Crop Residues: A Potential Bioenergy Resource

Maninder Kaur and Sandeep Dhundhara

Abstract Most of the population in India relies on agriculture and livestock for their livelihood as the country is bestowed by the nature with a variety of geographical regions vacillating from high mountains to wetlands, myriads rivers to plains, thus making most land fertile and suitable for a variety of food crops. The crop residues like rice straw, leaves, roots, bagasse, etc. that remain in fields after harvesting and processing are proving to be a major concern as these residues are frequently burnt by the farmers in the open fields causing environmental pollution leading to serious health problems. On the other hand, the share of bioenergy in power generation is significantly low as compared to the other available resources in the total energy mix of the country. The biomass can provide reliable and consistent power supply to the end-user in comparison with solar and wind energy resources, therefore, preferred as a renewable energy resource over other resources. Due to dependency on the season, the solar and wind energy resources fluctuate over short and large time frames. Thus, provides unreliable and inconsistent supply to end-user however biomass seems to be a feasible alternative to fossil fuels. So, the solar, wind, and biomass due to their different characteristics provide an opportunity for hybrid utilization of these resources to compensate for their individual drawbacks. Hybridization of these resources helps to utilize the biomass efficiently and provides electricity to end-users reliably and consistently. Hence, biomass-based hybrid power plants are tremendously promising energy systems in near future. Biogas production through anaerobic digestion from such crop residues can offer great potential for replacement of the fossil fuel for our energy requirements.

Keywords Anaerobic digestion · Crop residues · Biogas · Energy mix · Biomass

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M. Kaur (✉)
Dr. S.S.B. University Institute of Chemical Engineering and Technology, Panjab University, Chandigarh 160014, India
e-mail: maninderkaur2780@gmail.com

S. Dhundhara
College of Agricultural Engineering & Technology (COAE&T), CCS Haryana Agricultural University, Hisar 125001, Haryana, India

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1 Introduction

The socio-economic development of any country is highly reliant on the availability of electrical energy. For this, the installed capacity of power needs to be raised at the same pace as that of rapid urbanization, and an increase in population. As per reports from UNDESA (United Nations Department of Economic and Social Affairs), the world population will be raised to 9.7 billion by the year 2050, so this will employ extra pressure on the agriculture and energy sector. The power sector leads in the consumption of fossil fuels mainly in developing countries such as India, where most of the growing load demand is fulfilled by coal-based power plants. The installed capacity of 121 GW power plants in India consumes 503 million tons of coal which emitted a large amount of GHGs in the year 2010–11 (Guttikunda and Jawahar 2014). The GHGs emission resulted in 20 million asthma cases and approximate 80,000–115,000 premature deaths on exposure to $PM_{2.5}$ pollutions alone which costs wastage of the public and Government in crores. The open field burning of residues in the field stimulates the existing pollution due to coal-based power plants resulting in the emission of various air pollutants including GHGs (Lohan et al. 2018).

Therefore, renewable energy has gained more attention as promising means of increased energy security and provides multiple environmental benefits, and also plays a crucial role to replace fossil fuels based conventional energy resources. The sustainable utilization of crop residue in a biomass-based hybrid power plant through the biochemical conversion pathway of anaerobic digestion is very significant in current scenario.

1.1 Biofuels Classification

Due to the increased concerns about GHGs emissions and energy, biofuels have attracted a lot of attention these days. The renewable energy sources will approximately grow to 15% of the world energy market by 2035 as reported by "International Energy Outlook" And liquid biofuels such as biodiesel, bioethanol will cover about 29% of world energy demand. The accelerated reliance on biofuels is associated with the abundance availability of biomass for biofuel production. Thus, bioenergy is a key contributor to provide sustainable energy for developing industrialization and developing nations. Biofuels are classified as liquid, gaseous, and solids fuels that are produced from biomass. Biofuels utilize unprocessed biomasses like wood chips, pellets, fuel woods, etc. are referred to as solid fuels or primary fuels. Biomasses after processing and transformations get converted into liquids and gaseous biofuels also known as secondary biofuels (Dahman et al. 2019). Fig. 1 represents the biofuels classification according to the biomass source used for biofuel production.

First-generation biofuel utilizes edible biomasses which are meant for food purposes like carbohydrate-rich crops such as wheat and corn fermented into bioethanol, lipid-rich crops such as soya for biodiesel, and both carbohydrate and

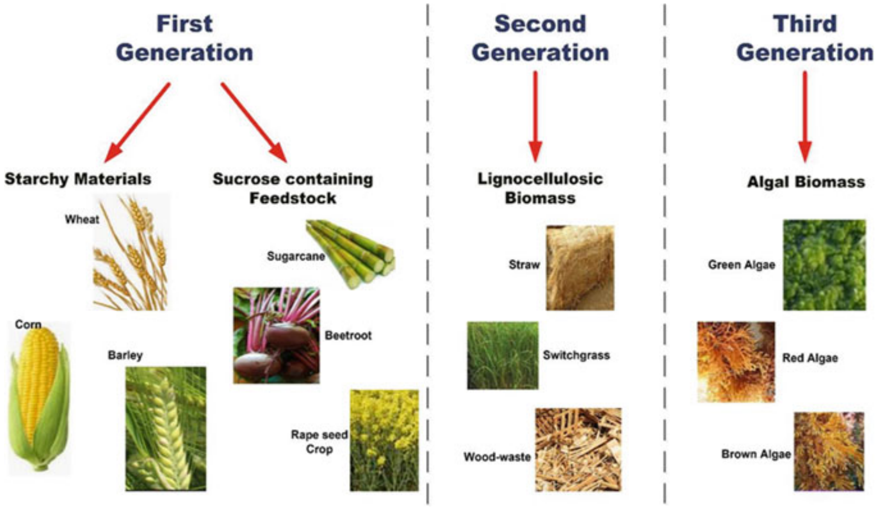

Fig. 1 Biofuel classification

lipid-rich crop for methane production. However, the increase in the cost of production, energy spent in cultivation, and inefficient utilization of resources limits the use of first-generation biofuel. The augmented biofuels demand from first-generation biomass has been reflected in the US Energy Independence and Security Act of 2007 which sets the target of 21 billion gallons of biofuels such as biobutanol by 2022. Biofuels produced from edible products such as sugars, starch, and vegetable oil are not advisable as they may cause food scarcity in developing countries like India (Dahman et al. 2019).

The second-generation biofuel production is based on more effective renewable alternatives by utilizing non-edible lignocellulosic biomass of crop residues such as straw, stalks, sorghum, stover, etc. The use of lignocellulosic biomass for biofuel production has the advantage as available in abundance worldwide. Crop residues correspond to the waste that remains in the fields after food extraction without any extra land required for their production (Balat and Balat 2010). The fermentation of these residues in the soil, open field burning, manure management, etc. results in approximately 47% of global methane emissions. The biogas production through anaerobic digestion of crop residue could be one of the sustainable options to remove the crop residue from the fields and capture the methane as a renewable energy resource simultaneously (Ohman et al. 2006).

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Among the biofuel production from second-generation (biodiesel, bioethanol, biogas, etc.) by biochemical conversion pathway, the biogas production through anaerobic digestion of lignocellulosic biomass could be one of the sustainable options for increasing the renewable resources share in the energy sector of the country. As bioethanol can be derived from the fermentation of cellulose, however, both hemicellulose and cellulose can be utilized to produce methane. Secondly, methane can be mixed with the natural gas grid once purified and compressed, which can be further used for various applications such as electricity production, heat, or as vehicle fuel. Finally, the digestate obtained from the anaerobic digestion process being rich in nitrogen and phosphorous can be utilized as fertilizer for agricultural plants (Kleinert and Barth 2008).

Microalgae, the third generation of biofuels is another viable alternative renewable energy source that can be used to produce biomethane, bioethanol, and biodiesel (Frigon and Guiot 2010). However, the large areas, high initial cost, and huge amount of water required for cultivation remain a major disadvantage that limits third-generation biofuel commercialization (Nigam and Singh 2010).

1.2 Anaerobic Digestion

Anaerobic digestion, a biochemical process comprising the conversion of complex organic matter present in biomass into a valuable product such as biogas in the absence of oxygen. Methane, the main component of biogas is the highly combustible component that can be used as the energy source for cooking, lighting, and heating. The anaerobic digestion process optimization requires the understanding of different biological processes along with associated chemical reactions. Mainly, the process involves four key phases namely; hydrolysis, acidogenesis, acetogenesis, and methanogenesis:

In the first step of hydrolysis, the complex organic matter is directly utilized by the bacteria to decompose it into soluble molecules with the effect of hydrolytic enzymes (Azapagic and Stichnothe 2011). The organic matter gets converted into monosaccharides (simple sugars), fatty acids, amino acids, and peptides in this process. The hydrolysis of carbohydrates is a fast process that takes only a few hours however, the hydrolysis of lipids and proteins takes few days thus making the degradation of lignocellulosic biomass slow and incomplete. The hydrolysis process can be chemically explained as follows:

$$nH_2O + (C_6H_{10}O_5)_n \rightarrow nC_6H_{12}O_6 + nH_2 \tag{1}$$

The breaking of β-1,4-glycosidic linkages as shown in Eq. (1) is an essential step for cellulose ($C_6H_{10}O_5$) conversion as it opens the possibility of catalytic transformation.

Acidogenesis is also known as the fermentation process that results in volatile fatty acids after attack by acidogenesis bacteria. Then, acidogenic bacteria convert the hydrolysis product into CO_2 and H_2. The most significant organic acid CH_3COOH is produced in this stage which is further used as a substrate by microorganisms (Appels et al. 2011). The following Eqs. (2)–(4) represent the sequence of reactions taking place in the acidogenic stage of the anaerobic digestion process:

$$C_6H_{12}O_6 \leftrightarrow 2CO_2 + 2CH_3CH_2OH \tag{2}$$

$$2H_2 + C_6H_{12}O_6 \leftrightarrow 2CH_3CH_2COOH + 2H_2O \tag{3}$$

$$C_6H_{12}O_6 \rightarrow 3CH_3COOH \tag{4}$$

Acetogenesis is also known as the dehydrogenation stage of the anaerobic digestion process. The volatile fatty acids produced in the acidogenesis are broken down into CH_3COOH, H_2, and CO_2 in this stage. As some amount of H_2O is still available from the previous stages so the conversion of the volatile fatty acids is possible (Appels et al. 2011; Anukam et al. 2019). Equations (5) to (7) represent the chemical reactions taking place in this stage.

$$3H_2O + CH_3CH_2COO^- \leftrightarrow CH_3COO^- + H^+ + 3H_2 + HCO_3^- \tag{5}$$

$$C_6H_{12}O_6 + 2H_2O \leftrightarrow 2CO_2 + 4H_2 + 2CH_3COOH \tag{6}$$

$$CH_3CH_2OH + 2H_2O \leftrightarrow H^+ + 3H_2 + CH_3COO^- \tag{7}$$

However, there is no clear distinction between acidogenic and acetogenic reactions as H_2 and $CH3COO^-$ produced in both types of reactions, which act as a substrate for methanogenic bacteria.

Methanogenesis, results in the breaking down of the acetic acid and volatile fatty acids molecules into methane (CH_4), carbon dioxide (CO_2) (Li et al. 2019). The bacteria responsible for the conversion in this process are known as methanogens. Although methanogens grow slowly and are extremely sensitive to environmental changes but can easily absorb and digest the substrate. The chemical reactions Eqs. (8)–(10) represent the conditions taking place in this stage of the anaerobic digestion process.

$$CH_3COOH \rightarrow CO_2 + CH_4 \tag{8}$$

$$CO_2 + 4H_2 \rightarrow 2H_2O + CH_4 \quad (9)$$

$$CO_2 + 2CH_3CH_2OH \rightarrow CH_4 + 2CH_3COOH \quad (10)$$

The two groups in which methane-producing bacteria can be divided are Acetophilic and hydrogenophilic. Acetophilic has based the production of methane by decarboxylation of acetate as represented by Eq. (10) whereas in hydrogenophilic group methane production takes place by reduction of CO_2 and H_2 as represented in Eq. (9).

1.3 Pretreatment of Crop Residues

Lignocelluloses have a complex organic polymer structure composed of physical and chemical associations among hemicelluloses, cellulose, and lignin which are difficult to be decomposed by anaerobic bacteria to produce biogas. Cellulose is the most abundant component of lignocellulose biomass represents 35–40% of dry matter while hemicellulose and lignin represent 25–40% and 10–20% of total dry matter of biomass.

Thus, lignocellulose is one of the most abundantly available biopolymers, having various structural and compositional characteristics which provide recalcitrance to its biological degradation thereby reducing biofuel conversion efficiency. Pretreatment of biomass is an essential step to break the outer layer of lignin, thereby decreasing the crystallinity of cellulose and aggregate the obtainability of carbohydrates. The various methods of pretreatment of lignocellulose like physical, biological, and chemical are used to produce second-generation bioethanol.

1.3.1 Physical Pretreatment

Physical pretreatment of residue involves size reduction using ball mill, grinding, chipping, mechanical extrusion, and irradiation. Milling or mechanical grinding can be done through the knife, ball milling, hammer, colloid mill, etc. The size of biomass can be reduced to 5–30 mm through chipping however, with the help of ball milling and grinding the size of particles may be reduced to 0.2 mm. However, the specific kind of biomass, duration of milling, and types of milling are the main factors that affect the degree of polymerization, disruption in the crystalline structure, and surface area enhancement of lignocellulosic biomass. The physical pretreatment reduces the particle size and enhances the surface area of biomass for enzymes accessibility (Kratky and Jirout 2011).

Mechanical Pretreatment

The results of mechanical pretreatment of lignocellulosic biomass are diverse as reported by various researchers, suggesting that the effect on methane production depends upon the methods used (cutting, chopping, milling, grinding). For instance, it has been observed that biogas production enhanced by 22% as the size of sisal fiber particles reduced from 10 to 2 mm (Mshandete et al. 2016). Similarly, the mechanical pretreatment of barley and wheat straw resulted in an increase of methane potential by 54% and 83.5% with a reduction in particle size to 0.5 cm and 0.2 cm, respectively (Menardo et al. 2012). However, the hydrolysis of sweet corn and ensiled maize mixture was not affected by the reduction in particle size ranging between 2 mm and 5 mm (Ficara and Malpei 2011). Therefore, it becomes more effective if combined with other pretreatment methods such as liquid hot water pretreatment, chemical pretreatment method, etc.

Microwave Irradiation

The enhancement in the digestibility of residue can be observed by the use of irradiation techniques such as microwave irradiation, gamma rays, ultrasound, and electronic beam to increase the enzymatic hydrolysis of lignocellulosic biomass. Irradiation pretreatment leads to cleavage of β-1,4-glucan bonds thus reducing the crystallinity of cellulose (Takacs et al. 2000; Chandra et al. 2012). Microwave irradiation has several advantages such as easy operation, minimum generation of inhibitors, and high heating capability in short duration. Studies using the microwave irradiation technique of physical pretreatment show that it is more effective with mild alkali reagents. Wheat straw pretreatment at 150 °C using microwave radiation resulted into methane enhancement by 28% in comparison with untreated wheat straw (Jackowiak et al. 2011).

Ultrasound Pretreatment

Ultrasound pretreatment is a relatively new technique used for pretreatment in which waves produce both chemical and physical effects on the morphology of biomass. Prolonged saponification has no additional effect in terms of sugar release and delignification after a certain limit (Kumar and Sharma 2017). For cellulosic feedstock accessibility of cellulose enzymes to cellulose increases with ultrasound irradiation by disrupting the cell wall. Ultrasound pretreatment can enhance sugar yield in the hydrolysis process by changing the surface morphology of lignocelluloses material. Further, it has been observed that combined use of NaOH and Ultrasonic irradiation pretreatment effectively disrupts the intermolecular hydrogen bonding of bagasse resulting in the extraction of more than 90% of glucose yield within the duration of 70 h (Velmurugan and Muthukumar 2012).

Steam Explosion Method

Steam explosion pretreatment, involves mechanical forces as well as chemical effects. The biomass is subjected to high temperature (160–260 °C) with sufficient pressure of 1–7 MPa ranging from few seconds to minutes resulting in hydrolysis of hemicelluloses. Wheat straw pretreatment by this method of the steam explosion at 180 °C for 25 min showed 31% enhancement in biogas production (Bauer et al. 2010). Another study reported that pretreatment of bulrush represents 24% enhancement in methane yield at steam pressure 1.72 mPa with 8.14 min of residence time (Wang et al. 2010). However, the steam explosion method on paper tube residuals represents no change in biogas production and has shown the negative effect of a pretreatment when the time was increased from 10 to 30 min in the case of paper tube residuals. The steam explosion method limits the complete disruption of the LCC's and thus formation of inhibitors and unwanted degradation of the cellulose takes place (Kumar et al. 2009).

Liquid Hot Water

The liquid hot water method of pretreatment involves cooking of biomass in hot water without using any chemicals or catalysts. Water at high pressure easily breach into the biomass and it hydrates the cellulose and takes out hemicellulose along with some part of lignin. Corn fiber (de-starched) after the liquid hot water pretreatment at 160 °C for 20 min dissolved 75% of the xylans (Dien et al. 2006). Further, it has observed that liquid hot water pretreatment dissolved hemicellulose completely at the higher temperature of 220 °C with partial removal of lignin within 2 min (Sreenath et al. 1999).

1.3.2 Chemical Pretreatment

Chemical pretreatment of biomass includes alkaline pretreatment, ionic pretreatment acidic pretreatment, and wet oxidation. The concentration of chemical used, time, and temperature of pretreatment significantly affects the effectiveness of the chemical pretreatment method on delignification of crop residues. Various chemical pretreatment methods reported in the literature depending on the nature of the chemical used are as follows:

Acidic Pretreatment

Acids are commonly used to increase the enzymatic hydrolysis of biomass. Acid pretreatment can be carried out either at high temperature (120–170 °C) for a short duration (1–5 min) of time or at low temperature (about 25 °C) for a long duration of time (hours, days). Sulphuric acid is the most commonly used acid for pretreatment, while hydrochloric acid has also been used in various studies (Kumar et al. 2009; Taherzadeh and Karimi 2008). Chemical pretreatment of corn cob using 2%(w/w) H_2SO_4 at 121 °C for 1 h resulted in 17% delignification with the increase in cellulose from 35.9 to 54.78% (Ayeni et al. 2015). The production of inhibitory products mainly furfural, derived from hemicellulose degradation and corrosion of reactors limits its use.

Alkaline Pretreatment

Alkali pretreatment alters the crystalline structure of biomass and enhances enzymatic hydrolysis without producing inhibitors as was observed in the case of acid pretreatment. Calcium hydroxide, sodium hydroxide, ammonia, and potassium hydroxide are the most commonly used alkalis used for the chemical pretreatment of biomass. Sodium hydroxide (NaOH) is the most common alkali reagent used for chemical pretreatment. Alkaline pretreatment dosages ranging between 1–30 g NaOH per 100 gm substrate at a temperature ranging between 10–200 °C and time for the pretreatment varying from few minutes to days are reported in the literature. Also, it can be used for various lignocellulosic biomasses like wheat straw, rice husk, corn stover, sunflower stalks.

Wheat straw pretreatment with 4% NaOH (g/g TS) increased the methane production to 166 L/kg VS from 78 L/kg VS at a temperature of 37 °C for five days (Chandra et al. 2012). And 2% NaOH pretreated corn stover for 3 days at 20 °C increased the biogas production by 72.9% and decreases the digestion time by 34.6%. KOH has effectiveness nearly equal to NaOH for pretreatment to increase biogas production (Zheng et al. 2010). NaOH and KOH pretreatment of the rice husk resulted into 50% increment in the biogas yield (Dong et al. 2009). Alkaline pretreatment results in swelling of fibers increasing the surface area and pore size thus facilitating the diffusion of hydrolytic enzymes.

Ionic Pretreatment

Ionic liquid pretreatment also referred to as "green solvents", is an effective technique to increase the proper utilization of lignocellulosic biomass (Dadi et al. 2006; Samayam and Schall 2010). Ionic liquids are salts in liquid form and generally made up of ions and short-lived ions pair. NMMO (N-methyl morpholine-N-oxide monohydrate) mainly used ionic liquid for the pretreatment to increase the yield of biogas. Wheat straw treatment with 85% NMMO for 7 h at 900 °C increased the methane yield by 47% along with increased porosity of treated straw (Purwandari et al. 2013). A significant increase in the production of biogas was reported after pretreatment of rice straw with NMMO at 130 °C for one hour (Teghammar et al. 2011). Pretreatment of an empty bunch of oil palm fruit with 85% NMMO for 3 h at 120 °C and reported 48% enhancement of methane (Purwandari et al. 2013). Ionic liquids were found to be efficient in lignin removal as reported that 40% of lignin removal of wood takes place after this pretreatment (Lee et al. 2009).

Ionic liquids pretreatment has advantages like minimal effect on the environment due to their low volatility and it can be reused after pretreatment. However, the high cost of ionic liquids makes the method expensive (Nguyen et al. 2010). Moreover, the application of ionic liquid for pretreatment to produce biofuels needs to be tested in order to validate the ability of the microorganism to attack the organic matter in presence of these solvents (Brodeur et al. 2011).

Wet Oxidation

The wet oxidation method of pretreatment utilizes oxidizing agents such as air, hydrogen peroxide, and oxygen along with water at high temperatures (above 120 °C) and high pressure. The crystalline structure of cellulose (Panagiotou and Olsson 2006). The high risk of formation of inhibitors such as aromatic compounds and furfural, cost of reagents are some major drawbacks which restrict its use for pretreatment.

Among various chemical pretreatment methods, alkaline pretreatment seems to be the most economic and effective in disrupting the crystalline structure of biomass without producing inhibitors.

1.3.3 Biological Pretreatment

In comparison with chemical and physical methods of pretreatment, biological pretreatment is considered to be an economical, easy, and environment-friendly pretreatment method. Biological pretreatment makes use of white-rot fungi, brown rot fungi, and soft fungi which mainly degrade lignin and hemicelluloses with a lesser amount of cellulose. A significant increase in methane production has been observed after the pretreatment of bagasse with acid combined with enzymatic pretreatment (Badshah et al. 2012). The white-rot fungi such as Phanerochaetechrysosporium, Pleurotusostreatus, Coriolus Versicolor, and Ceriporiopsissubvermispora have been used for pretreatment of various biomass feedstock for biofuel production through solid-state or liquid state fermentation. The degradation process of biomass through biological pretreatment is extremely slow therefore, not favored method among industries. Several studies on biological pretreatment combined chemical and physical pretreatment have proven to be more effective than biological pretreatment alone. Further, studies show that performing fermentation and saccharification processes at high-substrate concentration results in an increase in the concentration of inhibitors. Pretreatment with enzymes has been suggested to prevent the production of such inhibitors.

1.4 Prominent Factors Affecting Biogas Production

The main factors affecting bacterial activity are the pH, COD, total alkalinity, micronutrients compounds (Yadvika et al. 2003). All these parameters are dependent upon the process parameters such as temperature, pH value, carbon to nitrogen ratio, hydraulic retention time, etc.

Carbon to Nitrogen Ratio

Carbon is the main constituent present in organic wastes which are digested by bacteria to convert it into methane and carbon dioxide. The inadequate amount of nitrogen content slows down the microbial growth rate thus affecting the conversion of substrate into biogas (Wilkie and Colleran 1986). The C:N ratio of the biomasses varied widely between ratios 32:1 to 82:1, the high C:N ratio in the anaerobic digestion process leads to VFAs accumulation and lower pH, leading to inhibition. The optimum ratio of C:N to produce maximum biogas has been observed to vary from 25:1 to 30:1 (Ghatak and Mahanta 2014). Straw has high carbon content in comparison to nitrogen consequently having a high C:N ratio. Therefore, straw needs to be digested with organic matter rich in nitrogen (Yong et al. 2015).

Straw in co-digestion with food waste in ratio 1:5 resulted into C:N ratio of 31:1 which resulted in enhancement of methane production by 150% in comparison with straw and food waste only (Yong et al. 2015). Co-digestion of rice straw, food waste, and pig manure in ratio 1:0.4:1.6 resulted into 72% increase in methane production (Ye et al. 2013). In a study, the co-digestion of oat straw with cow manure in ratio 1:2 resulted in biogas enhancement by 26.64% and also stated that the addition of cow manure above this ratio resulted in inhibition (Zhao et al. 2018).

Temperature

Temperature of digester has a strong influence not only on the quality but also on the quantity of biogas production. Anaerobic digestion mainly takes place at either mesophilic temperature or thermophilic temperature. The change of temperature from 25 to 35 °C resulted in 24% enhancement of biogas (Lianhua et al. 2010). Further, a study reported the highest biogas production at 50 °C then followed by 60 and 40 °C respectively (Sambo et al. 1995). The positive effect of thermophilic conditions affects adversely if it is raised from 55 to 60 °C owing to suppression of bacteria due to high temperature. Moreover, if the digester operating at thermophilic conditions, it requires more technological efforts for insulation and high energy input therefore such conditions generally prove to be uneconomical.

pH Value

pH is an important variable strongly impacting the degradation of organic matter through anaerobic digestion. The pH value ranging between 6.25–7.50 has been reported to be most optimum for effective biogas production (Ghatak and Mahanta 2014). Methanogenic bacteria are very sensitive to pH value and do not thrive below 6.5.

Hydraulic Retention Time and Organic Loading Rate

Hydraulic retention time is the period for which a given quantity of substrate remains in the digester for methanogenesis bacterial attack. HRT is a temperature-sensitive parameter and usually varies between 20 and 120 days. HRT in India varies between 40–60 days and about 100 days for colder countries. Optimal HRT must allow 75% degradation of the substrate (Castillo et al. 1995). However, longer HRT requires installation of large dimensions which consequently results in high operating and construction costs.

Organic Loading Rate represents the quantity of raw materials fed per day per unit volume of the digester capacity. OLR has a significant effect on the biogas production of straw. Methane production increases with diminished OLR owing to the accumulation of VFA and lowering of pH as OLR has been increased from 2.80 kg SV m-3d-1to 6.97 kg SV m-3d-1 (Kaparaju et al. 2009). Total solids concentration is not affected by an increase in the retention time of solids (Pohl et al. 2012). The various studies concluded that overfeeding the plant will adversely affect performance as acids will accumulate and bacteria cannot survive in the acidic situation on the other hand if it is underfed even then production will be low due to alkaline solution.

Dilution/Solid Concentration

The concentration of total solids in the feedstock is one of the main parameters considered for the effectiveness of the anaerobic digestion process. The total solid content of the substrate is less than 10–20% TS result into wet anaerobic digestion system and total solid content of substrate greater than 20–40% leads to dry anaerobic digestion system. Wet anaerobic digestion takes little time to start up but at the same time, it tends to float more foam. On the other hand, dry anaerobic digestion takes a long time to produce the optimum content of methane, but the digestion process is stable.

However, wet anaerobic digestion under thermophilic conditions was found to be more effective in enhancing methane production than dry anaerobic digestion under the same conditions (Lianhua et al. 2010). As high temperature and high total solid concentration, both factors may induce the accumulation of acids thus adversely affecting biogas production. However, according to the findings of TERI, fresh cattle waste consists of approximately 80% of water and 20% total solids (TS). For optimum gas production through anaerobic digestion the appropriate dilution is required as if the slurry is too diluted then the solid particles will settle down in the digester and if it is too thick then the particles hamper the flow of gas formed at the lower part of the digester. In either case, the gas production will be less than the optimum value.

Co-Digestion/Inoculum

The anaerobic digesters are initially seeded with bacteria to improve the start-up process of digestion. Usually, the animal or municipal organic matter or digested sludge from active biogas plants are taken as inoculum. It has been reported that when both S/I and total solid content were high, the reduced amount of available microorganisms relative to substrate led to the failure of the digestion process (Liew et al. 2011).

2 Biomass Potential in India

India produces a large number of crops such as wheat, sugarcane, rice, corn, etc. as result most of the population relies on livestock and agriculture for their livelihood.

The agriculture sector in India contributes to 17.32% of Gross Domestic Product (GDP) with 48.9% employability as per reports from National Sample Survey Office (NSSO). India has the second-largest cultivated area (159.7 million ha or 394.6 million acres) in the world after the United State of America and the irrigated crop area in the country amounts to 82.6 million ha.

The country has seen tremendous growth in crop production which has been increased from 476 MT in 2003–04 to 511 MT in the year 2017–18. Total 511 MT of crop residue generated in India out of which 145 MT are available as surplus crop residue which can be utilized to generate electricity (Ravindra et al. 2018; Bellarby et al. 2008). Rice and wheat together contribute to a maximum of 63% of primary crop residue in India. Wheat straw is mainly used as fodder by the farmers, but rice straw due to its high silica content and low digestibility is not considered suitable for the health of livestock. Therefore, rice straw is frequently burnt by farmers in the open fields. Overall, around 15.9% of the residue is burned in the fields owing to the small window of rabbi and Kharif cropping pattern system, weeds removal, etc., thereby causing the increase in GHGs emissions, resulting in severe air pollution. Indian agriculture sector contributes to nearly 12% of the world's total GHGs emissions (Bellarby et al. 2008; Maraseni and Qu 2016; Cardoen et al. 2015a, b; Thambi et al. 2018; Central Electricity Authority (CEA) 2020). The uncontrolled burning of crop residues leads to severe atmospheric pollutants such as carbon dioxide, particulate matter, carbon monoxide, sulfur dioxide, and nitrogen oxide, methane, polycyclic aromatic hydrocarbons, volatile organic compound, elemental carbons, etc. Thus, declining air quality due to the burning of biomass in the open fields and its dispersion in the surrounding areas are of great concern to the Government as it has an adverse impact on human health. Rice straw and bagasse being lignocellulosic materials rich in organic matter can be utilized in a sustainable way to produce biogas in the anaerobic digestion process.

The total crop residue saving energy potential is about 7236.2 PJ/Year with 100% collection efficiency and 3618.1 PJ/Year with 50% collection efficiency of residue as reported for open burning for the year 2017 (Ravindra et al. 2018). Further, it has been estimated that this can produce 120 TWh of electricity amounting to be 10% of total power production in India.

3 Contribution of Bioenergy in Total Energy Mix

The energy demand in India is going to accelerate as expected to have emerged as the fastest-growing economy in the future globally. Consequently, the predicted installed capacity has to be raised to in the same stride. Although, India has shown immense progress in the renewable energy sector during the last few years but still nearly 27 million houses do not have access to electricity, and many people still using biomass as the heating source for daily cooking purposes (Central Electricity Authority (CEA) 2020). The enhancement of renewable energy resources shares to 40% by the year 2022 in power production will help the country to surpass the Paris

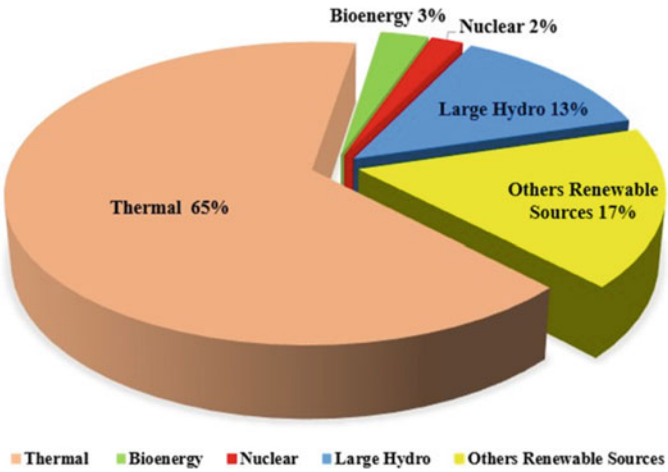

Fig. 2 Contribution of different energy resources

Agreement on environment change. The further enhancement of 45% by renewable energy contribution in the power sector may help to reduce the emissions significantly. At present coal-based power plants contributes to a maximum of around 56% of total demand being followed by renewable energy from solar, wind with 17% of total contributions by different energy resources. And the share of bioenergy is just about 3% as of March 2020 (CEA 2020) represented in Fig. 2 (Central Electricity Authority (CEA) 2020).

The renewable energy sector in India has reflected incredible growth during the period 2011–2020 as can be seen in Fig. 3. The grid-connected renewable installed capacity has increased from 19.974 to 77.004 GW (CEA 2020) during the last decade and the grid-interactive bioenergy contribution has accelerated from 2.6 to 10.339 GW during the same interval. In the last decade, the country's energy sector has observed average annual growths of renewable energy and bioenergy reaching to 5.7 and 0.75 GW, respectively. However, in order to fulfill the commitments made under the Paris Agreement on climate change the share of renewable energy resources has to be enhanced to 12.92 GW/year from the existing share of 5.9 GW/Year (Central Electricity Authority (CEA) 2020; Bisht and Thakur 2019).

The bagasse-based co-generation power plants lead the bioenergy sector in India. The Indian state Uttar Pradesh which is tops in sugarcane production has also stood first in total installed bioenergy capacity with the contribution of 2.13 GW being followed by Maharashtra and Karnataka with installed capacities of 2.08 and 1.62 GW, respectively. These three states have set targets for the year 2022 to enhance their capacities to 3.5, 2.47, and 1.42 GW respectively, from existing installed capacities. The south, north, east, west, and north-eastern regions of India have set targets of 3.18, 2.89, 0.5, 2.5, and 0.014 GW respectively as bioenergy potential in the energy mix by the year 2022. The two regions eastern and southern have accomplished their targets set for the year 2022 (Central Electricity Authority (CEA) 2020; Bisht and

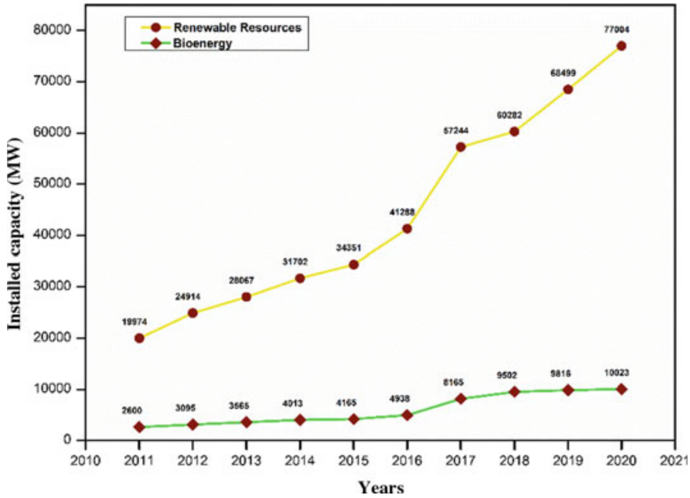

Fig. 3 Bioenergy contribution and other renewable energy resources contribution in total energy mix during one decade

Thakur 2019). The agrarian state of India, Punjab has a bioenergy potential of about 3300 MW out of which the state has installed a capacity of 322 MW as of the year 2018.

4 Biomass to Electricity Generation

Crop residues can be converted into energy through thermochemical conversion techniques and biochemical conversion techniques. Thermochemical conversion techniques of biomass involve combustion, gasification, and pyrolysis whereas the biochemical conversion pathway includes anaerobic digestion and fermentation as seen in Fig. 4. In the first method of combustion, biomass can be directly fired to generate steam which in turn runs the turbine for electricity generation. Biomass gasification results in incomplete combustion of biomass resulting into the release of harmful gases such as carbon monoxide, traces of methane, and hydrogen. The resulting gas produced after gasification is also known as producer gas which is used to run an internal combustion engine to generate electricity.

Pyrolysis is another method for power production based on slow and fast pyrolysis. Slow pyrolysis takes time to complete the process and produces more char along with organic gases which can be utilized for firing the boiler to produce steam and subsequent power production. However, in fast pyrolysis organic matter is heated at the temperature of 450–600 °C in absence of air to produce syngas in seconds (Woods and Hall 1994). The syngas is further utilized for power production. It has been

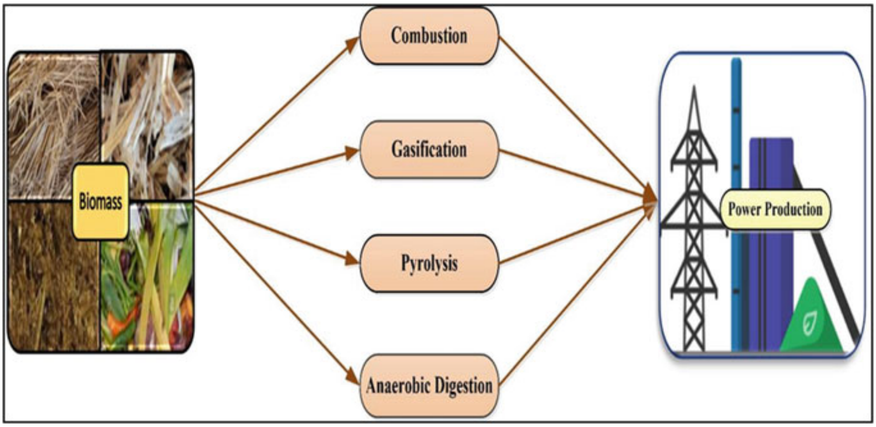

Fig. 4 Different methods to convert biomass into bioenergy for power production

observed that gasification plants work efficiently till 2 MW capacity and pyrolysis plants work beyond 2 MW capacity.

Biogas production through anaerobic digestion can be efficiently utilized in small size rural and off-grid locations. The rising competition of waste disposal methods may improve its economic usefulness. Anaerobic digesters are used both at small-scale and large-scale levels. Industrial applications mainly process large amounts of feedstock. This would require a well-developed logistical system for feedstock collection and effluent disposal. Overall, power production from anaerobic digestion is quite well established as a technology, though the economics of this route is still evolving. The slurry remained in the digester after biogas production can be utilized as fertilizer in the field.

Hybrid Power System

Indian power sector mostly relies on coal-based thermal power plants. However, coal deposits in the country are confined in north-eastern and eastern regions. Power generation capacity expansion through the thermal route via coal would also require increased transportation of coal (Singh 2016). High losses occurring during transmission and distribution of electricity add difficulty to remote villages electrification, so power shortages are major issues in India, where fossil fuel-powered plants suffer from supply shortages. Therefore, decentralized power generation through micro-grids based on renewable energy resources available locally is the best option for reliable electrification of these villages.

Although solar and wind power had gained significant momentum in the last few years in the energy sector. Solar photovoltaic energy system along with battery storage system has observed to be favorable among the counties which have most of the sunny days in a year such as India to provide electricity to the off-grid locations, commercial buildings, and residential loads. However, the extra cost involved due to the requirement of battery storage and low conversion efficiency has led to substantial growth in wind power generation. But the stochastic nature of wind and solar energy raised concern about the reliability of power to the end-user.

However, abundantly available biomass can complement the intermittent nature of solar and wind energy resources thereby reducing GHGs emissions. Biomass-based microgrids system can help the world to reduce the dependency on non-renewable energy and to become fossil-free by 2050 especially in agriculture rich countries like India. For instance, the thermodynamic study of solar-biomass power generation systems represents that cost of electricity has been reduced to 74.94 $/MWh for hybrid systems along with the reduction in CO_2 emission to 0.62 T/MWh (Sarkis and Zare 2018). The increase in fuel efficiency has been observed from 15 to 32% of solar energy in solar-biomass hybrid power plants without energy storage (Srinivas and Reddy 2014). The PV-Biomass-based microgrid system was found to be capable of full-fill the load demand of a village with more than 80% reduction in GHGs emission (Kaur et al. 2020). In another study, a biomass-based microgrid system with the battery as a backup system was found to provide the load demand of an educational institute in Bhopal, India at an economical cost of energy of 15.064 Rs/kWh with excess electricity generation (Singh and Baredar 2016).

5 Conclusion

In the last few years solar energy, wind energy has originated as emerging renewable resources and presented competition to fossil fuels in terms of cost also. But the irregular nature of these resources provides a hindrance to the existence of a standalone solar wind-based energy system. Renewable energy resources based hybrid energy system requires diesel generator or other energy storage devices as the backup to full-fill load demand. The use of diesel generators in hybrid power systems not only raises the cost of the system but also adds to the GHGs emissions. The biomass can provide a reliable and consistent power supply to the end-user in comparison with solar and wind energy resources, therefore, preferred as a renewable energy resource over other resources. The intermittent nature of solar and wind energy resources can be adequately complemented by the biomass power plant. So, solar, wind, and biomass due to their different characteristics can compensate for their individual drawbacks. Hybridization of these resources helps to utilize the biomass efficiently and provides electricity to end-users reliably and consistently. Hence, biomass-based hybrid power plants are extremely promising energy systems. As biomass not only avoids ecological and social damage but also helps to mitigate pollution being a carbon–neutral process.

So, among the renewable energy sources options, biomass seems to be a more reliable source of energy that can help the world to reach their long-term energy strategy to become fossil-free by 2050 especially in agriculture-rich countries like India.

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