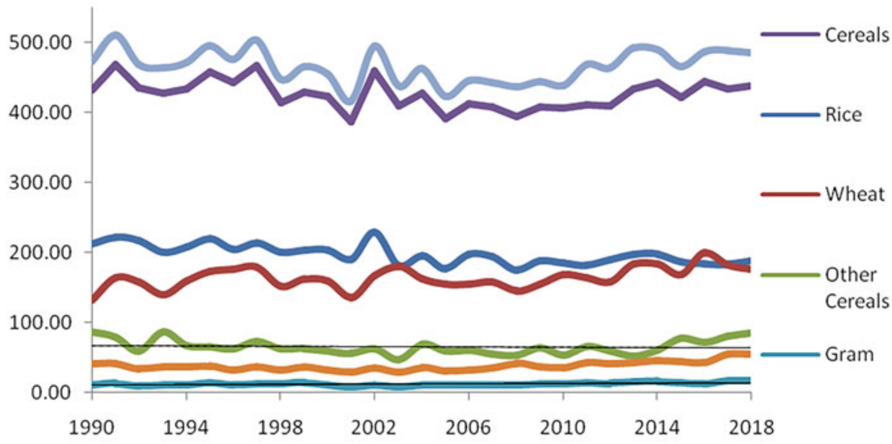

Fig. 1 Per capita net availability of food grains (g/day), India, 1996–2018

Current agricultural food production has prevented famine and starvation by supplying carbohydrates. Over the last 20 years, total per capita food-grain availability increased only from 475 to 484 g day^{-1} where pulse production is improved (by 66%) to 55 g/capita/day (GoI, 2019) (Fig. 1). Now is it adequate to tackle undernutrition and the rising incidence of community diseases like corona?

Staple-grain-focused policies restricted farmers from expanding their production toward high market-demanding nonstaple food, e.g., fruits, livestock, and vegetables. However, there is utmost demand for promotion from calorie sufficiency to diversified food system approaches. The current dietary average intake pattern is far below sufficiency. It is mainly for declining rice and wheat intake over a period, i.e., 204–186 and 176–174 g day^{-1}, respectively (GoI, 2019) (Fig. 1), and exiguous livestock and vegetable consumption which fail to fill the gap. Till now, about one-fifth population could not get dietary fruits or milk, while more than half of urban and rural people are devoid of animal proteins. Only a small section has access to balanced diets, leaving many Indian households only cereal dependent. Irrespective of poverty, the nation faces hidden hunger, poor immune function against any infection like COVID-19, and increased mortality risk. Different nutrients have been found deficient in both groups of people in separate patterns or intensities (Fig. 2) (Kumar et al., 2016).

6 Spatial Food Security and Sufficiency: Need of the Hour

The ongoing global health disaster from COVID-19 is impacting every societal aspect. It is a situation like "The most severe crisis since the Second World War." With severe public health hardship, employment losses are a global concern for approximately 2.7 billion workers, and food systems are under enormous distress

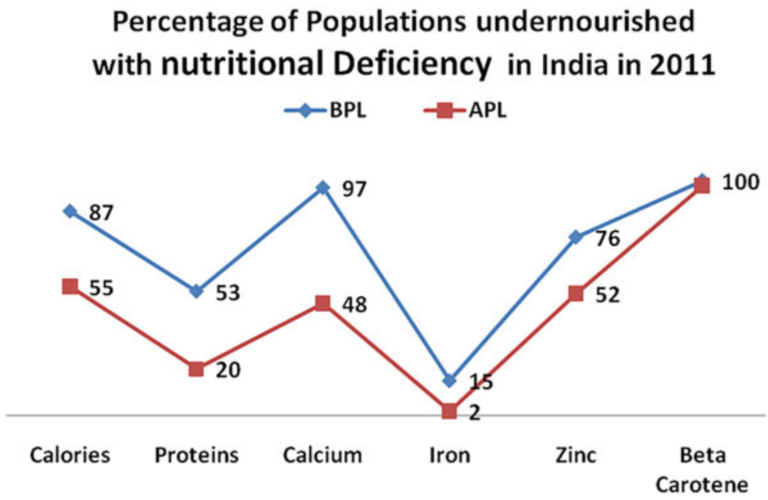

Fig. 2 Percentage of the population undernourished in India in 2011. (Note: *BPL* population below the poverty line, *APL* population above the poverty line. Source: Computed from NSS consumer expenditure data (NSSO, 2012))

(ILO Monitor, 2020). The world is moving toward a massive recession, whereas in India, a sharp downturn already began last year and now forces toward more shock.

Food prices (WPI) for most items, particularly vegetables, namely, onion, potato, and tomato, jumped up and continued to the top in 2020. The lockdown, followed by supply bottlenecks nationwide, impels much higher prices for consumers for a range of perishable foods. India's food-grain output projection is higher, but spatial food security and access are at threat due to more transportation costs and associated uncertainty from farm gate to market. At the same time, farmers risk losing their market precisely in the trades of horticultural, fishery, and animal husbandry, resulting in sharp falls in their farm-gate prices.

Poor storage and marketing channel, inadequate postharvest processing, and inadequate infrastructure are escalating the difficulties of harvesting current crops and planning for the next session. Migrant workers are forced to return to their homes, leaving agricultural operations with associated high costs. FAO estimated that nearly one-third of the world's food is lost or wasted (FAO, 2015b), the value of which may be Rs. 92,651 crores or more in India (PIB, 2016). Feed shortage is also a crisis forcing low-cost livestock products to distress selling. The situation is triggered by higher consumer costs, limiting farmers' income.

Of late, 70% of Indians are residents of rural regions, of which 40% occupancy is still devoid of transport facilities. Total 82% of farmers are under the small and marginal category (FAO, 2019) and facing all sorts of troubles. The country has witnessed acute supply and demand imbalances sporadically due to intensified single crop policy, which is wreaking havoc under this COVID outbreak. Unemployment, income loss, deprivation, and rural distress are the associated outcome of this prolonged lockdown.

Therefore, particular short-term actions, maintaining supply chains mechanism, planned procurement, and allocating adequate credit and agricultural inputs with government interventions, are urgent during this challenging time for regional upscaling of food security and farmers' income. Highly perishable seasonal agricultural commodities are crucial now for household nutrition. Assuring diversified locally available food produce per local demand through smoothened prices under agri-allied sectors is needed.

In this panic moment, the poorest and the weakest part of society, including jobless migrant workers, laborers who depend upon public food assistance programs, and school children who rely on school meals to meet their nutritional necessities, are facing a "crisis within a crisis" situation. These larger sections are weak and vulnerable to disease attacks. With their independent regional resources, they need scaling-up assistance of free food and agricultural stability, the temporal dimension of food and nutrition security. Serious multifaceted challenges and a variety of shortcomings are undergoing millions of struggling lives. Stability minimizes external risks such as the COVID-19 pandemic. Some fundamental changes and appropriate government policies to build resilience at the state or district level may help society beat the situation.

7 Food Safety and Traceability

Food safety is a serious global issue, and unsafe food markets like Wuhan, China, can have a far-reaching worldwide resonance (Galimberti et al., 2020). Foodborne illness, which is attributed to significant societal costs, emphasizes the need for holistic food safety measures (probability of food to deter consumer health risks) (Souza-Monteiro & Hooker, 2013) and their traceability (ability to detect the origin and spread of the hindrance to safe food consumption from farm gate to the consumer's plate) (Golan et al., 2004). However, the inability to link food chain records, and inaccuracy and errors and delays in obtaining essential data serve as major setbacks to authentic food safety and traceability (Badia-Melis et al., 2015). To ensure food safety, a traceability system must encompass breadth (quantity of information), depth (tracking of information in both forward and backward directions), and precision (accuracy and assurance of food transshipment).

The traceability systems accrue three significant benefits for the producing firms: improve management of supplies, trace back food safety and quality, and attribute marketable differentiation for quality food promotion. It helps build trust, confidence, and peace of mind as a consumer. This approach further ensures end-to-end supply chain management (Aung & Chang, 2014). Seventy-six million cases of foodborne diseases are reported annually in the USA alone. Whereas in India, the food market is governed by small and medium enterprises with poor agricultural practices: Inadequate postharvest storage and management infrastructures, knowledge, and technology and awareness gap create more difficulties in maintaining safety and traceability standard. Several agencies have cropped up, including FSSAI, APEDA, GS1 India, NABARD, FPO, ITC's eChaupal, Reliance industry, etc.

The current COVID-19 pandemic has put forward the necessity of ensuring food safety and security. A wide range of social, economic, and in many cases environmental consequences are attributed to foodborne anomalies. The pandemic has quite aptly emphasized that food quality should not be synonymously coined with food safety. A product that may appear high quality (i.e., well-colored, appetizing, flavorful, etc.) may be unsafe because it might be contaminated with undetected pathogenic organisms, toxic chemicals, or physical hazards. COVID-19 is not foodborne. The disease is reported to be transmitted by respiratory droplets from person to person. There is report of the virus neither causing COVID-19 (SARS-CoV-2) to be transmitted through food packaging, nor can it multiply in food (Mardones et al., 2020). However, there are some reports of infected cases by imported food (Marti et al., 2021). However, most food business operators globally have taken sufficient safety protocols to curb the spread of the disease by food workers in food items or food packaging.

Thus, thorough evaluation approaches by hologram, genomic analyses for foodborne pathogen identification and traceability, barcode, radio frequency tags, geographical identification tags, biotracing, tools adapted from landscape ecology (species distribution and niche modeling), Social Network Analysis for predicting patterns of disease outbreaks, nano-sensor for precise GPS identification, and information and communication technology must be ensured with specific governmental policies and standard marketing channels for safer food to the consumers along with better price for the producers (Dandage et al., 2017). Furthermore, proper demand-driven marketing hubs, effective supply chain management, strict food safety laws and regulations, and hygiene practices in food and livestock marketing processes must ensure better human health protection for future pandemonium.

8 Soil and Carbon Footprint Impact Under the Pandemic Situation

Soils are fundamental to our lives and must be recognized and valued for their importance in global climate change feedback, particularly their enormous potential to mitigate climate change. However, the role of soil organic carbon (SOC) or soil organic matter (SOM) in ensuring food security is often forgotten, which is achieved by enhancing soil productivity and maintaining consistently high yields, particularly by increasing water and nutrient holding capacity and improving soil structure, thus improving plant growth conditions (Zdruli et al., 2017). Many studies have precisely quantified the contributions of SOC in food production that a 1-tonne increase in the SOC pool of degraded cropland can increase wheat yields by 20–40 kg ha^{-1}, maize by 10–20 kg ha^{-1}, and cowpeas by 0.5–1 kg ha^{-1}. Therefore, the sustainable use of soils is a critical issue in the climate change context. Maintaining or improving soil fertility is a prerequisite for many essential ecosystem services, including sustainable food and fibers. The most immediate impacts of the COVID-19 pandemic on soil and vice versa are human activities resulting from a decline in human consumption, giving rise to surplus food being disposed of and added to the soil. Reduced consumption of meat led to food waste. This has long-term consequences for land use, groundwater quality, biodiversity, human health, and land value. A potato glut has occurred due to a decline in the consumption of French fries, resulting from the cancellation of sporting and cultural events and the closure of restaurants. This huge potato surplus impacts soil when farmers plow under crops and plan to discard surplus potatoes currently in storage by working them into the soil on a scale never seen before (Bernton, 2020). A similar supply-chain-soil situation is faced by dairy farmers (discarding millions of gallons of milk per day) and also impacting beef producers. A reduction is following this in acreage being planted to adjust to decreased demand. Sustainable management of soil toward nutrition-enhanced food production through the restoration of soil health is critical to reducing the risks of food and nutritional insecurity. The nutritional quality of organically grown food may be better than fertilizer- based management (Murphy et al., 2008). The functions and services enable soils to support the primary supply of food and natural products required by the human population, even under high external pressure. They have moved the importance of soil functions higher on the agenda in soil science research (Vogel et al., 2019) and in a policy setting.

In addition to the primacy of human health care, the maintenance of all critical infrastructures and, in particular, the supply of the population with food and natural products from agriculture, forestry, and fisheries have the highest priority, and this has increasingly been challenged under the COVID-19 pandemic (Moran et al., 2020). Besides nutrition, the social dimension, such as disruptions in food prices, is also important (Barrett, 2020). A decline in soil health and resiliencies is also a constraint to advancing the Sustainable Development Goals of the UN which have been aggravated due to COVID-19. The effects of countermeasures happened to have been tested out by the COVID-19 pandemic event, during which an abrupt drop in CO_2 emissions equivalent to 17% of the total for 2019 was recorded in the first 4 months of 2020. Jeff Tollefson (Data Story, Nature) reported that global carbon dioxide emissions, after rising steadily for decades, reduced by 6.4% (equivalent to 2.3 billion tonnes) in 2020, because of the squelched economic and social activities in the worldwide COVID-19 pandemic situation. However, Zhu Liu, an Earth-system scientist at Tsinghua University in Beijing who coleads the International Carbon Monitor Program, expressed his concern: “The emissions decline is already less than what we expected. I imagine that when the pandemic ends, we probably will see a solid rebound.” Notably, the aviation sector, being the most affected energy sector due to the pandemic, experienced a significant 48% reduction in emissions during 2020-2021 compared to 2019, primarily attributable to the constraints imposed by pandemic restriction. The United Nations Environment Programme estimates that the world needs to cut carbon emissions by 7.6% per year for the next decade to prevent the globe from warming by more than 1.5 °C above preindustrial levels – a goal set in the 2015 Paris climate agreement. However, the pandemic has changed the view of challenges to fighting climate change.

There is no evidence directly linking the COVID-19 outbreak to climate change. However, COVID-19 is testing our resilience in responding to potential climate-related disasters. As such, the COVID-19 crisis can provide lessons about the vulnerability of our societies to high-impact global shocks and the critical role of public policies in mitigating the risks by reducing greenhouse gas emissions and boosting investments in long-term resilience and prevention. Its global nature is also a reminder that global shocks – pandemics, economic crises, and climate-related disasters – are best overcome through coordinated international action and by following scientific advice. Recovery policies must be prepared to integrate economic, social, and climate change objectives. Over 100 countries have already adopted carbon neutrality goals for 2050, requiring a transformative change in many economic sectors. Careful preparation of recovery policies presents opportunities to simultaneously address recovery and climate objectives, which depend on actions and investments over the next decade. The COVID-19 crisis has reduced emissions but will not reduce climate change if emission reductions remain temporary. The lockdowns imposed across the globe and the associated collapse of economic activities have caused significant reductions in greenhouse gas emissions (along with life-shortening air pollutants) from transportation and industrial activity. For example, in China, industrial shutdowns are estimated to have caused a 25% drop in CO2 emissions in February 2020 compared with the same month in 2019.

9 Strategies for Reducing Food Loss and Waste

During the initial phase of the COVID-19 lockdown, food loss (production point up to retail) was mainly due to a shortage of labor, closure of SMEs, and restrictions on movement and border closures resulting in poor handling, storage, processing, and packaging. Also reduced demand for perishables, poor quality, the inability of consumers to purchase food, and the closure of public markets accentuated food loss. Policy responses like creating pooling platforms through the development of transport apps, building rural collection centers, and decentralizing storage sites along transport routes will help reduce food loss during handling, storage, and distribution. Demand-driven logistics and cold chain systems must be developed in place of traditional production-oriented fragmented multilayered channels. To reduce food waste (from retail to consumer), the promotion of alternative processing options in the supply chain (e.g., freezing vegetables) and good-quality packaging with improved capacity for sound postharvest technology, including solar drying of fruits and vegetables, need to be adopted.

10 Requisite Policies and Alignments: Toward Postpandemic Food and Nutritional Sustainability

The multifaceted efforts by the governance of different countries across the globe since the beginning of Covid-19 are trying to combat the loss. However, the past few complete shutdowns of all economic activities in several phases have had an adverse impact in the long run and have already reflected in absolute poverty. Even before the pandemic started, Kharas et al. (2018) estimated that extreme poverty (measured at the international poverty line of $1.9 per day per capita) would increase by

50 million globally. Per their prediction, in India, the extremely poor will increase by 10 million during the current decade.

Food security is a flexible socio-type, ecological, and conceptual framework, and interactions with the community determine an individual's survival strategies. Under great stress and hardest hit by the pandemic, multidimensional interventions, implementation, and policy innovations are the crux of agricultural development, food access, and current nonfarm economic options. Lockdown has jeopardized the system through failing income and work deficiencies for the monumental populace; therefore, short-term steps toward public food distribution programs must be strengthened along with respective long-term policies for agri-food sustainability. A COVID-19 pandemic-resilient framework for food security has been provided in Fig. 3.

India's subsidized food security under National Food Security Act (NFSA) and newly introduced Pradhan Mantri Garib Kalyan Yojana (PMGKY) are the most significant social safety network in the world, costing about 6% of the total budget. This scheme supplies free food grain to women, the poor, senior citizens, and farmers. During the first phase lockdown in India, PMGKY offered 5 kg of food grain and 1 kg of pulses per household to 80 crore individuals covered under NFSA until November 2020. Are all lower-rung populations covered and rightly exercised by NFSA, or are the damage, leaks, or procurement loss minimized?

NFSA scheme covers 67.22% population including migrant labors and agricultural wage workers across the states through different government schemes (NFSA+PMGKAY). However, these relief packages were insufficient to combat the deep economic breakdown under COVID-19, especially the malnutrition and poverty situations that have been downgraded among women and children. Holding sufficient procurement food stocks year-wise is a good reason for national security. Also, maximum release from the stock free of cost to the underprivileged in continual mode may be the win-win approach to feed the hungry and vulnerable, which ensures minimum procurement loss. Different NGOs, cooperatives, the Women Self Help Group (SHG), and volunteer organizations may be used under food distribution functionaries.

In this COVID catastrophe, medium and long-term interlinked challenges and alleviative measures rely on eco-regional planning for production sufficiency, particularly for high-value commodities and agricultural pricing policy. There is an urgency for functional governance of the food market and prices with a total capacity to prevent price volatility across the seasons. Cheaper information technology and software, Aadhar-based beneficiary identification, and tracking are also opportunities for the modernization of the supply chain. Due to the high unemployment rate, economic nourishment must be prioritized by ensuring direct, optimal payment to the growers for farm produce and proper functioning of government food and nutritional programs.

Negative ramifications of farm labor shortage must be rectified by facilitating more machinery involvement through custom hiring centers (CHCs) and Farmer Producer Organizations (FPOs) soon. NREGA scheme may be effectively linked with rural agriculture to reduce farmers' monetary load and secure labor income. The major portion of all livestock components is devoid of established marketing networks, resulting in a lack of feed availability and unsold or half-priced milk and meat from the farmers. They must be considered for immediate credit assistance

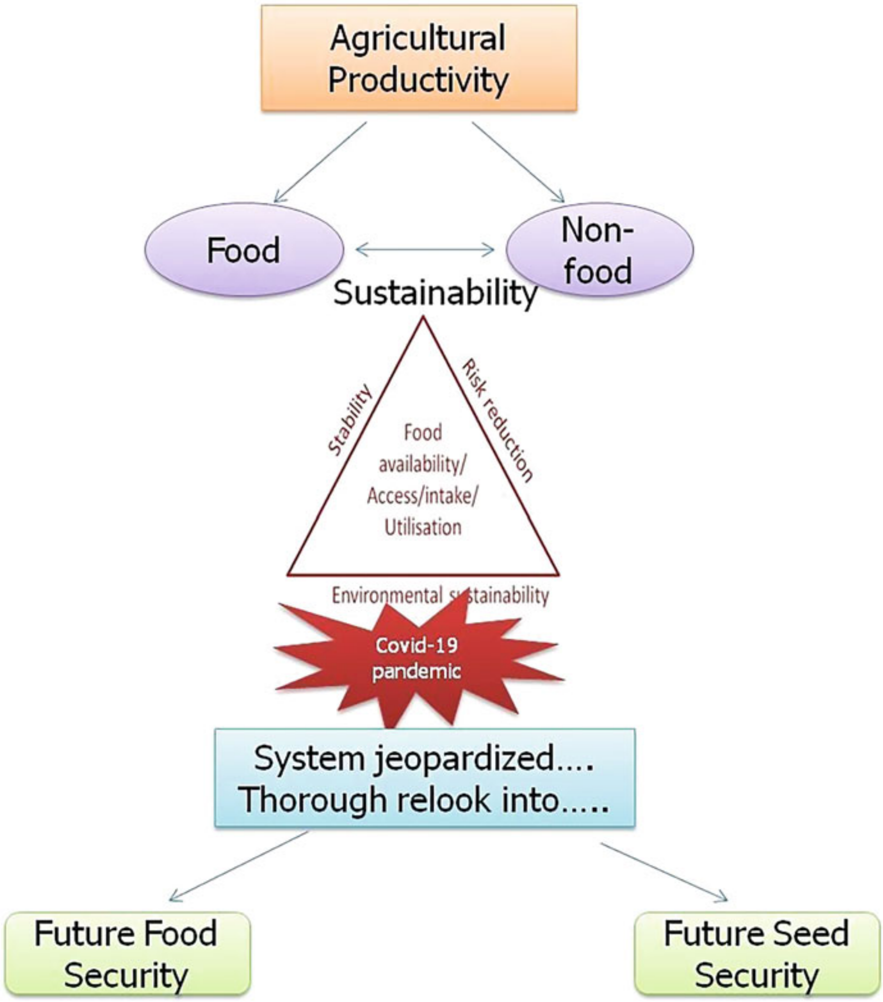

Fig. 3 COVID-19 pandemic-resilient framework for food security

and more targeted help. Cooperatives, farmers' clubs, and enterprises should be boosted with crop loans.

Multifaceted challenges during pandemics have brought urgency to look forward toward commercialized and diversified agricultural produce with more prominence on natural resource management and crop improvement technologies. Promotion and marketing framework for organic farming, pulses, coarse cereals, and value addition will be the key to achieving regional food security and economic resilience. In these ways, with a comprehensive and systematic policy framework, regional planning, and executions, we can manage the SDG target for eliminating extreme poverty and nutritional security by 2030.

11 Conclusion

COVID-19 is now becoming the most unprecedented and unfolding life threat globally. Its health, economic and social consequences, and vulnerabilities have been compounded, prompting severe panic and disruption in daily livelihood. Climate change, economic breakdown, poverty, inequality, and malnutrition are further threatening issues to aggravate the disease potential (see Sect. 2). Food systems and nutrition are exigent for restraining the food catastrophe amid this pandemic, unique region-specific policy design, intelligibility, and synergism for allover agriculture. Potential public and private mechanisms, innovations for securing cultivating networks during imminent agrarian seasons, streamlining value chains, and better accessibility together with market price stability have to be prosecuted for tackling the crisis. The crucial thresholds for every opportunity, precedence, and scheme must be mutually achieved toward nutritional nourishment for healthy lives, resource-based ecosystem sustainability for future balance, and productive investment for a resilient agrarian rural economy. Spirited endeavors, concerted development assistance, and awareness pushed by empathy and feelings for our society's poorest and fragile segment are the absolute urgency to reach scale-neutral nationwide food security.

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Energy Budgeting of Rice-Based Cropping Systems in the Indian Subcontinent

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Abstract

There is a driving consensus to shift our food production systems toward low-carbon economies. The cropping systems of Gangetic Plains or South Asian countries are mostly rice-based or resource-intensive, which are practiced by smallholder farmers. Agricultural sustainability would be overlooked unless we estimate the energy footprint. Earlier, the performance of an agricultural system was judged by economic analysis only. Eventually, scientists are recommending including the energy cost for audits. In this chapter, we discussed energy indices and the relationship of energy input and output in rice, the agroecosystems. Our understanding of energetics will create options to reduce the energy requirements and increase the energy-use efficiency of cropping systems. Interventions to reduce our dependency on nonrenewable energy inputs will be crucial in solving the socioeconomic and environmental challenges of agroecosystems.

Keywords

Energy inputs · Energy outputs · Energy indices · Rice agroecosystem

1 Introduction

National policies related to energy consumption got attention after the oil crisis in Denmark in the 1970s and the 1980s (Mendonça et al., 2009; Sovacool & Tambo, 2016). A number of strategies were framed regarding energy consumption to obtain an optimal reduction in the use and explore renewable energy sources. Energy has been recognized as an important and valuable input source in a crop production system. Current crop production systems are energy-intensive (Choudhary et al., 2017). In crop production, energy is consumed either directly or indirectly from a combination of different inputs like seed, organic manures, fertilizers, plant protection chemicals, irrigation, and machinery (Fig. 1). Energy is the quantitative property that must be transferred to a body or physical system to perform work on the body or to heat it. Study of the energy use in agriculture with a variety of methodologies may be termed energy budgeting, energy analysis, energy accounting, and energy costing.

As the law of conservation of energy states, energy can neither be created nor be destroyed, it can only be converted from one form to another. This shows a crop production system always has the same amount of energy unless the energy is added from the outside. Energy is provided in the form of farm inputs, and the output is in the form of economical yield as well as biological yield. Energy is transferred between the inputs and the end product through various conversion processes or forms. These include primary, secondary, final, and useful energy. Primary energy

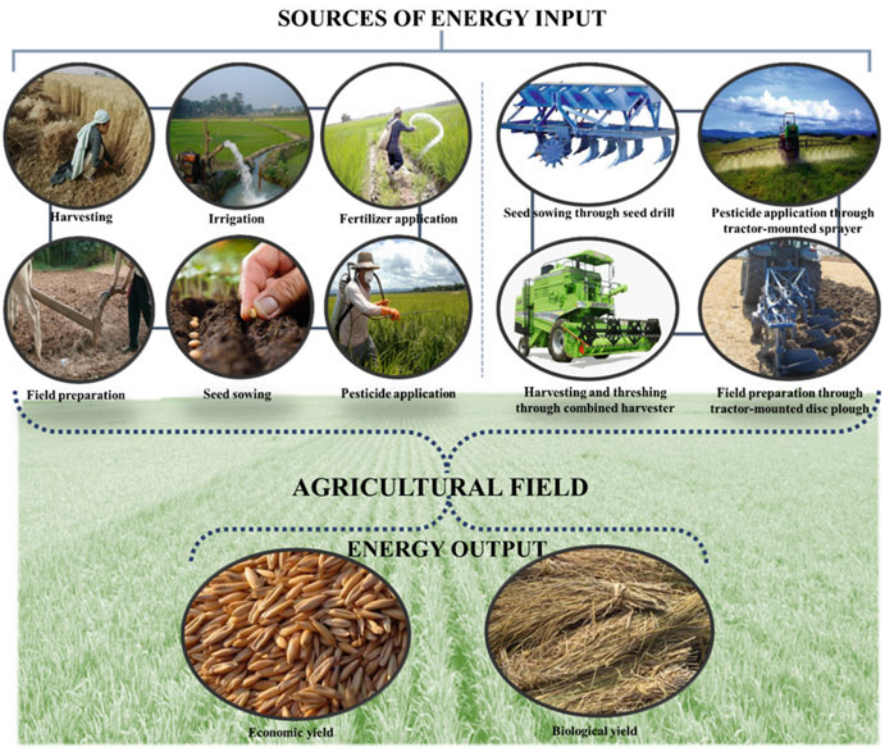

Fig. 1 Specifics of energy budgeting

represents energy sources available in the natural environment like fossil fuel. The energy that is transmitted or transported is known as secondary energy. Final energy is the energy that the end user receives at the market. The energy for end-use application is useful energy. Part of the primary energy is converted during the conversion to useful energy. Energy conversions imply energy losses into other forms, which ultimately decreases the energy efficiency (output energy/input energy) during conversions. Radiation, kinetic, mechanical, electrical, chemical, potential, and thermal energies are the various forms of energy. Chaudhary et al. (2006b) suggested increased production, productivity, profitability, and agricultural sustainability by the efficient use of different forms of energy.

In modern agriculture, energy use and costs are ever-increasing. Energy input–output relationships in cropping systems vary with the type of soils, type of tillage operations practiced, crop sequence, nature and amount of organic manures and chemical fertilizers, plant protection measures, harvesting and threshing operations, and economic and biological yield levels (Singh et al., 1997; Ozpinar and Ozpinar, 2011; Rakshit, 2019; Sarkar et al., 2021a).

India is rich in various natural resources, is predominantly agricultural and diverse in soil and climatic conditions, and thus it has been divided into 15 agro-climatic zones based on its physiography, cropping patterns, soil type, and climate.

The climatic condition of the country suits various crops, including cereals (paddy, wheat) and pulses (chickpea, pigeon pea, black gram, green gram), which are predominant (Dash et al., 2021).

Rice (*Oryza sativa* L.)-based cropping systems are one of the most important cropping systems in the Indian subcontinent. India produces a significant amount of paddy, accounting for 21% of the world's white rice (Ministry of Statistics and Program Implementation, 2012). The important crops grown in rotation with paddy are wheat, potato, mustard, various rabi pulses like green gram, black gram, chickpea, and lentil, maize, and other legumes. Irrespective of their growing seasons, paddy cultivation consumes the highest energy among all crops (Chaudhary et al., 2006a, 2009). Similar reports were recorded by Yadav et al. (2017), emphasizing that rice had the highest energy input followed by that for maize and the least for lentil. When compared to other crops, rice has the highest energy consumption because it requires more amount of inputs, including tillage, as it is conventionally grown under puddled situation. The highest consumption of energy in rice is mainly due to a higher number of tillage (grown under conventional tillage with puddling) and fertilizer requirement compared to other crops. Although maximum energy is expended for rice cultivation, it is a staple and a main crop of India and other South East Asian countries in the monsoons, where the annual rainfall is more than 1500 mm; thus, it is very difficult to replace rice with other crops (Mandal et al., 2015).

In order to feed the growing population and achieve other social and economic objectives, a sufficient amount of energy must be employed in agricultural production, processing, and distribution (Chaudhary et al., 2014). It was estimated by Sharma et al. (2021) that large farmers as opposed to medium and small category farmers consumed more energy in rice and wheat crop cultivation. The crops cultivated in the Indian subcontinent consume more energy while cultivation, and it is important to identify the crops and cropping systems that require less energy.

2 Energetics

Energy fluxes were determined by using crop management operations (various inputs used, amount of input used, human labor required, and machinery used) and biomass production data. To study the energy input and output of each cropping system, a detailed record of all inputs (seeds, fertilizers, agro-chemicals, fuel, human labor, and machinery power) and outputs (marketable main product and by-product) was prepared. These sources of energy required in crop production have various energy values and some amount of energy is expensed to produce such sources of energy. Energy coefficients for various sources of energy may thus be defined as energy equivalence of such sources of energy, taking into account all forms of energy input to their production (Mittal & Dhawan, 1989). Based on energy input for every crop grown across all of the seasons of each cropping sequence, the energy value of

Table 1 Details of energy coefficients of conventional inputs other than seed

Inputs other than seed	Units	Energy equivalent (MJ)	References
Human power			
(a) Adult man	Hour	1.96	Nassiri and Singh (2009)
(b) Adult woman	Hour	1.57	Nassiri and Singh (2009)
Tractor	Hour	332	Gopalan et al. (1978); Binning et al. (1983)
Fuel (diesel)	Liter	56.31	Singh and Mittal (1992)
Electricity	kWh	11.93	Singh and Mittal (1992)
Irrigation water	m^3	1.02	Ebrahim (2012)
Farmyard manure	kg	0.30	Gopalan et al. (1978); Binning et al. (1983)
Chemical fertilizers			
(a) Nitrogen	kg	60.60	Gopalan et al. (1978); Binning et al. (1983);
(b) Phosphorus	kg	11.10	
(c) Potassium	kg	6.70	
(d) Micronutrients (Zn/Mn/Fe)	kg	120	Mandal et al. (2002)
(e) Zinc sulfate	kg	20.90	Taewichit (2012)
(f) Biofertilizers	kg	10.00	Devasenapathy et al. (2009)
Biocides			
(a) Herbicides	kg	238	Tuti et al. (2012)
(b) Insecticides	kg	199	Helsel (1992)
(c) Fungicides	kg	216	Tuti et al. (2012)
(d) Granular chemicals	kg	120	Datta et al., 2014
(e) Liquid chemicals	Liter	120	Datta et al., 2014

each cropping system was determined. Inputs were translated from physical units to energy units by multiplying by conversion coefficients (Table 1). The energy input and productivity were calculated using the following equation (Datta et al., 2014):

$$\text{Energy input (MJ ha} - 1) = \sum_{i=1}^{n} (C1 + C2 + Ci).$$

where C1, C2, . . .Ci are the energy inputs of each component input.

Energy productivity (kg MJ^{-1}) = Crop yield/Energy Input

To select an efficient cropping system, the effective use of different energy sources, the energy usage costs, and its impacts on the environment should be taken into account (Dorning et al., 2019). Energy analysis is done based on field operations (tillage operations, sowing or planting, fertilizer application, spraying of chemicals, and harvesting), as well as on the direct (fuel and human labor) and indirect (seed, machinery, fertilizer, and pesticide) energy sources involved in crop production (Bockari-Gevao et al., 2005; Sarkar et al., 2021b).

3 Input Energy

Summation of energy equivalents was done to obtain an estimate of the total input energy. Utilization of energy in farm operations was calculated on the basis of energy consumed in field preparation and planting, fertilizer application, irrigation, intercultural operations like weeding, plant protection, and harvesting and threshing (Saad et al., 2016). Energy sources in agriculture may be in the form of direct and indirect energy; commercial and noncommercial; and renewable and nonrenewable. Commercial energy arrives on farm in the form of machinery, fuel, irrigation water, chemical fertilizer, pesticides, etc. Solar and wind energy is available in non-commercial form (Kiamco and McMennany, 1979). The direct and indirect source-wise energies (viz., human labor, water, seed, crop residue, diesel, plant protection chemicals, fertilizers, and machinery) is calculated for each farm operations on a hectare basis (MJ ha^{-1}). Different types of energy are calculated as

Direct energy (MJ ha^{-1}) = Energy from Human labor (E_m) + Energy from fuel (E_f) + Energy from electricity(E_e)

Indirect energy (MJ ha^{-1}) = Energy from seed (E_s) + Energy from fertilizers (E_f) + Energy from pesticides (E_p) + Energy from tractor (E_t) + Energy from machinery (E_m)

Renewable energy (MJ ha^{-1}) = $E_h + E_s$

Nonrenewable energy (MJ ha^{-1}) = $E_d + E_e + E_f + E_p + E_t + E_m$

Commercial (MJ ha^{-1}) = $E_d + E_e + E_p + E_t + E_m + E_s$

Noncommercial (MJ ha^{-1}) = E_h

3.1 Human Labor Energy

A total of 68% of human energy is consumed for 8 hours of work per day, 21% for 6 hours of other activities, and 11% for 10 hours of rest (Doering, 1980). In Indian conditions, 1.96 and 1.57 MJ/person-h energy coefficients from men and women are used to obtain the human energy from average body weight, age, and daily activities as human labor (Gopalan et al., 1978; Binning et al., 1983). The following formula may be used to calculate human energy input:

$$E_m = E_c x\ N \times T$$

where E_c = 1.96 and 1.57 MJ/person-h energy coefficients from men and women

N = number of laborers used for an operation on the farm

T = time actively spent on human labor on a farm, in hours

The total human labor and their working hours required for each operation were recorded and converted into man-hour. All other factors affecting manual energy were neglected. In India, 42.6% of the labor force were employed in agriculture (Neil, 2022); thus, a huge proportion of the input energy is provided in the form of manual labor to the production system. Human labor energy input is higher in rice because conventional paddy production involves manual transplanting (Chaudhary et al., 2009).

3.2 Fuel

Various operations in farming, such as tillage, sowing, harvesting, threshing, etc., are performed using a diesel-operated tractor. Mechanical energy input from fuel is evaluated by quantifying the amount of diesel consumed during various farm operations (Omar, 2003; Siddique et al., 2021). The time spent in the field operation is also considered. So, the fuel input energy is considered for each operation where tractor-based input is required. For example, a low horsepower diesel engine coupled with a centrifugal water pump may be used to raise water from underground sources for irrigation of crop production. Hence, diesel consumption in pumps has to be taken into account during each irrigation as per the volume of water for every crop. The total energy input through irrigation is added to the total energy input. Gopalan et al. (1978) and Binning et al. (1983) reported that the diesel energy coefficient is 56.31 MJ l^{-1} in India. The following formula is used to calculate the energy input of diesel fuel:

$$E_f = E_{cf} \times A$$

where E_f = fuel input energy, MJ ha^{-1}
E_{cf} = energy coefficient of diesel
A = amount of fuel consumed, l ha^{-1}

3.3 Electricity

Electricity is also another important resource used in various agricultural operations such as an electric motor, which is used for pumping irrigation water. At the start and end of the irrigation operation, the energy meter reading is recorded. The difference in the readings provides the electricity consumption in kilowatt-hours (kWh). The energy coefficient per kWh is 11.93 MJ. The following formula is used to calculate the energy input of electricity:

$$E_e = E_{ce} \times h$$

where E_e = energy from electricity, MJ ha^{-1}
E_{ce} = energy coefficient of electricity
h = hours for which electricity was required, h ha^{-1}

3.4 Seed

Seed is the primary input in crop production. The seed rate or amount of seed required for the production of a particular crop per unit area of land decides the input energy to be consumed from seeds.

The energy input of seeds is estimated using the following formula:

$$E_s = E_{cs} \times S$$

where E_s = input energy from seeds, MJ ha^{-1}
E_{cs} = energy coefficient of seed
S = amount of seed utilized (kg)

3.5 Fertilizers

Energy is required for the production and transport of commercially synthesized chemical fertilizers. Samootsakorn (1982) estimated it to be 80 MJ kg^{-1}, 14 MJ kg^{-1}, and 9 MJ kg^{-1} for N as anhydrous ammonia, P as normal super phosphate (P_2O_5), and K as muriate of potash (K_2O), respectively. Pimentel (1992), Tippayawong et al. (2003), and Chamsing et al. (2008) reported similar findings. In India, the fertilizer energy coefficient is considered as 60.6 MJ/kg for N, 11.10 MJ/kg for P, and 6.70 MJ/kg for K (Table 1).

The energy input of fertilizer N, P, and K may be computed using the following formula:

$$E_f = E_{cf} \times A$$

where E_f = input energy from fertilizers, MJ ha^{-1}
E_{cf} = energy coefficient of the concerned fertilizer
A = amount of nutrient applied, kg ha^{-1}

Fertilizer use was one of the most important input energies in the paddy–wheat and paddy–potato cropping systems, comprising approximately 58% and 51% of the total input, respectively (Soni et al., 2018). Fertilizer alone accounted for approximately 40% of total energy (Sharma et al., 2021) in rice–wheat cropping systems.

3.6 Pesticides

Pesticides, that is, insecticides and herbicides, are mostly commonly used in all cropping systems because of the intensive attack of insect pests and different kinds of weeds. The manufacture of herbicides and insecticides consumes approximately 238 MJ/l and 101.2 MJ of energy, respectively (Doering, 1980). Similar observations were recorded by Pimentel (1992); Hulsbergen et al. (2001); Anonymous (2004). The amount of pesticide energy input (120 MJ kg^{-1}) is adopted as reported by Binning et al. (1983). The energy input of pesticides is computed using the following formula:

$$E_p = E_{cp} \times A$$

where Ep = pesticide input energy, MJ ha^{-1}
E_{cp} = energy coefficient of pesticides
A = amount of pesticide applied

3.7 Tractor and Farm Machinery

Mechanization reduces human drudgery, ensures timeliness of farm-related activities, and increases farm output in terms of yield (Faidley, 1992). In developing nations like India, where the expansion of arable land is not feasible and an increase in total production is also an urgent requirement, the productivity per input applied has to be increased. It is made possible with the use of efficient machineries for various farm operations like proper water, nutrients, pesticides, and weed management. The energy coefficients of various machineries are listed in Table 2. To calculate the input energy in the production of machinery and maintenance or repair, the following formula may be used:

$$E_m = (E_{cm} \times M)/(L \times Ce)$$

where E_m = machinery input energy, MJ ha $^{-1}$
E_{cm} = energy used to manufacture, transport, and repair
M = mass of machinery, kg
L = life of machinery, h
Ce = effective field capacity of farm machinery, hha^{-1}

Table 2 Details of energy coefficient of mostly used farm implements

Power source equipment	Energy coefficient (MJ h^{-1})
Sickle	0.031
Manual spade	0.314
Sprayer	0.502
Animal plow (pair-hr)	10.100
Cultivator	1.881
Disk harrow	3.135
Seed drill/planter	1.254
Mouldboard plow	2.508
Disk plow	3.762
Cultivator	3.135
Disk harrow	7.336
Self-propelled machinery	68.400
Reaper	5.518
Rotavator	10.283
Combine harvester	47.025
Thresher/sheller	7.524
Centrifugal pump	1.750
Electric motor 35 hp	0.343
Diesel engine	0.581
Tractor (>45 hp)	16.416
Self-propelled combine harvester	171.00

Source: Gopalan et al. (1978), Binning et al. (1983), Singh and Mittal (1992)

Increase in mechanization will also result in the increase in use of fuel. According to Soni et al. (2018), fuel was the second highest contributor, responsible for 22% and 15% of the total energy inputs in paddy–wheat and paddy–potato cropping systems, respectively. Most of the fuel-based energy inputs were attributed to the consumption of diesel oil in various on-farm agricultural activities, with gasoline consumption mainly attributed to spraying operations during plant protection measures. Higher fuel consumption in the paddy–wheat system can be attributed to higher mechanization in that system compared to the paddy–potato system. According to Ghosh et al. (2021), the relative distribution of energy from different inputs was the highest in diesel (59.62–77.61%), followed by human labor (17.32–26.70%), seed (2.43–9.55%), land preparation (0.77–2.82%), and irrigation (0.03–0.05%) in rice–maize–green gram cropping system. The difference in contribution of input for various farm operations is solely dependent on the mechanization of the farm.

4 Output Energy

The farm output, that is, grain yield, is converted in terms of energy (MJ) and considered as the output energy using units of energy as available for different crops as followed in the rice-based cropping system (Gopalan et al., 1978). The grain and straw yields of crops are converted in terms of energy (MJ ha^{-1}) using their corresponding energy coefficients recorded in Table 3. The energy output of a crop is the sum total of the energy equivalent of grain and straw yields. The grain yield or the economical yield is considered, and in case of the straw yield, it is considered only in cases where it has some economic purpose. For example, the

Table 3 Details of energy coefficient of outputs

Outputs	Energy equivalent (MJ)	References
Economic yield		
Rice	14.70	Gopalan et al. (1978); Binning et al. (1983)
Wheat	15.70	Chaudhary et al., 2014
Chickpea	15.06	Chaudhary et al., 2014
Mustard	22.64	Chaudhary et al., 2014
Garden pea, field pea, and lentil	14.70	Yadav et al., 2017
Green gram and black gram	14.03	Yadav et al., 2017
Maize	15.10	Datta et al., 2014
Potato	3.60	Nassiri and Singh, 2009
Linseed	25.00	Mittal and Dhawan (1989)
By-product yield		
Straw	12.50	Mittal and Dhawan (1989)
Stalk	18.00	Mittal and Dhawan (1989)

straw of rice is considered for the calculation of the output energy equivalent, but in case of potato only the tubers is considered while calculating the energy equivalent.

$$\mathrm{Eo} = \left(\mathrm{Y_g x E_{cg}}\right) + \left(\mathrm{Y_s} \times \mathrm{E_{cs}}\right)$$

where Eo = output energy
Y_g = grain yield (kg ha^{-1})
E_{cg} = coefficient of grain (MJ kg^{-1})
Y_s = straw yield (kg ha^{-1})
E_{cs} = energy coefficient of straw (MJ kg^{-1})

4.1 Energy-Use Pattern

Energy consumption for field preparation is the highest energy in conventional tilled plots that is reduced to zero in case of zero tilled fields. According to Choudhary et al. (2017), crop residues (renewable energy) contributed the highest input energy followed by other nonrenewable resources, viz., diesel, chemicals like fertilizer, pesticides, and machineries. Conventional tillage practices were regarded to be energy-intensive (Pratibha et al., 2015) and poor in resource utilization (Parihar et al., 2017). About 25–30% of energy was required for field preparation and crop establishment (Tomar et al., 2006). About 53% less energy was used for paddy direct sowing and drum seeding compared to manual transplanting in a puddled field (Chaudhary et al., 2014). Chaudhary et al. (2006a) revealed that the highest energy was consumed in fertilizers followed by diesel fuel for pumping irrigation water, operational energy in machineries, labors, and seed in rice–wheat, rice–chickpea, and rice–mustard cropping systems. According to Pandey and Dave (2014), fertilizer application accounted for 22–44% share of energy input followed by fuel (19–25%) and electricity required for various farm operations (16–23%). Ray et al. (2020) also observed similar findings where all the rice-based cropping systems under study consumed the maximum amount of input energy from fertilizers followed by diesel and labor. The lowest energy input (0.5–3%) was observed through chemicals in rice-based crop production. They also reported that the highest energy output–input ratio was accounted from rice–chickpea (10.73) cropping system, followed by rice–linseed (8.78) and rice–wheat system (8.39). About 87.5% more energy was used for land preparation and sowing with conventional tillage compared with zero tillage (Saad et al., 2016). They also reported that raised-bed planting of crops saved about 33% energy in irrigation as water-use efficiency was high and labor requirement was lesser compared to flat-bed irrigation.

When rice crop was cultivated under mono cropping, the highest energy input was electricity (34%), followed by fertilizer (33%), diesel (19%), farmyard manure (4%), human (4%), machinery (including tractor) (3%), seed (1%), and chemical (2%) in terms of energy (Modi et al., 2018).

Irrigation operation consumes a large amount of energy compared to other agricultural operations, and the major share of energy consumed by irrigation operation is obtained from fossil energy, which is nonrenewable (Mittal et al., 1985). Recently, a study claimed that combination of organics like *panchagavya* (cow product) with recommended dose of fertilizers increased the energy-use efficiency of rice grown in eastern Indo-Gangetic Plains (Upadhyay et al., 2022).

5 Energy Indicators

Energy indicators may be calculated using the following equations.

5.1 Energy-Use Efficiency

In a crop production system, energy-use efficiency shows the efficiency in terms of energy input and output, and also indicates how efficiently the energy has been used in agriculture. For easy international comparison, a measure of energy-use efficiency in terms of energy output to unit energy input is befitting (Bockari-Gevao et al., 2005).

$$\mathrm{EUE} = \mathrm{E_O}/\mathrm{Ei}$$

where EUE = energy-use efficiency
$\mathrm{E_O}$ = total output energy, $\mathrm{MJ.ha^{-1}}$
Ei = total input energy, $\mathrm{MJha^{-1}}$

5.2 Energy Efficiency Ratio

It indicates the efficiency of the crop production system in which only the energy of the economic yield is considered compared to the total input energy.

$$\mathrm{EER} = \mathrm{Eom}/\mathrm{Ei}$$

where EER = energy efficiency ratio
Eom = output energy of main product, $\mathrm{MJha^{-1}}$
Ei = total input energy, $\mathrm{MJha^{-1}}$

5.3 Specific Energy

In a crop production system, specific energy ($\mathrm{MJkg^{-1}}$) predicts the amount of energy utilized to produce a unit quantity of grain. The lower the value of specific energy, the more efficient is the cropping system. Specific energy is defined as

$$SE = Ei/Y_e$$

where SE = specific energy
Ei = total input energy, $MJha^{-1}$
Y_e = economic yield, $kgha^{-1}$

5.4 Net Energy Return

Net energy return, also referred to as energy gain, is the difference between the total output energy from the crop production and total input energy during various operations, and is considered an important parameter when arable land availability is limited for crop production.

Net energy return from a crop production can be determined as

$$NR = E_O - Ei$$

where NR = net energy return from a particular crop, $MJha^{-1}$
E_O = total output energy, $MJha^{-1}$
Ei = total input energy, $MJha^{-1}$

5.5 Energy Intensiveness

It indicates the energy intensity of a cropping system. It may be calculated with the following equation:

$$EI = Ei/COC$$

where EI = energy intensiveness of a cropping system ($MJ\ Rs^{-1}$)
Ei = total Input energy $MJ\ ha^{-1}$
COC = cost of cultivation ($Rs.\ ha^{-1}$)

6 Comparison of Different Rice-Based Cropping System Based on Energetics

The comparison of the input and output energy among the various rice-based cropping systems cultivated in the country is listed in Table 4. The rice-based cropping system listed in the table will give an overview of the differences in the energy inputs applied in different agro-climatic zones of the country.

Among seven different rice-based cropping systems, rice–rice required the highest energy input (27.35×10^3 MJ ha^{-1}) while rice–chickpea required the lowest (17.70×10^3 MJ ha^{-1}) and subsequently rice–rice system produced the highest output energy followed by rice–peanut (Parihar et al., 1999). In the coastal areas of

Table 4 Comparison of input and output energy of different rice-based cropping systems

Cropping system	Agro-climatic zone	Treatment variability	Energy input	Energy output	References
Paddy–Wheat	Trans Gangetic Plains	Large farms	70166.56	282150.00	Sharma et al.(2021)
		Small farms	69133.60	276967.00	
Paddy–wheat	Upper Gangetic Plains	Dry bed, drum seeding of paddy	42027.00	211,361	Chaudhary et al. (2014)
		Unpuddled manual transplanting of paddy	39984.00	206,613	
		Puddled condition	44,332.00	193,483	
Paddy–chickpea	Upper Gangetic Plains	Dry bed, drum seeding of paddy	38,238.00	166,410	
		Puddled transplanting	40,543.00	149,253	
Paddy–mustard	Upper Gangetic Plains	Dry bed, drum seeding	32,741.00	153,078.00	
		Unpuddled manual transplanting of paddy	30,698.00	139,939.00	
		Puddled condition	35,046.00	138,392.00	
Paddy–wheat	Middle Gangetic Plains		39460.00	250890.00	Soni et al., 2018
Paddy–potato	Middle Gangetic Plains		65820.00	236950.00	
Paddy–green gram	Lower Gangetic Plains	Manual harvesting along with thresher	19934.77	84554.00	Dash et al., 2021
		Combined harvester used	18010.62	91167.77	
Paddy–black gram	Lower Gangetic Plains	Manual harvesting along with thresher	20824.44	93690.86	
		Combined harvester used	10164.14	95831.10	
Paddy–linseed	Eastern Plateau and Hills		22749.00	199906.00	Pandey and Dave, 2014
Paddy–toria	Eastern Himalayas		25254.00		Yadav et al., 2017
Paddy–lentil			22486.20		
Paddy–field pea			23690.10		
Paddy–garden pea			24027.20		
Paddy–green gram			22573.30		
Paddy–black gram			22542.00		
Paddy–maize			28655.60		

West Bengal, the lower Gangetic Plains, the highest specific energy was in the rice–sunflower system (2.5 MJ kg^{-1}) followed by rice–rice cropping system and the least for rice–bitter gourd and the rice-pointed gourd systems (0.5 MJkg^{-1}) (Ray et al., 2020). According to Pandey and Dave (2014), the rice–chickpea cropping system is one of the most cost-effective and energy-efficient rice-based cropping systems compared to others such as rice–linseed and rice–wheat cropping system in the Eastern Plateau and Hill region.

The rice–wheat cropping system, a very important cropping system followed in the Indian sub-continent, recorded a high consumption of input energy (43,534.3 MJ ha^{-1}) and the output energy recorded was 3,29,555.6 MJ ha^{-1} (Paramesh et al., 2017). The rice–maize (0.27 kg/MJ) cropping system and rice–green gram/black gram (0.28 kg/MJ) systems recorded the lowest energy productivity, primarily because of the lower economic yield, REY, and high-energy input (Yadav et al., 2017). Maximum energy productivity was observed with rice–green pea–summer moong cropping system (0.32 kg MJ^{-1})and minimum in case of rice–gobhi sarson (0.27 kg MJ^{-1}) due to better utilization of resources and maximum productivity of the system (Walia et al., 2019).

Eco-efficiency, also expressed in terms of economic gain per unit energy inputs for a unit area (Rs. MJ^{-1}), was higher in paddy–wheat cropping system (41.7 ± 23.9 Rs MJ^{-1}) compared to paddy–potato (35.39 ± 8.07 Rs MJ^{-1}) (Soni et al., 2018)

7 Conclusion

Productivity and profitability parameters of a cropping system have long been proclaimed as judging parameters, but recently the holistic approach of energy budgeting has emerged as more empirical (Ray et al., 2020). As already discussed, rice is a high-energy-requiring crop. The input energy is quite high in rice-based cropping systems, so the energy balance may be maintained by including low-energy-requiring crops in the cropping system. Instead of following a paddy-based cropping system, other kharif crops like soybean and groundnut may be introduced in the farm, followed by low-energy-requiring crops in the *rabi* season. Rice–wheat cropping system, compared to maize–wheat, soybean–wheat, and groundnut–wheat, was found least efficient in energy production through grain. Alternative cropping systems like groundnut–wheat sequences proved to be very effective (Singh et al., 1997). Paddy being our staple crop may not always be possible to be substituted with other crops and thus may be rotated with other low-energy-requiring crops like pulses in the cropping sequence.

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Farmers' Knowledge, Perception, and Practices Toward the Use of Sugarcane Trash

Logistic Regression Model

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Abstract

Sugarcane trash is used for a variety of purposes, including mulching, composting, fodder, burying infield to increase soil fertility, fuel for cogeneration plants, biogas generation, ethanol production, and pulp and paper industries, despite the fact that farmers refer to the open burning of sugarcane trash. Therefore, predicting farmers' knowledge, perceptions, and behavior is important in determining the appropriateness of information for decreasing the hazards associated with the open burning of sugarcane trash, and it did with the logistic regression model. The study proved that age ($p < 0.05$) and training ($p < 0.005$) were statistically significant toward the burning of sugarcane trash. As a result, training programs are required to improve their knowledge and abilities in the safe use of sugarcane trash for beneficiaries. The farmers were found to have a good understanding of how to use sugarcane trash as organic manure (77.4%) and for mulching (75.2%), despite the fact that they undertake field burning of sugarcane trash (61.3%) to prevent the load of trash on the next crop; the risk of rodents, scorpions, and snakes; the lack of a market; the damage to weeds and their breeding places; and the lack of technical understanding. Using an effective implementation of policy and technology, it is possible to prevent the open burning of sugarcane trash.

1 Global Status of Sugarcane

Sugarcane is one of the world's oldest cash crops, produced commercially in tropical and subtropical climates (Pierossi & Bertolani, 2018). Brazil is the world's largest producer of sugarcane, followed by India, Thailand, China, Mexico, Pakistan, and Australia (Dotaniya et al., 2016). Brazil and India account for roughly half of the world's sugarcane production (Dotaniya et al., 2016). According to the Food and Agricultural Organization (FAO), global sugarcane production for 2018–2019 is expected to be 179.3 MT (Food and Agriculture Organization, 2020), with ST production expected to be nearly 279 MT (Chandel et al., 2012). ST is comprised of green sugarcane tops (GSTs) and dry sugarcane leaves (DSLs) left over during sugarcane harvesting. A sugarcane field yields roughly 6–8 tons of ST per hectare (Chandel et al., 2012). Sugarcane is grown on around five million hectares in India, yielding 25–26 MT of sugarcane production and 6.5 MT of sugarcane trash each year (Food and Agriculture Organization, 2020).

2 Global Trends and Policies Toward Utilization of Agriculture Waste

The burning of agricultural wastes is prohibited in India under various laws, including "Section 144 of the Civil Procedure Code (CPC) to prohibit paddy burning," "The Air Prevention and Control of Pollution Act, 198," "The

Environment Protection Act, 1986," and "The National Tribunal Act, 1995." As a result, the burning of agricultural wastes in the states of Punjab, Haryana, Uttar Pradesh, Delhi-NCR, and North India has been reduced by 41% in 2018 compared to 2016 (Bhuvaneshwari et al., 2019).

The Association of Southeast Asian Nations (ASEAN) was founded in 1967 and presented a guideline for the execution of ASEAN's zero-burning policy. Brunei Darussalam, Cambodia, Indonesia, the Lao People's Democratic Republic, Malaysia, the Philippines, Singapore, Thailand, and Vietnam are members of the alliance. Thailand's government enacted the Alternative Energy Development Plan (AEDP) in 2012 (Kumar et al., 2020). Thailand is one of the world's major producers of rice paddy and sugarcane, accounting for 83% of total burnt residue. To address this issue, the Thai government has created measures such as the Alternative Energy Development Plan (AEDP) in 2012 and a zero-burning policy for sugarcane, which target both the use of residue and the practice of burning (Kumar et al., 2020).

> In 1995, the Colombian Ministry of Environment issued a Decree (No. 948 of 1995) prohibiting agricultural waste burning as of 2005, prompting the Colombian sugar industry to develop technological solutions to accomplish this goal. (Bhuvaneshwari et al., 2019)

In Brazil, the states of São Paulo, Minas Gerais, and others enacted Law No. 11.241 to prohibit the burning of agricultural waste. Approximately 40% of Brazil's sugarcane is no longer subjected to preharvest fire. The state of São Paulo is responsible for more than 60% of cane production, and the crop occupies around 4.5 Mha or 18% of the total area of the state. This resulted in legislation being passed in this state in 2003 mandating that all preharvest burning of cane in São Paulo be phased out by the year 2022. Only on terrain with a slope of more than 12%, where machine harvesting is impractical, will burning be permitted until 2032 (Machado Pinheiro et al., 2010).

The New South Wales government proposed the "Protection of the Environment Operations (Clean Air) Regulation 2010." According to the POEO Act, "Section 133 empowers DECC to restrict open burning, conditionally or unconditionally, on days when weather circumstances indicate that burning is likely to contribute to considerable air pollution" (NSW, 2019).

3 Challenges and Opportunity to Use Sugarcane Trash for Beneficiaries

Sugarcane is mainly composed of 72% clean stalk, 8% GSTs, and 20% DSLs. One ton of harvested sugarcane generates 140 kg of trash in the field (Alonso Pippo et al., 2011). ST's energetic potential was reported by Gómez et al. (2014). Heating value, ash, volatile matter, and fixed carbon content of ST are 4774 kcal/kg, 9.22%, 81.83%, and 8.95%, respectively. It also contains elements like silica, potassium, sodium, and phosphorus.

Mulching, composting, fuel, fodder, thatching, and paper and pulp industries are all use sugarcane trash for its benefits. Mulching ST increases total agricultural production, protects the soil from erosion, maintains soil temperature, protects the soil from direct radiation, increases biological activities in the soil, improves water infiltration in the soil, prevents evapotranspiration, suppresses weed growth, improves soil moisture, increases organic matter in the soil, and increases carbon sequestration (Rossetto et al., 2010). Nonetheless, it has certain negative effects on crops, such as reduced ratoon sprouting, increased fire danger, waterlogging in the field, nitrogen losses from the soil, pest and disease occurrences, and difficulty in farm operations (Hass & Lima, 2018).

ST composting occurs in two stages, namely, intensive decomposition and curing. The extensive breakdown process is further divided into two stages: mesophilic (45 °C) and thermophilic (>45 °C). Composting increases soil porosity by adding more humus, enhances plant development, minimizes soil erosion and discharge of water, and increases the nitrogen, phosphorus, and potassium content in soil (De Figueiredo & La Scala, 2011; Nakashima et al., 2017; Mohan & Ponnusamy, 2011). The composting process takes around 180 days. This is a significant impediment in the composting process.

GSTs have traditionally been utilized as animal fodder in India. The ST, on the other hand, is unpalatable and has poor digestion, bulky fibrous components, a low amount of nitrogen, soluble carbohydrates, and a low number of minerals and vitamins. Furthermore, because it includes a higher concentration of lignin, it is unsuitable for use as livestock fodder (Rathod et al., 2017). As a result, the value addition of ST is required to meet the nutritional standards of the animals.

Global energy demand is increasing on a daily basis (Smithers, 2014). To meet this energy demand, there is a need to explore alternate energy producing methods (Powar & Gangil, 2015). The agricultural sector has a large potential to address this energy need (Bhuvaneshwari et al., 2019). A hectare of sugarcane land can yield 6–8 tons of ST (Chandel et al., 2012). Sugarcane trash can be used directly for cogeneration, biochemically converted (ethanol) or thermochemically converted (bio-oil, bio-char, and producer gas) for energy. The heating value of sugarcane trash suggests that it could be used in a cogeneration facility (Bhardwaj et al., 2019) However, the higher silica content limits the usage of ST in the boiler (Bhardwaj et al., 2019). The fouling effect in the boiler is caused by high silica and ash concentration. It reduces boiler efficiency and causes boiler choke (Gómez et al., 2014). However, it is feasible to utilize it in a boiler with bagasse and wood (Patil, 2019).

Gasification, pyrolysis, and charring are the thermochemical conversion processes for using ST as fuel. Producer gas and bio-oil created from sugarcane trash have heating values of 3.56–4.82 MJ/Nm^3 and 15.48 MJ/kg (before dehydration), respectively (Treedet & Suntivarakorn, 2011).

ST contains higher amount of cellulose, hemicellulose, and lignin (Chandel et al., 2012). The higher amount of lignin content limits the ST for biochemical conversion process. The use of ST for biological conversion is possible with the conversion of cellulose, hemicellulose, and lignin into simple sugar monomers (arabinose, glucose, mannose, xylose, galactose, etc.) (Chandel et al., 2012). But the conversion process requires higher energy, pressure, and temperature in the reactor. The cost involved in this process is high.

4 Impact of Open Burning of Sugarcane Trash on the Environment

The open burning of ST is a typical practice among farmers all across the world. It has drawbacks such as the loss of organic matter and nutrients from the soil, as well as the emission of greenhouse gases such as CH_4, CO, and CO_2 (De Figueiredo & La Scala, 2011; Powar et al., 2021). The unavailability of labor and less time to prepare the next crop are the major reasons behind it (Jain et al., 2014). Furthermore, some farmers believe that open burning promotes the emergence of sugarcane bud. But Savitha and Suma (2014) discovered that open burning of ST produces intense heat, which is responsible for a 32% reduction in bud germination rate.

The aforementioned potential and problems in front of the farmer for successful utilization of sugarcane trash were provided by a global researcher. Farmers, on the other hand, refuse to embrace any of the foregoing technologies and instead resort to open burning of sugarcane trash. There is a need to comprehend the underlying cause. As a result, a case study was conducted to predict farmers' knowledge, perceptions, and behavior about the utilization of sugarcane trash for beneficiaries.

5 Case Study

The case study highlights the methodology that predicts farmers' knowledge, perception, and practices toward the use of sugarcane trash using logistic regression model. The study aims to understand farmer's mindset toward utilization of sugarcane trash.

6 Study Area

The research was carried out in the Kolhapur district of Maharashtra, which is located in the state's southernmost region. Kolhapur has a mild climatic condition of 16° 41′ 28″ N and 74° 14′ 41″ E. Kolhapur's average annual rainfall, humidity, and temperature are 1239 mm, 71.8%, and 24.8 °C, respectively (Powar et al., 2020). The study area is shown in Fig. 1.

7 Logistic Regression Model

In the 1940s, logistic regression was proposed as a way to get around the constraints of ordinary least squares (OLS) regression when dealing with binary outcomes. In epidemiological studies, logistic regression is commonly used. In the meantime, the

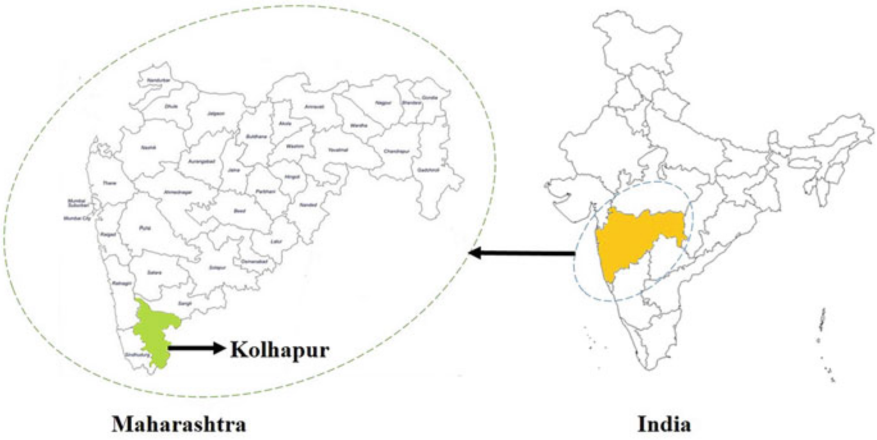

Fig. 1 Study area (Kolhapur district, Maharashtra, India)

usage of logistic regression in social and medical science is increasing (Peng, 2016). The categorical data is not processed by the linear regression model. It is feasible to process using the logistic regression model, which establishes a link between dependent and independent variables. It also predicts the value of independent variables by utilizing the dependent variable. A linear relationship between the response and the explanatory factors is ignored in logistic regression (Abdulqader, 2017). The binary logistic regression model is used to process categorical data that is merely “yes/no” (2 values), while the multinomial and ordinal logistic models are used to process categorical data that is “poor, fail, good” (more than two values). Figure 2 shows the logistic regression model process.

7.1 Sample Size

Historical data on the utilization of sugarcane trash for beneficiaries are not available in the study area. Thus 95% confidence, 5% desired degree of accuracy, and 50% predicted prevalence were used to estimate the sample size (Agmas & Adugna, 2020). A minimum of 50 cases are required for each explanatory variable (Abdulqader, 2017). The sample size is calculated using Eq. (1).

$$n = \frac{1.96^2 \times E_p \times \left(1 - E_p\right)}{D_{ap}} \tag{1}$$

where:

E_p = expected prevalence, %.
D_{ap} = desired degree of accuracy, %.

7.2 Collection and Preparation of Data

The data were collected from farmers of the study area using prepared questionnaire. At time of data collection, the progressive farmers, government agriculture officers, teachers, and agriculture graduates were considered as data source. The data were collected from the period of January to February 2021. The designed questionnaire has both open- and closed-ended questions to fulfill the objectives. The questionnaire was composed of two sections (Table 1). The first section included questions

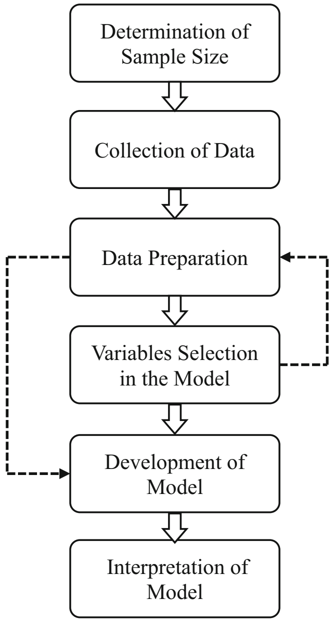

Fig. 2 Logistic regression model process

Table 1 A survey of farmers' knowledge, behavior, and experience toward use of sugarcane trash

Part 1: Basic information
Age
Education
Major income source
Part 2: Farmers' knowledge, behavior, and experience toward use of sugarcane trash
After harvesting, do you burn the sugarcane trash in the field?
Do you know the significance of sugarcane trash in organic farming?
Do you know the burning of sugarcane trash can pollutes the environment?
Is there any influence on nearby crops owing to the burning of sugarcane trash in the field?
Have you heard about how to use sugarcane trash to improve soil fertility from the media, newspapers, magazines, or research articles?
Are you using sugarcane green tops as fodder for animals after harvesting of sugarcane?
Have you used dried sugarcane leaves as a mulch?
Is there any benefits of burning of sugarcane trash in the field?

related to basic social information such as age, education, and major income source. The second part included questions regarding farmers' knowledge and behavior toward utilization of sugarcane trash (Table 1). The collected data were entered into MS Excel sheet and coded in format such as "Yes =1" and "No = 0."

8 Variables Selection and Model Estimation

The selection of variables is the most important step in a logistic regression analysis. This strategy removes elements from the model that don't have a strong relationship with the dependent variables. The binary regression model was used in this study, with the dependent variable having one of two values. The basic form of a logistic regression model is shown in Eq. (2) (Abedin et al., 2016).

$$E(Y/X) = \mathrm{In}\ \frac{\pi}{1-\pi} = \beta_0 + \beta_1 X_1 \tag{2}$$

where:

$Y =$ outcome variable.
$X =$ predictor.
$\pi =$ the probability of occurring the outcome Y.
$(1 - \pi) =$ probability of not occurring the outcome.
β_0 and $\beta_1 =$ regression coefficient.

If there are multiple predictors (n), the extended form of the logistic regression equation is shown in Eq. 3 (Abedin et al., 2016).

$$E(Y/X) = \mathrm{In}\ \frac{\pi}{1-\pi} = \beta_0 + \beta_1 X_1 + \ldots + \beta_n X_n \tag{3}$$

Therefore, the probability of success is found using Eq. (4).

$$\pi(x) = P(Y/X = x) = \frac{e^{\beta_0 + \beta_1 X_1 + \ldots + \beta_n X_n}}{1 + e^{\beta_0 + \beta_1 X_1 + \ldots + \beta_n X_n}} \tag{4}$$

The regression coefficient represents the relation between the predictor (X_1, X_2,......X_n) and the output variable "Y" or logit of Y. If the regression coefficient is greater than zero, it indicates that there is a direct proportional relationship between the predictor and the outcome variable; if it is less than zero, it indicates an indirect proportional relationship between the predictor and the outcome variable; and if it is equal to zero, there is no relationship between the predictor and the result variable (Abedin et al., 2016).

The maximum likelihood (ML) technique or the weighted least squares method (Abedin et al., 2016) can be used to determine regression coefficients; however, the maximum likelihood method has been more widely used for obtaining logistic regression coefficients than the least square method (Abedin et al., 2016). Therefore, maximum likelihood (ML) technique was used for estimating regression coefficients in this study. The maximum likelihood (ML) is determined using Newton-Raphson method. The probability density function is given in Eq. (5) (Abedin et al., 2016):

$$P(Y/\pi) = \prod_{i=1}^{n} \pi^{y_i}(1-\pi)^{1-y_i} \tag{5}$$

The log likelihood is determined using Eq. (6). The log likelihood is always negative, with larger values (closer to zero) indicating a better fitting model (Anonymous, 2021).

$$\log\ L(\pi/Y) = \sum_{i=1}^{n} \log\ \left(1 + e^{(1-2y_i)x_i\beta_i}\right) \tag{6}$$

The gradient of the likelihood with respect to the estimated coefficient is given in Eq. (7) (Abedin et al., 2016).

$$\frac{\partial \mathrm{InL}}{\partial \beta} = \sum_{i=1}^{n} (y_i - \pi_i)x_i \tag{7}$$

Similarly, the odds ratio or the delta p is employed in order to comprehend regression coefficients. The odds ratio is used for categorical data, whereas the delta p is used for continuous data (Abedin et al., 2016). In this study, the odds ratio interpretation approach was used. The odd ratio is determined using Eq. (8).

$$\text{odds}\ (n) = \frac{p}{1-p} \tag{8}$$

where p is the probability value that ranges between $0 \leq p \leq 1$. If the odd ratio is greater than zero, it indicates that the predictor is associated with increased risk of outcome; if it is less than zero, it indicates that the predictor is associated with decreased risk of outcome; and if it is equal to zero, there is no association between the predictor and outcome (Abedin et al., 2016). The likelihood ratio (LR) test or pseudo R^2 test can be used to assess the overall model significance, whereas Wald's test can be used to examine the statistical significance of the regression coefficient. The LR test compares the fit of one model to the fit of the other by estimating two models and comparing their fits. The Wald test is similar to the LR test, but it has the advantage of only requiring one model to be estimated (Anonymous, 2021). LR and weld's tests are calculated using Eqs. (9) and (10), respectively (Anonymous, 2021).

$$LR = -2 \ln \left(\frac{L(m_1)}{L(m_2)}\right) \tag{9}$$

where:

m_1 = more restrictive model.
m_2 = less restrictive model.

$$\text{Wald} = \frac{\beta_1}{SE\,\beta_1} \tag{10}$$

where:

β_1 = maximum likelihood estimate of regression coefficient.
$SE\,\beta_1$ = estimate of standard error.

9 Goodness-of-Fit Test

The goodness-of-fit statistic is used to evaluate the fit of a logistic model to the actual outcome (Peng, 2016). In this work, four distinct tests were used, namely, McFadden's R^2, Cox and Snell's R^2, Nagelkerke's R^2, and Hosmer-Lemeshow test, which are represented by Eqs. 11, 12, 13, and 14, respectively (Anonymous).

$$R_L{}^2 = 1 - \frac{LL_1}{LL_0} \tag{11}$$

$$R_{cs}{}^2 = 1 - e^{-\frac{2}{n}(LL_1 - LL_0)} \tag{12}$$

$$R_N{}^2 = \frac{R_{cs}{}^2}{1 - e^{\frac{2LL_0}{n}}} \tag{13}$$

$$HL = \sum_{i=1}^{g} \sum_{j=1}^{2} \frac{\left(\text{obs}_{ij} - \exp_{ij}\right)^2}{\exp_{ij}} \tag{14}$$

The analysis was carried out using "Charles Zaiontz's" software "Real Statistics Using Excel."

10 Results and Discussion

10.1 Sample Size

The total sample size required for analysis was calculated using Eq. (1). The total sample size based on Eq. (1) was expected to be 384. In the present study, the surveyed data were collected from 390 farmers. Also, care should be taken that a minimum of 50 cases are included for each explanatory variable (Table 1).

Table 2 Respondents' socioeconomic profiles ($n = 390$)

Age (year)	20–30	30–40	40–50	50–60	>60
Percentage (n)	13.13 (52)	35.89 (140)	18.20 (71)	18.46 (72)	14.10 (55)
Education	Agriculture		Non-agriculture		
Percentage (n)	44.35 (173)		55.64 (217)		
Main income sources	Agriculture		Other than agriculture		
Percentage (n)	49.74 (194)		50.25 (196)		

11 Socioeconomic Profiles of the Surveyed Farmers

The age of a person is determined by a set of well-defined ordinal scale categories (Table 2). Table 2 reveals that the 30–40 age group had the largest percentage of responders (35.89%), followed by 18.46% in the 50–60 age group, 18.20% in the 40–50 age group, 14.10% in the >60 age group, and 13.13% in the 20–30 age group, with the least number of respondents. In terms of educational attainment, non-agriculture sector respondents account for 55.64% of the sampled population, followed by non-agriculture sector respondents, who account for 49.74% of the sampled population. The major income sources of surveyed respondents are from other than agriculture sector (50.25%), followed by agriculture sector (49.74%). The above data clearly defined that agriculture is the primary source of income for over half of all surveyed farmers. Furthermore, the information gathered is sufficient for further statistical analysis (Agmas & Adugna, 2020).

12 Respondents' Knowledge and Activities on the Management of Sugarcane Trash

Table 3 represents the respondents' knowledge and activities on the management of sugarcane trash. Respondents were asked how they handle sugarcane trash after harvesting (on a range of Yes = 2 to No = 1) on a nominal scale. The data revealed that 61.3% of farmers burn sugarcane trash in the field after harvesting sugarcane, while 38.7% used sugarcane trash for other applications. Dhanushkodi and Padmadevi (2018) reported the major constraints behind the open burning of sugarcane trash, viz., lack of technological awareness, poor purchasing ability of the farmer, and unavailability of market. Additionally, inadequate training, demonstration, and extension activities are also responsible for sugarcane trash burning. 95.7% of the respondents very well know that burning of sugarcane trash pollutes the environment, whereas 4.3% are unaware of the adverse effect of open burning of sugarcane trash. It emphasizes the necessity for a comprehensive policy on how to use sugarcane trash for beneficiaries. Similarly, 73.1% of respondents said that burning of sugarcane trash in the field has an impact on surrounding crops, while 26.9% said they don't believe the above cause. It depicts the cumulative effects of the intense heat liberated from burning field on nearby trees and crops. 58.1% of

Table 3 Respondents' knowledge and activities on the management of sugarcane trash ($n = 390$)

Activity	Percentage		Mean	Standard deviation
	Yes	No		
After harvesting, do you burn sugarcane trash in the field? (%)	237 (61.3)	153 (38.7)	1.61	0.49
Are you aware of the significance of sugarcane trash in organic farming? (%)	297 (77.4)	93 (22.6)	1.77	0.42
Do you know that burning sugarcane trash pollutes the environment? (%)	365 (95.7)	25 (4.3)	1.95	0.20
Is there any influence on nearby crops owing to the burning of sugarcane trash in the field? (%)	281 (73.1)	109 (26.9)	1.73	0.44
Have you heard about how to use sugarcane trash to improve soil fertility from the media, newspapers, magazines, or research articles? (%)	165 (41.9)	225 (58.1)	1.42	0.49
Are you using sugarcane green tops as fodder for animals after harvesting of sugarcane? (%)	357 (93.5)	33 (6.5)	1.93	0.25
Do you utilize green sugarcane leaves as animal fodder during the growth period of sugarcane? (%)	281 (73.1)	109 (26.9)	1.73	0.44
Have you used dried sugarcane leaves as mulch? (%)	133 (33.3)	257 (66.7)	1.33	0.47
Is there any benefits of burning of sugarcane trash in the field? (%)	165 (41.9)	225 (58.1)	1.42	0.49

Note: The survey data was converted to "Yes = 2" and "No = 1" to determine the mean and standard deviation

respondents said they got information on how to use sugarcane trash to improve soil health from the media, while 41.9% said they didn't. As a result, it is obvious that nearly 42% of farmers do not have access to media. Therefore, policymakers must concentrate on extension activities.

93.5% of respondents said they use sugarcane green tops as fodder for animals, while 6.5% never use sugarcane tops as fodder for animal. Green sugarcane tops have been utilized as cattle fodder in India from centuries (Rathod et al., 2017). They are unpalatable and have poor digestible and bulky fibrous components, low nitrogen, soluble carbohydrates, and minimal mineral and vitamin content. It also includes a greater level of lignin, making it unfit for use as cattle fodder (Rathod et al., 2017). As a result, value addition of ST is required to meet the nutritional requirements of the animals. Sugarcane trash is used for mulching by 33.3% of respondents. However, 66.7% of farmers do not appreciate mulching due to the influence of rodents, snakes, and scorpions in their area. Finally, farmers were asked if burning of sugarcane trash has any advantages, and 41.9% replied with a "yes," while 58.1% said "no." There are certain advantages to burning sugarcane trash on the field. It destroys seeds of weeds and pests and their breeding places, as well as clear the field for the next crop (Powar et al., 2018).

13 Selection of Model

Table 4 shows the selection of variables in the model. There are four different variables, viz., age, education level, occupation, and training. Variable age and training significantly ($P < 0.05$) affect the burning of sugarcane trash in the field, while education and occupation do not significantly affect burning of sugarcane trash even at 10% level of significance. Therefore, variable age and training were selected for further analysis.

Table 5 shows the estimation of logit regression model for the burning of sugarcane trash in the open field. The selected variables, viz., age and training, are statistically significant at $P < 0.001$ of level. Also the intercept of model is highly significant at $P < 0.001$ of level. It indicates that the model is perfectly fit for the analysis. The regression coefficient for age and training predictor are −0.02183 and −0.7760, respectively. Both predictors have a negative sign; the negative sign of age indicated that older age increases the probability of burning of sugarcane trash in the field to relapse. Similarly, the negative sign of training indicated that proper training activity to farmers increases the probability of burning sugarcane trash in the field to relapse.

The odds ratio shown in Table 5 indicate the information of each predictor. The odds ratio for age is 0.9784 and ranged between 0.9589 and 0.9982. This indicated that with each unit increase in age, the odds ratio increased the probability to relapse by 0.9784. Similarly, the odds ratio for training is 0.4602 and ranged between 0.2854 and 0.7418. This also indicated that with training, there is less likely relapse by 0.4602 versus with no training on utilization of sugarcane trash. Similar types of interpretation were also done by Abedin et al. (2016) to measure probability of relapse cases among drug addicts.

Table 6 represents the classification table to compare predicted values with the observed values. Table 6 revealed the improvement when the predictors' age and training are included into the model compared to the null hypothesis. The improvement can be evaluated by comparing the overall accuracy. In the present case, the predictors are classified with an overall accuracy of 60%. This model is able to classify correctly 93% of the respondents who burn sugarcane trash in the field, with 8.3% who do not take part in burning of sugarcane trash.

Table 4 Selection of variables in the model

Dependent variable	Independent variables	B	S.E	Wald	DF	Significance (p value)
Burning of sugarcane trash	Age	−0.02479	0.011085	4.999733	1	0.025351*
	Educational level	−0.28516	0.257733	1.224168	1	0.268544^{ns}
	Occupation	0.079285	0.222488	0.126989	1	0.721575^{ns}
	Training	−0.66283	0.26357	6.324228	1	0.01191*
	Intercept	1.57054	0.470995	11.11898	4	0.000854***

Level of significance: $^{***}(P < 0.001)$; $^{**}(P < 0.05)$, $^{*}(P < 0.1)$, ns = not significant

Table 5 Estimation of logit regression model

Variables	Coeff.	S.E.	Wald	p-value	Exp(b)	Lower	Upper
Intercept	1.417458	0.381021	13.83956	0.000199***	4.126618		
Age	−0.02183	0.010248	4.536906	0.033172**	0.978408	0.958951	0.998259
Training	−0.77605	0.243609	10.14831	0.001444*	0.46022	0.285499	0.741866

Level of significance: ***($P < 0.001$); **($P < 0.05$), *($P < 0.1$), ns = not significant

Table 6 Classification table for comparing predicted values with the observed values

Parameters	Observed success	Observed fail	Total
Predicted success	213	131	344
Predicted fail	16	12	28
Total	229	143	372
Accuracy	0.93	0.083	0.60

Table 7 Goodness of fit of the model

Goodness of fit	Cox and Snell R^2	Nagelkerke R^2	Hosmer and Lemeshow
Values	0.031	0.042	0.024

The amount of variation in dependent variables is explained by Cox and Snell's R^2 and Nagelkerke's R^2. The values of Cox and Snell's R^2 and Nagelkerke's R^2 given in Table 7 are 0.031 and 0.042, respectively. It explained the variability between 3.1% and 4.2% by this set of variables. Through the Hosmer and Lemeshow goodness-of-fit test, the model is considered as a poor fit if the significance value is less than $P < 0.05$. The value of chi square is 11.92 with corresponding p-value equal to 0.0025. The corresponding p-value is less than the 0.05; thus, it indicates that the model is not well fitted.

14 Conclusions

The data revealed that 61.3% of farmers burn sugarcane trash in the field after harvesting sugarcane, while 38.7% used sugarcane trash for other applications. 95.7% of respondents very well know that burning of sugarcane trash pollutes the environment, whereas 4.3% are unaware on the adverse effect of open burning of sugarcane trash. It emphasizes the necessity for a comprehensive policy on how to use sugarcane trash for beneficiaries. Similarly, 73.1% of respondents said that burning of sugarcane trash in the field has an impact on surrounding crops, while 26.9% said they don't believe the above cause. It depicts the cumulative effects of the intense heat liberated from burning field on nearby trees and crops. 58.1% of respondents said they got information on how to use sugarcane trash to improve soil health from the media, while 41.9% said they didn't. As a result, it is obvious that nearly 42% of farmers do not have access to the media. Therefore, policymakers must concentrate on extension activities. 93.5% of respondents said they use sugarcane green tops as fodder for animals, while 6.5% say otherwise. Sugarcane trash is used for mulching by 33.3% of respondents. However, 66.7% of farmers do not appreciate mulching due to the influence of rodents, snakes, and scorpions in their area. Finally, farmers were asked if burning of sugarcane trash has any advantages, and 41.9% replied "yes," while 58.1% said "no." There are certain advantages to burning sugarcane trash on the field. It destroys seeds of weeds and pests and their breeding places, as well as clears the field for the next crop.

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Production and Use of Biofuel from Agricultural Resources

Transition Towards Low Carbon Economy

Shiv Prasad, M. S. Dhanya, and Amitava Rakshit

Contents

Abstract

Agricultural biomass resources-based energy production and use is the key to enabling the transition towards a low-carbon economy. It has gained momentum at the national, regional, and global levels due to its potential to mitigate climate change, energy security, access, and reduce air pollution. Biofuel is regarded as an eco-friendly and sustainable alternative to fossil fuels. Biomass resources-based energy can reduce global CO_2 emissions and temperature elevation to 1.5 °C by 2050. Several thermal and bio-chemical routes are currently used to produce

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biofuel in the form of solid, liquid, and gaseous fuels from agricultural resources. This chapter discusses the prospect of agricultural biomass, scientific and technical advancements, opportunities, and challenges globally and in Indian contexts. Although crop biomass is a renewable resource, its open-field burning is often causing several environmental issues. Nevertheless, if existing biomass is used efficiently, it can meet India's and many other countries growing biofuel demand. It could also minimize fossil fuel dependency in transport, agriculture, industrial, and many other sectors.

Keywords

Agricultural resources · Low carbon economy · Thermochemical · Bio-chemical · Biomass biofuel · Sustainability

1 Introduction

Fossil fuel use has negatively impacted the environment due to the discharge of toxic air pollutants and is responsible for global climate change (Prasad et al., 2014a, b; Sheetal et al., 2017; Ambaye et al., 2021). In order to fight these impacts, intensive measures are being taken globally to switch from a high-carbon fossil fuels economy to a lower-carbon renewable fuels economy (Prasad et al., 2021a). Biofuel production from farm resources is an eco-friendly option to fossil fuels. Its use is considered helpful in the transition toward a low-carbon economy (Prasad et al., 2007, 2021a). Therefore, the domestic production and usage of biofuel from agricultural resources are anticipated to achieve an overall balance of energy demand and significant roles in the circular economy and energy supply chain (Prasad et al., 2019, 2020a, b; MNRE, 2021).

Globally share of bioenergy in the total primary biofuel supply is expected to rise from 14% in 2015 to 63%, where biofuel from farm resources alone will account for around two-thirds in 2050 (Gielen et al., 2019). However, in India, almost 32% of the primary energy supply is still obtained from farm resources, which fulfills more than 70% of the country's biofuel demands. The availability of plant biomass in India is assessed to be more than 500 MMT (million metric tons) annually, including crop biomass residues. It has a potential of almost 18,000 MW (megawatts). An excess of 7000 MW of biofuel could be fetched by sugarcane bagasse co-generation (MNRE, 2019).

Renewable biofuel is generated from various agricultural resources, reduces C-footprint, and enhances air quality because crop plants absorb CO_2 from the air and perform photosynthesis in sunlight to produce biomass. Utilization of agricultural biomass for biofuel production through thermal and biochemical processes has several benefits: (i) substantial assistance to direct energy supply, (ii) notable declines in greenhouse gases (GHGs) emissions and less CO_2 emission than fossil fuels, (iii) energy security (iv) positive influence on socio-economic development (v) and promote and execute strategic wastes reduction, reuse, and its recycling (Prasad et al., 2014a, b; Sheetal et al., 2017; Alzate et al., 2018; IRENA, 2019; Poveda-Giraldo et al., 2021).

Strategies to achieve a low-carbon or decarbonized economy must focus on: (a) reducing fossil fuel demand, changing lifestyle and power consumption patterns through efficiencies, and; (b) shifting towards new technologies by developing products with low CO_2 emissions and lower pollution during production and use (c) promoting carbon capture in biomass resources and storage to achieve net-zero CO_2 in the production system. Several scientific and technical advances have been made in biofuel production from agricultural resources. They are essential in moving towards a high-low-carbon economy (Prasad et al., 2021a). However, it currently has many challenges, especially in developing and underdeveloped countries. Biowaste and crop residue valorization is among the most advantageous sectors for expansion in renewable biofuel generation (Kiesecker et al., 2020; Gupta et al., 2021; Prasad et al., 2021b).

On the other hand, burning agricultural biomass reduces air pollution and mitigates global climate change (Prasad et al., 2014a, b; IRENA, 2019; Poveda-Giraldo et al., 2021). Therefore, if agricultural resources are adequately used to produce biofuel like ethanol, biodiesel, bio-oil, methane, hydrogen, and fuel gas via thermal and biochemical techniques. It can handle multiple problems, including energy self-sufficiency, the use of surplus farm waste, and environment-related problems in India (Prasad et al., 2019). Furthermore, energy production from biowaste similarly protects the atmosphere from emissions due to its proper disposal and management (Prasad et al., 2021b). This chapter examines agricultural resources' physico-chemical composition, scope, recent advances in accessible technologies, and the economic feasibility of converting them to various biofuels. It highlights biofuel-related challenges, prospects, and opportunities toward moving a low-carbon economy within global and Indian contexts.

2 Transition Towards a Low Carbon Economy

A transition towards a low-carbon economy (decarbonization) could be achieved by decreasing fossil fuel consumption and consumption patterns. It includes developing products and technology with low CO_2 emissions, lower pollution during production, use, waste recycling, and capturing CO_2 in biomass resources (Prasad et al., 2021b). However, worldwide energy consumption and CO_2 emissions have risen rapidly over the last two decades, becoming obstacles to achieving sustainable development goals despite various efforts to realize sustainable economic development (Prasad et al., 2014a, b, 2020a). Achieving a low carbon targeting of the economy will not be easy. However, a recent report identified the following points to achieve net-zero CO_2 in the production system by 2050.

2.1 Waste Reduction, Reuse, and Recycling

An inter-governmental body of the UN, the globally known Intergovernmental Panel on Climate Change (IPCC), already recognizes that biomass waste reduction, reuse, and recycling are at the center of a low-carbon economy that aims to reduce waste and keep materials in use for longer. The most practical way to decrease waste is not to create it first (Prasad et al., 2021b). Although many countries have their top agendas to minimize unnecessary consumption worldwide, cutting demand for energy puts a premium on efficiency. Organic waste, including sewage sludge, municipal waste, and waste from the agro-food industry, can produce biofuels, especially bio-oil, low-sulfur fuel, and methane. They can be reused in production cycles to achieve a lo*w-carbon* circular economy by reducing waste and lowering GHG from the entire production system (Prasad et al., 2021a).

2.2 Enhancement in Use of Bio-Based-Electric and Biofuels

In order to achieve decarbonization and zero-emission goals, there is a need to enhance bio-based electric and biofuel use in the total energy mix and emerging economies. Agricultural biomass resources-based energy in solid, liquid, and gaseous forms is currently used to generate electricity. However, ultra-low C-biofuels, and other forms of renewable bioenergy, hold a promising future in reducing CO_2 emissions at the national, regional, and global levels. Biofuel use can limit the global temperature rise to 1.5 °C by 2050. At the 26th UN Climate Change Conference (COP26) worldwide, many countries have decided to limit global warming, and industries and companies are trying to achieve net-zero CO_2 in the production system by 2050.

2.3 Carbon *capture*, Storage, and Sequestration

Governments, industries, and consumers are committed to moving to a lower-carbon world. Incorporating carbon capture and sequestration/storage (CCS) has gained momentum due to climate change mitigation. Economy-expanding programs that create high carbon sinks in the environment represent numerous environmental benefits, including energy security, climate resilience, trade promotion, employment, and health benefits. Worldwide, capturing CO_2 from industries has been admitted as a credible tool to decrease CO_2 emissions in the environment. However, the conversion of agricultural biomass resources (organic material) into heat, electricity, or liquid or gaseous biofuel and combining biofuel production with carbon capture and sequestration can lead to net harmful emissions as carbon is stored by photosynthesizing biomass.

3 Utilization of Agricultural Biomass Resources for Biofuel

Agricultural biomass resources can be expressed as organic matter from harvesting different crops and vegetation, such as waste residues from harvesting and processing corn stover, bagasse, rice, and wheat straw. Nowadays, dedicated biofuel crops, known for high biomass productivity per unit area, such as switchgrass, and miscanthus, are promoted worldwide for biofuels. These biomass resources mainly contain fiber/fibrils, particularly cellulose, hemicellulose, and lignin. Biomass fibrils in plant cell wall matrices and their structural matrix are presented in Fig. 1.

These fibrils, mainly cellulose, hemicellulose, and lignin in plant cell wall matrix in farm biomass resources, decide the potential of biofuel production from them. The chemical properties of plant fibrils in cell walls are shown in Table 1.

The structural composition of significant biomass resources is demonstrated in Table 2. Usually, agricultural resources contain up to 50%, 30%, and 25% cellulose, hemicelluloses, and lignin, respectively (Table 2). The biomass resource availability is estimated at around 500 MMTs annually from agriculture, forestry, and other biomass waste produced in India. India produces massive agricultural farm waste and is ranked second globally in agro-based economies (Kumar et al., 2019). In addition, field-based crop waste and other fibrous materials such as lignocellulosic biomass, straws, grain husks, crop sticks, corn stalks, leaves, roots, bagasse, and coconut shell are important agricultural resources.

According to a current investigation by Venkatramanan et al. (2021), agricultural biomass resources are surplus and can be used as a sustainable feedstock for biofuel. The surplus of major crop residues and their contribution to the national average is presented in Fig. 2. At the national level, surplus fractions of various major crop residues, especially cereals, oilseeds, pulses, sugarcane, horticultural, and other crops, contribute 29, 30, 38, 39, 42, and 38%, respectively.

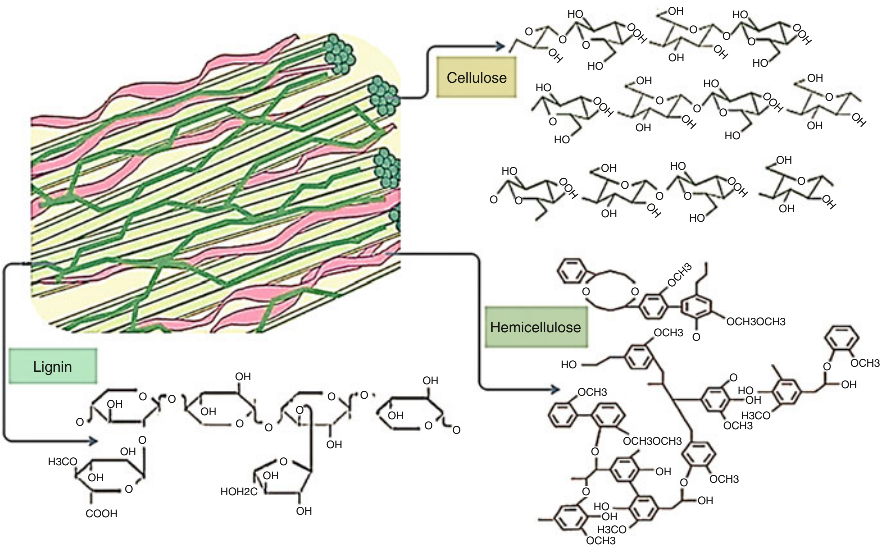

Fig. 1 A structural configuration of cellulose, hemicellulose, and lignin in plant cell wall matrix

Table 1 Chemical properties of cellulose, hemicellulose, and lignin in plant cell walls

Component	Cell wall structure	Polymerization	Polymer	Sub-component	Bonding in subcomponent	Bonding between three components
Cellulose	3D, amorphous area, a linear molecular combination of crystalline area	100–10,000	β-Glucan	D-Pyranglucose component	β-1, 4-Glycosidic	No chemical bonding
Hemicellulose	3D, minor crystalline area, inhomogeneous molecular	<200	Polyxylose, Galactoglucomannan (Gal-Glu-Man), glucomannan (Glu-Man)	D-Xylose, mannose, L-arabinose, galactose, glucuronic acid	β-1.2-, β-1.3-, β-1.6-glycosidic bonds inside chains, β-1,4-Glycosidic bonds in main chains	Chemical bonding with lignin
Lignin	Amorphous, nonlinear polymer 3D, nonhomogeneous	4000	G lignin, GS lignin, GSH lignin	Guaiacyl (G), syringyl (S), hydroxyphenyl(H)	Carbon-oxygen and carbon-carbon bond, ether bonds (mainly β-*O*-4)	Chemical bonding with hemicellulose

Table 2 Structural composition of important agricultural biomass resources

Agricultural biomass resources	Structural composition		
	Cellulose (%)	Hemicellulose (%)	Lignin (%)
Sugar cane	51.8	27.6	10.7
Wheat straw	38.9	21.1	18
Corn stover	35.3	28.9	19.9
Corn cobs	37.6	31.6	20.8
Barley straw	31–34	24–29	4–15
Sugarcane bagasse	32.06	29.20	23.30
Oat straw	31–37	27–38	16–19
Cottonseed hairs	80–95	5–20	00
Sunflower hull	26.7	18.4	27
Cotton stalk	39.4	19.2	26.4
Rye straw	33–35	27–30	16–19
Sorghum stalk	35.4	17.4	18.8
Mustard stalk	39.5	18.7	22.5
Groundnut shell	33.7	17.3	29.7
Jute fiber	43–53	18–22	21–28
Miscanthus	50.34	24.83	12.0
Switch grass	45	31.4	12.0
Rye grass	21.3	15.8	2.7
Banana waste	13.2	14.8	14
Napier grass	47	31	22
Pineapple stem	37	34	20
Pearl millet straw	25.2	36.4	15.6
Sponge gourd fibers	66.59	17.44	15.46
Bermuda grass	25	35.7	6.4

Source: Prasad et al. (2018), Mishra and Mohanty (2018), Kumar et al. (2019) and Prasad et al. (2021a, b)

4 Biofuel Production in India

Due to insufficient infrastructure and complex processing, agricultural biomass resources are not utilized commercially at a large scale for biofuel production (Hiloidhari et al., 2014). Therefore, more emphasis must be given to developing infrastructure and stopping open-field biomass burning, causing several environmental problems and health hazards and contributing to global warming (Prasad et al., 2019). Nevertheless, they are utilized to produce biofuel efficiently. In that case, it will help to meet India's growing energy demand sustainably and minimize the dependence on non-renewable fossil fuels for transport and industrial sectors (Venkatramanan et al., 2021; Ambaye et al., 2021). In the Indian continent, the total estimated potential for agricultural resources for biofuel equivalent to power is approx. 26,000 MW (megawatts). Currently, 18,000 MW of power is produced from various agricultural crop residues and agro-industrial biomass waste (Annual Report, 2018–2019).

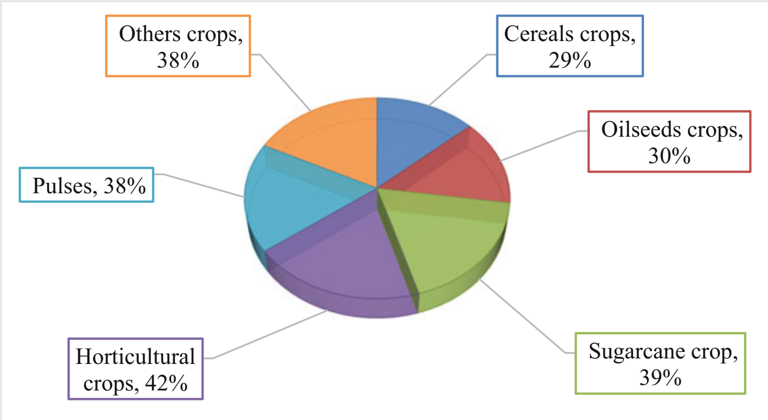

Fig. 2 Surplus of major crop residues and their contribution to the national average

Furthermore, the Indian government also emphasizes maximized economic profits of small and marginal farmers through job creation by renewable biofuel production (Pande et al., 2021). As a result, over 500 agricultural resources-based cogeneration projects with a total power generation of 9103.5 MW were commissioned in 2019 in various states of India. The leading state was Maharashtra, with the maximum grid-connected agricultural resources/bagasse power installed capacity (2499.7 MW). The second leading power generation state was Uttar Pradesh (1957.5 MW). State-wise commissioned grid-interactive agricultural resources power generation as of 31st March 2019 is shown in Fig. 3.

The Indian government plans to generate 50,000 MW of bioenergy from agricultural resources in the near future under the Clean Development Mechanism (CDM) scheme. About 200 biomass power generation projects have been registered, mostly related to sugarcane bagasse power co-generation (Elavarasan et al., 2020).

5 Biofuel Conversion Technologies for Agricultural Resources

Agricultural resources can be transformed into biofuels through physico-chemical, thermo-chemical, and biological technologies. Current biomass to biofuel technological progress has been discussed below with the following sub-headings.

5.1 Physical and Thermo-chemical Transformation of Biomass to Biofuels

Physico-thermal biomass conversion processes to biofuel principally work on application of pressure or heat to dandify biomass to pellets and briquettes. While in

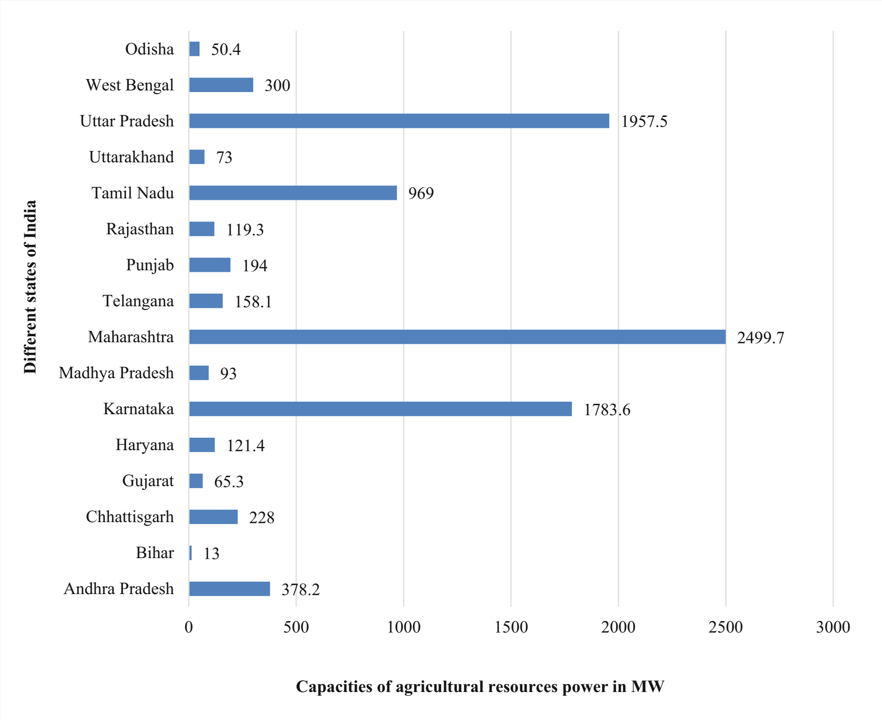

Fig. 3 State-wise grid-interactive biomass power commissioned capacities in India

thermochemical biomass to biofuel conversion processes, biomass combustion is done in regulated temperature, pressure, and oxygen content. Depending on biomass compositional contents and moisture present in it. Through this process, agricultural resources are concerted into char, bio-oil, and many other fuel products, such as gaseous fuel, oils, and methanol (Ayiania et al., 2019). Table 3 summarizes the advantages and disadvantages of thermo-chemical biofuel-making processes. Some critical studies on the thermo-chemical conversion of biomass waste to biofuels are presented in Table 4.

5.1.1 Biomass Pelletisation and Briquetting

Agricultural biomass pelletization and briquetting are performed based on densification under high compressive force by compacting them into briquettes and pellets. Moisture content plays a significant role in pelletization and briquetting, usually 12–18% and 15–30%, respectively, for better grinding and storage properties (Thurber et al., 2014). In contrast to pelletization, briquetting does not always require a binder, like molasses or tar pitch. Briquette and pellet may have 6–50 mm cylindrical diameters. As a result, they have a higher heating value, are resistant to moisture uptake, have better combustion efficiency than biomass raw materials (Brachi et al., 2017), and can be used for heating, cooking, and co-firing coal-fired power plants.

Table 3 Advantages and disadvantages of thermo-chemical biofuels production processes

Process	Pelletisation and briquetting	Combustion	Gasification	Liquefaction	Pyrolysis
Agricultural biomass	Crop residues and other biomass wastes	Crop residues and other biomass wastes	Crop residues and other biomass wastes	Diverse agricultural resources	Agricultural and other biomass wastes
Products	Pellets and briquette	Heat/electricity	Producer gas, dimethyl ether, hydrogen, synthetic natural gas	Bio-oil, biopolymers, polyurethane, resins, and adhesives	Bio crude (synthetic fuel oil) charcoal
Advantages	More densified pallete and briquette provide more energy than loose biomass combustion	Co-combustion of coal and agricultural resources; does not require modifications to current power plants; relatively simple process	Production of such biofuels is economically viable and less polluting than combustion, flexible in adaptation to market conditions	Liquid biofuels are chemically stable fuels high H/C ratio, less polluting than combustion	Direct application in electricity production
Disadvantages	After burning, it emits many pollutant gases like NO_x, SO_x, HC, CO, and particulate matter pose harmful effects on the environment and humans	Emission of pollutant gases like NO_x, SO_x, HC, CO, and particulate matter harm the environment and humans	Tar can block lower gasification efficiency, and downstream processes require heat input to drive chemical reactions	Pre-processing times are longer, biofuel-intensive downstream processing, and inferior yields	Corrosive and less thermal stability

Table 4 Some important studies on the thermo-chemical biomass conversion to biofuels

Thermo-chemical technique	Feedstock	Bioenergy yield/recovery	Operating conditions	References
Torrefaction	Sorghum biomass and pellets	Higher heating values (HHV), energy yield above 85%	Temperature 280 °C, 5 °C/min	Liu et al. (2020)
	Olive biomass waste	Higher heating values (HHV) 5830 cal/g	275 °C, residence time 30 min	Martín-Pascual et al. (2020)
Thermal gasification	Solid biomass/hazardous waste	Electric generation efficiency 41%, and total energy 81 megawatts	MSW co-gasification 90% by weight, O_2 volume 95%	Mazzoni et al. (2017)
	Pine chips and waste	Syngas composition: H_2: 26–42%, CH_4 8–11%	Temp 700–900 °C, steam and fuel ratio 0.3 kg/kg	Ngo et al. (2011)
	Rice biomass straw	Fuel gas 34%, composition H_2 5.5%, CH_4 0.5%	Temp 600–800 °C, O_2 ratio 33%, airflow 0.6 Nm^3/h, feeding rate 1.12 kg/h	Liu et al., 2018
Thermal liquefaction	Ponds sewage	Crude bio-oil 44.4%	Temp 300 °C, reaction time 15 min, water, and biomass ratio 10/1	Couto et al. (2018)
	Jatropha	Crude bio-oil 41.5%, energy recovery 54.8%	Temp 250 °C, reaction time 40 min	Lu et al. (2017)
	Microalgae	Crude bio-oil 60.0%	Temp 350 °C, and reaction time 15 min	López et al. (2015)
Thermal pyrolysis	Leaves and tops from sugarcane processing	Bio-oil 52–59%	Temp 403 °C and 429 °C N_2 gas flow rate 7 L/min, feeding rate 300 g/h	Pattiya and Suttibak (2017)
	Coffee waste	Syngas composition CO 4.7 mol%, H_2 1.6 mol%,	Temp 700 °C, reaction time duration 110 min	Cho et al. (2018)
	Pinyon chips	Hydrodeoxygenation (HDO) bio-oil 48 wt%	Temp 350 °C catalyst Ni/red mud, feeding rate 0.9 kg/h	Jahromi and Agblevor (2018)

In addition, it can address concerns associated with waste disposal (Prasad et al., 2021b). The process of agricultural biomass pelletization and briquetting is presented in Fig. 4.

Fig. 4 Process of agricultural biomass pelletization and briquetting

5.1.2 Process of Biomass Waste Combustion

Biomass waste combustion is the exothermic reaction where agricultural residues or wastes are ignited or burned at temperatures between 800–1000 °C aerobically or presence of air. In this process, steam is produced to generate electricity by steam turbines (Brown, 2019). The only drawback is the release of NO_x, CO_2, CO, ash, dust, and soot particles. However, co-combustion is now attractive due to its high energy production efficiency. Boumanchar et al. (2019) have reported that biomass co-combustion, especially in coal-fired power plants, has a bright future. The process of direct agricultural biomass combustion and steam-operated turbine electric generation system is presented in Fig. 5.

In this process, at high-temperature lignocellulosic biomass material react with O_2 and form CO_2, water vapour, and heat, as shown in Eqs. 1 and 2.

$$\text{Lignocellulosic material} + O_2 \rightarrow CO_2, + \text{Water} + \text{Heat} \tag{1}$$

Lignocellulosic material combustion (exothermic chemical reaction) and its thermochemical conversion.

$$CH_{1.44O0.66} + 1.03\ O_2 \rightarrow CO_2 + 0.72\ H_2O + \text{Heat} \tag{2}$$

Nussbaumer (2003) reported, on average, 20 MJ of thermal power produced from 1 kg of biomass waste. Lignocellulosic material combustion plants produce 20–50 MWe with 25–30% electrical efficiencies. Furthermore, the prime markets are predicted to raise an average of 31,000 MWe by 2030. India has made significant power production. For example, Heat Treatment and Fettling Service Private Limited, Hosur Tamil Nādu, has a 250 kg/h capacity. Another combustion plant Auromira, Chennai, has currently working with a potential capacity of 17.5 MW.

5.1.3 Biomass Pyrolysis Process

In the pyrolysis process, agricultural biomass resources are transformed into charcoal, bio-oil, and fuel gas by heating at temperatures between 300 °C and 800 °C

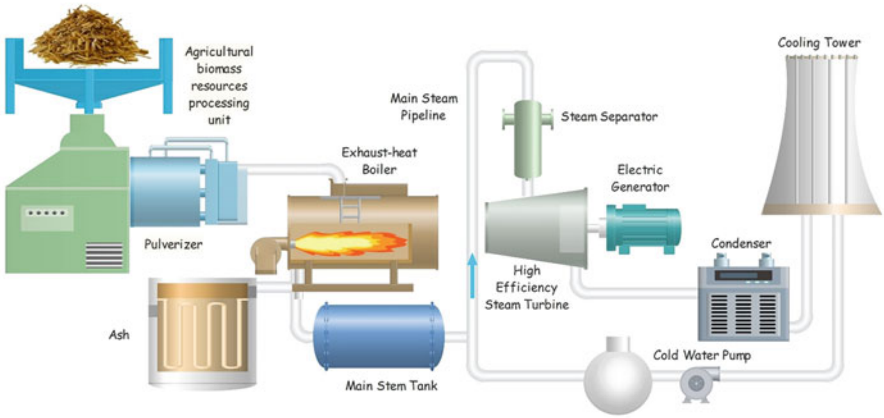

Fig. 5 Direct biomass combustion/steam turbine electric generation system

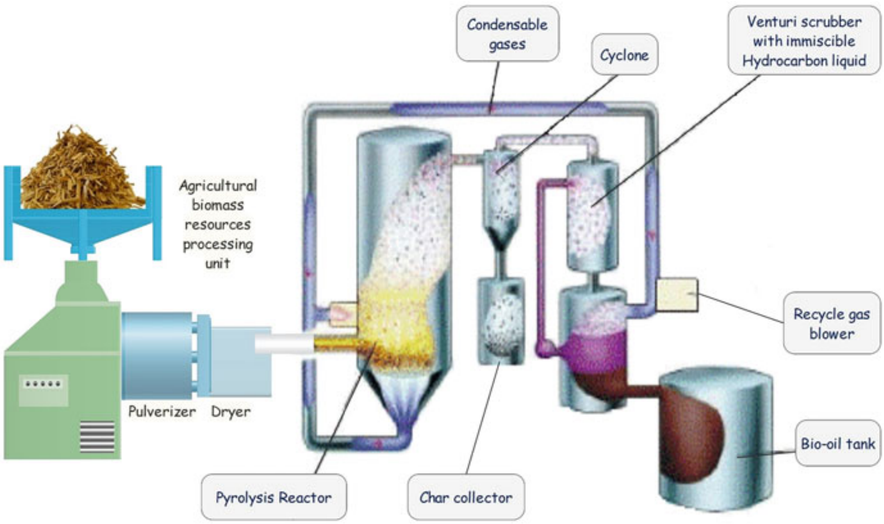

Fig. 6 Biomass pyrolysis system for producing biochar, bio-oil, and fuel gas

under a vacuum/inert condition or in the absence of oxygen. A typical biomass pyrolysis system is shown in Fig. 6. The thermo-chemical reactions during the process of pyrolysis take place as follows:

$$\text{Biomass} + \text{heat} \rightarrow \text{liquid (bio-oil)} + \text{solid (bio-char)} \\ + \text{gas (fuel gas/bio-syngas)}$$

Table 5 Classification of pyrolysis on the basis of temperature and residence times

Types of pyrolysis	Operating conditions	Energy products (wt%)
Slow	Temperature 300–700 °C; residence time 10–100 min, heating rate- 0.1 to 1 °C/s, biomass particle size- 5 to 50 mm	Bio-oil 30; biochar 35; fuel gas ~35
Fast	Temperature 400–800 °C; residence time- 0.5–5 s; heating rate 10–200 °C/s	Bio-oil 50; biochar 20; fuel gas 30
Flash	Temperature 800–1000 °C; residence time l to 0.5 s; biomass particle size l–0.2 mm	Bio-oil 75, biochar 12, fuel gas 13

Pyrolysis can be generally classified based on operating conditions, such as heating rate, temperature, and residence time, into three categories: (1) slow pyrolysis, (2) fast pyrolysis, and (3) flash pyrolysis. As shown in Table 5, operating conditions of various pyrolysis favor bio-oil, bio-char, and fuel gas production. Long hydrocarbon (HC) chains in agricultural biomass are split into small molecules during this process. For example, hemicellulose has high O_2 side branches, permitting the moderate breakdown of the HC chain, which help synthesize many organic acids, including acetic, furans, and sugars (Basu, 2018; Xiong et al., 2018). Flash pyrolysis yields 60% bio-char and 40% bio-oil and fuel gas, while fast pyrolysis produces more bio-oil with less biochar. Slow pyrolysis generates an almost equal amount of bio-oil, bio-char, and fuels-gas (Laird et al., 2009; Prasad et al., 2014a, b). The resulting bio-oil is utilized for fueling automobiles, engines, and turbines. They are also used as raw materials for refineries to produce various chemicals.

Significant drawbacks of this conversion process are limited thermal stability, technical complications, and corrosivity. Furthermore, upgraded bio-oils through hydrogenation and catalytic cracking require specific applications and reduction of O_2 content and alkali removal (Dhyani & Bhaskar, 2018). This process left high carbon residues of almost 35% in conventional or slow pyrolysis (Ranta et al., 2017).

5.1.4 Biomass Gasification Process

The gasification of lignocellulosic waste to energy is an endo-thermic reaction. This process is performed at 800–1000 °C temperature in partial O_2 oxidation or steam to convert biomass to syngas (Parmigiani et al., 2014; Basu et al., 2018). A typical model for the biomass gasification process with an electric generation system is presented in Fig. 7. In this mechanism, biomass thermochemically transformed into CH_4, H_2, CO, CO_2, C_2H_4, and C_2H_6, water, and tars, as shown below in Eq. 1:

$$\text{Biomass} \rightarrow CO + H_2 + CO_2 + CH_4 + \text{Tar} + H_2O + H_2S + NH_3 + C(\text{char}) + \text{trace gases} \tag{3}$$

The versatility of gaseous products as an energy source is the primary driver in biomass gasification. Carbon-to-Hydrogen mass ratio changed in this process,

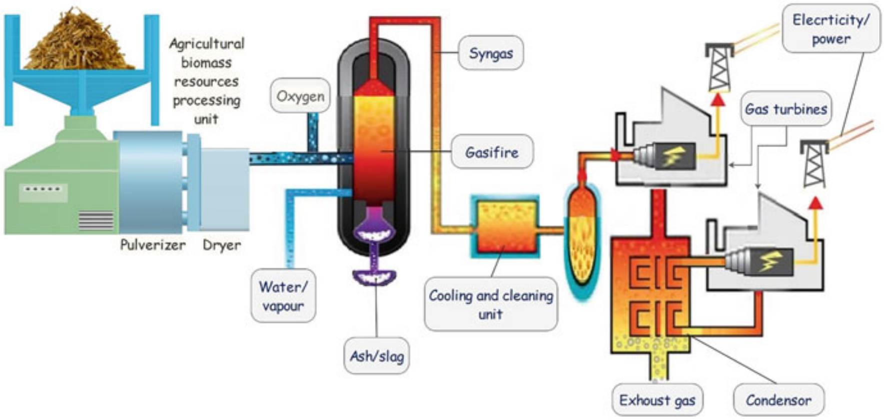

Fig. 7 Biomass gasification process with the electric generation system

especially the H_2 fraction increased and enhanced the calorific value of output gaseous product, which may be around 4–6 MJ/Nm^3. However, compared to mature combustion technology, gasification still had some challenges during downstream processing, especially the production of tar and other trace impurities, which cause problems in the operational process.

Gasification/combined cycle (BIG/CC) is currently known to have high conversion efficiency in transforming fuel gas to electricity by employing gas turbines. Syngas produced from gasification can be converted into H_2 gas as a transportation fuel (Yao et al., 2018). India has made a greater effort to achieve 125 MW of power based on co-generation by agricultural resources. The recently established Chennai-based Clenergen gasification plant has 80 MW capacity, while in Patna, a husk power gasification-based power generation plant has a capacity of 35–100 KW.

5.1.5 Liquefaction Process

Considering either water or organic solvent used in the liquefaction process, it is grouped into (i) solvent or (ii) hydro-thermal. Hydro-thermal liquefaction (HTL) is widely used to thermo-chemically convert agricultural biomass resources into liquid biofuel, e.g., bio-crude oil. Usually, it is performed in a closed O_2-free chamber at pressures between 100–200 bar and higher temperatures ranging from 250 to 350 °C. The liquefaction process produces more biofuel as compared to the pyrolysis method. The liquefaction process is considered best for biomass feedstock with higher moisture content. The bio-crude oil from HTL has less O_2, resulting in higher energy density than pyrolysis (Guo et al., 2015). Ethanol is widely used in HTL as a solvent due to its H_2 donation ability compared to other solvents like water or acetone. Bio-crude oil produced with water as a solvent usually has a higher viscosity. However, organic solvents like ethanol could be used to solve this problem. Solid catalysts, e.g., Na_2CO_3, $CaOH_2$, $BaOH_2$, etc., are applied to accelerate the HTL reactions to maximize bio-crude oil yield. Bio-crude oil produced

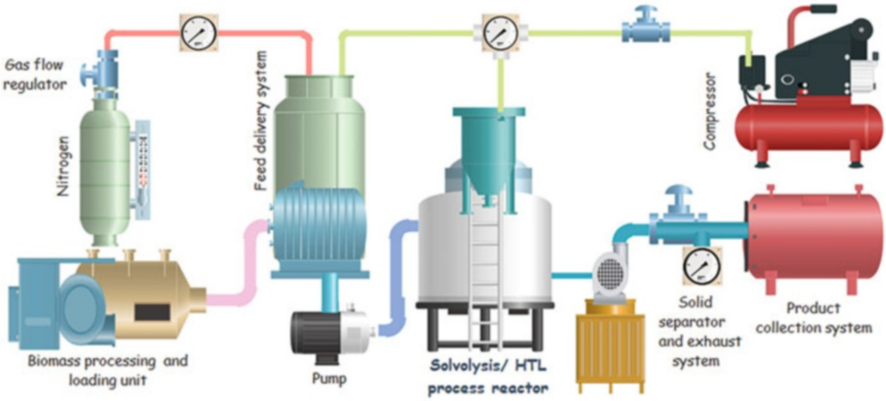

Fig. 8 Biomass to biofuel production scheme for solvolysis/HTL process

from HTL can be considered as a renewable fuel and a viable solution to satisfy future energy demands. The biomass-to-biofuel production scheme for the solvolysis/HTL process is presented in Fig. 8.

5.2 Bio-chemical Conversions

Biochemical conversions of agricultural biomass resources to biofuels employ various micro-organisms/consortia under anaerobic digestion (biogas) and fermentation (ethanol). In addition, transesterification (biodiesel) is also used worldwide, which is discussed below with followed sub-headings. Some important studies on the biochemical transformation of biomass waste to biofuels are presented in Table 6.

5.2.1 Anaerobic Digestion (AD)

AD process is widely used to transform a wide range of biomass/organics into biogas. Biogas contains CH_4, CO_2, and H_2S and is used for lighting, cooking, fueling gas turbines, and spark ignition engines to generate electricity. Removal of CO_2 from biogas makes it high-quality natural gas. In addition, the leftover digested slurry can be utilized as a biofertilizer for the agricultural crop (Prasad et al., 2017; Zehnsdorf et al., 2018). During anaerobic digestion, biomass is hydrolyzed into simple sugars, peptides, and fatty acids by bacteria, e.g., *Bacteroides*, *Bifidobacterium*, *Lactobacillus*, etc. (Reddy et al., 2018). Acidogens like *Ruminococcus* and *Clostridium* help convert simple sugars peptides and fatty acids into volatile fatty acids in the next step. Acetogenic bacteria like *Desulfovibrio* and *Acidaminococcus* convert volatile fatty acids to acetate (CH_3COOH). Finally, methanogens *Methanosalsus*, *Methanohalobium*, and *Methanosaeta* convert acetate into CH_4 (Sharma et al., 2014; Prasad et al., 2017) (Fig. 9).

Table 6 Some important studies on the biochemical conversion of biomass to biofuels

Biochemical techniques	Feedstock, bioenergy compositions & energy recovery	Operating parameters and conditions	Reference
Anaerobic digestion (AD)	Microalgae and bacterial co-cultured biomass, CH_4 recovery 325.0 mL CH_4/g of volatile solids	AD temperature 35 °C, biomass pretreatment by CaO at 72 °C, reaction time 24 h	Solé-Bundó et al. (2017)
	Sewage sludge, CH_4 recovery 181.0 mL CH_4/g volatile solids	AD temperature 35 °C, pH 7.0, reaction time 10 h	Passos et al. (2015)
	Mixed culture of algae, CH_4 recovery 146.0–171.0 mL CH_4/gCOD	Temperature for AD of sludge 35 °C, NH_4 level 250 mg/L, reaction time 14 h	Molinuevo-Salces et al. (2016)
Alcoholic fermentation	Pretreated rice straw, ethanol yield 25.30 g/L	Microwave-assisted 2% v/w NaOH, fermentation by *P. stipitis*, time 72 h	Prasad et al. (2020a)
	Algae biomass, ethanol yield 0.18 kg/kg of biomass	Temperature 37 °C, pH 5.5, thermal and enzymatic hydrolysis, retention time 2.5 days	Hwang et al. (2016)
	Algae (*Chlorella* sp.), and butanol, yield 0.32 g/L/h	Hydrolysis by 2% H_2SO_4 and residue detoxification by resin L-493, under anaerobic condition	Gao et al. (2016)
	Pine biomass, ethanol recovery 0.148 g/g)	*Schizosaccharomyces pombe CHFY0201*	Vaid et al. (2018)
Biological H_2-production	Microalgae (*Chlorella* sp.), H_2-recovery 11.65 mL/L	Temperature 30 °C, pH 6.8, anaerobic condition, light intensity 48 μmol per m^2/s, and duration of photo-fermentation 24 h	Sengmee et al. (2017)
	Chlamydomonas reinhardtii CC124, bio-H_2-yield 0.6 mL/L/h	Nanoparticle 40 mg/L, anaerobic, reaction time 72 h	Giannelli and Torzillo (2012)
	Chlamydomonas sp., bio-H_2-yield 1.05 mL/L/h and 1.3 mL/L/h	Anaerobic, photo-fermentation time 120 h, light intensity 50 μE/m^2/s	Oncel and Kose (2014)
Transesterification process	Waste cooking oil and biodiesel yield 98%	Temperature 55 °C at 20 min, catalyst MgO + CaO and methanol, reaction time 4–6 h	Tahvildari et al. (2015)
	Jatropha oil and biodiesel yield 90%	Temperature 60 °C, reaction time 3 h, catalyst and methanol mixture	Yunus Khan et al. (2018)

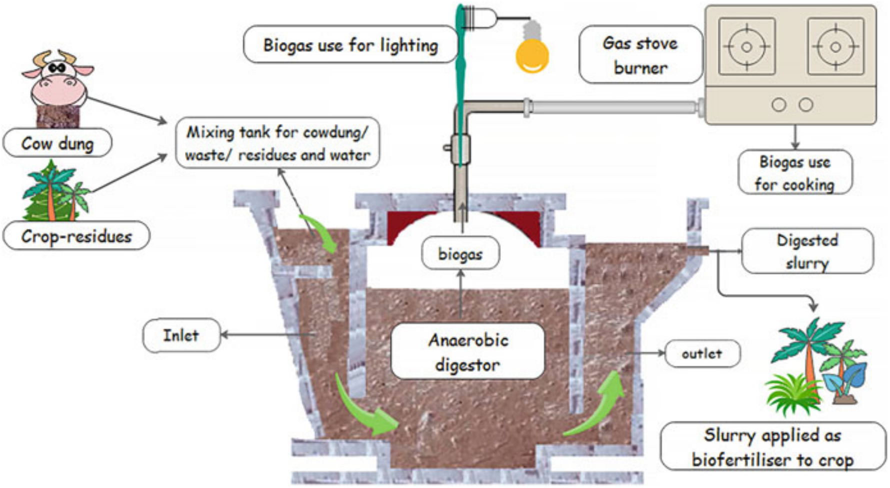

Fig. 9 Biomass to biogas fuel production scheme for anaerobic fermentation

5.2.2 Fermentation Process

In fermentation, yeasts convert glucose molecules into alcoholic products like ethanol and methanol (Sheetal et al., 2019; Prasad et al., 2020a, b). Usually, feedstock materials containing direct simple sugars like glucose and sucrose do not need pretreatment before alcoholic fermentation. However, biomass feedstocks-containing starch, cellulose, and hemicellulose were pretreated (Ambaye et al., 2021, then saccharified into glucose and fermented to produce ethanol (Sheetal et al., 2019; Prasad et al., 2020b; Gupta et al., 2021). Fungi are reportedly very efficient for enzymatic saccharification and ethanol production from lignocellulosic biomass waste and can play an essential role in making its economically viable option (Prasad et al., 2020b). A scheme for converting agricultural biomass resources to ethanol is presented in Fig. 10. In various countries, agricultural biomass resources, like rice straw, sugar cane and bagasse, sugar beet, wheat straw, and maize stover, are commercially exploited to produce bioethanol (Prasad et al., 2021a, b). The inclusive biochemical reactions involved in biomass hydrolysis and alcoholic fermentation are shown in given in Eqs. 4 and 5 (Prasad et al., 2007):

$$\text{Biomass hydrolysis: } (C_6H_{10}O_5)_n + nH_2O \rightarrow nC_6H_{12}O_6 \tag{4}$$

$$\text{Fermentation: } C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2 + \text{energy (ATP)} \tag{5}$$

5.2.3 Transesterification

Transesterification is the physico-chemical conversion process used to produce biodiesel from vegetable edible and non-edible seed oil, waste cooking oil (WCO), and microbial and algal-derived lipids. In the transesterification reaction, the triglycerides present in seed oil/fat/lipids are transformed into methyl/ethyl esters

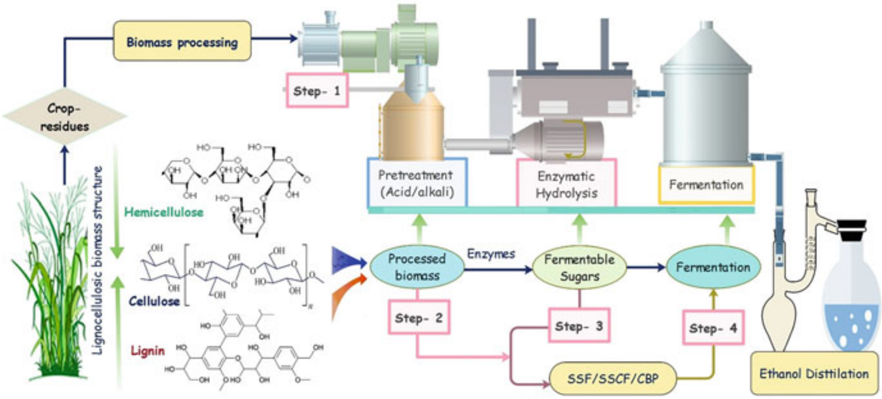

Fig. 10 Scheme for conversion of agricultural biomass resources to ethanol

(biodiesel) by a chemical reaction of alcohol and catalysts like NaOH/KOH. The optimum temperature range for transesterification is at 50–70 °C) and standard atmospheric pressure. The scheme for converting vegetable/seed oil to biodiesel and glycerol is presented in Fig. 11.

After completion of the transesterification process, obtained bio-crude is separated using a phase separator, then glycerol and biodiesel, purified by water-washing to remove residual catalysts and soaps. Glycerol obtained during esterification has various valuable applications in industries and pharmaceuticals. Several private and governments are promoting biodiesel as an alternative to fossil diesel. For example, Bio-Diesel Association of India (BDAI), Reliance Industries Ltd., Aatmiya Biofuels Pvt., Ltd., Gujarat Oelo Chem Limited, and Nova Biofuels Pvt., Ltd. Invested in promoting biodiesel in India (Priyadarshi & Paul, 2019). Biodiesel physico-chemical characteristics are very close to fossil diesel. It has high oxygen content, which helps complete biodiesel combustion in diesel engines.

6 Opportunities and Challenges in Biofuel Production from Agricultural Resources

Agricultural resources are abundantly available and have many opportunities and benefits due to their renewability and carbon-neutral nature: several biofuel policies and monetary support for renewable biofuel production globally. In India, adopting renewable biofuels has been promoted to achieve sustainability and energy security (Prasad et al., 2020a). However, biofuel production from agricultural resources is also facing challenges. For example, converting agricultural lignocellulosic biomass waste to biofuels needs many chemicals and enzymes that make this process costlier. In addition, inhibitory compounds like furfural and 5-hydroxymethylfurfural (HMF) also lower ethanol yields during fermentation (Prasad et al., 2018; Gupta et al., 2021).

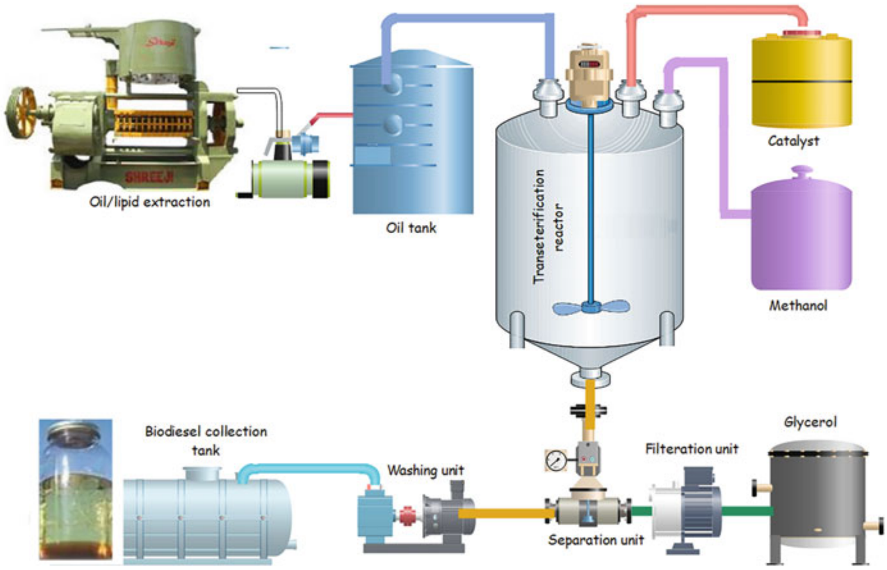

Fig. 11 Scheme for converting vegetable/seed oil to biodiesel and glycerol

Similarly, the thermochemical conversion of biomass to biofuel faces carbonization and ash-related issues in its commercial and efficient utilization. Therefore, extensive research must focus on making this energy generation processes more productive, environment-friendly, and cost-effective (Sheetal et al., 2019). Furthermore, a lack of infrastructure to transport biomass to biorefinery has shown potential barriers to biofuel production (Reid et al., 2020). The market-oriented infrastructure is still poor in many countries, including India. Mechanization in agriculture, transportation, efficient biomass conversion facility, and sustained agricultural resources supply at reasonable prices can lead to more opportunities and lower biofuel production costs. More attention should be given to refining processes, marketing, and sufficient infrastructure to bring biofuel production into line with policy and develop economic perspectives. Some critical points, like the development and strengthening of logistical infrastructure for systemic collection, storage, and transport of agricultural, industrial, and urban wastes, need to be considered in future programs to promote sustainable biofuel production practices in India (Prasad et al., 2020a).

7 Conclusion

India produces large amounts of crop residues. However, its burning cause many environmental problems. The current advances in energy technologies, such as thermal gasification and pyrolysis, biological anaerobic digestion (AD), and alcoholic fermentation, are economically reported as very viable technologies. However, efficient agricultural biomass resource utilization, improved technologies for biofuel production, and adequate policies for the sustainable development of biofuels must be prioritized. Furthermore, inadequate infrastructure strategies contribute to a significant biofuel gap in demand and supply. Therefore, there is a need to maximize adequate infrastructure strategies to harness the potential of agricultural resources to generate more biofuel and integrate it into national biofuel planning. Undoubtedly, it will provide new renewable biofuel, employment, sustainability, and opportunity to mitigate climate change problems and other environmental issues through low-carbon fuel use.

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Challenges in Implementation of the Solar Water Pumps in Rural Agricultural Areas

Richa Parmar

Contents

Abstract

An increase in fuel prices and power poverty impacts the water provision to agricultural demands. The population of India majorly depends upon the agriculture and to overcome irregular energy supply and continuous increase in diesel cost, agriculturalists are adopting solar water pumps to fulfill water demands to cultivate their lands and to also conserve water and energy. The Government of India has taken various policy measures to fulfill its commitment made in the Paris Climate Agreement in 2015 to have 40% of installed power generation capacity from non-fossil fuel sources by 2030. The PM-KUSUM Scheme primarily aims for the benefits of the farmers and aims to provide both financial security and more sustainable water access for farmers by generating solar power in their farms and use the clean entity to

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replace their diesel water pumps. This chapter describes the challenges faced in the implementation of the solar water pumping systems in rural areas.

Keywords

Indian farmers · Solar energy · Solar water pumping systems · PM-KUSUM Scheme

1 Introduction

On Earth, for thousands of years, our civilizations are harnessing solar power in several ways. In ancient time persons depended on the sun's energy for warmth, comfort, and necessities of life. Then as people become more civilized the dependency on non- renewable sources like coal, gases and petroleum increases. Solar energy has existed as long as the sun (Spencer, 1989); for about 5 billion years, in early civilization, buildings had openings facing the sun that were warmer and brighter even in cold weather. Solar energy is essential to agriculture cultivating land producing crops and raising livestock. Developed about 10,000 years ago, agriculture had a key role in the rise of civilization. Solar techniques such as crop rotation increased harvests. Drying food using sun and wind prevented crops from spoiling. This surplus of food allowed for denser populations and structured societies. At present, solar water pumping system is one of the ideal technologies to harness the energy coming from the sun with zero pollution emission (Chandel et al., 2015; Langridge et al., 1996). This chapter describes the technologies of the solar water pumping system and its benefits, challenges, and difficulties faced by the manufacturer as well as end user in the implementation and installation of the solar pumps.

2 Solar Water Pumping Is a Solution to Various Problems for Farmers

For irrigation, the main objective is to maintain the right level of moisture according to the crop for the proper growth of the plants. Irrigation water can be available through well, rivers, ponds, springs, and rain, but it's quite difficult in those areas where the groundwater level is very deep; for those areas, farmers buy water at a very costly rate and then cultivate their fields (Singh et al., 2013). Therefore, solar-powered irrigation systems provide a clean alternative to fossil fuels with no carbon emission and are best suitable for areas with no or unreliable access to the utility grid. Reduction in electricity bills and getting rid of long power cuts are also one of the reasons for the switch to solar energy. The PM-KUSUM Scheme (Ministry of New and Renewable Energy Guidelines for Implementation of Pradhan Mantri Kisan Urja Suraksha evam Utthan Mahabhiyan (PM KUSUM) Scheme, 2017) is a brilliant scheme that will catalyze the adoption of solar energy as the primary power source in rural areas.

See Table 1.

Table 1 Challenges in the implementation of the solar water pumps

S. no.	Problems	Description	Corrective actions
1.	Site selection	Solar pumping plants require sufficient area to mount structures	Can take the help of aid provided by the government to select an apt site for appropriate and optimum output results which leads to the value of money for the consumers
2.	Accessibility and sources	Connectivity, local authority assistance, transport taxes, and clearance	Convenient mode of transport for interior parts of the village where heavy load pulling vehicle can be moved directly underlining the help of "PMGSY." permanent support of local bodies and time-bound support in taxes for initial outreach at reasonable costs for better awareness and acceptability among consumers
3.	Cost	Solar PV pumping is an expensive technology; every farmer is not capable to adopt this technology	The government provides subsidiaries under the newly launched PM-KUSUM scheme. The government has set a target of installing 22,000 standalone solar pumps in Haryana within 1 year; under this scheme, the farmers in Haryana have to provide 40% of the cost of the pump, while the central and state governments subsidize the 60% for solar pumps
4.	Lack of education and technical awareness	Still being at the struggling stage to accept the change, people rely more on diesel-based systems due to ease of working and better outputs	Educate farmers by initiating awareness programs that can encourage farmers to use smart farming practices like solar based water pumping systems, drip irrigation, sprinklers etc. for the intended outcomes under the climatic circumstances in India which also leads to less consumption of fossil fuels, utility grid.
5.	Theft issues along with damage caused because of animals	Uncontrolled areas and non-negotiable activities of the local residents cause heavy financial losses to low-earning farmers	Manufacturing facilities are providing 5-year warranty against damages and insurance against thefts
6.	Technical support	End user is hesitant to adapt new and improved technology due to the Non availability of skilled technicians to fix the regular errors like system overheating, failure of motor or pump, not getting proper sunlight etc.	In order to increase the availability of technicians for immediate support to end users, the government has launched skill development training programs like Varunmitra and Suryamitra.

2.1 Introduction to Solar Water Pumping System

The main source of power is the sun for solar water pumping systems as a clean alternative to diesel generators. In those rural locations where the local electricity grid is not available, solar water pumping systems are eco-friendly, require no fuel consumption (Wazeda et al., 2017), and demand very low maintenance.

The following are the main elements for solar water pumps (Fig. 1):

Water source: The source of the water for the solar water pumping system can be a borehole or groundwater source or natural water bodies like a lake, pond, river, canal, etc. An artificial water storage tank like cemented/concrete tank is also a smart way to store water. Its size and capacity are based upon the required number of days for storage and ensure 24-hour constant availability of water depending upon the design of the tank to store enough water (Rathorea et al., 2018) to fulfil user demand at night as well as in monsoon season and cloudy days during winters.

Photovoltaic (PV) array: Solar PV modules generate DC power from the sun during sunshine hours. Solar PV module array is a combination of series and parallel connections of SPV modules mounted on a module mounting structure. Three times a day tracking in the direction of the sun and suitable sunlight exposure during sunshine hours at the location are required to get maximum water output (Bansal & Minke, 1990; Parmar et al., 2019).

The pump: The selection of the type of technology either submersible type or surface type (Bansal & Minke, 1990; Chergui & Bourahla, 2011) can be determined by the type of water source available at the particular site where the

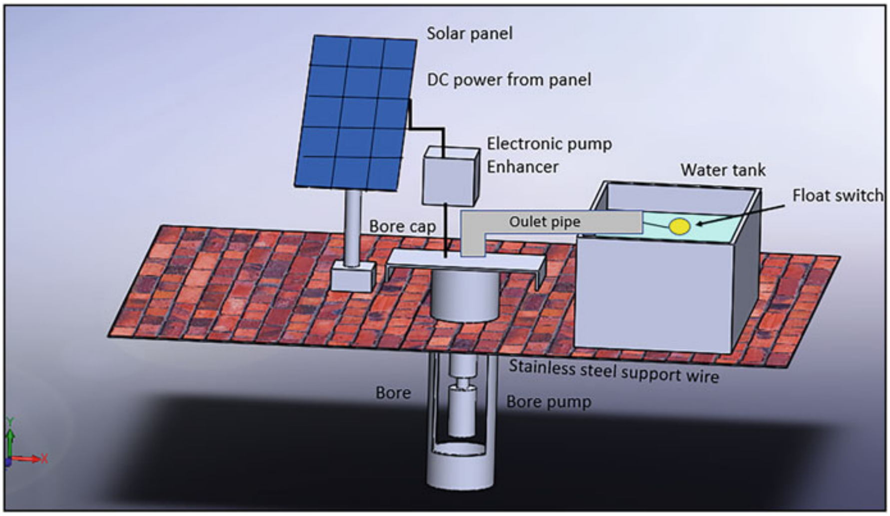

Fig. 1 Solar water pumping system

pumping system needs to be installed. Low operation and maintenance cost and high efficiency of the DC pumping systems attract end users, while AC pumping system has high reliability.

Pump controller: Pump controllers (IEC 61683, n.d.) are used in AC systems; these controllers allow the pump to be systematic and synchronized to connect to the pump and electrical grounding system. Pump controllers are the main brain of the pumping system. It protects the system during overvoltage and short circuits (EN 50530, n.d.). Pump controllers also regulate the speed of the motor and maintain the frequency concerning irradiance by using VFDs (Improving Motor and Drive System Performance, n.d.).

2.2 Various Applications of Solar PV Pump

2.2.1 Emergency Water Supply

Solar water pumping systems are relatively lightweight, compact, suitable for transportation, and even quick to assemble in the field. These systems are easy to install and commission. Solar water pumping systems are relatively lightweight, compact, suitable for transportation, and even quick to assemble in the field. These systems are also used in disaster relief and refugee camps because of their unique features; they can serve as temporary drinking water treatment units and evolve into an efficient way of quickly providing clean drinking water to needy in such serious situations of natural calamities.

2.2.2 Irrigation and Agricultural Systems

The most common application of solar water pumping systems is to provide water for irrigation (Kumar et al., 2015) as well as for livestock by pumping water from groundwater wells or surface water bodies like rivers and ponds. A well-designed solar-powered pumping system can reduce the money spent on generator fuel by farmers mainly in areas where grid power is not available or not reliable (Senol, 2012).

2.2.3 Dewatering Systems

Dewatering means the removal or separation of water from solid waste materials or sediments. Thus, dewatering process requires continuous pumping normally, and by using grid or fuel generators, there is a loss of fuel and money; the process is eco-friendly as well. Hence, using a solar water pumping system for the dewatering process can reduce cost, and these pumps play a vital role in reducing energy loss by displacing part of the conventional power sources used to run dewatering pumps (Nicoleta et al., 2017).

2.2.4 Remote Habitations

Solar water pumping systems can be a good, cheaper, and zero fuel cost alternative source to generate water as well as the power supply for the long term in remote areas.

Fig. 2 Solar water pump system showing its different uses

2.2.5 Construction Sites

Solar water pumping systems can be a great way to provide water to mining sites and construction sites to supply drinking water for workers as a temporary drinking water source.

Other uses for solar pumps include fountain pumps, pool pumps, transfer pumps, and circulation pumps in ponds, providing water for livestock (Fig. 2).

2.3 Types of Pumps and Their Configurations

Pumps are mainly classified as submersible pumps and surface pumps, and these are available to run on alternating current (AC) as well as on direct current (DC) power by using solar photovoltaic technology (Benghanem et al., 2018).

2.3.1 Submersible Pumps

The operating and installing procedure is different to surface pumps as submersible pumps are submerged in water while surface pumps are installed above water level like river or pond and cannot be used for too deep below ground-level water applications (approximately 6-meter depth). Submersible pumps are used to pump groundwater from deep wells or boreholes up to 450 meters, and they are specially designed for higher discharge heads and deep well or borehole water applications; they have a small outside diameter so that they can easily be suspended below the water level in the borehole and connected with a riser pipe which extends up to the surface (Fig. 3).

The right selection of the pump for each application will depend on the required pumping heads, cost, and space to drive water. Submersible pumps are durable and can tolerate water with relatively high levels of salinity.

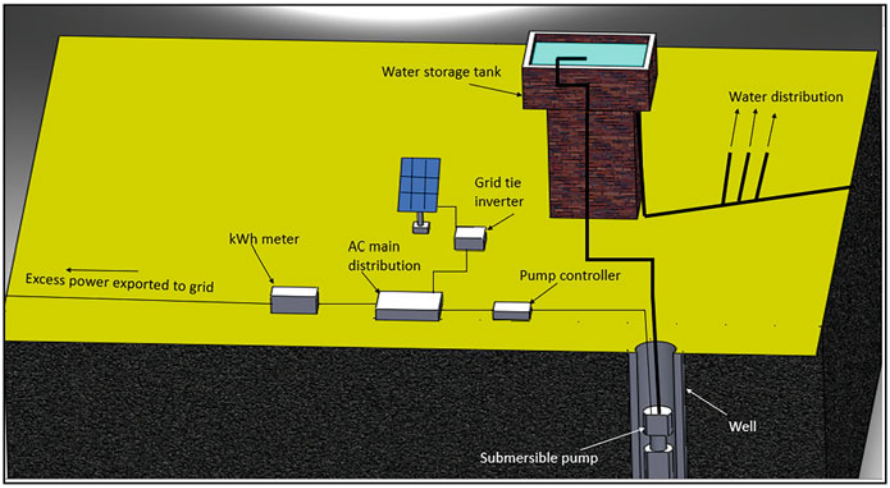

Fig. 3 Submersible pumps

2.3.2 Surface Pumps

These pumps draw water using the suction principle, and they are used to move water from shallow wells, ponds, streams, and tanks, where the pump itself can be located within approximately 6 meters above the water level. There are many types of pumps available in the market, but the choice of the pump will depend upon how much water per day needs to be driven and the height and distance to the delivery point water sources. The performance of the overall pumping system can also be improved if the suction head can minimize by just a few meters. These types of pumps are used to maintain pressure or flow, and they are generally used in towns or communities with unreliable water pressure mainly at the time of high demand. These pumps are used to move water from one place to another. Some of them are capable of high pressure, while others are mainly projected to move large volumes of water at low pressure. These pumps are regularly used for pressurizing small water systems in buildings, homes, schools, industries, and hospitals (Fig. 4).

2.4 Step-by-Step Design for a Typical Solar PV Water Pump

For the installation of a solar water pump, the first step is to determine the type and number of stages to meet the set of operative conditions and the specific gravity of the fluid. The design and selection criteria of the solar based pumping system considered the desired set of operating as well as geographical conditions (Chapman, n.d.; Lee & Ha, 2015).

a) **Water Requirement:** Different water sources like wells, ponds, rivers, springs, and groundwater would be selected according to the sites and water requirements.

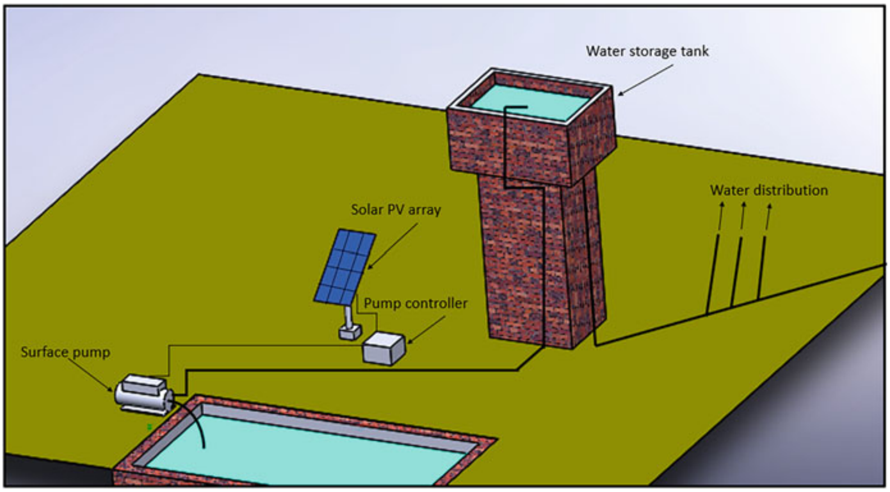

Fig. 4 Surface pump

The underlying features like water quality and steadiness of wells and boreholes make them feasible for farming. On the other hand, the construction of wells is costly at places where water tables are deep. Water sources present on the surface like rainwater depend on the seasons. Therefore, the amount and quality of water could be low during the summer. The underlying features like water quality and steadiness of wells as well as boreholes make it feasible for farming.

Factors to be determined for wells or boreholes:

- Season-to-season depth variations.
- Water quality.
- Recovery rate.
- Stagnant water level.

Factors to be determined for surface water sources:

- Water quality, containing mud, pebbles and organic debris, etc.
- Seasonal variations.

2.4.1 Analyze the Solar Insolation Level

The water source site must be examined for its suitability in installing the PV-powered water pumping system. According to the water pump type, i.e., surface or submersible, pump controllers, water storage system, and other system components, the location for installing the system must be specified. The PV array should be constructed near the pump to minimize the installation cost and wire size. The orientation of the PV panels should be south-facing with no significant shading.

1. **Calculate the daily flow rate of the pump:** The daily water requirement is defined as the total amount of water needed in 24 h. If significant amount of water is needed as per the end user perspective. Then storage of water in terms water storage tank is needed which enough to hold at least one and a half times the required limit and can be used during night also.
2. **Calculate the total dynamic head (TDH) for the pump:** The total dynamic head is defined as the submission of pressure head, elevation head, and friction losses.

$$\text{TDH} = \text{Pumping Level} + \text{Vertical Rise} + \text{Friction Loss} \tag{1}$$

The two major factors required for the calculation of the TDH are:

Flow Rate: It is defined as the volume of liquid flows per unit time. SI unit of flow rate is m^3/s. It can be written in a term of liters per minute as:

$$\text{Liters per minute} = \frac{\text{Liters per day}}{\text{peak sun hours per day}} * \frac{\text{hours}}{60\ \text{minutes}} \tag{2}$$

Vertical Lift: It is the height up to which a pump can draw the water. Submersible well pumps provide the lift to overcome head pressure.

- **Select the pump to meet the daily flow rate:** The sizing of the pump is to determine the approximate size of a pump used for a particular location and to fulfil the daily requirement of the user. After calculating the head required, the sizing of the pump can easily be done. The sizing of the pump can also be easily determined by the nature of its application whether it is used for commercial purposes or the irrigation purpose for a particular size of land as well as depending on the crop to be grown on that land. Table 2 shows the consumption of water for different applications.
- **Select the solar array power or size of the solar water pump:** The orientation and tilt angle of the PV system have to be determined to maximize its performance. Depending on the site location, PV panels are roof-mounted, ground-mounted, or post-mounted. As the sun's path varies from day to day, we have to follow the sun for maximum radiation. As per MNRE guidelines, three times a day tracking is advisable to get maximum water output.

3 Suitability of the Site for Solar

For the installation of the solar-powered water pumping system, the site of a water source should be sustainable. The solar panels should be south-facing with no significant shading. There should be a particular location set for the water pump (surface), controller, storage tank, and other system components. The solar array should be installed near the pump to minimize the wire size and cost. For water

Table 2 Daily consumption rate average values for different applications

Sr. no.	Application	Unit	Daily consumption rate (liter/day)
1	Residential	Inhabitant	50–275
2	Livestock	Milking cow	95
		Horse or dry cow	76
		Sheep or goat	7.6
		Chicken	1.5
3	Irrigation	Rice (1 ha)	100
		Cereals (1 ha)	45
		Vegetables (1 ha)	50
		Sugar cane (1 ha)	66

storage and pressure tank, a warm place is considered (Rodríguez et al., n.d.; Kumar et al., 2015; Sharma et al., 1995).

4 Daily Operation

- The solar water pumping system should be switched off properly when water is not required.
- Never run solar water pumps dry; before switching them on, put some water on the delivery pipe.
- Always check wire connections and cuts for safe operation.

5 Regular Maintenance

- Panels should be cleaned with water and a soft cloth once a week. Water should be splashed on the front side, not on the backside.
- In 6 months, trim the trees if there is any shadow on the panel.
- Once a year, check and clean the foot valve, switches, fuse, junction box wiring, and all the other necessary connections.
- The carbon brushes of the surface pumps need to be replaced once in 2 years.

6 Do’s

- Regular cleaning of the panels.
- At night, as there is no sunshine, they should be switched off properly.
- Avoid shadow on solar panels to perform pumping system efficiently.
- In the case of surface pumps, the solar pumps should be kept in a shed/covered place to protect from rain and sun.

- Always use good-quality pipes; there should be no leakage in pipes.
- In case of strong winds and thunder, solar photovoltaic modules should be kept in zero degree position.

7 Don'ts

- The pump should not be switched on and off fast. There should be a minimum gap of 15 s between turn on and off time.
- The junction box should be covered properly.
- The pumping level should not be changed once installed to remove the risk of damage.
- Always check loose connections of wires and no wire is left un-insulated.
- Avoid running the pump on a cloudy and rainy day.
- Never start a solar pump on a dry run.
- There is no reduction in pipe size.
- Avoid leakage on joints.
- The motor should not be covered with a plastic sheet to protect it from rainwater. Instead, wrapping a canopy with sufficient room for air should be used.

8 Precautions

- Avoid excessive vibrations which would result in excessive noise and can damage the magnetic stator. Therefore, one must rigidly mount the surface pump on the base plate.
- The pump should be covered adequately with a proper air vent.
- Avoid loose joints and sharp bends in pipelines.
- For proper functioning, daily run solar pumps for a minimum of 15 min.
- At the time of the operation of the pump, never cover solar panels with any cloth or material.
- Carbon brushes should slide freely in the brush holders; otherwise, they will fail the motor.
- Delivery and suction pipelines should be air-tight.
- If the solar pump stops working, one must not try to repair themselves. Always inform the authorized service division immediately so that a skilled technician will be sent to repair it.

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Use of Smart Technology in Agriculture for Energy Management

Developed and Developing Countries

Abdul Majeed, Zahir Muhammad, Rehmanullah, and Sami Ullah

Contents

Abstract

The current and expected increase in the population of the world would exert unprecedented pressure on agriculture for greater yield and productivity. An increase in population coupled with land degradation and high input of different forms of energy could reduce energy efficiency in the agricultural sector throughout the world. In recent decades, the imbalanced use of chemical, mechanical, and fuel energy in agriculture has increased agricultural productivity; it has concurrently raised concerns about environmental sustainability and climate changes. To cope with expected pressure for agricultural production and environmental issues, efficient management of energy in agriculture is required on an emergent basis. Replacing traditional strategies with the use of smart technology can serve as mitigating agents to attain energy efficiency and consequent implications of the

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unbalanced use of energy in agriculture. Promoting organic agriculture, adopting precision agriculture, using solar energy as alternatives to fossil fuels, and using computer-simulating models to forecast rains and winds are some of the examples of smart strategies that could significantly contribute to energy management in agriculture. In this chapter, the application of smart technologies in the agricultural sector is discussed comparing the developed and developing countries.

Keywords

Fossil fuels · Solar energy · Organic agriculture, precision, and digital agriculture · Greenhouse gas emission · Internet of things · Agricultural sustainability

1 Introduction

According to the United Nations' estimations, the current human population of the world is 7.7 billion which is likely to increase to 10.9 billion by the year 2100 (Roser, 2013). Human beings rely upon food, feed, raw material, processed products, and energy which are provided by agriculture. Agriculture is an important driver in sustaining human beings' life through the provision of food and energy. The projected increase in the human population would increase pressure on the agricultural sector to provide more food to meet the demand of the increasing population of the world. Currently, global agricultural productivity is sufficient in most parts of the world to fulfill the need of the population; nevertheless, an anticipated increase in the human population would certainly press for extraordinary efforts for increasing the yields and productivity. Elferink and Schierhorn (2016) estimate that by the year 2050, 59–98% increase in demand for food would exert pressure on agriculture for enhancing the production of crops which would certainly bring transitions in agricultural patterns which are currently followed. Over the last few years, crop production has been increased threefold by the use of energy input mainly by fertilizer's use and fuel application for machinery (Pellegrini & Fernández, 2018). In the USA alone, almost 24% of fossil fuel energy is used in agriculture or related processes of agriculture (Pimentel, 2006). According to the Food and Agriculture Organization (FAO), the energy use in the agriculture sector in developed countries is in the range between 3% and 5% of the total energy as compared to roughly estimated 4–8% in the developing countries.

In both developed and developing countries, manual methods and intensive labor activities in agriculture have been shifting toward energy-driven practices. In the agricultural sector, energy is used mainly in the form of fuel and electricity to run machinery, provide lightening to farms, and synthesize agrochemicals (Schnepf, 2004). Although during the last few years, greater input of direct energy uses (fuels for running agro-equipment, irrigation, etc.) and indirectly through the production of agrochemicals (fertilizers, pesticides, and soil amendments) has significantly increased yields and production concurrently, it has also led to reduced efficiency in energy management in the agricultural sector throughout the world besides its implication on the environment and the rise in prices of energy sources. Since the 1980s, a significant increase in energy input in agriculture has been observed in the developed countries which have increased the emission of greenhouse gases and reduced the efficient management of energy (Schneider & Smith, 2009). Currently, most of the energy sources used for agricultural activities in developed and developing countries are fossil fuels (natural gas, petroleum, gasoline, etc.) which are non-renewable and are the main causes of greenhouse gas emission, a leading cause of environmental degradation and global warming (Chel & Kaushik, 2011; Bolyssov, 2019).

To sustain agricultural activities and environmental stability, efficient energy management in agriculture is crucial. Employing strategies of energy efficiency in agriculture will lead to reduced reliance on non-renewable resources of energy (Alluvione et al., 2011). Energy management in agriculture can be attained by reducing the input of direct and indirect energy sources (Baptista et al., 2013). "Smart energy management" comprehends the idea of using non-traditional strategies in agriculture to manage energy efficiently in a manner to attain maximum output of agriculture while sustaining the environment. This may include a shift in agricultural practices from reduced input of agrochemicals and use of fossil fuels to greater reliance on eco-friendly like solar, wind, hydro, tidal, and other sources of renewable energy (Chel & Kaushik, 2011). The use of crop plants that require lesser input of agrochemicals, computer technology, and forecasting models can achieve efficient management of energy in agriculture. This chapter focuses on extending the idea of efficient management of energy in agriculture by employing smart strategies and technology. The status of such strategies for energy management in developing and developed countries is discussed.

2 Energy Use in Agriculture and Its Implications

Millions of people throughout the world rely on agriculture for livelihood. Agriculture provides food, feed, and raw and processed material that sustain life on earth. The output of agricultural products greatly depends on input and agricultural strategies. Agriculture in ancient times relied primarily on energy sources provided by humans and animals. In modern agriculture, various forms of energy resources are used as input to produce maximum output. The industrial and agricultural revolution during the eighteenth century caused a massive transformation in England and subsequently in other parts of the world which significantly increased agricultural productivity (Allen, 1994, 1999). Those transformations included the employment of machinery for reducing labor at farms, irrigation, harvesting, and processing products and the use of fertilizers for enhancing soil fertility and pesticides for crop protection. The introduction of machinery and the need for agrochemicals hastened the input of energy in the agricultural sector.

Currently, energy consumption in agriculture is attributed to producing greater output in terms of yields and processed products. In farms, energy is mostly used for irrigation (running tube wells and other water sources), harvesting, and transportation of plants' products. A greater proportion of direct consumption of energy is in the form of electricity, natural gas, diesel and petrol, oil, and coal which are used for operating agricultural equipment, irrigation purposes, and lighting (Warwick & Park, 2007). Apart from direct energy uses, the agricultural sector heavily relies on indirect energy sources for agrochemicals, machinery, and processing of products (Cleveland, 1995; Mikkola & Ahokas, 2010). Energy consumption in agriculture whether direct or indirect is variable in developed and developing countries. Although it is difficult to record the exact amount of energy used in agriculture in different parts of the world due to several constraints in collecting accurate data, studies have been conducted to present estimated values. According to an estimate, annual consumption of non-renewable energy sources (mostly fossil fuels) in the developed countries account for 70% while 30% in developing countries (Pimentel et al., 1999), of which a significant proportion is utilized either directly or indirectly in agriculture.

Benefits of energy use in agriculture are well recognized as improved crop production, agricultural products, and livestock production have been observed during the last few decades. Besides its significant role in improving agricultural productivity, the direct and indirect uses of fossil fuel energy in agriculture have drastic effects on ecosystem stability (Fig. 1). One of the leading issues of the use of fossil fuels is the emission of greenhouse gases (GHGs) such as CO2, methane, and nitrous oxide to the atmosphere causing weather fluctuations, global warming, and ecosystem degradation (Gomiero et al., 2011). Studies have estimated that intensive agricultural activities and increased input of energy in agriculture correspond to more than 50% emission of GHGs notably methane, nitrous oxide, and carbon dioxide which portrays an alarming situation about climate change (Vlek et al., 2003). McCarl and Schneider (2000) reported some empirical studies which depicted that global GHG emissions from agriculture range between 20% and 70% notably for NO2, NH4, and CO2. They reviewed that most GHG emissions in developed countries arise as a result of fossil fuel use in agriculture, while in developing countries, the main cause is land degradation. Pathak et al. (2010) estimated that due to the increased use of fertilizers in Indian agriculture, GHG emission during the 2007 war recorded between 0.217 and 3.37 million tons. Lesschen et al. (2011) noted that European agriculture heavily relies on fossil fuels and fertilizers. The authors revealed that the livestock sector of European agriculture emits GHGs on average between 28% and 38% annually. According to Ghosh et al. (2020) and other estimates, energy input in agriculture contributes to almost 14% of GHG emissions. Gołasa et al. (2021), on the other hand, presented many published sources which indicate that 16–27% of GHG emission comes from energy use in agriculture. Estimates for GHG emission mainly through agriculture show variations in developed and developing countries. Due to the negative consequences of GHGs, international agencies have been active for quite a long time to devise mechanisms for reducing the emission, but those efforts are not followed by some countries due to legal and political issues. The Kyoto Protocol is one such leading initiative that was signed by 176 countries in 1998 with the objectives of mitigating GHG emissions and safeguarding climate change. However, the objectives of the protocol have not been fully attained due to several constraints.

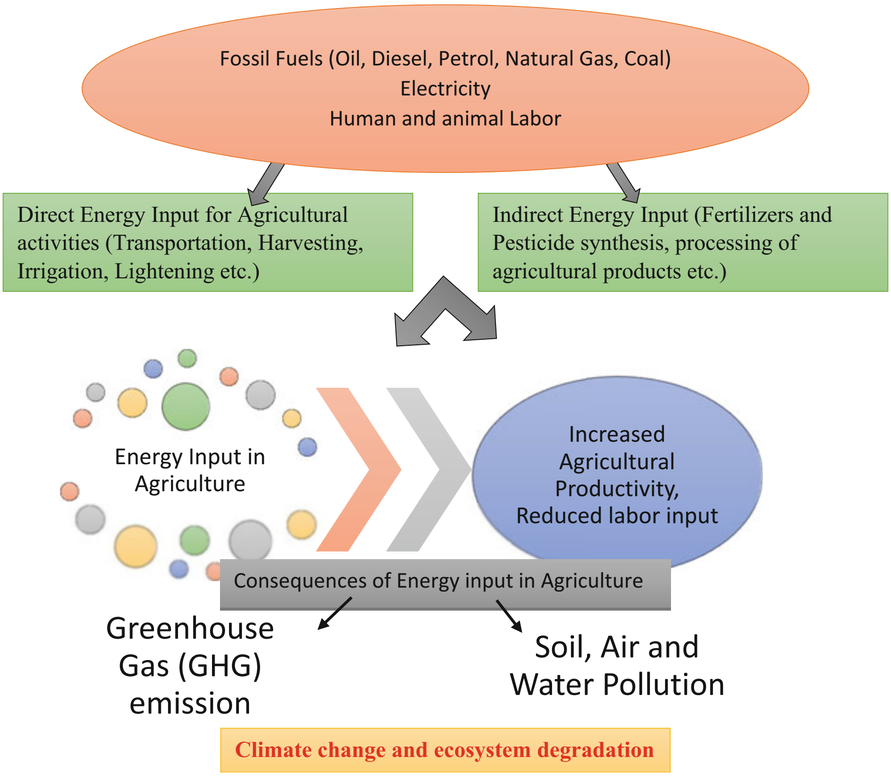

Fig. 1 A schematic presentation of the use of fossil fuel energy in agriculture and its impact on agricultural production. Energy input in agriculture is one of the leading causes of GHG emission and environmental pollution

Besides GHG emissions, energy use in agriculture is also responsible for soil, water, and air pollution. Excessive fertilizer and pesticide application, which is an indirect use of energy input in agriculture, cause massive water pollution throughout the world (Chen et al., 2017). Ukaogo et al. (2020) outlined that intensive agricultural activities and the use of agrochemicals (fertilizers and pesticides) are threatening ecosystem sustainability by polluting the environment. Agricultural pollution arises not only due to the excessive application of fertilizers and other agrochemicals but also due to the transportation of such substances to and from farming sites (Wagner, 2018). During industrial operations, while synthesizing agrochemicals, huge quantities of wastes are released into the environment causing water, soil, and air pollution. Machinery used in agriculture for irrigation and harvesting purposes use fuels which may cause all three types of pollution when fuel energy is burnt. Accidental leakage of oils and diesel and petroleum products during agricultural activities contributes to pollution and consequently to ecosystem degradation.

Abbasi et al. (2014) reiterated that agriculture is the third-largest sector that contributes to environmental pollution by using fossil fuels and agricultural chemicals. Chitra and Priya (2020) pointed out that chemical fertilizer and pesticide application, soil erosion, and sedimentation are the leading causes of agricultural pollution.

3 Energy Management in Agriculture by Employing Smart Technologies and Strategies

As it is evident from studies that direct or indirect input of energy in agriculture causes GHG emission and environmental pollution besides the steady decline in non-renewable energy resources, efficient management of energy in the agricultural sector could lead to providing a solution to ecosystem degradation and a minimum reliance on fossil fuel energy. Efficient management in agriculture refers to the use of energy in a way that could reduce wastage of energy and environmental issues leading to sustainability. For achieving efficiency in energy management, a shift from conventional practices to non-conventional approaches in agriculture needs consideration on a priority basis. Several strategies can work in achieving the target of reducing fossil fuel energy input in agriculture which ranges from opting for renewable energy sources to employing digital and forecasting technologies. Here we discuss some important strategies and the use of smart technologies in agriculture for the management of energy and reducing the cost of environmental sustainability.

3.1 The Choice of Organic Agriculture

Conventional farming requires the use of synthetic fertilizers particularly N fertilizers for producing greater outputs; hence, it is dependent on indirect energy use. Organic farming and organic agriculture mainly focus on minimal use of fertilizers and pesticides, promoting crop rotation, improving soil fertility via organic means instead of the agrochemical, and recycling of nutrients (Muller et al., 2017). Ideally, organic agriculture at both the farming level and production side promotes strategies of least dependency on fossil fuels and ecosystem stability. Smith et al. (2015) reviewed the benefits of organic agriculture, and they considered it as more sustainable than conventional system of agriculture because it contributes to lesser energy use and GHG emission. Reganold and Wachter (2016) further highlighted the significance of organic agriculture by discussing its characteristics (e.g., use of organic materials as alternatives to chemical fertilizers, natural pest management, conservation of water and soil, and limited input of fossil fuel energy). The authors further elaborated that organic farming effectively controls GHG emissions and environmental pollution. Hoeppner et al. (2006) reported efficient energy management and an almost 50% reduction in energy input in organic agriculture as compared to conventional agriculture. Guzmán and Alonso (2008) attributed a significant energy efficiency management of non-renewable sources in organic agriculture to its counterpart. Scialabba and Müller-Lindenlauf (2010) stated that organic agriculture provides an efficient alternative to the conventional system because it effectively manages GHG emissions, fertilizer's use, and input of energy. Alluvione et al. (2011) observed that integrated farming techniques – a key component of organic agriculture – reduced energy input and improved the efficiency of energy management. Gomiero et al. (2011) concluded that under organic agriculture systems, energy input and output are better than the conventional agricultural system. They remarked that organic agriculture manages energy efficiently because it discourages the use of nitrogen and mineral fertilizers and pesticides which are the major energy consumptive drivers. Several other studies have documented that organic agriculture – if focused, flourished, and adopted – could lead to reducing GHG emissions; energy efficiency and management; issues of climate change; reliance on synthetic fertilizers, pesticides and herbicides; and pollution and can attain greater agricultural and environmental sustainability (Dhiman, 2020; Nedumaran, 2020; Nesterenko et al., 2020; Rahmaniah et al., 2020; Moracanin et al., 2021; Saffeullah et al., 2021).

3.2 The Use of the Precision System and Digital Technology

In precision agriculture, technologies and strategies are employed to collect information and make a decision about agricultural input and output, maximizing profitability, the environmental impact of agricultural activities, and energy management (Brisco et al., 1998; Gebbers & Adamchuk, 2010; Jawad et al., 2017). Digital agriculture employs computers and digital technologies for addressing the issues of agricultural sustainability, energy efficiency, and productivity (Ozdogan et al., 2017; Lajoie-O'Malley et al., 2020). In digital and precision agricultural systems, the use of digital and information technologies is integrated into agricultural activities to monitor, assess, and modify the required inputs for obtaining maximum output without compromising ecosystem sustainability (Basso & Antle, 2020; Cook et al., 2021). Although the terms digital and precision agriculture seem different, both terms reflect similar strategies to produce agricultural output intelligently by using smart techniques, information technology, connected devices, GIS and GIP, and smart machinery keeping into account the energy input, fertilizer's application, and environmental issues (Fig. 2).

Precision and digital agriculture are based on time and space concerning crop productivity and agricultural activities by using technologies and strategies to manage anticipated discrepancies which could lead to enhanced efficiency in energy management, agricultural outputs, and climatic stability (Pierce & Nowak, 1999; Stafford, 2000). Ahmad and Mahdi (2018) described precision agriculture as a smart strategy that utilizes geographical information system and global positioning system to collect information about crops, soil, water, requirement of fertilizers, harvesting, and energy input and to process and manage that information in a precise manner to gain the desired outputs. According to Friedl (2018), precision agriculture is based on the principles of using data from various sources to manage farm practices, application of fertilizers and pesticides, and irrigation by employing remote sensing,

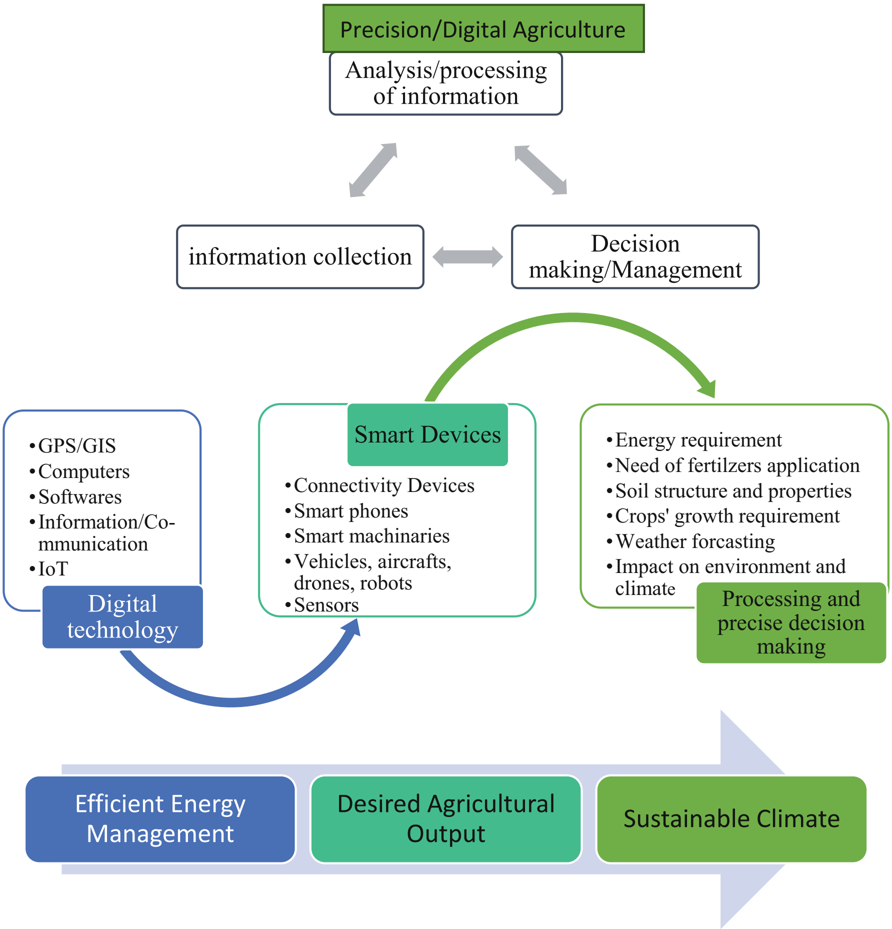

Fig. 2 An illustration of the precision/digital agriculture for the efficient management of energy and climatic sustainability

unmanned vehicles, and satellite technology. Singh et al. (2020) revealed the importance of precision agriculture in the modern day especially under increasing demand for food and study decline in resources. They noted that the application of remote sensing coupled with GIS, GIP, variable rate technology, and digital and smart devices is crucially necessary for enhancing agricultural yield and the input of energy and agrochemicals and safeguarding the ecosystem. The ultimate objective of collecting, analyzing, and processing information about farming and agricultural activities is to utilize the available resources efficiently for improving crop productivity, energy management, and agricultural input. The decision made based on collected data takes into consideration environmental issues related to agricultural activities; thus, precision agriculture provides an eco-friendly choice to farmers.

According to published sources (Ahmad & Mahdi, 2018; Sahu et al., 2019; Mishra, 2022), primary tools used in precision and digital agriculture are:

- Geographical information system (GIS)
- Global positioning systems (GPS)
- Computers and applications
- Sensors
- Smart devices (phones, connectivity devices, smart machinery, etc.)
- Internet of things (IoT)
- Variable rate technology
- Big data analytics
- Specifically designed aircraft, drones, and vehicles
- Other devices

Using modern technology, smart devices, communication technology, and the internet in precision agriculture, farmers and agricultural stakeholders tend to precisely perform agricultural tasks. The use of smart technologies like those of remote sensing, internet and communication, big data, and smart unmanned aerial crafts in agriculture is rapidly reshaping conventional agriculture in terms of yields, monitoring soils and crops, application of fertilizers and pesticides, weed management, and environmental factors leading to maximum productivity and lesser input of resources (Sinha & Dhanalakshmi, 2022). The first step in performing such tasks is to gather information about fields and farms through remote sensing, GIS, and GIP. Spatial and temporal factors such as seasonal patterns, geographic characteristics of the land, and climatic variables are important drivers that affect the growth and productivity of crops as well as the whole agricultural performance whose monitoring through remote sensing and GIS/GIP can contribute to the efficient and precise management of agricultural activities (Atzberger, 2013). Data regarding farm sites can be collected using digital technology. This enables the farmers to know about the topographic and soil properties of their farms and climatic conditions and leads them to decide which crop to grow in which climatic conditions and to apply agrochemicals when needed. This significantly reduces the input of energy in agriculture. Succeeding steps are collection and storage of data and analysis of data, based on which decisions are made and agricultural patterns are accordingly modified precisely in time and space.

Banu (2015) portrayed the basic features of precision and digital agriculture. The author discussed that in precision agriculture, computers, GIS/GPS, and sensors are used to monitor farms' characteristics. Based on the analysis of the collected information, required measures are accomplished to maximize agricultural outputs while sustaining the available resources. Akhter and Sofi (2021) presented the role of the internet of things (IoT) in the efficient management of energy. The authors argued that wireless sensors, GIS and GIP, and smart devices could be implemented to construct soil maps and monitor yields and agronomic conditions of farms. Based on those maps and collected data, variable rate technology may be used to regulate irrigation and the use of fertilizers and pesticides. In recent years, IoT has been widely used to collect precise information about farms, climate, energy sector and agriculture (Tao et al., 2021; Sinha & Dhanalakshmi, 2022).

Currently, several technologies and smart devices are used in agriculture to promote energy efficiency, maximize profitability, and reduce adverse effects of agricultural practices. According to Walter et al. (2017), weed management, fertilizer application, harvesting of crops, disease control, the process of fertilization, and biomass calculation can be managed by using unmanned aerial vehicles, high-resolution cameras, and autonomous and robotic vehicles. Sarker et al. (2019) suggested that big data collection and analysis in garniture from seed sowing to harvesting of crops is a revolutionary approach aimed at the efficient management of agricultural resources and this can be accomplished through the use of drones, computers, sensors, hardware, and software and mathematical models. Saiz-Rubio and Rovira-Más (2020) reflected the role of artificial intelligence and robotics in agriculture as effective measures to precisely perform agricultural operations. Maddikunta et al. (2021) outlined that the use of unmanned aerial vehicles could efficiently manage energy and agricultural activities by monitoring and collecting information about farms and crops' health. Mizik (2021) also presented similar views regarding the utilization of IoT, artificial intelligence, robotics, and smart equipment which could enhance agricultural production while maintaining input of resources at a desirable level and achieving the goals of smart climate.

3.3 Opting for Renewable Sources of Energy

Exhaustive application of fossil fuels and other non-renewable resources of energy in agriculture and other sectors is an alarming threat to sustaining such resources besides its potential impact on the environment. Consistent use of non-renewable resources is linked with their decline and rising prices. To manage energy issues in agriculture, the utilization of renewable and eco-friendly energy sources in agriculture is needed on a priority basis. Several opportunities for farmers and agricultural stakeholders exist in the context of opting for eco-friendly and renewable energy sources. Chel and Kaushik (2011) outlined some possible sources of renewable energy which have a possible application in agriculture with low costs and little impact on the environment. These resources include generating biofuels and solar, tidal, and wave-generated energy. Some of these energy sources may not be applicable on large scale and in certain specific sites; however, future focus and research on using such resources in agriculture may create ample possibilities and feasibilities in the future. Bolyssov et al. (2019) pointed out that hydro-generated, solar, wind, and biomass energy have potential applications in agriculture for reducing reliance on non-renewable energy uses and environmental issues and are a step toward achieving the United Nations' Sustainable Developmental Goals. One of the best alternatives to fossil fuel energy is the use of solar energy which can be applied in various agricultural activities like irrigation, lightening, processing, etc. (Ali et al., 2012). Solar energy panels can be implanted at farms for irrigation, lighting, and driving solar-dependent vehicles and harvesting machines. At production sites, solar energy can be utilized to process agricultural raw material and drive heating and cooling processes at the manufacturing level. Wind energy is generated by the movement of wind through specifically designed wind turbines. It is an indirect form of solar energy because wind movement is stimulated by the sun-driven heating of the earth (Herbert et al., 2007). Chikaire et al. (2010) reviewed the uses of solar energy in agriculture. The authors identified many areas like water pumping; crop and grain drying; heating of greenhouses, water, and space; and remote supply of electricity. Acosta-Silva et al. (2019) revealed that solar and wind energy has potential application in agriculture for replacing fossil fuels and reducing the emission of GHG and environmental hazards associated with the traditional usage of non-renewable energy sources. Khojasteh et al. (2018) assessed the use of tidal and wave energy in agriculture and found it a promising approach toward minimizing dependency on fossil fuel energy. In several other studies, renewable energy resources like solar, wind, hydro-generated, tidal and wave, biofuel, and geothermal have been proposed as alternative strategies for adoption in agriculture to sustain productivity, manage energy, and control climate issues (Khan et al., 2018; Sircar & Yadav, 2018; Dalla Longa et al., 2020; Hranić et al., 2020; Tavira et al., 2022).

4 The Scenario of Developed and Developing Countries

Energy use in the agricultural sector greatly varies in developed and developing countries due to spatial, cultural, social, and technical factors. Since agricultural activities in any part of the world are linked with energy consumption (required for operating machinery, irrigation, transportation, etc.), fossil fuels are the major energy input in both developed and developing countries. In recent years, a great consensus has been developed in technologically advanced countries over the GHG emission and potential harms associated with fossil fuels, and there is an increasing tendency in developed countries to employ renewable resources of energy in agriculture. To manage energy efficiently in agriculture, developed countries have been focusing on "organic agriculture," "smart farming," "precision agriculture," and using "smart technologies" to sustain energy input in agriculture and environmental integrity since the 1980s (Gomiero et al., 2011; Mulla & Khosla, 2016). Recent advances in the area include the use of GPS, GIS, internet, variable rate technology, autonomous vehicles (unmanned aerial vehicles, drones, tractors, etc.), and robots which have been successfully used to monitor yields, growth conditions, fertilizer management, and pest control in different countries (Kern, 2015). Alongside, greater emphasis has been put up on creating renewable sources of energy to replace non-renewable resources in agriculture for energy management. In Europe, transitions from conventional energy use in agriculture to geothermal, wind, solar, and other renewable sources have occurred since the 1970s which is sought to be a major drive to reduce GHG emission (Popovski & Vasilevska, 2003; Chel & Kaushik, 2011). The USA, China, Japan Germany, and many other advanced countries are investing more in renewable energy sources for utilizing them in agriculture and other sectors

(Bolyssov, 2019). The transition toward "climate-smart agriculture," "precision and digital agriculture," and "energy-efficient agriculture" in developed countries is because of:

- The anticipated decline in non-renewable resources
- Climate change and environmental issues
- High literacy rate and awareness about the possible impact of traditional agriculture on ecosystem and climate
- Availability of technology and financial resources
- Increased level of GHG emission
- To decrease labor and cost input
- To manage energy efficiently

The picture of developing countries is almost different from developed countries in adopting energy-efficient management strategies for the agricultural sector. In developing countries, farmers merely use traditional agricultural practices which are based on high-throughput application of fertilizers and pesticides for enhancing soil fertility and crop yields and huge input of fossil fuel energy for diverse purposes related to agriculture. Despite the significance of modern and smart technology in energy management, the adoption rate of these technologies in agriculture is very low in developing countries as compared to advanced nations (Goel et al., 2021). Several reasons can be assigned to the low adaptability rate of smart agriculture in developing countries. Shankhdhar et al. (2021) pointed out that lack of awareness about the significance of smart technologies, hesitation to acceptance of such technologies, and relatively high cost of smart technologies are some of the hurdles in developing countries to fully adopt smart farming practices. Developed countries have the upper hand in a diverse range of technologies that developing countries are lacking in. Lack of interest of stakeholders and policymakers in the transition toward smart agriculture in developing countries is linked with little success of precision agriculture and its progress. Walter et al. (2017) outlined that lack of comprehensive knowledge about smart agricultural practices and their benefits, little expertise, lack of access to smart technologies, and financial issues are the primary hurdles in developing countries to adopt smart and precision agriculture.

Despite several underlying hurdles, developing countries are trying to adopt precision agriculture and invest in modern technologies for their utilization in the agricultural sector. India – a growing economy in South Asia – for instance, has a growing interest in adopting precision agriculture, and it has made some progress in the field (Mondal & Basu, 2009). According to Mondal et al. (2011) and Math and Dharwadkar (2018), advancement in satellite technology in India has enabled the country to use positioning systems and other smart technologies for the efficient management of energy in agriculture. Shafi et al. (2019) also argued that developing countries need a rapid transition from traditional agricultural practices to more precisely controlled smart agriculture where ample space is present for applying wireless sensors and other several technologies. Mahmood et al. (2013) suggested that improvement in agriculture and food production in Pakistan can be attained by opting for precision agriculture in the country. Onibonoje and Nwulu (2021) stated that in most developing countries, precision agriculture and relevant technologies are not fully adopted; however, in the next few years, those countries will make progress in that area. In China, smart farming and precision agriculture have been rapidly developing, and the country is using state-of-the-art technologies in the agricultural sector to promote productivity and yields, reduce labor and input of energy, and minimize environmental hazards (Zhang et al., 2002; Li et al., 2020).

5 Challenges and Opportunities

The use of smart technologies in agriculture has yielded desirable results in many countries where precision agriculture is adopted. Despite the significant contribution of precision agriculture to precise monitoring of agricultural activities which has led to greater yields, pest management, lower energy inputs, and reduced GHG emission, several challenges persist in the optimum utilization of smart technologies in agriculture. In developed countries, the availability of resources and accuracy of smart technologies are important drivers in those countries which have enabled farmers to use them for precise farming. In developing countries, such resources are scarce, and there is a gap in the promotion of precision agriculture and smart technologies. Special variability in different parts of the world hinders the smooth functioning of certain smart technologies adopted in agriculture which often reduces the validity and reliability of collected information about crops, diseases, fertilizers, and climatic conditions. High costs and lack of expertise required for operating smart devices and technologies in precision agriculture are some other limiting factors in promoting precision agriculture. Ofori and El-Gayar (2021) highlighted that high cost, issues related to data protection, the complex nature of smart technologies, and their availability serve as some of the obstacles in the adoption of precision agriculture. Yazdinejad et al. (2021) identified cyber security as a major threat to the gathered information in precision agriculture.

Despite the prevalence of obstacles, the future of precision agriculture is promising if policymakers focus on the potential benefits associated with precision agriculture. Arrangement of awareness campaigns in those countries where the rate of accepting precision agriculture is slower is necessary which would help farmers to realize that precision agriculture is an ideal alternative to traditional agriculture because it is based on the principles of utilizing minimum resources and producing maximum outputs while sustaining the climatic integrity. There is a dire need to invest in the production and employment of smart technologies which are the core components of precision agriculture. Major efforts are necessary for developing countries to the provision of affordable smart technologies and relevant skills to farmers. Minimizing dependency on non-renewable resources of energy by opting for renewable sources such as wind, solar, thermal, and hydropower and their robust use in agriculture could achieve efficient energy management and reduced GHG emission.

6 Conclusion

Agricultural activities are highly dependent on the use of direct and indirect input of energy. Because of an anticipated decline in fossil fuels and non-renewable sources of energy and their role in GHG emission and impact on climate change, efficient management of energy and adopting climate-smart agricultural practices are crucially necessary for ecosystem sustainability. Precision agriculture provides several opportunities to farmers, agricultural stakeholders, and policymakers to precisely monitor and control crop production, fertilizer application, disease assessment, and energy use. Precision agriculture employs modern technologies and information tools which include the use of computers, the internet, communication devices, specific software and applications, GIP, GIS, unmanned aerial vehicles, drones, smart tractors and machinery, robots, sensors, variable rate technologies, and several other smart technologies which work in an integrated manner to collect information about soil, plants, and climatic conditions, and after analyzing the collected information, precise decisions are made about how, when, and where to apply suitable farming techniques.

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Sustainable Manipulation of Agricultural Residues in Bioenergy Production

Asian Perspective

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Abstract

In the present farming situation, agricultural residues are becoming increasingly problematic. Their disposal, proper utilization, and management practices are not sufficient. In most cases, farmers either leave the residues in the field for decomposition or simply burn in situ. As a result, these are causing a serious threat to the environment. Lignocellulose-rich agricultural leftovers can be converted into various bioenergy forms such as methane, ethanol, hydrogen, etc. through biochemical or thermochemical conversion processes. As agricultural crop wastes are by-products of agricultural crop production, harvesting these does not necessitate additional land, and these are profusely available at a lower price. Asia is the largest continent in the world, and energy demand for its burgeoning population is increasing day by day. Therefore, energy production in sustainable ways has become the need of the hour. There are plenty of agricultural residues with high calorific value in Asian countries like China, India, Vietnam, Indonesia, Japan, Bangladesh, Sri Lanka, etc. In order to mitigate environmental hazards and to attain energy security, agricultural residue-based bioenergy production may open a new aspect in sustainable energy production in terms of renewability, eco-friendliness, cost-effectiveness, and social acceptability. As an alternative energy source, this can also help lower the amount of greenhouse gases released from fossil fuel burning. Consequently, it can contribute to attain the seventh goal of sustainable development goals (SDGs), which is to secure access to affordable, reliable, modern, as well as sustainable energy for all. In this present chapter, attempts are made to address the sustainable manipulation of agricultural residues for bioenergy production specifically for Asian countries. The availability of different agricultural residues, their potential for bioenergy production, and logistics in several Asian countries have been explored along with their SWOT (strengths, weaknesses, opportunities, and threats) analysis.

Keywords

Agricultural residues · Bioenergy · Energy security · Environmental hazards · Sustainable development goals · SWOT analysis

1 Introduction

Agriculture is undoubtedly the backbone of our society. Food demand for the escalating world population is being mitigated by agriculture. Green revolution was inevitable to ensure the food security for this enormous population, with the development of numerous high-yielding crop varieties. With the increase in food grain production, the production of crop residues also increases. Crop residue includes plant materials, straw, leaves, stalks, stubbles, seed pods, bagasse, husk, etc., which are left in the field after crop harvest. The characteristics of residues may vary with crops, species, and environmental conditions (De Bhowmick et al., 2018;

Ramesh et al., 2019). In rural areas, crop residues are used as feedstuffs for animals and/or fuel for cooking purposes (Prasad et al., 2018), and a huge amount of crop residues are left unutilized on the field (Prasad et al., 2020). In most of the cases, farmers either leave the residues in the field for decomposition or simply burn in situ, resulting in generation of greenhouse gases that pose a serious threat to the environment by causing environmental pollution. For this reason, proper management of crop residues has become a momentous challenge (Kumar et al., 2016; Prasad et al., 2020).

Petroleum and fossil fuels are major energy sources in our modern life. They are nonrenewable energy sources causing serious environmental hazards such as air pollution, global warming, climate change, etc. To satisfy the energy demand and to ensure energy security for future generations, researchers have started thinking of alternative energy sources (Behera & Prasad, 2020; Venkatramanan et al. 2021a, b, c; Prasad et al., 2021). Renewable energy sources have become an alternative to fossil fuels. These are also gaining popularity due to their renewability, high availability, and low cost (Ramesh et al., 2019). At this stage, attention is naturally concentrated on biomass as a promising and eco-friendly energy resource that can definitely address the current energy crisis of the society (Tao et al., 2013). Lignocellulosic biomass feedstocks are the potential contenders among the various biomass resources to promote the shifting from petroleum-based economy to bioeconomy for a long-term development. It lowers the dependency on foreign money and oil imports (Raman et al., 2015; Xu et al., 2016; Ramesh et al., 2019). Agricultural crop residues are the most significant lignocellulosic biomass resources. The lignocellulose-rich agricultural leftovers can be converted into various bioenergy forms (such as methane, ethanol, hydrogen, etc.) through thermochemical and biochemical conversions processes. As agricultural crop residues are by-products of agricultural crop production, harvesting them does not require additional land, and these are profusely available at a lower price.

Asia is the world's largest continent comprising about 16% of the total land area of the earth. The Asian continent is mainly located in the eastern and northern hemispheres. Asia is also the most populous continent, consisting of almost 55% of the world's population. The population density of Asia is around 1.87 persons per hectare as compared to the world average (0.54 person per hectare) (Roy et al., 2021). The energy demand for this burgeoning population is increasing day by day. Therefore, energy production in sustainable ways has become the need of the hour. In the context of climate change and energy security, bioenergy is critical to support the UN Sustainable Development Goals (SDGs). In the question of environmental sustainability and protection of the planet, the production of renewable energies like bioenergy has a huge concern (IRENA, 2021). There are plenty of agricultural residues with high calorific values in Asian countries like India, Vietnam, Pakistan, China, Bangladesh, Nepal, Bhutan, Sri Lanka, Japan, Indonesia, etc. Agricultural residue-based bioenergy production may open a new horizon toward achieving energy security through successful residue management and environmental hazard mitigation. In this chapter, attempts are made to address the sustainable manipulation of agricultural residues for bioenergy production in Asian countries.

2 Crop Residues

Agricultural crop residues are materials that are left after crop harvesting or processing or both operations (Sharma et al., 2018; Ramesh et al., 2019; Prasad et al., 2020). These may be solid or semisolid. The nature of crop residue depends on the products obtained from the crop. Agricultural crop residues are of two types – (a) primary residues and (b) secondary residues (Ramesh et al., 2019). The leftovers in the field after harvesting the main agricultural produce are primary residues, e.g., leaves, straw, stalks, plant materials, etc. During processing of the main agricultural produce, secondary residues are generated, e.g., rice husk, wheat pod, maize cob, groundnut shell, sugarcane bagasse, etc. The primary and secondary agro-residues production pathways are shown in Fig. 1. Agricultural crop residues are heterogeneous in nature. Their characteristics vary with particle size, moisture content, bulk density, geographical location, etc. The chemical composition also varies with species, harvest period, and physical composition including harvest practices, length of storage, etc. (Mohammed et al., 2018).

2.1 Biochemical Composition of Crop Residues

Agricultural crop residues are mainly composed of lignin, cellulose, and hemicellulose. The content of these lignocellulosic components varies from crop to crop. The biochemical compositions of various crop residues (wheat, rice, maize, barley, oat, sorghum, jute, groundnut, tobacco, coconut, cashew nut) have been presented in Table 1.

2.2 Thermochemical Composition of Crop Residues

The thermochemical compositions (net calorific value, gross calorific value, volatile matter, non-volatile matter, carbon, nitrogen, oxygen, sulfur, chlorine, hydrogen, ash content) of selected crop residues have been presented in Table 2.

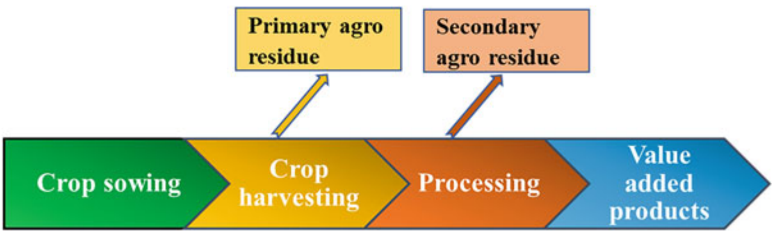

Fig. 1 Representation of primary and secondary agro wastes obtained after agricultural crop harvesting and processing

Table 1 Biochemical composition of different agricultural residues

Crops	Residues	Lignin (%)	Cellulose (%)	Hemicellulose (%)	References
Wheat	Straw	5–21	29–49	22.3–50	McKendry (2002); Ballesteros et al. (2006); Mani et al. (2006); Butler et al. (2013); Saini et al. (2015); Cai et al. (2017); Bharathiraja et al. (2017); Gaurava et al. (2017); Ramesh et al. (2019)
	Bran	8.3–12.5	10.5–14.8	35.5–39.2	Bilal et al. (2017); Ramesh et al. (2019)
	Shell	4–8	10–15	30	Bertero et al. (2012); Ramesh et al. (2019)
Rice	Straw	4.84–23.3	28.1–43.77	20.47–31.42	Rai et al. (1989); Prasad et al. (2007); Sarnklong et al. (2010); Chen et al. (2011); Phan et al. (2014); Cai et al. (2017); Ramesh et al. (2019)
	Husk	7.28–31	25–44.12	12.0–29.3	Nordin et al. (2007); Wang et al. (2012); Braga et al. (2013); Cai et al. (2017); Ramesh et al. (2019)
Maize	Straw	8.2–19	27.9–42.6	14.8–21.3	Diaz et al. (2015); Bilal et al. (2017); Ramesh et al. (2019)
Barley	Straw	6.3–19	31–45	21.9–38	Mani et al. (2006); Saini et al. (2015); Nigam et al. (2009); Cai et al. (2017); Ramesh et al. (2019)
Oat	Straw	16–19	31–39.4	27–38	Nigam et al. (2009); Sanchez (2009); Ramesh et al. (2019)
Sorghum	Straw	15.0–21.0	2.0–35.0	24.0–27.0	Cai et al. (2017); Ramesh et al. (2019)
Jute	Fibre	21–26	45–53	18–21	Bilal et al. (2017); Ramesh et al. (2019)
Groundnut	Shell	30.2	35.7	18.7	Dhyani and Bhaskar (2017); Ramesh et al. (2019)

(continued)

Table 1 (continued)

Crops	Residues	Lignin (%)	Cellulose (%)	Hemicellulose (%)	References
Tobacco	Stalk	27	42.4	28.2	Dhyani and Bhaskar (2017); Ramesh et al. (2019)
Coconut	Coir pith	41–45	36–43	0.15–0.25	Saini et al. (2015); Ramesh et al. (2019)
Cashew nut	Shell	40.1	41.3	18.6	Dhyani and Bhaskar (2017); Ramesh et al. (2019)

Table 2 Thermochemical composition of selected crop residues (Benova et al., 2021)

Parameters (Dry basis)	Rice straw	Rice husk	Sugarcane bagasse
Net calorific value (MJ/Kg^1)	16.80	16.15	16.47
Gross calorific value (MJ/Kg^1)	18.01	17.33	17.80
Volatile matter (% by weight)	73.65	70.78	72.41
Non-volatile matter (% by weight)	15.98	15.43	15.72
Carbon (C) (% by weight)	44.90	43.89	45.19
Hydrogen (H) (% by weight)	5.56	5.43	6.08
Oxygen (O) (% by weight)	38.10	35.86	35.44
Nitrogen (N) (% by weight)	0.80	0.91	1.30
Sulphur (S) (% by weight)	0.23	0.09	0.02
Chlorine (Cl) (% by weight)	0.04	0.03	0.06
Ash (% by weight)	10.37	13.79	11.91

3 Status of Agricultural Residues in Asian Countries

A huge amount of crop residues is generated every year in different countries of Asia. The production of crop residues (in terms of N content) in Asia is reportedly increasing each year (Fig. 2). Only a small proportion of crop residues is used by farmers as feed for livestock, fuel purposes, bedding material, and mulching. The rest are dumped or burned in situ to get rid of huge volumes of crop residues. Such improper management of crop residues causes the excessive emission of greenhouse gases like methane, nitrous oxide, etc.

The average share of nitrous oxide emission from the decomposition of residues of different crop types from 2010 to 2019 is shown in Fig. 3, where it was found that the residue of rice had the highest amount (48%) of N_2O emission from decomposition in Asian countries followed by wheat (25.3%), maize (16.4%), soybeans (3%), and potato (2.3%).

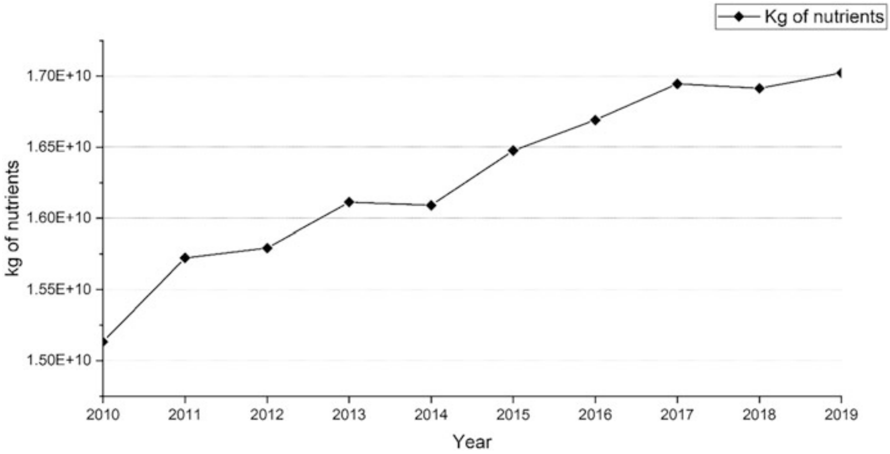

Fig. 2 Year-wise (2010–2019) crop residue production (nitrogen content) in Asia (FAOSTAT, 2019)

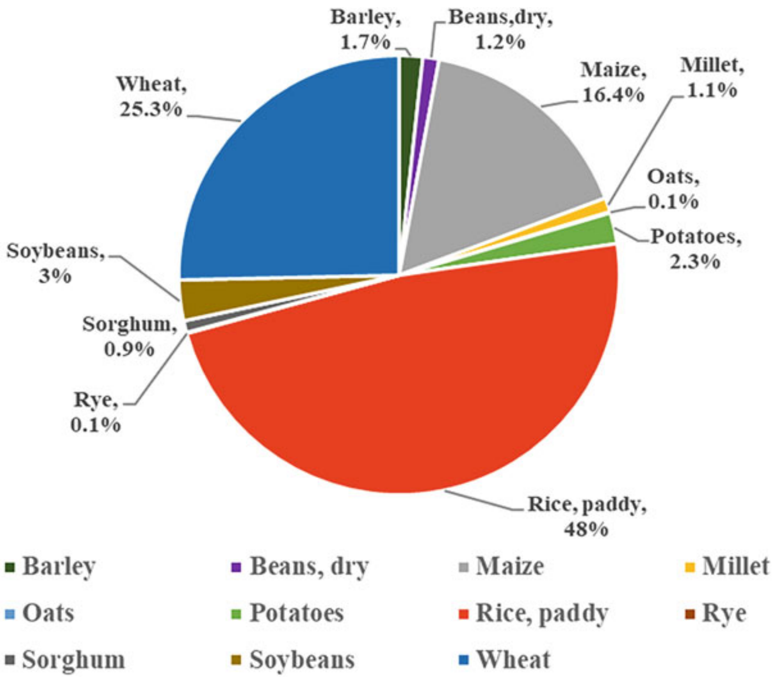

Fig. 3 Average share of nitrous oxide emission from decomposition by different crop residue types in Asian countries (2010–2019) (FAOSTAT, 2019)

3.1 Crop Residue Burning in Asian Countries

Lion's share of the farmers of Asian countries follows residue burning. It is considered to be a simple solution for farmers as it instantly clears the fields for timely sowing of the next crops (Ahmed et al., 2015; Prasad et al., 2020). The status of crop residues burned in different Asian countries in 2019 is presented in Table 3.

3.2 Environmental Impact of Crop Residue Burning

The burning of crop residues is a major cause of concern as it emits a large amount of air pollutants and hazardous gases such as nitrogenous oxides (N_xO_y), carbon monoxide (CO), carbon dioxide (CO_2), ammonia (NH_3), sulfur dioxide (SO_2), volatile organic compounds (VOCs), as well as aerosols, black carbon smokes, and particulates, resulting in negative health effects, particularly respiratory ailments like asthma, lung cancer, etc. (Torigoe et al., 2000; Kumar et al., 2015). The release of major greenhouse gases like CO_2, CH_4, and N_2O makes significant contribution to global warming and climate change in a large context. Crop biomass burning might contribute up to 40% of gross CO_2 and 38% of ozone (O_3) to the troposphere (Prasad & Dhanya, 2011; Bhuvaneshwari et al., 2019). The status of emissions of methane (CH_4) and nitrous oxide (N_2O) from the onsite burning of various crop residues in different Asian countries is shown in Table 4.

Table 3 Status of crop residue burned in 2019 in Asian countries (FAOSTAT, 2019)

Country	Crop residue burned (tons) (year 2019)			
	Maize	Rice	Sugarcane	Wheat
Afghanistan	94,910	70,141.5	1074.45	933,600
Bangladesh	445,099	6,334,104.15	52,690	132,139.2
Bhutan	13,146	643.55	8.45	401.6
China	41,309,740	16,478,036.3	924,725.75	9,493,024
India	9,027,130	24,079,000	3,289,708.5	11,727,516
Indonesia	5,644,775	5,872,837.85	288,319.85	–
Japan	54	848,100	13,837.85	84,640
Nepal	940,886	820,459.2	46,556.25	281,596.8
Pakistan	1,413,246	1,668,680.75	675,855.05	3,471,092
Philippines	2,516,723	2,558,319.5	246,514.45	–
Sri Lanka	63,449	526,677.8	8424	–
Vietnam	991,088	4,108,439.5	151,701.55	–
Iran	204,305	240,477.1	73,547.5	3,214,375
Iraq	100,594	70,220.15	0	617,326.4
Israel	3350	–	–	16,520
Myanmar	515,714	3,806,581	118,402.7	23,546.4
Turkey	638,065	69,530.45	–	2,732,742

"–" stands for "data not found"

Table 4 Emissions of methane (CH_4) and nitrous oxide (N_2O) from the onsite combustion of crop residues in different countries of Asia (FAOSTAT, 2019)

	CH_4 and N_2O emissions (in kilotons)							
	Maize		Paddy		Sugarcane		Wheat	
Country	CH_4	N_2O	CH_4	N_2O	CH_4	N_2O	CH_4	N_2O
Afghanistan	0.2563	0.0066	0.1894	0.0049	0.0029	0.0001	2.5207	0.0654
Bangladesh	1.2018	0.0312	17.1021	0.4434	0.1423	0.0037	0.3568	0.0092
Bhutan	0.0355	0.0009	0.0182	0.0005	0	0	0.0011	0
China	111.5363	2.8917	44.4907	1.1535	2.4968	0.0647	25.6312	0.6645
India	24.3733	0.6319	65.0133	1.6855	8.8822	0.2303	31.6643	0.8209
Indonesia	15.2409	0.3951	15.8567	0.4111	0.7785	0.0202		
Iran	0.5516	0.0143	0.6493	0.0168	0.1986	0.0051	8.6788	0.225
Iraq	0.2716	0.007	0.1896	0.0049	0	0	1.6668	0.0432
Israel	0.009	0.0002					0.0446	0.0012
Japan	0.0001	0	2.2899	0.0594	0.0374	0.001	0.2285	0.0059
Myanmar	1.3924	0.0361	10.2775	0.2665	0.3197	0.0083	0.0636	0.0016
Pakistan	3.8158	0.0989	4.5054	0.1168	1.8248	0.0473	9.3719	0.243
Philippines	6.7952	0.1762	6.9075	0.1791	0.6656	0.0173		
Sri Lanka	0.1713	0.0044	1.422	0.0369	0.0227	0.0006		
Vietnam	2.6759	0.0694	11.0928	0.2876	0.4096	0.0106		

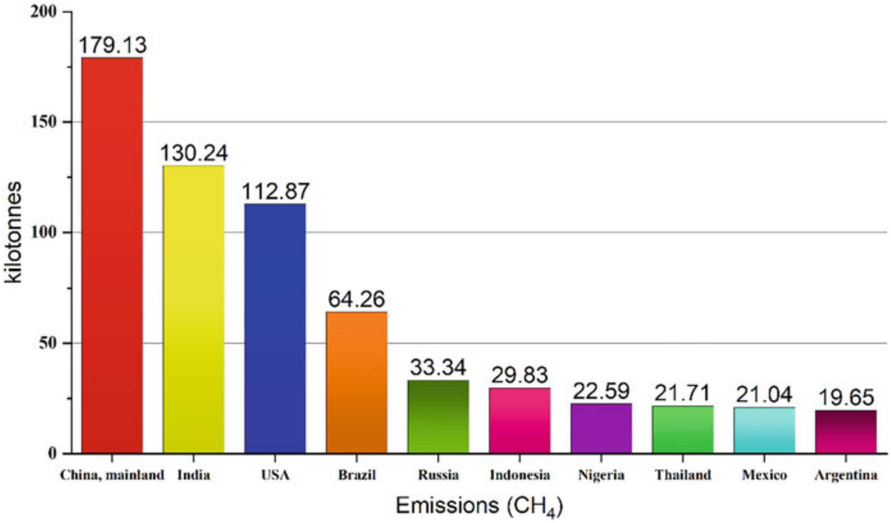

Fig. 4 Top ten emitter countries of the world for emissions of CH_4 from agricultural crop residues onsite burning (as per average of 2010–2019) (FAOSTAT, 2019)

Among the top ten methane (CH_4) emitter countries in the world from agricultural crop residue onsite burning as per average of the recent 10 years (2010–2019), five are from Asia, viz., China, India, Russia, Indonesia, and Thailand, where China recorded the highest emission of 179.13 kilotons of CH_4 (Fig. 4).

3.3 Impact of Residue Burning on Soil Health

Burning of crop residues affects the environment, causing pollution and degradation of soil health (Prasad et al., 2020). The heat generated while burning raises the soil temperature, which drastically reduces the beneficial soil microbial population from the top layer of the soil, and causes a reduction in carbon and nitrogen content. A study entitled "Effect of fire on chemical forms of iron and manganese in forest soils of Iran" carried out by Norouzi and Ramezanpour (2013) reported that there was a significant increase in pH, sand, soluble K, exchangeable K, magnesium (Mg), available P, calcium (Ca), base saturation (BS), and electrical conductivity (EC) and a remarkable decrease in organic carbon, cation exchange capacity (CEC), and clay of soil due to forest fire.

4 Potentiality Assessment of Crop Residues for Bioenergy Production

Currently, lignocellulosic biomass is being extensively studied by many researchers across the globe for developing cleaner as well as sustainable energy that may work as an alternative to fossil fuel systems (Prasad et al., 2007, 2021). Only a small proportion of crop residues is being used by farmers as feed for livestock, and the rest of these is plowed back into the soil or burned to get rid of the huge volumes of biomass before planting the next crop. The biggest advantage of utilizing agricultural residues lies in the fact that crop residues, being by-products of agricultural production, do not hamper normal crop production, and hence, energy production from the crop residues is quite economical (Mohammed et al., 2018).

4.1 Estimation of Bioenergy Potential of Crop Residues

4.1.1 Residue-to-Product Ratio (RPR)

The amount of residues produced for a particular crop can be predicted through RPR (Hiloidhari et al., 2014; Ramesh et al., 2019). RPR is the ratio between the weight of residue obtained from the crop to the total weight of agro-product yield for the crop. By multiplying the crop yield with the RPR value, we can calculate the quantity of residues generated from the selected crop. RPR value generally ranges from 0.05 to 4.0 for the primary residues and 0.15 to 2 for the secondary residues (Table 5).

$$\mathbf{RPR} = \frac{\text{Weight of the residue obtained from the crop}}{\text{Total weight of agro product yield of the crop}}$$

4.1.2 Gross Residue Potential

It is the total amount of residue generated after harvesting of crops. It depends on the area coverage, yield and RPR value of the crop.

$$\text{Gross residue potential} = \text{Area coverage (ha)} \times \text{Yield (ha)} \times \text{RPR value}$$

4.1.3 Surplus Residue Potential

It is the amount of residue left after any competing uses (such as animal bedding, cattle feed, organic fertilizer, heating, and cooking fuel).

$$\text{Surplus residue potential} = \text{Gross residue potential} \times \text{Surplus residue fraction}$$

4.1.4 Bioenergy Potential

The bioenergy potential of crop residue is measured by the following formula:

$$\text{Bioenergy potential} = \text{Surplus residue potential} \times \text{Heating value}$$

5 Logistics of Agricultural Crop Residue-Based Bioenergy Production

There should be a perfectly designed logistics for an uninterrupted supply of agricultural crop residues to the energy conversion plant (Gold & Seuring, 2011). There are certain steps to be followed for the proper logistics of crop residues. The

Table 5 RPR and heating value of different crop residues

Crop group	Crop	Residue		RPR	Heating value (MJ/Kg)	References
Cereals	Rice	Primary	Straw	1.50	15.54	Hiloidhari and Baruah, (2011a, b)
		Secondary	Husk	0.20	15.54	Singh et al. (2008a, b, c)
	Maize	Primary	Stalk	2.00	16.67	
		Secondary	Cob	0.30	17.39	
	Wheat	Primary	Stalk	1.50	17.15	
		Secondary	Pod	0.30	17.39	
	Bajra	Primary	Stalk	2.00	18.16	Friedl et al. (2005)
		Secondary	Cob	0.33	17.39	Hiloidhari et al. (2014)
			Husk	0.30	17.48	Raveendran et al. (1995)
	Jowar	Primary	Stalk	1.70	18.16	Friedl et al. (2005)
		Secondary	Cob	0.50	17.39	Hiloidhari et al. (2014)
			Husk	0.20	17.48	Raveendran et al. (1995)
Oilseeds	Mustard and rapeseed	Primary	Stalk	1.80	17	Singh et al. (2008a, b, c)
	Sesame		Stalk	1.20	14.35	Zabaniotou et al. (2008)
	Sunflower		Stalk	3.00	17.53	Zabaniotou et al. (2008)
	Safflower		Stalk	3.00	13.9	Hiloidhari et al. (2014)
	Linseed		Stalk	1.47	14.35	Hiloidhari et al. (2014)
	Niger		Stalk	1.00	14.35	Hiloidhari et al. (2014)
	Soybean		Stalk	1.70	16.99	Kis et al. (2009)
	Groundnut	Primary	Stalk	2.00	14.4	Jekayinfa and Scholz (2009)
		Secondary	Shell	0.30	15.56	
Pulses and legumes	Lentil	Primary	Stalk	1.80	14.65	Hiloidhari et al. (2014)
	Green gram	Primary	Stalk	1.10	16.02	Singh et al. (2008a, b, c)
Sugar crop	Sugarcane	Primary	Top and leaves	0.05	20	Singh et al. (2008a, b, c)
		Secondary	Bagasse	0.33	20	
Fiber crops	Cotton	Primary	Stalk	3.80	17.4	Jekayinfa and Scholz (2009)
		Secondary	Husk	1.10	16.7	Hiloidhari et al. (2014)

(continued)

Table 5 (continued)

Crop group	Crop	Residue		RPR	Heating value (MJ/Kg)	References
			Boll shell	1.10	18.3	Caglar and Demirbas (2001)
	Jute	Primary	Stalk	2.00	19.7	Asadullah et al. (2008)
	Areca nut	Primary	Frond	3.00	18.1	Hiloidhari et al. (2014)
		Secondary	Husk	0.80	17.9	Pilon (2007)
	Coconut	Primary	Frond	4.00	10	Rahman (2006)
		Secondary	Husk and pith	0.53	19.4	Minowa et al. (1998)

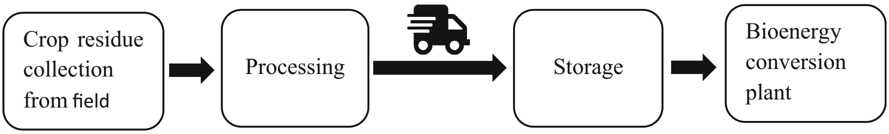

Fig. 5 Flow chart for logistics of crop residue-based bioenergy production

residues are collected from the crop field followed by processing and loading for transportation. Different types of balers may be a potent option for this purpose. Then the processed crop residues are shifted to storage. Finally, these are transported to a bioenergy conversion plant (Fig. 5). As a result, the entire supply chain must be adequately maintained to ensure ceaseless functioning (Jana et al., 2018).

6 Conversion Technology for Bioenergy Production

We can generate bioenergy utilizing agricultural crop residues through many available modern technologies. At present, bioenergy production from crop residues is given more emphasis as this promotes residue recycling as well as the generation of renewable energy. Bioenergy produced from crop residues can be utilized in power sectors, industry, residents, public transport, etc. The lignocellulose-rich agricultural leftovers can be converted into various bioenergy forms such as methane, ethanol, hydrogen, etc. through thermal, thermochemical, and biochemical pathways (Fig. 6).

6.1 Thermal and Thermochemical Conversion Processes

6.1.1 Direct Combustion

Direct combustion is a thermal conversion process by which heat is generated as a result of complete combustion of agricultural residues under excessive aerated

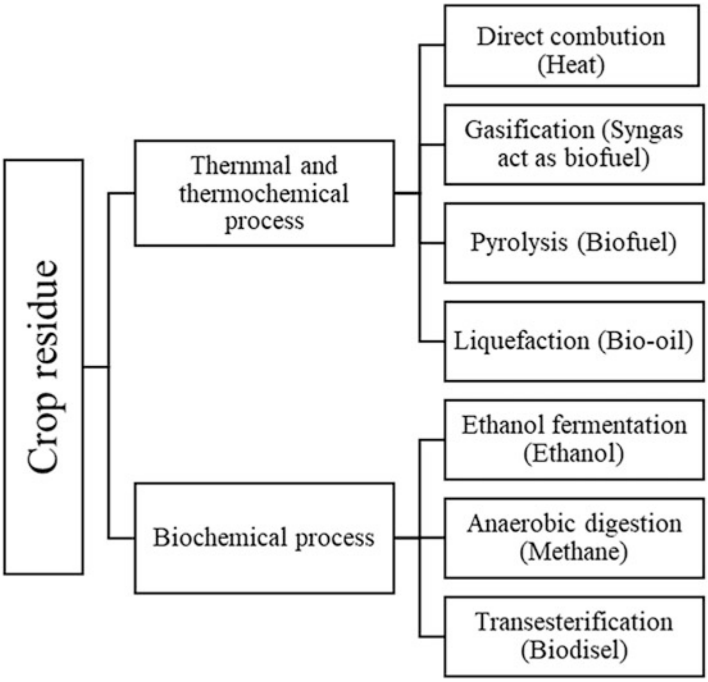

Fig. 6 Thermochemical and biochemical conversion processes of bioenergy production from crop residues

conditions. In the direct combustion process, agricultural crop residues are directly burnt to produce heat and electricity (Clini et al., 2008; Prasad et al., 2021). In the industrial furnace, agricultural residues are burnt to generate thermal energy, which produces steam in the boiler, which turns the turbine, which is attached with an electrical generator (Chambers, 2003).

6.1.2 Gasification

It is a thermochemical conversion process in which gaseous biofuel is produced from crop residues. Under the partial presence of oxygen, at temperatures 500–1800 °C, syngas is produced, which is used to generate heat and electricity (Prasad et al., 2021). Syngas consists of carbon dioxide, carbon monoxide, hydrogen, hydrocarbon, and methane (Sarkar et al., 2020). Wet agricultural residues are not preferred in the gasification process (Tock et al., 2010). For wet residues, supercritical water gasification (SCWG) is used (Prasad et al., 2021).

6.1.3 Pyrolysis

In the process of pyrolysis, thermal degradation of agricultural residues takes place at temperatures 350–500 °C under the absence of air, resulting in the formation of solid, liquid, or gaseous biofuel (Ramesh et al., 2019). In this chemical reaction, the nature of the end products depends on particle size, reaction temperature, and reaction time (Chen et al., 2017).

6.1.4 Liquefaction

In this process, bio-oil is produced under low temperature and elevated pressure in the presence of hydrogen. In the hydrothermal liquefaction (HTL) process, biofuel is produced under temperatures 250–374 °C with 40–220 bar pressure utilizing sub-critical water (Sarkar et al., 2020; Dimitriadis & Bezergianni, 2017).

6.2 Biochemical Conversion Process

In the biochemical conversion process, bioenergy is generated through the action of enzymes. These conversion technologies are considered more environment-friendly than thermal and thermochemical technologies (Prasad et al., 2021). Ethanol fermentation and anaerobic digestion for methane production are the main biochemical conversion technologies for bioenergy production.

6.2.1 Ethanol Fermentation

Ethanol is a widely used biofuel worldwide. As the carbon in ethanol comes from the plant, it is called as a carbon-neutral biofuel, which means that when it is burned, it does not cause an increase in carbon dioxide emissions (Hsieh et al., 2002; Prasad et al., 2021). The findings of Zhang et al. (2021) demonstrate that crop residue energy utilization has carbon emission factors of 0.09–0.18 kg (CO_2 eq per 1 MJ) and a net carbon emission decrease of 0.03–0.15 kg (CO_2 eq per 1 MJ) when compared to conventional power or petrol. Ethanol has been advocated as an alternative fuel source due to its anti-knocking characteristics, which help enhance octane ratings and ameliorate fuel efficiency (Prasad et al., 2014, 2021). Sugar-based biomass (like sugarcane, sugar beet) can be used for ethanol production. In this case, ethanol can be produced directly by the fermentation process. Ethanol can also be produced from starch-containing crops like wheat, maize, etc. Hydrolysis is required before fermentation for ethanol production from starch-containing biomasses. Another source of ethanol production is lignocellulosic biomass. In this case, biomass is pretreated, and then it is saccharified to produce fermentable sugar. After that, through the fermentation and distillation process, ethanol can be produced (Jana et al., 2018). The remaining residues can be transformed into worthy products via liquefaction, pyrolysis, and gasification (Sarkar et al., 2020).

6.2.2 Anaerobic Digestion

Anaerobic digestion is also known as bio-methanation process. Through this process, gaseous biofuel and digested slurry are produced under controlled anaerobic conditions. Most of the agricultural residues are suitable for biogas production via anaerobic digestion process (Adney et al., 1991; Ramesh et al., 2019). Agricultural residues containing moisture up to 90% can be used in this process (Sarkar et al., 2020). The entire digestion system can be carried out in a well-designed anaerobic digester (Prasad et al., 2021), and the whole process can be separated into three steps – hydrolysis, fermentation, and methanogenesis (Sarkar et al., 2020). In the hydrolysis process, complex biomolecules are converted into simple biomolecules. In the fermentation process, simple biomolecules are transformed into acetic acid, alcohol, fatty acid, CO_2, and H_2. In the methanogenesis process, biogas is produced, which contains methane (60–70%) and CO_2 (30–40%) (Cantrell et al., 2008; Prasad et al., 2021).

6.2.3 Transesterification

Biodiesel is another source of bioenergy, which can be produced from vegetable oil. Vegetable oils due to their high viscosity and low volatility cannot be directly used in engine. For this reason, biodiesel is produced through the transesterification process. Transesterification is a process of transforming triglycerides in vegetable oils into a mixture of fatty acid esters using alcohol (mostly methanol) and catalyst (mostly alkali catalyst) to obtain high biodiesel yields (Jana et al., 2018). Methyl or ethyl esters are obtained, with much more similar properties to those of conventional diesel fuels. The main by-product obtained is glycerol. As a source of oil, rapeseed oil, soybean oil, and palm oil can be used.

A bird's-eye view on Table 6 revealed the bioenergy production and consumption data of various Asian countries for the year 2019. It is worthy to mention that both the total production and consumption of biofuel is highest in Indonesia, followed by China and India. The rest of the countries had comparatively low production as well as consumption of biofuel.

7 Bioenergy and Sustainability

Bioenergy plays a significant role in sustainability. The Brundtland Commission defined "sustainable development" as "development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs" (United Nations, 1987). Because of the multidimensional effects of bioenergy, it is critical to conduct a sustainability assessment in order to identify a long-term sustainable solution using bioenergy (Scarlat & Dallemand, 2011). The sustainability of crop residue-based bioenergy production can be assessed with social, economic, and environmental dimensions through the indicators developed by Global Bioenergy Partnership (GBEP, 2011). The indicators with these dimensions are shown in Table 7. Environmental indicators include the impacts on hydrosphere, atmosphere, and lithosphere. On the other hand, socioeconomic indicators consist of various changes in life standard, land use, energy diversity, and income (Jana et al., 2018).

Table 6 Biofuel production and consumption status in different Asian countries (USEIA, 2019)

Country	Biofuel production (terajoules)			Biofuel consumption (terajoules)		
	Total production	Fuel ethanol	Biomass based diesel	Total consumption	Fuel ethanol	Biomass based diesel
China	144,533.16	101,787.57	42,745.59	158,229.89	103,747.86	54,482.03
India	63,422.57	56,665.99	6756.58	63,244.26	56,665.99	6578.27
Indonesia	284,502.14	0	284,502.14	220,489.79	0	220,489.79
Japan	643.58	4.22	639.36	18,997.33	18,652.33	345.00
Pakistan	120.28	120.28	0	0	0	0
Philippines	15,378.49	7555.25	7823.24	23,821.05	15,819.51	8001.54
Vietnam	3540.77	3540.77	0	3540.77	3540.77	0

Table 7 Global Bioenergy Partnership (GBEP) indicators (GBEP, 2011; Hayashi et al., 2014)

Dimension	Sustainability indicators
Social	Allocation and tenure of land for new production
	Change in income
	Jobs in the bioenergy indicators
	Price and supply of a national food basket
	Change in unpaid time spent by women and children collecting biomass
	Change in mortality and burden of disease attributable to indoor smoke
	Bioenergy used to expand access to modern energy services
	Incidence of occupational injury, illness and fatalities
Economic	Productivity
	Gross value added
	Net energy balance
	Training and re-qualification of the workforce
	Change in consumption of fossil fuel and traditional biomass
	Energy diversity
	Infrastructure and logistics for distribution of bioenergy
	Capacity and flexibility of use of bioenergy
Environmental	Lifecycle GHG emission
	Soil quality
	Emission of non-GHG air pollutants
	Harvest levels of wood resources
	Water use and efficiency
	Water quality
	Land use and land use change related to bioenergy feedstock production
	Biological diversity and landscape

8 SWOT Analysis

A SWOT analysis is a simple and strategic planning to determine the internal strengths and weaknesses as well as external opportunities and threats. A SWOT analysis of crop residue-based bioenergy production has been presented here (Fig. 7). The analysis discloses that the production of bioenergy through crop residues has some concrete strengths such as availability of ample amount of crop residues, solution of residue disposal problems, a competitive alternative against fossil fuels, ability to meet the energy demand as well as secure the future energy requirements, etc. However, it also has several internal weaknesses, viz., scarcity of efficient agri-waste supply chains, costly technologies, absence of compensation and subsidy facilities for crop residue-based energy production systems, etc. There are various opportunities too in this bioenergy production system such as providing knowledge and imparting skill on a regular basis through training, organizing various promotional and demonstration programs, offering incentives, subsidies,

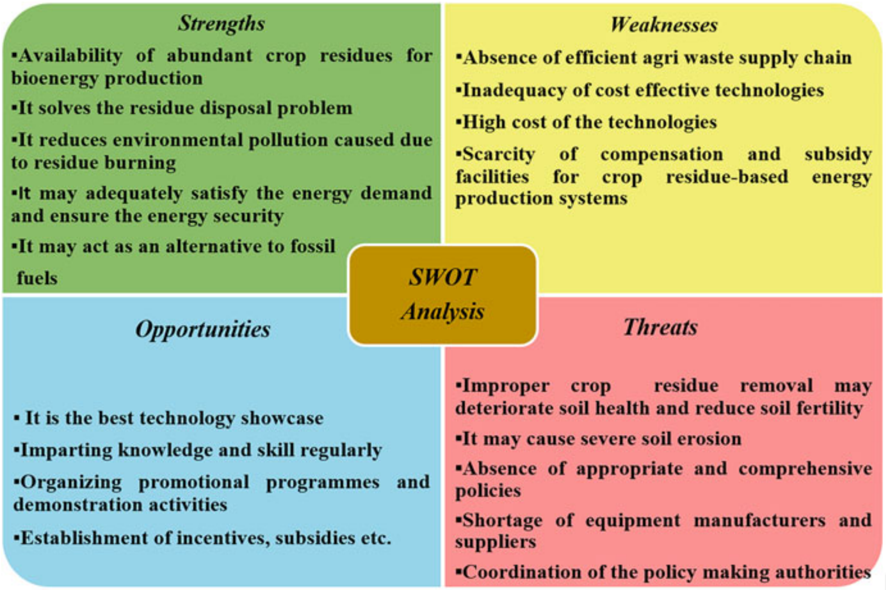

Fig. 7 SWOT analysis of agricultural crop residue-based bioenergy production

etc. Different threats also exist in this system like severe soil erosion, improper crop residue removal, reduction of soil fertility, lack of appropriate and comprehensive policies, paucity of equipment manufacturers and suppliers, etc.

9 Conclusion

In Asian countries, agricultural crop residue-based bioenergy production is one of the best ways to manage crop residue sustainably. This approach not only meets the energy demand of Asian countries but also mitigates the environmental pollution, which occurs due to improper management of residues. In a large context, it will definitely add to accomplish the climate change redressing goals and other environmental and social goals and obviously try to meet up the seventh goal of the United Nations sustainable development goals, i.e., “to secure the access to affordable, reliable, modern as well as sustainable energy for all.” To get sustainability in crop residue-based bioenergy production, the logistics of agricultural waste should be properly adopted. Bioenergy production with agricultural wastes has a lot of strengths and opportunities. It also has several weaknesses and threats. To minimize those negative aspects, proper implementation of policies, subsidies, and financial incentives are required.

10 Cross-References

- ▶ Bioenergy Crops
- ▶ Biomass
- ▶ Biomass Energy from Agriculture
- ▶ Crop Residues Potential, Technology, Policy, and Market
- ▶ Production and Use of Biofuel from Agricultural Resources

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Smallholder Farmers' Access to Microcredit and Energy Efficiency in Crop Production

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Contents

Abstract

Small-scale farmers constitute a significant proportion of the agriculture sector in developing countries, facing various challenges in adopting modern farming technologies and methods. Microcredit has been widely used to address the financial constraints of smallholders, enabling them to purchase improved inputs and efficient technologies, resulting in higher crop yields. Access to credit has also been found to have a positive impact on the adoption of improved technology and efficient cultivation methods. However, increased use of inputs is closely associated with higher energy use in crop production,

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and microcredit can have varying effects on the use of different input and output energies. This chapter explores the relationship between access to microcredit and energy use efficiency in crop production among small farmers in developing countries.

1 Introduction

Poverty, food security, and climate change are the formidable challenges faced by the world. Each of these problems are serious, and a proportion of the victims is high in developing countries. Majority of the population in developing countries lives in rural areas and earn their livelihood from agriculture. Agriculture is an important source of food, and its contribution to national economies of developing countries is significant. Common characteristics of agricultural population in these countries are high dependence on agriculture for livelihood, greater number of small farms, subsistence farming, widespread poverty, and victim of natural disasters. It is estimated that four out of five people below the poverty line live in rural areas. Similarly, about 132 million rural poor lives in areas with high flood risk (World Bank). The World Bank (2013) described that the growth in agriculture proves to be more effective at poverty reduction than the growth originating from the other sectors of an economy. However, farmers need access to advanced technologies, information, markets, and credit to adapt to new production systems and to cope with the challenges that the agriculture sector is facing (FAO, 2016). Climate change is also an emerging threat to agriculture. Climate change is both a cause and effect of poverty and food insecurity.

To meet food demand of growing population, which is expected to reach 9 billion in 2050, the world must increase food production almost by 70% (IFAD, 2010). Without developing nations, developed world alone may not achieve this target. Therefore, improving the productivity of smallholder farmers in developing countries will serve a twin objective of food security and poverty eradication. However, smallholders are resource-scarce farmers, and without easing the burden of resource scarcity, food security will remain a dream. To ensure increase in productivity of smallholder farmers, provision of microcredit has been advocated at large by many researchers. According to them, microcredit helps smallholder farmers in buying improved inputs and adopt technology. However, another challenge related to subsistence farming is environmental sustainability. The poor tend to be more preoccupied with immediate survival and less concerned with resource conservation and environmental protection. This is not to say that only the poor think in short time frames. However, their tendency to do so is often more acute due to the drive to meet basic needs first (Lal & Israel, 2006). On one hand, microcredit is a financial activity, which eases budget constraints of smallholders; on the other hand, it may have consequences for agricultural and environmental sustainability. Therefore, the aim of this chapter is to discuss access to microcredit, and its impact on input energy use efficiency in agriculture.

2 Microcredit

Microcredit and microfinance are used interchangeably, but there is a difference between both.

> Microfinance offers poor people access to basic financial services, such as loans, savings, money transfer services, micro insurance and other financial products targeted at poor and low-income people. (CGAP)

On the other hand, microcredit refers to shorter loans offered to small and medium enterprises as well as to smallholder farmers for agricultural production. Such micro-loans are offered by thousands of financial institutions worldwide, ranging from government to non-government financial institutions like formal banks and public institutes. Microfinance has existed in different forms for centuries and even longer in Asia, where informal borrowing and lending stretches back to a thousand years. The term microcredit is new, and the term was invented by Muhammad Younas in the mid-1970s. The concept behind this term is to provide small loans to people with lower/weaker socioeconomic background. The concept of lending to people with lower socioeconomic background goes back to the period of the 1700s in Ireland. However, microcredit was established in Bangladesh with the aim that poor people are also bankable without the conventional collateral (Islam, 2011). The owner of the idea advocated that "microcredit is a unique innovation of credit delivery to enhance income generating activities" (Yunus, 1998). Microcredit emerged with the establishment and experiment of Grameen Bank and BRAC (Bangladesh Rehabilitation Assistance Committee) in the 1970s with new models of lending. The new vision of providing microcredit was introduced during the 1970s–1980s. In 1983, Muhammad Younas decided to open a Grameen Bank in Bangladesh to realize his microcredit model. He was looking for a practical solution for poverty in the rural areas of Bangladesh. The first ever examples of microcredit originated from the group of 42 women who were making stools in Jorba village in Bangladesh. The women were earning very less profits of $0.02 on each bamboo stool because of the early repayment to suppliers. Muhammad Younas was shocked to find that the entire borrowing needs of 42 women is equivalent to $27. He thought if women were provided with loan amount, then they could meet their business needs, sustain their business, and get out of poverty trap. The 42 women were loaned $27 from his own resources as an experiment and allowed to sell their bamboo stools at reasonable prices and come out of this debt cycle. The experiment later leads to the establishment of Grameen Bank.

The Grameen Bank, known as "Village Bank," came to existence and today works in more than 80,000 villages across Bangladesh and serves more than six million active borrowers. Inspired with the success of Grameen Bank, many new microfinance institutes came to existence around the world, many of them are started by several NGOs and funded by subsidies and grants from private and public sources. They signify/reveal that poor people could be relied on repaying their loans, even without collateral and microfinance is potentially a very feasible business. Generally, microfinance institutes (MFI) lend microcredit to that segment of the society which is ignored by conventional large banks for not having collateral. According to CGAP (2010), MFIs disburse microcredit to low-income population, especially women, through a group lending and liability method. Loan size is gradually increased if existing loans are repaid fully and timely. Majority of the poor living in rural areas of developing countries are deprived of access to an array of financial services, because conventional banks face many obstacles in accessing poor people such as poor infrastructure, high cost of operation, and more importantly collateral limitations. Consequently, majority of the rural people in developing countries rely on informal sources of credit like family loans, commission agents, shopkeepers, and traders. Borrowings like these often have high implicit and explicit costs that land borrowers into vicious cycle of poverty for generations (Qayyum & Munir, 2006). The absence of a formal credit source in rural areas has contributed to the popularity of microcredit. Microcredit has become a popular source of credit to many financially constrained farm households (Morduch & Haley, 2002).

3 Smallholders and Their Needs for Credit

Smallholders are subsistence farmers who grow a variety of crops for their families' survival. The agricultural landscape of South Asia and Africa is dominated by smallholders. Common characteristics of farmers in these regions are landholding less than 2 hectares, resource poor, lack of access to markets and information, high reliance on family labor, vulnerable to risk, and utilization of traditional methods of production (Joseph and Townsend, 2012; Imran et al., 2020). These problems contribute to low productivity of farmers in developing countries, which results into poverty in rural areas and threatens economic prosperity of the country. Sustained growth in agriculture production and productivity is a necessary condition for economic prosperity of developing countries because majority of the developing countries are predominantly agrarian. Farm profitability is dependent on agricultural productivity, and improvement in productivity will increase revenue and lower cost of production. Hence, productivity will have multidimensional benefits: (i) it will increase the standard of living of rural farmers with increased income; (ii) increased productivity will ensure food security of growing population; and (iii) urban poor will benefit from decreased per unit cost. However, productivity is dependent on quality and quantity of inputs and use of modern technology. Availability of sufficient financial capital is necessary for use of quality inputs and modern technology. Smallholders in developing countries are resource constrained especially financial capital is low. Therefore, there is a high demand for credit among these farmers; on the other hand, there is a huge gap between need and availability of affordable credit sources. Lack of funds is the main reason for low productivity. Microcredit has emerged as a viable solution for smallholders to ease credit constraints (Sumelius et al., 2011). In the past years, microfinance institutions and conventional banks have encouraged the access to microcredit to increase the adoption of innovative practices (FAO, 2016).

4 Impact Evaluation of Microcredit

There has been a growing interest to evaluate impacts of microcredit. Many researchers have conducted studies in different parts of the world to assess its impacts on poverty, women empowerment, sustainability, efficiency, income, education, etc. Mahmud et al. (2017) conducted a study on impact of microcredit on income and expenditure of female borrowers in Bangladesh. They found that microcredit has significantly contributed to the income and expenditure of the borrowers. Similarly, positive impacts of microcredit on poverty, women empowerment in health and education, and asset ownership have been reported by Djossou et al. (2016). Another study in Bangladesh showed significant impact of microcredit on increasing participation in the overall decision-making process, in legal awareness, independent movements, and mobility, as well as enhancing living standards to encourage sustainable women empowerment (Akhter & Cheng, 2020). Positive impacts of microcredit on short-term and long-term food consumption were reported in Vietnam (Phan et al., 2019). Islam (2015) stressed that microcredit has more positive impact on the poorest of the poor participants and effects are stronger for female participants than male participants. On other hand, a study in Indonesia found no impact of microcredit on poverty alleviation (Takahashi et al., 2010). No gains in income and consumption due to accessing microcredit were found in a study conducted in Morocco (Crépon et al., 2015). Friawan and Nasrudin (2015) discussed that they did not find evidence of increased self-employment activities and business ownership due to microcredit; rather microcredit was linked with decreased household savings.

Analysis of the microcredit impacts in the agriculture sector has also gained substantial attention to scholars. Mariyono (2018) discussed that microcredit has positive direct and indirect effects on prosperity of rural areas. The indirect effects are mainly due to technology adoption. In Bangladesh, Wadud (2013) found that access to microcredit is positively linked with farm income and which can lead to increased food security. A review of experimental studies on impact of microcredit on farm performance showed that access to microcredit has a positive impact on adoption of agricultural technology and investment (Lawin et al., 2018). Positive impact of microcredit on adoption of agricultural technologies has been confirmed by Abate et al. (2015). Access to microcredit is linked with adoption of new agriculture technologies such as improved seed and with intensified use of fertilizer and pesticides. Microcredit was also found to improve variety of rice (Islam et al., 2012). Higher input use by farmers who availed microcredit has been confirmed by researchers (Tadesse, 2014). On the other hand, researchers like Chowdhury et al. (2020) said that microcredit access does not lead to adoption of technology by smallholders.

5 Productivity, Efficiency, and Microcredit

The very objective of microcredit is to increase the productivity and profitability of the farmers and in turn raising their standard of living and ensuring food security. However, there is no unanimous consensus on the positive impact of microcredit.

Null effect of microcredit on farm income has been found by studies of Giné and Mansuri (2011) and Desai et al. (2013). Access to microcredit leads to increased use of inputs such as fertilizers and hired labor, which sometime leads to positively impact farm profit. But magnitude of the impact is very limited, as Banerjee et al. (2015) argued that micro-entrepreneurs have no credit constraint at the interest rate offered by microfinance institutions, and therefore, the impact of microcredit on their profits is limited. Similarly, Ibrahim and Bauer (2013) discussed that microcredit is a small amount of credit offered to borrowers, which is not sufficient to cause real change in agricultural production.

Sustainable agricultural growth stresses on efficient use of resources. Inefficient use of resources threatens the sustainability of agriculture and rural life, as agriculture is greatly affected by climate change (Imran & Ozcatalbas, 2021). Again, evidences on impacts of microcredit on efficiency of farmers are mixed. Access to microcredit is positively linked with higher technical efficiency of cocoa farmers in Nigeria; farmers with access to microcredit adopt more efficient production techniques and used inputs more effectively (Awotide et al., 2015). Credit has also been found to be a major factor explaining the differences in technical efficiency of farmers in Cameroon (Binam et al., 2003). In some parts of the world, a null or negative impact of microcredit on technical efficiency has also been reported. In Kenya, credit has no impact on technical efficiency of maize farmers (Mghenyi, 2015). The similar kind of findings has been presented by Taylor et al. (1986) in their study in Brazil. In Ghana, smallholder rice farmers who availed microcredit have significantly lower technical efficiency than the farmers who did not. Researchers recommended that credit should be channeled to farmers who are committed to increase their productivity by improving technical efficiency (Anang et al., 2016). Rezitis et al. (2003) indicate that although the credit allows farmers to use modern production inputs more intensely, other types of inputs such as better use of resources, access to information and better management of the farm are needed to improve technical efficiency, which means that technical efficiency and productivity of farmers are not only tied with access to microcredit.

6 Microcredit and Input use

Variety of inputs are used in production of crops. To increase the production, it is necessary that all the farm inputs should be of good quality and are timely available. The production process of crops begins from land preparation and ends with marketing of produce after harvest (Fig. 1). Farmers need different inputs at different production stages; some are purchased from the market, while others are supplied by households (e.g., labor). At the first stage, which is land preparation, the important inputs used are agricultural machinery, diesel fuel, and human labor. At the next stage, labor, seed, diesel fuel, machinery, etc., depending on the sowing method, are required to complete the sowing activity. Following this, crop management is a very crucial stage of crop production, in which the farmers need to apply the necessary inputs like fertilizer, minerals, chemicals, etc. based on the crop requirements. At

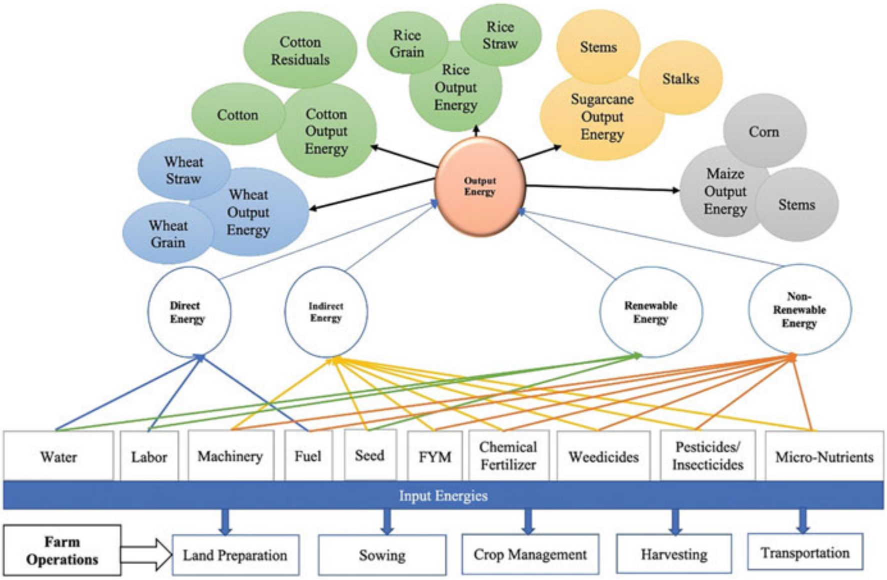

Fig. 1 Input-output energies in crop production

harvesting and transportation, labor, machinery, and fuel are mostly used. Consequently, at each stage of crop production, all inputs are very crucial, and their timely application cannot be compromised.

Figure 1 describes the input-output energies and their categorizations. There are some farm operations including land preparation, sowing, crop management, harvesting, and transportation that are undertaken by each farmer regardless of the cop. All these farm operations need input energies which come from different types of inputs used during crop production. These inputs include human labor, chemicals, machinery, fertilizer, FYM, etc. All these inputs are major sources of input energy, and they can be categorized into different types of energy. Based on the mode of usage of the inputs, all inputs may be categorized into direct and indirect energy. Direct energy includes those which are directly consumed during crop production, and indirect energy comprises sequestered energy (Shah et al. 2019). Human labor, fuel, and water for irrigation are types of direct energy inputs, and all remaining inputs like chemical fertilizer, pesticides, machinery, FYM, and micronutrients are indirect energy inputs. Moreover, the energy used in agricultural production process is also categorized as renewable and nonrenewable energy. Input energy such as labor, water for irrigation, and seed are renewable energies, while machinery, fertilizers, fuel, micronutrients, FYM, weedicides, and pesticides are nonrenewable energy.

All these input energies consumed during crop production are converted into output energy. Many crops are cultivated at farm, and all crops require a similar kind of input energy. When input energy is converted into output energy, there are different types of output energy generated based on the crops cultivated. For example, wheat crop consisted of two types of output energy, i.e., wheat grain and wheat straw. Cotton output energy comprises of cotton and cotton residuals. Rice, the third major crop, also generates rice grain and rice straw as output energy. In sugarcane, stems and stalks are the major source of output energy being produced at farm by using different input energies. Maize is also one of the major crops that use different input energies and generate output energy in the form of corn and stems. All this process of conversion from input to output energy in different crops' production describes energy efficiency. Therefore, producing the given level of output energy by consuming the minimum level of input energy is called energy efficiency.

However, efficiency is not the objective of every farmer. Smallholder farmers are especially concerned about cost minimization because they have certain constraints, such as credit constraints. When the farmers have credit constraint, it would not be able to make the optimal decisions regarding input use (Bokusheva & Kumbhakar, 2008), which may affect the optimal use of inputs. Moreover, prices of farm inputs like high-yielding seeds, fertilizer, pesticides, and improved farm machinery increase day by day. This makes the purchase of these inputs difficult for the marginal and poor farmers who have low budget. This also makes the farmer inefficient in crop production (Bokusheva & Kumbhakar, 2008). Therefore, micro-credit assists the farmers to purchase the variable inputs and facilitates timely application of these inputs, which ultimately increases crop productivity (Nosiru, 2010). Credit can also enhance the farmer's agricultural productivity and efficiency by allowing them to use optimal quantities of agri-inputs and hire labor at the right time. On the other hand, farmers who have limited resources and credit constraints are more likely to invest less and misallocate their resources. Timely provision of microcredit also allows the farmers to smoothly run their farm operations. However, microcredit can also lead to inefficient or above-recommended-level use of inputs. There is a common belief among farmers that high level of input such as fertilizer increases productivity (Imran et al., 2020). Hence, if inputs are inefficiently used, that may not contribute to the gains in productivity. Microcredit role in purchase of inputs on time contributes to crop productivity, which ultimately lowers poverty and food insecurity in the rural areas (Nakano & Magezi, 2020; Baffoe et al., 2014).

7 Relationship Between Energy Use and Microcredit in Agricultural Production

In the future, agriculture has to feed hundreds of millions of more people using scarce resources efficiently while maintaining sustainability, which means the agriculture sector will be facing immense pressure due to increased demand for food. Over the years, wilderness and marginal land have been converted to meet food production. Beginning with green revolution, different methods and strategies have been developed to increase food production. Financing agriculture development through credit for inputs such as seeds, fertilizers, pesticides, and machinery has been focused by policymakers in the recent past. Provision of microcredit has been supported by many researchers and scholars due to its positive impact on poverty, education, income, etc. Proponents of microcredit have mainly criticized for it being a debt trap. Until now, an important potential negative impact of microcredit has been neglected by researchers.

Farmers have the objective of getting maximum crop production. This is possible only in the form of timely application of recommended level of different quality inputs. Day by day, hike in prices of farm inputs limits the capacity of farmers to purchase the inputs; if somehow they manage to purchase in many cases, there is a delayed application of inputs. Farmers' objective of maximizing crop production is constrained by the finance/credit. Figure 2 describes how access to credit affects productivity and energy efficiency. A farmer may have credit access or may not have access to a credit source. It can be hypothesis that a farmer with credit access purchases the quality farm inputs and apply recommended quantity at time. If inputs are applied timely and at a recommended level, then it will lead to energy efficiency. If a farmer applies inputs timely and uses the above recommended level, then use of energy will be inefficient, because access to credit eases credit constraints and farmer may use inputs above the recommended level. On the other hand, farmers who do not have credit access may not be able to purchase farm inputs, delay application of inputs, and apply inputs below the recommended level. This causes severe energy inefficiency and low productivity.

There is rich evidence that microcredit increases the use of inputs such as seed, fertilizer, machinery, pesticides, etc. Moreover, provision of credit is also related with conversion of wildlife habitat to farmland and deforestation (Chipikaa & Kowero, 2000). It has been said that credit contributes to habitat loss in developing countries (Lal & Israel, 2006). So access to microcredit may be related with

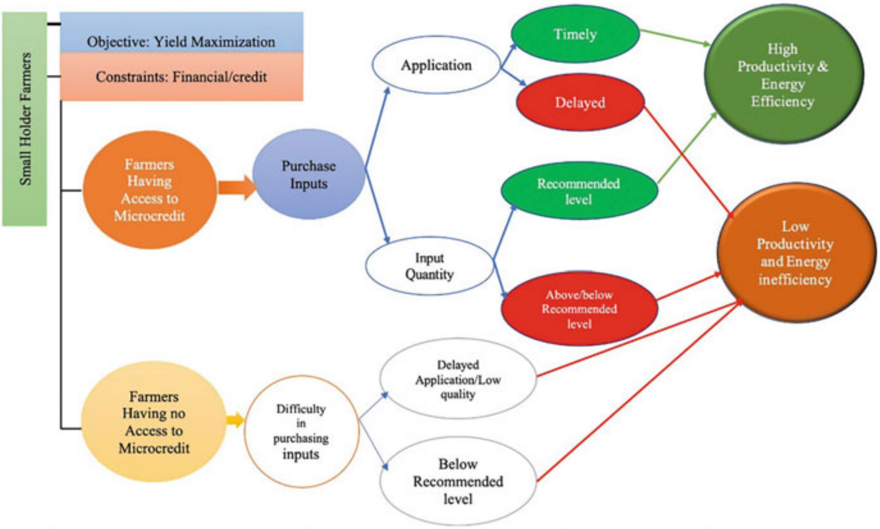

Fig. 2 Farmer's objective, constraints, and consequences

sustainability issues. Scientists have discussed that if a system is producing more energy than consuming, then it can be considered as an efficient. Now, the question is how to estimate energy used in agriculture. It is not surprising that like all other sectors, energy plays an important role in agriculture sector also. The relationship between energy and agriculture is very close and interrelated. Agriculture sector is considered as an energy supplier and energy user in terms of bioenergy (Alam et al., 2005). It uses a large amount of locally available non-commercial energies like animate energy, seeds, farmyard manure, and commercial energies directly or indirectly in the form of diesel, plant protection, electricity, irrigation water, chemical fertilizers, and farm machinery (Singh et al., 2002a; Jonge, 2004; Dyer & Desjardins, 2006). Nowadays, energy usage in agricultural activities has been increased due to growth in human population, limited arable lands, and desires to improve living standards. Similarly, additional usage of energy also threatens the environment and health of the public (Rafiee et al., 2010). At the farms level, energy has both direct and indirect uses. On one side, direct energy is used for crop production, which includes production of oilseeds, vegetables, fruits, and cereal grains, while production of animal products includes eggs, milk, and meat. Poultry production consists of hens, chicken, turkeys, etc. On the other side, indirect energy is used for off-farm activities like transportation and manufacturing of pesticides and fertilizers. Overall, the significance of energy has rapidly increased in all the fields as energy is used as one of the basic inputs in both the developed and developing countries for economic growth. However, increased use of energy doesn't guarantee increased profit; rather, it threatens agricultural and environmental sustainability. Efficient use of energy is a necessary condition for sustainable agriculture and economic development.

Efficiency is defined as the ability of producing more outputs with a minimum level of required resources (Sherman, 1988). In production, efficiency is considered as a normative measure and is defined as the ratio of weighted sum of outputs to inputs or as the actual output to the optimal output ratio. Efficient usage of energy in the agriculture sector is considered as the basic requirement for sustainable agricultural development; it provides financial savings, air pollution reduction, and preservation of fossil resources to strengthen energy efficiency. Conserving energy input and yield without effecting the output must be attempted (Singh et al., 2002b). Therefore, energy savings has been a critical issue for sustainable agricultural development systems. Efficiency criteria requires that output energy must be higher than input energy for the sustainability of the system. If 1 MJ of input energy used produces >1 MJ of output energy, for example, wheat, then the use of energy can be described as efficient. The energy used in agricultural production process is also categorized as renewable and nonrenewable energy. Input energies such as labor, irrigation, and seed are renewable energies, while machinery, fertilizers, fuel, and pesticides are nonrenewable energy. Different kinds of energy are used in production, which can be estimated by multiplying quantity of each input with its energy equivalent. Table 1 provides energy equivalent of different inputs and outputs.

Table 1 Conversion factor of inputs to energy (energy equivalent MJ/unit)

Inputs	Unit	Energy equivalent (MJ)	References
Human labor	Hours	1.96	Mohammadshirazi et al. (2010)
Machine	Hours	62.7	Imran and Ozcatalbas (2021)
Diesel	Liter	56.31	Zangeneh et al. (2010)
Nitrogen	Kg	60.6	Esengun et al. (2007), Mousavi-Avval et al. (2011), Rafiee et al. (2010), Unakitan and Aydin (2018)
Phosphate	Kg	11.1	
Potassium	Kg	6.7	
Micronutrients	Kg	120	Imran et al. (2022)
Farmyard manure	Kg	0.30	Heidari et al. (2012)
Green manure	Kg	15.9	Guzmán and Alonso (2008)
Herbicides	Kg	238	Nabavi-Pelesaraei et al. (2016)
Insecticides	Kg	199	Imran and Ozcatalbas (2021)
Fungicides	Kg	216	Imran et al. (2022)
Granular chemicals	Kg	120	Imran et al. (2022)
Underground water	m^3	1.02	Acaroglu and Aksoy (2005)
Electricity	KWh	11.93	Esengun et al. (2007)
Wheat seed	Kg	15.7	
Wheat straw	Kg	12.5	
Paddy rice	Kg	14.7	AghaAlikhani et al. (2013)
Rice straw	Kg	12.5	
Cotton seed	Kg	11.8	Singh (2002), Yilmaz et al. (2005)
Cotton	Kg	11.8	
Sugarcane Stem cutting	Kg	1.2	Sefeedpari et al. (2014), Kaab et al. (2019)
Stalks	Kg	1.2	
Moist bagasse	Kg	5.7	
Corn	Kg	104	Patzek (2004), Sartoni et al. (2005), Bilalis et al. (2013)
Output-maize	Kg	14.7	
Tomato	Kg	0.80	Ozkan et al. (2011)

8 Conclusion

As a major sector of the economy, agriculture contributes significantly to the economy of many developing countries. At the same time, this sector is facing major challenges including poverty, food insecurity, climate change, low productivity, small land holdings, low access to credit, and use of traditional production technologies. For sustainable agriculture and to achieve sustainable development goals like food security, climate change, and poverty alleviation, etc., productivity of farmers, especially of small landholders, should be increased. Therefore, farmers need high-quality inputs and modern technologies to increase crop yield or productivity. However, timely application of quality inputs and adoption of modern technologies are constrained by limited access to credit. Ensuring access to credit at easy conditions can lead to increased productivity. Likewise, microcredit facilitates farmers to purchase different necessary inputs during crop production. These inputs are the major source of input energy, which results in output energy. However, there are both positive and negative impacts of microcredit. On one hand, it contributes to poverty eradication, education, food security, income, and consumption. On the other hand, increased use of inputs by farmers availing microcredit can be considered as a threat to sustainability of agriculture and environment. For example, 1 kg of nitrogen has an embedded energy of 60.6 MJ, 1 liter of diesel is equal to 56.31 MJ, 1 kwh of electricity is 11.93 MJ, and 1 hour of machine use consumes 62.7 MJ of energy. As it is commonly believed by farmers that higher input use results in increased yield, credit may increase use of different input energies. Therefore, microfinance institutions should be careful while disbursing the credit. Credit should be channeled to farmers who have good knowledge about necessary and unnecessary inputs. Moreover, educating farmers about balanced use of inputs like fertilizer is very important for optimal use of energy and energy efficiency.

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