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REVIEW ARTICLE

Rice straw burning: a review on its global prevalence and the sustainable alternatives for its effective mitigation

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Abstract

Being one of the most important staple crops of the world, rice has played a vital role in slaking the calorie requirements of the masses in all the inhabitable continents of our planet. Regardless of this fact, there are many environmental concerns related to the rice production systems across the globe. One of the major worries is the emission of lethal greenhouse gases as a result of the different steps and procedures concerned with rice production and their contribution towards global warming. This study presents the status quo of the rice straw burning practice across the globe. It focuses on the greenhouse gas emissions as a result of the open field burning of rice residues and its direct effect on the environment, eventually contributing towards climate change. The study evidently shortlists the most profound regions contributing towards the open burning dilemma and the socio-political reasons associated with it. The study additionally discusses the different alternatives to straw burning with a clear-cut motive of throwing light on the opportunities that lie in the efficacious and sustainable utilization of homogeneous agricultural wastes. Different in-field straw management techniques related to the farmers and off-field methods related to the industry have been discussed. Predicated upon a survey of the life cycle assessment (LCA) studies across the globe, it is concluded that soil incorporation and electricity generation are the most environment friendly alternatives with an enormous scope of improvement in the coming future.

Keywords Climate changes · Environmental aspects · Greenhouse gases · Government policies · Life cycle assessment · Rice straw burning

Introduction

Rice is one of the most important crops across the globe feeding almost half of the world's population. It is among the three most paramount staple grain crops of the world and holds a vital position in slaking the energy needs of the masses. Its cultivation is indispensable for the current as well as the futuristic food security issues. On the other hand, it has also become an important means of earning foreign exchange for several countries and directly influences their economies. The past few decades have witnessed a steady upsurge in the rice production with minor and ignorable fluctuations. With a

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constant increase of global population, it is inevitable to enhance the production of staple food crops in order to meet the ever-increasing demand of food. Albeit the ecumenical yield of rice has been incrementing annually, the rate of its increment is falling at a leisurely pace (Bajwa and Chauhan 2017). There are estimations that by 2035 the requirement of rice may increase by a staggering 116 million tonnes with a major demand from the Asian and African countries (Seck et al. 2012). This highlights the value of incrementing the engenderment of rice, either by investing into research and development of better yielding varieties or by further incrementing the area under cultivation. Additionally, there are quite a few constantly growing environmental related to the rice cultivation throughout the world. The pollution caused as a result of the extensive burning of the leftover straw wastes in the fields is the most challenging task confronting the technical experts in this area. Nevertheless, many alternatives in lieu of straw burning are being researched and evaluated for reducing the environmental burden exerted by rice production.

Rice: a globally grown crop

Rice crop is grown in the cultivable areas of all the six habitable continents leaving aside the ice-covered continent of Antarctica where agriculture is not feasible. It has been a noticeable part of our cultures for the past several centuries with many festivals across the globe celebrated with regard to its heavy harvest. Rice is being grown in many countries with a gross cultivated area of nearly 160 million hectares and a production of nearly 760 million tonnes annually (FAO 2018).

Asia

According to the prevailing status quo, the Asian countries lead the production table, accounting for 90% of the world's total rice production followed by Latin America and Sub-Saharan Africa. Individually, China and India grow maximum quantity of rice with China producing an average of 210 million tonnes of rice in 2017–2018 followed by India at 170 million tonnes during the same period. They are followed by other Asian nations like Indonesia, Bangladesh, Vietnam, Thailand and Myanmar (Cosslett and Cosslett 2018). Together, these seven Asian nations conjointly supply 80% of the global rice production. In the nutshell, it would be fair to state that the rice production in Asia is indispensable for assuring the global food security. In addition to this, with the global population increasing, the demand for staple foods including rice is also expected to experience an upward swing over the next few decades, to which these Asian countries will be the chief caterers either by increasing the area under cultivation or with the assistance of higher yielding varieties (Bandumula 2018).

Africa

Regardless of the Asian supremacy in rice production and consumption, it is considered equally important in other parts of the world as well. It serves as the major food crop for most of the African countries. The brisk increase in the population over the past two decades has increased the demand for the crop which currently serves as the second most dominant source of energy in Africa. In fact, the current consumption rate of rice in Africa surpasses its production rate which is balanced with the assistance of effortless and sustainable imports from Asia (Zenna et al. 2017). Egypt, Madagascar and Nigeria are the prime growers of rice in Africa followed by countries like Mali, Tanzania, Sierra Leone, Senegal and Ethiopia. It is majorly grown in the countries forming the western as well as the eastern coast of Africa and has turned out to be a crop of paramount political importance. The episode of the rice crisis of 2007–2008 in Africa is a classic example of the extent of public unrest caused due to its shortage or price fluctuations highlighting its vitality (Seck et al. 2013).

The Americas

Rice cultivation is exercised in nearly 7.2 million hectares throughout the Northern and Southern American continents. While Brazil and the United States of America (USA) collectively produce more than 60% of the total production in both the continents, other nations like Mexico, Argentina, Bolivia, Chile, Colombia, Ecuador, Panama, El Salvador, Peru and Colombia also produce decent proportions of the crop. Brazil tops the lead board with 2.3 million hectares followed by 1 million hectares in the USA (Singh et al. 2017). Although, these regions are heavy consumers of wheat and maize as well as beans, rice still constitutes a good portion of the daily diet in countries like Brazil, Argentina, Costa Rica, Panama, Dominican Republic and Haiti. Over and above that, Brazil produces nearly half of the region's rice followed by Peru and Colombia. Coming to the USA, the production has been somewhat stable over the past decade with minor fluctuations. The state of Arkansas leads the production list with more than half of the country's rice production under its name.

Europe

In Europe, the trait of rice farming is restricted to only a few countries in the southern part of the continent. In 2015, the conjoint share of Italy and Spain constituted 75% of the continent's total sown area. Although wheat, barley, maize and oilseeds are considered important in Europe, countries like France, Greece, Portugal, Romania, Hungary and Bulgaria extensively grow rice. The share of Europe in the global rice pool is less than 1% due to which it cannot be regarded as a source of overproduction, but the internal demand is efficiently catered by the countries growing it or through import from Asia (Kraehmer et al. 2017). Moreover, the per capita consumption of rice is 3–5 kg in the non-growing countries and 6–18 kg in rice growing regions of Southern Europe. This is much lower than the consumption trends of most of the Asia and African countries, thus explaining its lower production in Europe.

Australia

In Australia, there has been a tremendous increase in the yield of rice per hectare area due to development of innovative and more efficient cultivation and irrigation techniques. Although, the area under rice (50,000 ha approximately) in Australia is minute when contrasted with the global giants, it is yet conspicuous as more than 85% of the country's engenderment is exported to proximately 68 countries across the world (Bajwa and Chauhan 2017). Although the recent fluctuations in the region's production due to scanty rainfall have restricted a highly upward trend in the area under the crop, neither has there been a decline. It is estimated that, in light of the modern techniques of irrigation and development of advanced, robust and better yielding varieties, the production of rice in the region shall sustain over the coming years.

It can therefore be stated that rice is a crop that is grown globally and is not limited to any specific region. As a result, its pros and cons are also shared globally by the equally spread growing regions. Table 1 lists the major rice growing countries across the different continents and their production in a major portion of the previous decade. It can be concluded that majority of the world's rice production comes from developing countries across all the six inhabitable continents.

Challenges in rice production—a vicious circle of being victim of and also a contributor towards climate change

Rice is grown in highly diverse climatic conditions ranging from the deserts of Africa to the Himalayan highlands of India and Nepal. But mostly, it is a crop of the tropical regions ranging between the tropic of Cancer and the tropic of Capricorn in the northern and the southern hemispheres respectively. In fact, a quarter of the world's rice production comes from countries lying in these areas. With rice being grown successfully across the globe, and the production recorded increasing steadily with each passing year, the future looks promising and steady as far as global food security is concerned. There are huge expectations from the major rice growing areas especially South East Asia, Sub-Saharan Africa and Latin America for catering the needs of the ever-increasing human population. Based upon the future projection of the United Nations, keeping the population growth and income in mind, the demand for rice is going to increase in the near future. The expected demand by 2035 is forecasted to reach 555 million tonnes compared to the current production of 503 million tonnes (milled rice) (FAO 2018).

The consumption trends of rice are experiencing variations in different global regions primarily as a result of the growth of income of the masses. In Asia, the expectations are to contribute nearly 67% to the overall expected increase in the rice production by 2035; meanwhile, countries like China, India, Indonesia and Vietnam have been witnessing a downward trend in their domestic rice consumptions. The probable reason for this can be the effect of increase in the income of majority of the population and the increased urbanization leading to a paradigm shift in the way people choose their diet. The story is entirely different in Africa though, where the consumption is expected to almost double in the coming couple of decades. Despite not being a staple crop in Africa, the consumption of rice continues to experience an upsurge in the underdeveloped countries like Nigeria, Tanzania, Chad, Angola, Central African Republic and Burundi. The growth in the income of majority of the population has led to such an increase. Similar trends are visible across Latin America and the Caribbean islands where an increase of 40% has been witnessed in the past two decades with the demand still increasing (GRiSP 2013). Even the developed countries/regions of North America and Europe have been reporting a steady increase in the consumption of rice. One reason for this can be the trend for inclusion of more fibre and less protein in the diet of the people while another can be the ever-increasing immigration of Asian people to these advanced nations.

There has also been a noticeable change where growers are turning towards cash crops like groundnut or potato which are more profitable where ever the soil quality is good. Therefore, it is quite clear that the area under rice cultivation is not going to increase to the extent of the expected increase in its consumption. The pressure is therefore going to be faced by the rice growing nations to increase their yields at a much faster rate as compared to the past. In fact, it is believed that, beyond 2020, the growth of yield will have to be over 1% annually in order to meet up with the future demands. It appears that this much annual increase can be easily attained with the incorporation of better growing and irrigation techniques accompanied by accelerated research towards developing better and high production seeds. It can also be expected that the steep increase in the demands of Africa and Latin America can be fulfilled by the dipping per capita consumption of some major Asian countries, but the equation is not as simple as it seems (Rehman et al. 2015).

The first and the major concern that can play a decisive role in the future growing patterns and yields of rice is the effect of climate change on rice production. The second is the exact opposite, i.e. the role of rice production in promoting negative climate change in future. The two cases are directly

Table 1 Global paddy production (FAO 2018)

	2013–2015 (average) Million tonnes (Mt)	2016	2017	2018 (estimation)
World	743.2	755.1	759.6	769.9
Developed regions	24.9	25.2	23.2	24.3
Developing regions	718.3	729.8	736.4	745.6
Asia	672.1	681.8	686.7	695.5
Bangladesh	51.8	52.1	50.8	53.0
Cambodia	9.3	10.0	10.4	10.6
China	207.7	208.7	210.3	208.1
India	158.3	164.5	166.5	169.5
Indonesia	71.7	72.6	73.9	74.5
Iran	2.4	2.9	3.1	3.0
Japan	10.7	10.7	10.4	10.4
Korea	5.7	5.6	5.3	5.2
Lao PDR	3.9	4.1	4.2	4.2
Malaysia	2.7	2.7	2.8	2.9
Myanmar	28.1	28.6	29.5	30.4
Nepal	4.7	5.2	5.2	5.3
Pakistan	10.3	10.3	11.1	11.3
Philippines	18.4	18.5	19.3	19.7
Sri Lanka	4.3	4.4	2.4	3.5
Thailand	31.9	32.4	33.7	34.5
Vietnam	44.7	43.2	42.8	44.2
Africa	29.2	32.6	32.1	33.3
North Africa	6.1	6.4	6.4	6.2
Egypt	6.1	6.3	6.4	6.1
Western Africa	14.9	17.0	18.0	18.3
Côte d'Ivoire	0.8	0.8	0.9	0.9
Guinea	2.0	2.2	2.2	2.2
Mali	2.2	2.8	2.9	2.9
Nigeria	5.7	6.5	7.0	7.2
Sierra Leone	1.1	1.2	1.4	1.4
Central Africa	0.5	0.7	0.7	0.7
Eastern Africa	3.3	4.2	3.2	3.9
Republic of Tanzania	2.6	3.4	2.5	3.1
Southern Africa	4.3	4.3	3.7	4.2
Madagascar	3.8	3.8	3.1	3.6
Mozambique	0.4	0.3	0.4	0.4
Central America and Car.	2.8	2.9	3.0	3.2
Cuba	0.6	0.5	0.5	0.6
Dominican Rep.	0.9	0.9	1.0	1.1
South America	24.9	23.2	25.0	24.0
Argentina	1.6	1.4	1.3	1.3
Brazil	12.1	10.6	12.3	11.4 G
Colombia	2.0	2.6	2.7	2.7
Ecuador	1.2	1.2	1.2	1.2
Peru	3.0	3.2	3.0	3.2
Uruguay	1.4	1.3	1.4	1.3
Northern America	9.2	10.2	8.1	9.2
United States	9.2	10.2	8.1	9.2
Europe	4.1	4.1	3.9	3.9
EU	2.9	3.0	2.9	2.8
Russian Federation	1.0	1.1	1.0	1.0
Oceania	0.9	0.3	0.8	0.8
Australia	0.9	0.3	0.8	0.8

intermeshed where in the first case it is visualized how a bigger global issue like climate change has the potential to effect the global rice production. In the second case, however, it is estimated how the current global rice production process is affecting the climate in a negative way. It shall therefore be fair to state that rice production is paradoxically a victim of and a contributor towards climate change as depicted in Fig. 1. It can be explained clearly on the basis of the GHG emissions released due to the different stages of paddy production including the stages like land preparation, irrigation and fertilization. Furthermore, the high water consumption also plays a vital role in aggravating the global warming. On the contrary, the global warming in return causes loss to the plant productivity due to contributory factors like reduced soil fertility, sea level rise and elevated temperatures. It also causes morphological and physiological changes in the crop alongside contributing to socio-economic factors as well due to the increased costs of production. Additionally, Fig. 2 clearly shows the contribution of rice farming towards the global GHG emissions. It is depicted that, besides the land use change and energy from non-agricultural and other sources, agriculture accounted for 13% of the global GHG emissions. Ruminants such as cattle contributed 47% of the total agricultural GHG emissions while 6% of the global GHG emissions in 2010. Nevertheless, rice production alone accounted for 10% of the total agricultural GHG emissions. Although it is one of the many parameters that influence climate change as expressed in Fig. 2, any possible effort for countering its negative effects on the climate can be considered highly valuable.

Climate change effecting global rice production

Considering the current global scenario of industrial and agricultural pollution, abrupt changes in the climate are expected. The steady increase in greenhouse effect is slowly raising the global temperatures and melting the polar ice caps. Many regions are experiencing unexpected variations in the patterns of rainfall. Such foreseeable changes are expected to have a direct impact on the crop yields throughout the world, jeopardising the future. Many studies have been conducted in different regions of the world in order to find the effects of temperature and rainfall on the productivity of the rice crop. Some regions may reap beneficial outcomes as a result of the climate change, but largely the effects are estimated to be negative.

China is by far the global leader in rice production. In fact, the last 50 years have witnessed its gross production getting tripled. The constantly increasing demand of rice has attracted many researchers from all over the world to explore the various possibilities in the near future and estimate the future production levels. Many studies have focussed on simulating the results of the production response to variations in the climatic conditions. Lu et al. performed simulations on the basis of the regional calibrated crop model and predicted a decline of 10–11% over a time frame of the next 50 years subject to unchanged dates of sowing of the crop (Lv et al. 2018). In a similar study over a decade back, Yao et al. used the regional climate model and the CERES-rice model to simulate the rice yield patterns in the latter half of the current century. The impact analysis was performed on eight chosen stations in different regions of China. It was concluded that, without considering the direct effect of carbon dioxide fertilization, the climatic change will have a negative effect on the yields in most of the stations (Yao et al. 2007). Although the issue of climate change has caught everyone's eyes in recent years, it was still under consideration during the last couple of decades of the previous century. Continuing with China, a study conducted back in 1995 by Jin et al. evaluated all possible outcomes of climate change on rice production. The effects of carbon dioxide and irrigational practices were analysed. The study showed the importance of rainfall patterns which could highly increase or decrease production. Shifting of rice production areas along latitudes and optimizing the sowing dates were concluded at the major mitigation procedures (Jin et al. 1995). These studies

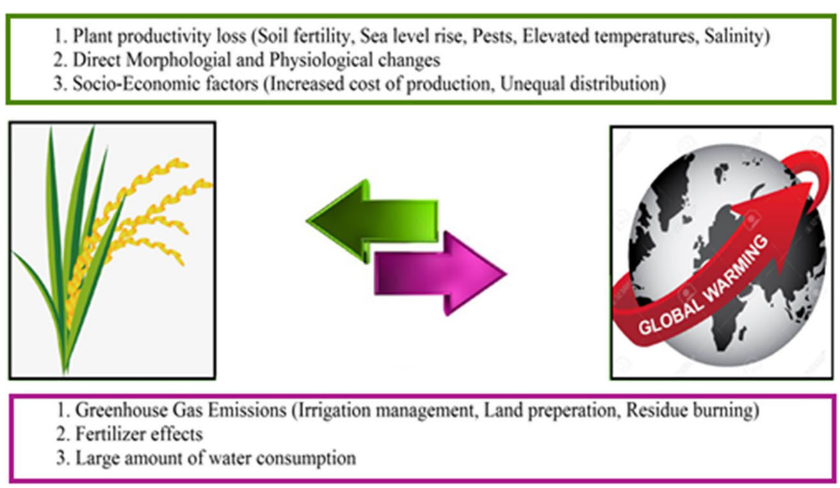

Fig. 1 Global climate change and rice cultivation—the relative inter-effects

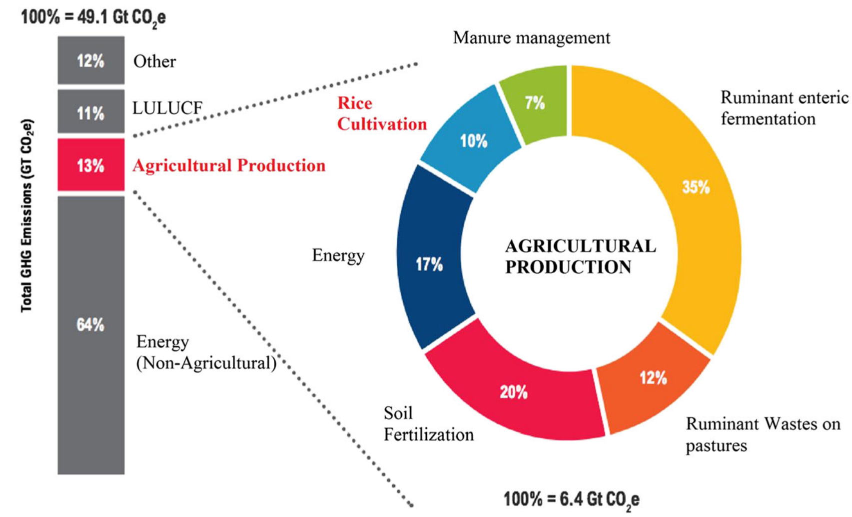

Fig. 2 Contribution of rice farming towards global GHG emissions in 2010 (Ranganathan et al. 2016). Figure may not equal 100% due to rounding. LULUCF: Land Use, Land-Use Change, and Forestry. Includes emissions from on-farm energy consumption as well as from manufacturing of farm tractors, irrigation pumps, other machinery and key inputs such as fertilizer. It excludes emissions from the transport of food. Excludes emissions from agricultural energy sources described above

conducted over three decades focus on similar parameters and suggest similar outcomes. Similar trends are expected in India, which is the second largest producer of rice in the world. In a report by WWF India in 2010, a sharp fall in the rice yields of the upper basin of the Ganges was predicted which is well on its way to become a true fact. It was further explained that the regions with heavy rainfalls may suffer losses as a result of further increase due to climate change on the basis of different climate prediction models (2010).

The variations in rice production are globally driven by a conjoint effect of parameters like genetics, agronomics and the climate. Therefore, understanding the individual effects of these drivers is of utmost importance in order to make agricultural adaptations possible. It can be easily understood by a study in the Philippines, where a group of researchers identified the El Nino - Southern Oscillation (ENSO) as a driver that may eventually effect the production. The soil moisture content is directly influenced by the ENSO which fluctuates the production by as high as 10%. The time period 1987–2016 was monitored and the need for accurate seasonal forecasting was highlighted. Conclusively, the need for better genetic research and agronomical processes was emphasized in order to mitigate the climate-induced variations (Stuecker et al. 2018).

Moving over to Africa, a study by Oort and Zwart comprehensively aimed at understanding the boosts and pitfalls in rice production throughout the continent. Simulations were carried out in order to estimate the future trends of rice production and it was concluded that, with the passage of time, the production along the eastern coast is expected to experience an upsurge as a result of better water availability and higher carbon dioxide concentrations. On the contrary, the production on the western coast will take a dip due to increased temperatures and less favourable rainfalls (van Oort and Zwart 2018). Though scientists have found similar patterns of good and bad effects of climate change on the production throughout the world, there is still enough evidence that the overall production will fall even in the low-temperature zones (Semenov et al. 2012).

Summing things up, it is very much expected that by 2050 the average rice yields in both developing and developed countries across the world are going to take a dip. The condition however seems more severe in the developing countries where the yields are expected to fall by 14–19% as compared to the 3–6% fall in the developed countries (Nelson et al.). What adds to the worry is the current distribution of rice production among the developing and the developed nations as addressed in Table 1. It can be clearly seen that currently over 95% of the world's rice produce comes from the developing countries. This decrease is also expected to be shared equally among the major rice growing regions of South East Asia, the Pacific and the Sub-Saharan Africa. The mitigation of the adverse effects of climate change using several sustainable techniques will go on hand in hand with the control of the harmful effects of rice cultivation on the environment, thus contributing towards climate change. Most studies reveal that variations in rainfall patterns, rising sea levels and increasing temperatures may cause noticeable modifications in land and water resources throughout the world.

Rise in sea level

The steady upsurge in the temperatures and the melting of the polar glaciers is slowly but steadily increasing the sea levels. According to a United Nations report, the global temperature increased by over half a degree in the previous century but may increase by 1.4–5.8 degrees until the end of the current century. It is also predicted that the sea level may rise by 0.88 m by 2100 (Nguyen 2004). This poses a serious threat to the rice production, a good percentage of which is exercised on the coastal areas. This steady rise of water levels will tend to make rice production highly vulnerable and eventually impossible along the coasts. For example, more than half of

Vietnam's rice farming is done along the coastal river deltas. Additionally, effect of the rising seas is already being felt in the rice producing areas of some major river systems of the world like the Nile, Ganges, Yangtze, Mekong and some other major rice growing river deltas of the world.

Salinity

Since the water levels are expected to rise, the salt content in the soil along the coastal areas may increase as a result of the seepage of sea water inwards along the coasts. The yields are expected to experience a nosedive under such conditions, subjected to the poor tolerance of rice crop towards such high levels of salt content in the soil. Under such conditions, the crop seizes to grow properly accompanied by rolling and drying of the lower leaves. The lands affected by the tidal waves usually result into lower production rates and the effect of such tides may be felt as far as 200 km from the coast. The salt contaminates the land by displacing important elements like potassium, iron, calcium, manganese and magnesium from the soil and further causes injuries to the crop, thus reducing the yield. This can be well understood from the example of India, where nearly 6.7 million hectares of rice crop gets affected by the soil salinity each year, experiencing loss of yields. This accounts for as much as 15% of India's harvested area (FAO 2014).

Raised temperatures and carbon dioxide levels

The slowly increasing temperatures are also expected to lessen the rice productivity. There are many issues linked to the raised temperatures like the increased respiration losses and sterile flowers that eventually lead to reduction in yields. In a recent study conducted in Punjab, Pakistan, it has been found that both temperature and untimely rainfall adversely affect the crop. It has been concluded that a rise in minimum temperature above 28 degrees in the region halts the reproduction process of the crop and results in sterile spikelets. Additionally, the changing pattern of rainfalls in the recent years has also affected the production (Abbas and Ali 2020). A similar study conducted in Thailand by Sinnarong et al. used the historic data from 1989 to 2009 for quantifying the effect of climate change on rice production. The results were simulated and expressed in terms of the mean production and the production variance. The empirical models developed predicted a decrease in the mean production by 4.56–33.77%, while an increase in the production variability by 3.87–15.70% during the latter half of the twenty-first century. The increasing temperature was concluded as the major driver (Sinnarong et al. 2019). The carbon dioxide concentrations usually tend to increase the production although this may be affected by the rising temperature. A study conducted in Japan predicted yield improvement of 7–8% with increasing carbon dioxide concentrations. However, it was also concluded that a rise of 2 degrees in the temperature can easily neutralize the benefits of the increased carbon dioxide concentrations (Horie et al. 1996). Considering the rate of climate change to remain stable in the coming years, development of varieties with better temperature and draught tolerances is the need of the hour.

Frequent flooding or water scarcity

Although rice can uniquely thrive under extremely wet conditions unlike other cereal crops, longer durations of water stagnation and complete submergence pose a danger to the crop. Currently, over 40% of the world's rice crop is rain fed while nearly 4 million hectares fall under the flood-prone zones (Jl and Dc 2003). Under flooding followed by complete submergence, over 50% of the plants die after 6 days, while 100% die after 2 weeks. Rainfall fluctuations can prove to be detrimental for the rice crop. With delay in the onset of rainfalls, the rain-fed zones experience unnecessary delays in sowing dates. Furthermore, in the highlands, heavy rainfall followed by long dry periods also leads to heavy loss of yields. With ever-changing climate and fluctuating rainfalls, these issues are going to get more common in the near future (Watson 2001). Where on one side flooding is expected to cause trouble, other regions may face shortage of rainfall with eventual draughts reducing yields. The combination of draught and the current carbon dioxide levels affects the crop at molecular, morphological, physiological and biochemical levels (Pandey and Shukla 2015). Besides these, the changes in the patterns of rainfall may also give rise to new forms of crop diseases like the sheath blight in some areas while attack of pests in others. The issue of weed infestation may also arise due to such deviations (Xie et al. 2014).

With a future vision of meeting up with the global food requirements and establishing food security, a sustainable increase in the production of such vital crops will have to be achieved through highly adaptive production techniques which are able to cope up successfully with the changing climate. Although climate change is a very important aspect and has a huge impact on rice production, on the contrary, the contribution of rice production towards climate change cannot be ignored. The following section will discuss these issues in detail.

Rice production effecting the global climate change

With the world moving towards sustainability, such environment-related concerns have forced most of the countries to frame suitable regulations and policies for controlling their greenhouse gas (GHG) emissions (Leggett et al. 2008; Haines et al. 2009; Lehuger et al. 2011; Bhuvaneshwari and

Hettiarachchi 2019). The air concentration of these anthropogenic gases has drastically increased dramatically beyond record levels in the recent decades as a result of changes in land use, agricultural practices and burning of fossil fuels. This in turn affects the global average temperature. As a joint global venture for controlling the GHG emissions, The United Nations Framework Convention on Climate Change (UNFCCC) was adopted as an international treaty in May 1992 and entered into force in March 1994 after sufficient global ratifications. The major objective of the UNFCCC is to regulate and stabilize the GHG concentrations to levels below the danger zones where they shall not interfere with the climate and the ecosystem. This framework mainly guides how the international treaties may be negotiated among nations for achieving these targets (IFDD 2017). The Kyoto Protocol was one such protocol adopted in December 1997 and was brought into effect in February 2005 (WA 1999). The protocol mainly enforced the developed industrialized nations of the world to reduce their emissions of carbon dioxide (CO_2) and other GHGs. The nations that chose to ratify were assigned certain limits of carbon emissions for particular periods. The European Union (EU) agreed to reduce its emissions by 8% while the USA and Canada by 7% and 6% respectively. The countries grouped as developing were exempted from the agreement. As a result, a conjoint effect of the emissions from developing countries like China and India and the failure of countries like the USA to meet the assigned target emissions led to a further increase of GHG concentrations by 40% between 1990 and 2009 (Cirman et al. 2009). Recently, the Paris Agreement was adopted to the UNFCCC on 12 December 2015 and entered into force on 4 November 2016. Unlike the Kyoto Protocol, it has been signed by nearly 190 countries who have accepted the shared responsibility of controlling the GHG emissions which accounts for 90% of the global emissions (Foran 2016; Rica and Salvador 2017). The raised interests of the entire global community towards controlling the climate changing activities highlight the importance of these desperate measures. In a study conducted by the University of Minnesota, GHG emissions from the major croplands of the world were indicated as depicted in Fig. 3. It can be clearly seen that the highest concentrations of the emission zones are in the eastern and south-eastern past of Asia which also happen to be the major rice growing areas of the world (Carlson et al. 2016).

Rice farming is indispensable for safeguarding global food security as it contributes more than 20% of the global calorie intake. Fulfilling the hunger needs of the world is not very cheap though, as it has its own harmful effects on the environment. Many groups and communities of environment-loving people around the world have already given up consuming meat and have switched over to using electric cars keeping in mind the adverse impacts these processes have on the environment. Very few people actually think or know about how much a bowl of rice costs to the ecosystem. The entire production process of rice involves many activities beginning with the land preparation up to the management of the straw waste left over after harvesting the crop. All of these processes leave some impact on the environment, be it the use of harmful pesticides, consumption of large quantities of water for irrigation or even the burning of fuel during land preparation and harvesting. One such concern is the release of harmful GHG during the growth and irrigation phase of the rice crop and further release during the post-harvest phase as a result of open field burning of the waste straw/stubble.

Greenhouse gas emissions from rice production

The global climate change and the role of GHG emissions have become the biggest concern in the twenty-first century. Some GHGs occur naturally in the environment while others are anthropogenic. Agriculture accounts for 20% of the anthropogenic GHG emissions (Hütsch 2001). Methane (CH_4) and nitrous oxide (N_2O) are the two critical greenhouse gases released by the agricultural industry. Their importance lies in the fact that their global warming potentials have values 28 and 265, respectively, when compared to CO_2 over a 100-year period. Additionally, the levels of these GHGs have increased drastically after the industrial revolution from 722 to 1830 ppb in the case of CH_4 and 270 to 324 ppb for N_2O according to a report by Myhre et al. 2013 (Huang et al.). In 2018, the levels of both gases reached record high values of 1869 ppb and 331 ppb respectively. With a major challenge of increasing global agricultural production in the future, a further increase in the use of nitrogenous fertilizers will be required, which is further expected to boost the levels of CH_4 and N_2O in the atmosphere (Jessie et al. 2014; Roy et al. 2014). These worrying figures have created a desperate global situation where controlling these GHG emissions has become vital for mitigating their adverse effects on the climate change.

Rice occupies more than 11% of the world's agricultural land area and contributes a huge 10.1% of the total agricultural GHG emissions. When considering the global anthropometric emissions, rice production accounts for 1.3 to 1.8% of the gross emissions (Narayan et al. 2017). These emissions are produced by different individual aspects of the rice production process like the water management techniques, fertilization schemes, cultivation methodologies and the post-harvest management of the leftover wastes, as shown in Fig. 4.

Straw burning: a global picture

For the in-field management of the waste straw, open burning is one of the most popular alternatives adopted by the farmers all over the world. Although, the past decade has witnessed many countries banning the open burning and governments aiding farmers to adopt other alternatives like fresh straw

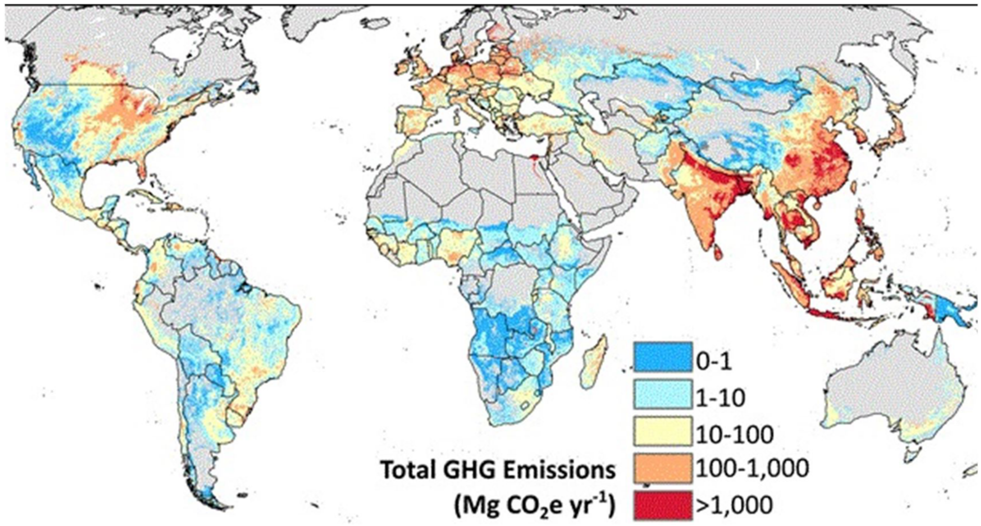

Fig. 3 GHG emissions from major global croplands (Carlson et al. 2016)

incorporation, bailing the straw and using for electricity generation and making compost or biochar, it is practiced on a large scale in most of the rice producing countries. Despite its well-known environmental, health and soil quality adverse consequences, most farmers prefer burning due to its lower cost and the ease of tillage as well as reduction of weeds in the next crop. Burning of rice straw emits GHGs like CO_2, CH_4 and N_2O in addition to other trace gases. These gases have been proven to influence human health in a negative way in addition to their global warming potential (Kim Oanh et al. 2006; Arai et al. 2015). Most studies consider the GHG emissions from burning to be much lower than the emissions from fresh straw incorporation without taking CO_2 emissions into account. However, if the CO_2 emissions are included, the immediate loss of a major percentage of carbon (C) makes the global warming potential of burning very close to that of the fresh straw incorporation (Lu et al. 2010). Figure 5 also depicts the global black carbon and methane emissions from various sources. Biomass burning turns out to be a significant contributor in both cases.

Fig. 4 GHG emissions from the burning straw (https://www.downtoearth.org.in/blog/agriculture/-thinking-glocal-to-solve-india-s-paddy-straw-burning-crisis%2D%2D62637)

The burning of freshly generated rice straw is very common especially among the Asian countries accounting for more than 70% of the world's rice production and hence the straw generation as well. After harvesting, the rice straw is openly burnt in the fields due to shortage of time before sowing the next crop. Figure 6 shows the pie chart distributions of straw wastes from different crops in some Asian countries. It can be seen that the proportion of rice straw is very high in countries like Japan and Republic of Korea. For mass producers like India and China, the proportions of straw wastes are more evenly distributed although rice straw does form the major portion. Therefore, it would be fair to conclude that management of rice straw is very critical taking into account its volume generated across the globe (FAO 2014).

China being among the leading producers of food grains in the world also produces huge amounts of waste straw from different crops. The annual straw production of China was estimated to be 700 million tonnes back in 2014 (Liu et al. 2015). Prior to the 1970s, rice straw was used mostly as cattle feed or as a domestic fuel. The previous decades have witnessed an upward trend in the sowing and production of rice and other grain crops followed by a heavy mechanization in the agricultural sector. As a result, the dependence on straw as a fuel and for cattle has experienced a nosedive. With a very little time gap between successive crops and increased cost of agriculture, the farmers prefer to burn the straw openly in fields instead of mechanically removing it.

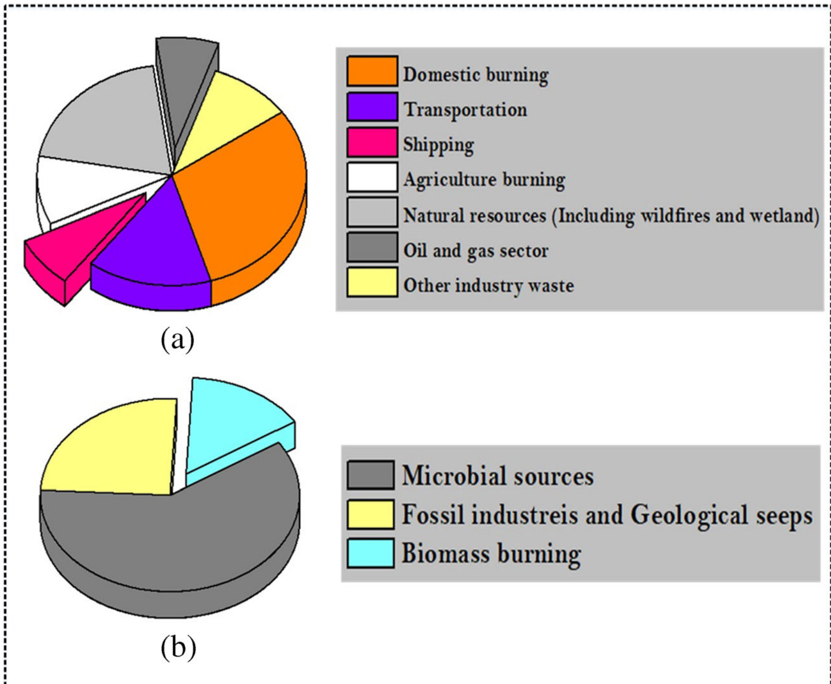

Fig. 5 **a** Global black carbon emissions from various sectors (source: Arctic Monitoring and Assessment Programme [AMAP]). **b** Global methane emissions from different sources (source: National Oceanic Atmospheric Administration [NOAA])

Guoliang et al. (2008) conducted a detailed analysis on the emissions that resulted from straw burning in China from 2000 to 2003. Table 2 shows the comparison between the grain output and the straw output from different crops in China during 2000–2003. Also, Table 3 shows the comparisons between the gross straw outputs and the relative percentage burnt in different Chinese provinces and municipalities during 2000–2003. It can be clearly witnessed that, even two decades back, rice straw was among the major contributors towards the gross straw production in China alongside wheat and corn. It was also concluded that, out of the 600 Tg of straw produced in China, nearly 140 Tg (23%) was burnt. The density of emissions recorded was very high on the eastern and northern side of the country and low towards the west of China (Guoliang et al. 2008). In another study by Shi et al., the straw burning in China was estimated to emit 140–240 billion kg of CO_2, 1.6–2.2 billion kg of $PM_{2.5}$ and 0.05–0.14 billion kg of black carbon into the atmosphere. The burning of rice and other agricultural residues also contributes towards regional haze and smog during the harvesting periods (Shi et al. 2014).

The burning of straw has witnessed a positive downward trend over the past decade in China as a result of a boost in straw utilization promoted by the government. In the time period 1995–2005, it was estimated that nearly 62% of the straw was openly burnt in the fields. On a positive note, the national straw utilization increased to as high as 80% by 2015. Despite a high percentage of utilization rates, the remaining quantity of straw is still burnt causing a lot of air pollution. A detailed review of the current scenario of straw burning and utilization by Ren et al. estimated that, with improvements in infrastructure for converting waste straw into bio-energy, an additional 5–10% of straw burning could be controlled by 2020. The results, however, would entirely depend on the efficiency of the government to intensively publicize the positive aspects and the technologies for converting waste straw into usable forms (Ren et al. 2019).

In a case study performed in Tianjin, China, by Guan et al., an emission inventory was established for the time period 1996–2014. Despite the municipal government of Tianjin imposing anti-straw burning policies, the straw burning continues at alarming rates. It was concluded that the emission of several pollutants like N_2O, CH_4, CO and CO_2 decreased from 1996 to 2000 but has been gradually increasing ever since (Guan et al. 2017). The failure of the government to publicize the utilization technologies and the ease of straw burning when compared to mechanical collection has contributed heavily towards the failure of several such nationwide policies.

India is unarguably the second largest agro-based economy in the world. A report by the India Ministry of New and Renewable Energy (MNRE) in 2014 showed that India generates a staggering 500 Mt of agricultural waste annually. It was also estimated that 140 Mt out of the 500 Mt gross residues are surplus out of which 92 Mt is openly burnt every year. The total waste generated by India is much more than the collective waste of other Asian agro-economies like Bangladesh, Indonesia and Thailand. According to a report by IPCC and Jain et al., 25% of the crop residue is openly burnt in India. Cereal crops contribute nearly 58% of the total waste generated

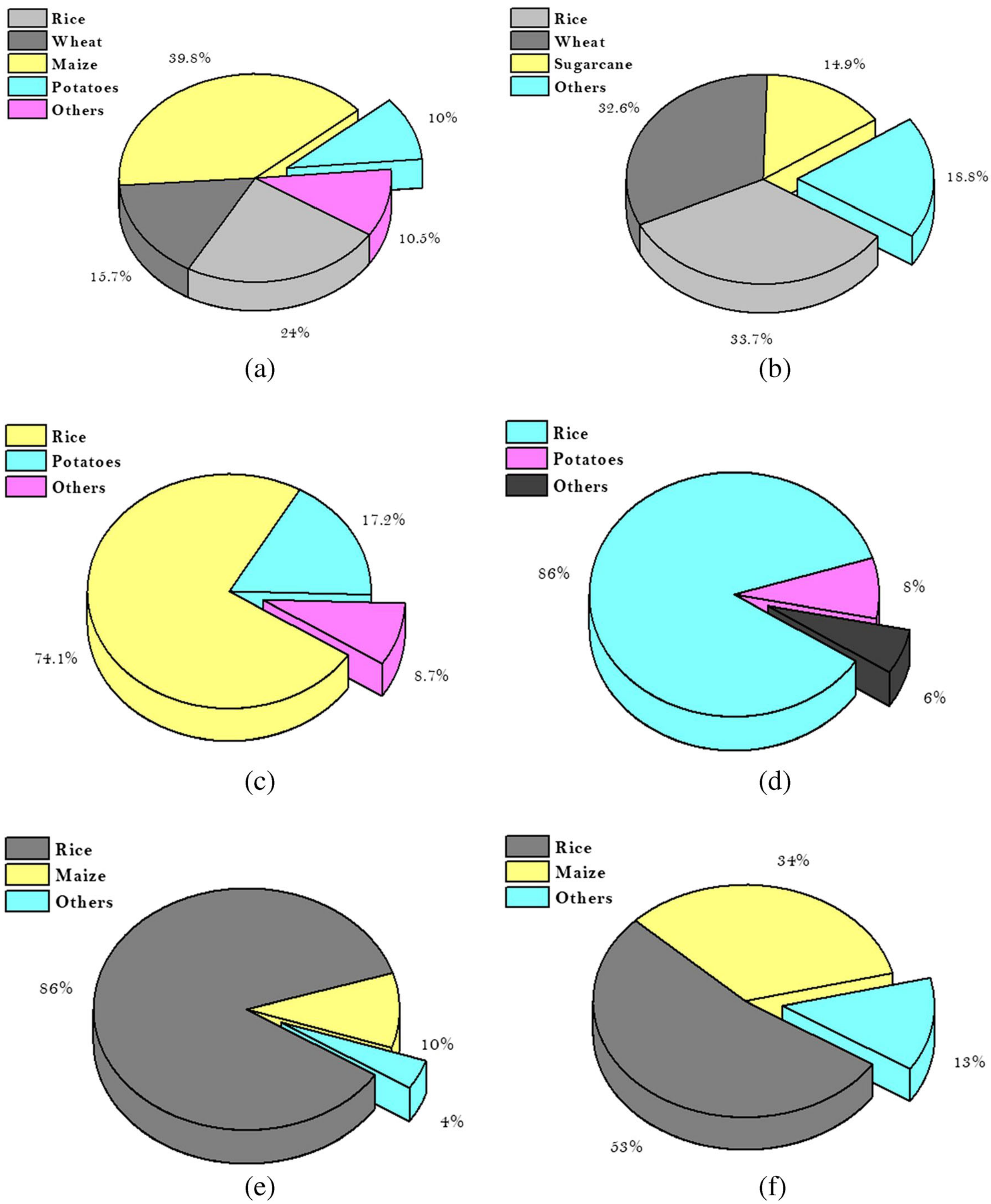

Fig. 6 Proportion of major straw types in **a** China, **b** India, **c** Japan, **d** Republic of Korea, **e** Bangladesh and **f** Nepal (FAO 2014)

by India, while the rest of the waste is generated by sugarcane (17%), fibres (20%) and oilseeds (5%). Rice contributes more than half of this cereal waste produced, as shown in Fig. 7. Additionally, Table 4 lists the amount of crop residues burnt throughout India in a state-wise list (Jain et al. 2015).

In another study conducted by Streets et al. (2003), it was estimated that a total of 730 Mt of biomass was burnt throughout Asia, out of which 18% was burnt in India (Streets et al. 2003). This amount of waste burning results into a heavy burden on the environment and often causes serious health issues as well as poor visibility in the region. The issue of smog over the national capital of New Delhi has been in the news over the past couple of years. The release of $PM_{2.5}$ particulates contributes majorly towards smog development. The WHO has emphasized on a safe limit of 10 μg/m^3, while New Delhi in October 2017 recorded a mean value of 98 μg/m^3 which is astonishingly 10 times higher than the recommended limit (Zehra 2017). The straw burning during the

Table 2 Output of crop straw in China (Guoliang et al. 2008)

Straw type	Output grain (Tg)				Output of crop straw (Tg)			
	Year							
	2000	2001	2002	2003	2000	2001	2002	2003
Rice straw	18791	17758	17454	16065	11707	11063	10874	10008
Wheat straw	9964	9388	9029	8649	13611	12823	12334	11814
Corn stover	10600	11409	12131	11583	21200	22818	24262	23166
Other crops	1177	1093	1185	1132	1177	1093	1185	1132
Bean stalk	2010	2053	2241	2128	3015	3079	3362	3191
Tubers	3685	3563	3666	3513	1843	1782	1833	1757
Oil-bearing crops	2955	2865	2897	2811	5910	5730	5794	5622
Cotton stalk	442	532	492	486	1326	1597	1475	1458
Fibre crop	53	68	96	85	90	116	164	145
Sugar cane	7635	8655	10293	9642	64	866	1029	96
Total					60643	60967	62311	59257

harvest season in the neighbouring states of Punjab and Haryana is considered to be the major reason for the capital's troubles. According to a report by the Ministry of Agriculture and Farmer Welfare, Punjab and Haryana together generated 28.10 Mt of paddy wastes in 2018, out of which 11.3 Mt was openly burnt. Haryana contributed 11.9% of the burning while Punjab contributed the remaining 88.1%. In a case study of Punjab, Kumar and Joshi estimated humungous amounts of soil nutrient losses as a result of straw burning with 3.85 Mt of organic carbon, 59,000 t of N, 20,000 t of P and 34,000 t of K being lost consequently due to burning of the residues. It was also concluded that burning led to a decline in the soil fertility as a result of the loss of organic matter (Kumar and Joshi 2013). Figure 8 displays the different scenes of straw burning openly in the fields as well as its after effects.

In developing countries like India, the reasons for burning are mostly socio-economic. Without government intervention, the farmers are unable to find long-term solutions on their own. Although the Indian government gives many incentives to the farmer in the form of subsidies on equipment for making the straw management easy, the reduction in the burning is still insignificant. According to Bhuvaneshwari and Hettiarachchi (2019), a three-step mitigation procedure has been recommended in order to control the burning issue where firstly the government should try to initiate a self-running mechanism instead of the isolated efforts and also empower the stakeholders assuring them full safety in investment. In addition, it has also been recommended to promote nexus thinking instead of the sectorial kind of thought process, as this issue touches many sectors like environment, education, agriculture, economy, energy and social sectors (Bhuvaneshwari and Hettiarachchi 2019). Thus, a higher level integration may prove to be fruitful for handling the status quo in an efficient manner.

Indonesia is a country consisting of over 17,000 islands. It is the third largest producer of rice in the world and among the largest consumers of rice as well. The rice growing area increased from 11.4 M ha in 1995 to 13.2 M ha in 2010. The crop yield has also increased over the past couple of decades as a result of technical improvement in the agricultural practices and the introduction of hybrid and robust rice varieties (GRiSP 2013). Apart from rice, cassava, corn and sugarcane are the other important crops that generate residue. The burning trends differ from one crop to the other. Table 5 clearly shows a comparison between the annual production and the annual waste burning in these four crops. The residue burning percentage is maximum in the case of cassava (76%) and minimum for rice (18%). Despite its low percentage, nearly 19.3 Mt of rice straw is burnt annually in Indonesia. In addition to this, the burning of rice straw emits 21,000 Gg of CO_2, 16,000 Gg of CH_4 and 3000 Gg of N_2O annually besides other harmful GHGs and particulates (Andini et al. 2018). In a study by Permadi and Kim Oanh (2013), it was established that the total global warming potential of the warming species in Indonesia from the open burning of biomass constituted 0.9–1.1% of that from the biomass open burning globally. Even more surprisingly, open burning of rice straw alone produced over 80% of these emissions in 2007 (Permadi and Kim Oanh 2013).

Bangladesh is the fourth largest producer of rice in the world producing over 50 Mt of rice in 2017 (FAO 2018). Unlike India where rice is grown extensively in few states, its production is uniformly distributed throughout Bangladesh and the per capita consumption of rice is almost thrice as compared to that of India (GRiSP 2013). Such a heavy production also generates a large amount of waste straw as well. Moreover, the rice straw contributes 70% of the gross agricultural residue generated by Bangladesh. The waste straw is either burnt or incorporated into the soil. In some cases, is it

Table 3 Amount of openly burnt straw (Excluding Hong Kong, Macao and Taiwan) (Guoliang et al. 2008)

	Output of crop straw (Tg)				Openly burnt straw (Tg)			
Province/municipality/autonomous region	2000	2001	2002	2003	2000	2001	2002	2003
Beijing	360	362	370	352	163	164	167	159
Tianjin	282	284	290	276	114	115	117	112
Hebei	4735	4760	4865	4626	1146	1152	1177	1120
Shanxi	1478	1485	1518	1444	310	312	319	303
Inner Mongolia Autonomous Region	2218	2230	2279	2167	472	475	485	461
Liaoning	2278	2290	2341	2226	480	483	493	469
Jilin	4013	4035	4124	3922	842	846	865	823
Heilongjiang	4455	4479	4578	4353	999	1004	1026	976
Shanghai	160	161	164	156	78	78	80	76
Jiangsu	3437	3456	3532	3359	1175	1181	1207	1148
Zhejiang	1053	1059	1082	1029	449	451	461	438
Anhui	3010	3026	3093	2942	562	565	577	549
Fujian	651	654	669	636	212	213	218	207
Jiangxi	1263	1270	1298	1235	272	275	282	268
Shandong	6938	6976	7129	680	1841	1850	1891	1798
Henan	5806	5837	5966	5674	1143	1149	1174	1116
Hubei	2465	2478	2533	2408	573	580	592	563
Hunan	1947	1957	2001	1902	434	436	446	424
Guangdong	1375	1382	1413	1344	501	504	515	490
Guangxi Zhuang Autonomous Region	1452	1459	1492	1418	243	244	249	237
Hainan	152	153	156	149	46	47	48	45
Chongqing	1099	1105	1129	1074	213	214	219	208
Sichuan	3309	3326	3400	3233	659	662	677	644
Guizhou	995	1001	1023	973	149	150	154	146
Yunnan	1395	1403	1434	1363	160	161	164	156
Xizang Autonomous Region	48	48	49	47	4	4	4	4
Shaanxi	1607	1616	1651	1570	238	239	245	233
Gansu	998	1003	1025	975	166	166	170	162
Qinghai	151	152	155	148	15	15	16	16
Ningxia Hui Autonomous Region	321	323	330	314	65	65	67	63
Xinjiang Uygur Autonomous Region	1191	1197	1223	1163	228	229	235	223
Total	60643	60967	62311	59257	13956	1403	1434	13637

also used as a domestic fuel and as feed for the cattle. A study by Haider estimated nearly 34% of the rice straw was burnt in 2010 (Haider 2010). In the absence of national data for Bangladesh, it can be estimated that the efforts of the government have reduced the burning instances by 10% and at a grain to straw ratio of 1:1.15, Bangladesh may have burnt nearly 14 Mt of rice straw in 2017. Although these are simply estimations, but provided the socio-economic conditions prevailing in Bangladesh are similar to those in the other South-East Asian countries or as in the remaining Indian subcontinent, the actual amount of straw burnt should be close to the assumed value. As a result, it can be concluded that, being among the top producers of rice, Bangladesh also has significant contributions towards the GHG emission through the rice straw burning.

In *Vietnam*, until 2014, 98% of the leftover rice straw was burnt after harvest in the winter-spring crop, according to a World Bank report. Similarly, high percentages of burning of rice straw were reported for the other cropping seasons as well (Cassou et al. 2017). Currently, there are two categories of widespread burning practices prevalent in Vietnam. First is in the hand harvested areas where the waste straw is piled and burnt. In the second case, the waste straw is burnt without piling in the mechanically harvested areas of the country. The Mekong River Delta produces a major portion of Vietnam's rice (45 M tonnes in 2018). Its area being only 10% of the total

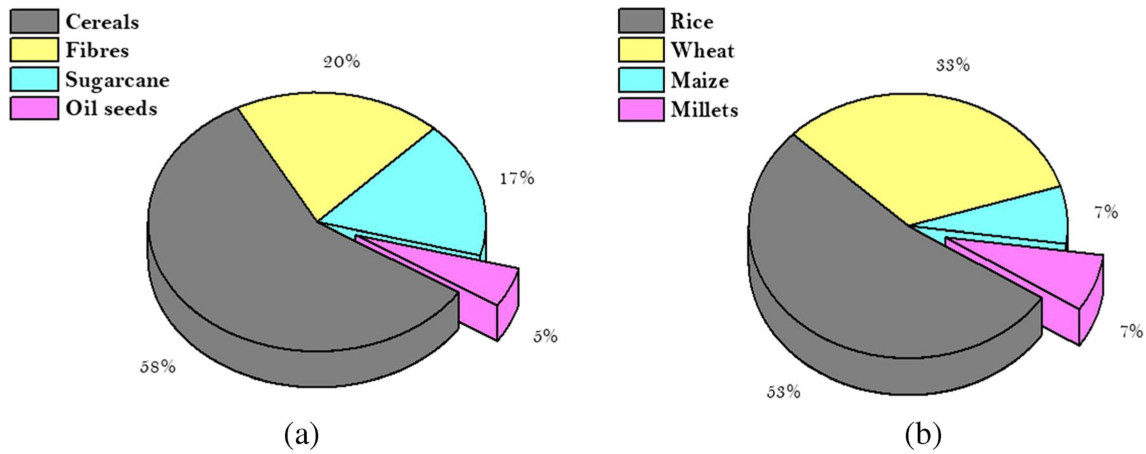

Fig. 7 **a** Residues generated by various crops. **b** Residues generated by cereal crops (Jain et al. 2015)

Table 4 Crop residues burnt in the different states of India in 2008–2009 (Jain et al. 2015)

State	Residue burned (based IPCC default coefficients)	Residue burned (based on [49])
Andhra Pradesh	12.60	5.29
Arunachal Pradesh	0.16	0.05
Assam	2.65	0.96
Bihar	5.21	3.35
Chhattisgarh	2.39	0.73
Goa	0.17	0.03
Gujarat	9.63	4.51
Haryana	6.85	9.18
Himachal Pradesh	0.25	0.42
Jammu and Kashmir	0.47	0.23
Jharkhand	1.90	1.28
Karnataka	5.52	5.93
Kerala	0.55	0.12
Madhya Pradesh	3.86	2.00
Maharashtra	10.96	6.82
Manipur	0.21	0.07
Meghalaya	0.14	0.05
Mizoram	0.03	0.01
Nagaland	0.21	0.09
Orissa	3.84	1.31
Punjab	13.30	21.32
Rajasthan	4.27	2.77
Sikkim	0.02	0.01
Tamil Nadu	5.57	3.37
Tripura	0.63	0.11
Uttar Pradesh	22.38	22.25
Uttarakhand	1.07	0.76
West Bengal	14.85	5.43
A and N Islands	0.01	0.00
D and N Haveli	0.01	0.00
Delhi	0.04	0.02
Daman and Diu	0.00	0.00
Pondicherry	2.11	0.02
All India	131.86	98.49

Fig. 8 **a** Paddy straw burning in the Indian state of Punjab (Courtesy: The Indian Express). **b** Farmer burning waste paddy straw in Bangladesh (Courtesy: India Today). **c** Smog in the Indian capital of New Delhi (Courtesy: The Economic Times). **d** Smog in Beijing's Tiananmen Square (Courtesy: AFP)

area highlights its significant contribution to the country's rice pool. The amount of straw produced is nearly one-fourth of the country's gross production. A study conducted by Arai et al. in 2015 aimed at calculating the GHG emissions from the triple rice copping system in the Mekong Delta itself. The measurements were made using the wind tunnel and the closed chamber methods. Comparisons were made among straw stacks of different sizes and with varying moisture contents. It was observed that the stacks with a high moisture content produced larger quantities of CO and CH_4 as a result of smouldering combustion although the N_2O emissions were recorded to be on the lower side. It was also observed that the piles with smaller size and higher produced abruptly higher GHG content. The emissions by rice straw burning were also compared with straw mushroom emissions and the former was concluded to be much more threatening in nature as compared to the latter (Arai et al. 2015).

Besides GHG emissions, very high concentrations of fine particulate matter ($PM_{2.5}$) have also been found in many south-east Asian countries including Vietnam, which are much higher than the recommended WHO air quality standards. It is estimated that rice straw burning also contributes (Kim Oanh et al. 2006). In a study on the same by Lasko and Vadrevu in 2018, it was observed that both pile burning and non-pile burning of waste straw contributed differently towards particulate pollution. Based on the data for the year 2015, it was estimated that the pile burning caused 180Gg ($PM_{2.5}$) emissions while the non-pile burning contributed 150Gg ($PM_{2.5}$) emissions in Vietnam. It was also concluded that the ($PM_{2.5}$) emissions caused by burning of waste straw contribute 14–18% of the total emissions from different sources (Lasko and Vadrevu 2018). Such emissions are also known to have a detrimental effect on human health and have been directly linked to diseases like tuberculosis or even premature death (Pope 2007). In the Red River Delta of Vietnam, Le et al. (2020) utilized satellite data in order to estimate the emissions from rice straw burning in the region. It was found out that the burning of 3.24 Mt of straw produced 3.84 Mt of

Table 5 Crop production and residue burning in Indonesia (Andini et al. 2018)

Crop	Annual production (Mt/year)	Straw burned (Mt/year)	Percentage straw burnt
Rice	70.85	19.3	18%
Cassava	23.44	18.5	56%
Sugarcane	2.58	0.40	76%
Corn	19.01	6.70	44%

CO_2 and 29.5 Gg of CO. It was also reported to emit 31 Gg of CH_4 and 7.4 Gg of NO_x pollutants (Le et al. 2020). Such studies present a very gloomy picture of the status quo concerning the rice straw management in Vietnam. Although the recent years have witnessed a trend in the processing of the waste straw and utilization for making usable products, the pollution share of rice straw burning continues to be much beyond the safe limits.

Thailand is the sixth largest producer of rice in the world. Despite its arable land decreasing from 16.8 to 15.3 M ha during 1995–2005, its area under rice cultivation witnessed an upsurge from 9.1 to 10.9 M ha during the same period. It has a high per capita consumption of rice at 133 kg per person per year. Geographically, the north-eastern part of the country contributes 60% of the gross rice production of the country followed by the northern and the central regions of the country (GRiSP 2013). The crop is grown in 2 or even 3 rounds per year. A study by Junpen et al. (2018) estimated approximately 61.87 Mt of rice residue generated by Thailand, out of which nearly 7–8% of the residue was openly burnt in the fields. It was estimated that rice residue burning emitted nearly 5.34 Mt of CO_2, 0.044 of CH_4 and 0.002 Mt of NO_x into the air. Burning was also concluded as the main source of PM_{10} particulate matter which increased to 1.9–2.1 times its normal levels. As per the study, Table 6 shows the area planted and the production from both in-season and off-season crops from 2010 to 2017 while Table 7 shows the data related to the rice straw generated and burnt in the different regions of Thailand in 2018 (Junpen et al. 2018).

In another study by Yodkhum and Sampattagul (2018), the GHG emission data was collected from Chiang Mai province of Thailand, which is notorious for the high rates of paddy straw burning. It was estimated that production of 1 kg rice led to 0.64 kg of CO_2 emissions and 0.42 g of PM_{10} particulate matter into the atmosphere. It was also concluded that the GHG emission due to straw burning contributed 2% of the total agricultural GHG emissions in Thailand (Yodkhum and Sampattagul 2018). The study also used the LCA concept to evaluate the GHG emissions from paddy crop. It was concluded that, although the field emission had a 70% share in the total emissions by paddy crop, in areas with straw incorporation techniques prevalent or by using the straw for electricity generation, the environmental impacts could be significantly reduced. It can therefore be concluded that the rate of burning in Thailand is already quite less as compared to its Asian counterparts.

Besides these major rice-producing countries, other Asian countries like Myanmar, Philippines, Japan, Pakistan, Korea and Sri Lanka also produce considerable quantities of rice annually which is accompanied by large-scale burning of the waste straw as well. In countries like the Philippines, straw burning is prevalent in 76% of the farms where nearly 32% of the annually generated straw is burned (Mendoza 2015). Although, it has been reported that nearly 95% of the straw generated in the Philippines was openly burnt (Menke et al. 2009). In a study conducted by Ahmed (2013) in Pakistan, it was noted that there are many prevalent techniques for rice straw management. Based on field experiments, it was recorded that nearly 47% of the rice straw was completely or partially burned by the farmers (Ahmed 2013). The conditions are much worse in Nepal, where studies have reported nearly 96% of farmers resorting to burning the paddy straw (Pant 2012). Although, another study by the same group of researchers suggested that the process of reverse auction of the rice straw by the farmers could lead to a staggering 86% decline in the burning cases in Nepal (Pant 2015). However, the conditions are much better in Japan, where the burning percentage has been reported to be as low as 4.6% while 62% of the straw is ploughed into the fields (Matsumura et al. 2005). There is no doubt that Asia is the largest producer as well as consumer of rice. Likewise, the issues of rice straw burning and GHG emissions by the continent have also touched alarming levels.

Africa generates 10% of the global agricultural residue from a variety of crops grown across the continent. In 2003, countries like Egypt, Nigeria and Madagascar together generated 62% of Africa's agricultural wastes and the patterns are similar to date (Yevich and Logan 2003). *Egypt* is one of the

Table 6 The planted area and rice production from in-season rice and off-season rice plantation in Thailand during 2010–2017 (Junpen et al. 2018)

	In-season rice		Off-season rice	
Year	Planted area (Mha)	Production (Mt)	Planted area (Mha)	Production (Mt)
2010	10.33	25.44	2.44	8.86
2011	10.45	25.87	2.58	10.14
2012	10.39	27.23	2.88	12.22
2013	9.93	27.09	2.57	10.77
2014	9.73	26.27	2.41	9.67
2015	9.29	24.31	1.35	5.35
2016	9.38	25.24	0.82	3.11
2017	9.43	24.07	1.67	6.62

Table 7 Paddy harvested area, rice straws generated in the field and the amount of rice residue burned in field categorized by regions in 2018 (Junpen et al. 2018)

Regions	Months												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Paddy harvested area in 2018 (Mha)													
Central	0.13	0.28	0.15	0.23	0.23	0.06	0.14	0.08	0.33	0.28	0.27	0.18	2.37
Northern	0.18	0.29	0.04	0.32	0.33	0.09	0.01	0.11	0.34	0.31	0.75	0.26	3.03
Northeastern	0.02	-	0.00	0.07	0.20	0.03	0.00	0.00	0.10	1.50	2.56	1.01	5.48
Southern	0.02	0.01	0.01	0.00	0.03	0.01	0.00	0.00	0.01	0.01	0.01	0.03	0.15
Total	0.34	0.59	0.21	0.62	0.80	0.19	0.15	0.20	0.78	2.10	3.59	1.48	11.03
Rice straw generated in the field in 2018 (Mt)													
Central	0.72	1.56	0.78	1.23	1.28	0.32	0.79	0.45	1.80	1.54	1.52	1.05	13.04
Northern	0.98	1.62	0.24	1.73	1.83	0.54	0.04	0.60	1.88	1.69	4.23	1.49	16.86
Northeastern	0.12	-	0.00	0.41	1.14	0.15	0.02	0.00	0.53	8.55	14.56	5.68	31.14
Southern	0.09	0.05	0.08	0.01	0.18	0.06	0.02	0.03	0.04	0.06	0.06	0.14	0.83
Total	1.91	3.23	1.11	3.38	4.42	1.07	0.86	1.08	4.24	11.84	20.37	8.35	61.87
The amount of rice residue burned in field in 2018 (Mt)													
Central	0.03	0.06	0.03	0.05	0.06	0.01	0.03	0.02	0.08	0.06	0.05	0.04	0.53
Northern	0.06	0.10	0.01	0.10	0.10	0.03	0.00	0.03	0.11	0.10	0.26	0.09	1.00
Northeastern	0.01	-	0.00	0.03	0.06	0.01	0.00	0.00	0.05	0.83	1.44	0.58	3.00
Southern	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	0.10	0.16	0.05	0.18	0.22	0.05	0.04	0.05	0.23	0.99	1.75	0.71	4.54

leading rice producers of Africa with an average production of 6.1 Mt recorded in 2017 (FAO 2018). With higher productions come higher residues, followed by the issues related to residue management. Based on the usual grain to straw ratios, Egypt generates 7–9 Mt of rice straw annually. The problem of large-scale straw burning has also been reported in the country. According to Ren et al. (2019), Egypt burnt 52% of its rice residue in 2013 (Ren et al. 2019). Abdelhady et al. (2014) also reported the burning of nearly 3.1 Mt of rice residues by Egypt in 2013 (Abdelhady et al. 2014). In a more recent study, Ramadan (2018) reported a widespread burning of rice straw in the Nile River Delta of Egypt. A detailed study about the effects and the extent of pollution was made. It was recorded that, for 24 h of continuous straw burning, 100 g/m^3 of CO, 241 μg/m^3 of total particulate matter (TPM) and 155 μg/m^3 of NO_x were emitted into the atmosphere (Ramadan 2018). The government has taken many steps in combating the environmental and health issues related to burning of the agricultural waste in the country by collecting the excessive straw from farmers at nominal prices. According to a report, the measures taken by the government helped in reducing the burning cases by 13–15% as per Egypt's environment minister.

Nigeria stood second to Egypt until 2016, but surpassed it to become the African leader in terms of the annual rice production (FAO 2018). Besides burning the residue, using it as fodder for cattle is the only major alternative with the local farmers. The concept of no-till farming or incorporating the straw into the soil is yet to become popular in majority of the African countries. There is no compiled data available regarding the burning of rice straw in Nigeria, but a field study by Aruya et al. (2016) found that nearly 27% of the agricultural waste was burnt in the fields in 2014. The bide zone was the major zone of rice production and hence the zone where maximum burning cases were observed (Aruya et al. 2016). In another similar study, Mamman and Folorunsho (2017) made a detailed assessment related to the burning of agricultural wastes in the Borno state of Nigeria. It was found that ten of the selected communities for the field study collectively generated 111 tonnes of rice straw. It was recorded that the amount of residue burnt in these communities varied in a range of 7.35–14.96% (Mamman and Folorunsho 2017). The focus towards reutilization of the waste straw is still at its infancy stage for most of the sub-Saharan countries. The major reason for non-adaptation is the financial constraint, as the farmers are not able to afford the cost of technology despite of knowing the harmful after effects of open burning. For instance, in Ghana, where large amounts of agricultural residues are produced, the cereal crops constitute 72.3% of the total residue generated. A recent study by Seglah et al. (2019) reported that the waste straw is to date under-utilized in the country. As a result, large-scale open burning of the straw takes place effecting the environment in a dreadful manner (Seglah et al. 2019). With similar conditions in many other

African countries, it can be concluded that more efforts from the governments are required in promoting the non-burning techniques among the masses and providing better infrastructure to the farmers in the form of better equipment for straw management and better transportation facilities for the waste straw.

Both *North* and *South America* comprise rice-producing countries. The quantity of rice produced is not as large as the Asian countries but yet noticeable. *Brazil* alone grows and produces nearly 50% of South America's total rice (FAO 2018). Besides rice, Brazil produces crops like corn, sugarcane, wheat, citrus and coconut with a total annual residue generation of 597 Mt (Fortes 2010). The current annual rice production of Brazil is 12 Mt, which generates nearly 15 Mt of waste residue subjected to a 1:1.3 ratio of the grain to straw. Back in 1985, nearly 42 Mt of agricultural residue was burnt by Brazil with a major percentage of sugarcane waste since Brazil produces nearly a third of the world's sugarcane (Yevich and Logan 2003). Its contribution towards the global rice production, however, is only 1.2%. Apart from Brazil, the other South American countries in the Andean regions also produce rice. Since glaciers are the major source of irrigation in these countries, global warming and its after effects are being taken very seriously by the governments and the farmers of these countries. In fact, South America is leading the way in no-till farming and non-burning of agricultural wastes. In 1990, Brazil had only 1 M ha under no-till farming which climbed up to 31.8 M ha in 2015. Similarly for Argentina, this figure increased from 2 to 27 M ha during the same period. Moreover, 80% of the crops in these countries are being sown on the no-till basis (Kristine Smukste). Although there is no official data and very little research on the percentage of rice straw currently burnt openly in the fields in South America, it can be assumed that the percentages are certainly not any higher than the rice-producing Asian countries. Since the gross production of South America is 24 Mt of rice annually, the total rice straw generated can be assumed to be around 25–35 Mt, which is lesser than what Thailand solitarily generates. Thus, with increasing trends of no-till farming across the continent and high efforts of the governments in reducing the open burning of crop residues, it can be assumed that the total rice straw burnt across South America should be less than 4 M t (the amount burnt in Thailand).

In the *United States of America*, the problem of straw burning had been reported nearly four decades back by Nelson et al. (1980). It was estimated that, back in 1976, nearly 45% of the rice straw generated by California was openly burnt in the fields (Nelson et al. 1980). Currently, the process of burning is not very common in the USA which produces nearly 10 Mt of rice annually. According to the United States Department of Agriculture (USDA) data of crop acreage in 2014 and the straw burning estimates for the same year, only 0.6% of the generated straw was burned in the country (Pouliot et al. 2017). This is not the case in *Mexico*, where open burning of agricultural wastes is practiced on a large scale. Corn, sorghum, sugarcane and wheat are the other crops grown in the country. But the area under rice is very small, which is further decreasing due to adverse climatic conditions in the region (USDA Foreign Agricultural Service 2016). It can therefore be concluded that the issue of paddy straw burning is not as adverse in Americas as it is in Asia.

Europe and *Australia* constitute miniscule shares of 4 Mt and 0.8 Mt, respectively, towards the gross global rice production. Moreover, the infrastructure and facilities provided by the governments are much better as compared to majority of the Asian and African countries. As a result, the paddy straw management is not as big an issue as it is in the developing countries. In Europe, *Italy* and *Spain* produce 80% of the continent's rice, while another 12% is produced by countries like Portugal and Greece. Besides these countries, France, Bulgaria, Romania and Hungary are the other rice-producing nations. Somehow, there have been some cases reporting burning issues in countries like Spain. Spain generates nearly 90,000 tonnes of straw, a significant proportion of which is burnt openly. Viana et al. (2008) studied the effect of open burning of rice straw on the PM_{10} concentration in Valencia, Spain. It was reported that the PM_{10} concentration increased by 10–15 $\mu g/m^3$ during the peak burning season (Viana et al. 2008). Outside the European Union (EU), Russian Federation (RF) and Ukraine are the prominent rice producers. The area under rice in the EU, RF and Ukraine is 450,000 ha, 170,000 ha and 25,000 ha respectively (Formatting Citation). Similarly, *Australia* on an average grows rice on 75,000 ha of land annually. According to a report, nearly 800,000 tonnes of straw is burnt annually in Australia (Vagg 2015).

Table 8 lists the major rice-producing countries from all the continents and the estimated quantity of straw burned by them on an annual basis. Since no compiled global data is available for the same, this table cannot be considered fully accurate, yet it provides a rough estimate based upon individual studies by researchers, scientists and academicians from all over the world. Figure 9 and Fig. 10 depict the graphical and diagrammatical representations of Table 8. It can be noticed that majority of the straw burning takes place in Asian countries of China, India, Vietnam and Indonesia. Nevertheless, the burning activities and their severity in the other continents cannot be taken lightly.

Sustainable alternatives to straw burning: opportunities for sustainable production/management

The previous section clearly provides the detailed view of the most sensitive areas in terms of the straw burning practice. It

Table 8 Rice straw burning comparison among the leading global producers

Country	Annual rice production (2017) (Mt)	Straw generated (assuming grain to straw ratio as 1:1.3) (Mt)	Straw burned (approximate value) (Mt)	Percentage straw burned
China (Asia)	210.3 (FAO 2018)	273.3	55–62.8 (Qu et al. 2012; Ren et al. 2019)	20–23%
India (Asia)	166.5 (FAO 2018)	216.4	62.7–69.2 (Jain et al. 2015; Bhuvaneshwari and Hettiarachchi 2019)	29–32%
Indonesia (Asia)	96.0 (FAO 2018)	96.07	18.2–19.2 (Andini et al. 2018)	19–20%
Bangladesh (Asia)	50.8 (FAO 2018)	66.04	4.6–6.6 (Haider 2010)	7–10%
Vietnam (Asia)	42.8 (FAO 2018)	56.6	45.2–50.9 (Pham et al. 2014; Hung et al. 2019) (Arai et al. 2015; Cassou et al. 2017)	80–90%
Thailand (Asia)	33.7 (FAO 2018)	43.8	3–4 (Junpen et al. 2018)	7–9%
Myanmar (Asia)	29.5 (FAO 2018)	38.3	7.6 (Lasko and Vadrevu 2018)	20%
Philippines (Asia)	19.3 (FAO 2018)	25.09	7.7–8.8 (Mendoza 2015; Stuecker et al. 2018)	30–32%
Pakistan (Asia)	11.1 (FAO 2018)	14.43	5.7–6.7 (Ahmed 2013; Ahmed and Ahmad 2013)	40–47%
Japan (Asia)	10.4 (FAO 2018)	13.52	0.54–0.67 (Matsumura et al. 2005)	4–5%
Cambodia (Asia)	10.4 (FAO 2018)	13.52	4 (Kosal 2019)	30%
Egypt (Africa)	6.4 (FAO 2018)	8.32	1.66 (Online 2017)	21%
Nigeria (Africa)	7 (FAO 2018)	9.1	2.43–2.73 (Aruya et al. 2016) (Mamman and Folorunsho 2017)	27–30%
Brazil (South America)	12.3 (FAO 2018)	16	3.2 (Kristine Smukste)	< 20%
United States of America	8.1 (FAO 2018)	10.53	0.063 (Ren et al. 2019)	0.6%
Peru (South America)	3 (FAO 2018)	3.9	0.78 (Kristine Smukste)	< 20%
Colombia (South America)	2.7 (FAO 2018)	3.51	0.70 (Kristine Smukste)	<20%
Italy (Europe)	1.35 (FAO 2018)	1.75	0.26	15%
Spain (Europe)	0.83 (FAO 2018)	1.07	0.16	15%
Australia	0.80 (FAO 2018)	1.04	0.8 (Bajwa and Chauhan 2017) (Vagg 2015)	75%

would be fair to state that the red and orange zones are the regions that desperately need to cut their GHG emissions caused by the in-field burning of rice straw. Nevertheless, every cloud has a silver lining and with bigger challenges come bigger opportunities as well. Many better alternatives have been developed in order to replace the straw burning activity with a view to lessen the environmental burden of the burning activities as well as providing the farmers with a more viable solution in order to convert the current gloomy scenario into a win-win situation. The major factor that has influenced the burning of rice straw is the recent advances in its harvesting techniques. In the past few decades, the use of combine harvesters has witnessed a major boom as it requires very little labour and is also less time-consuming. Previously,

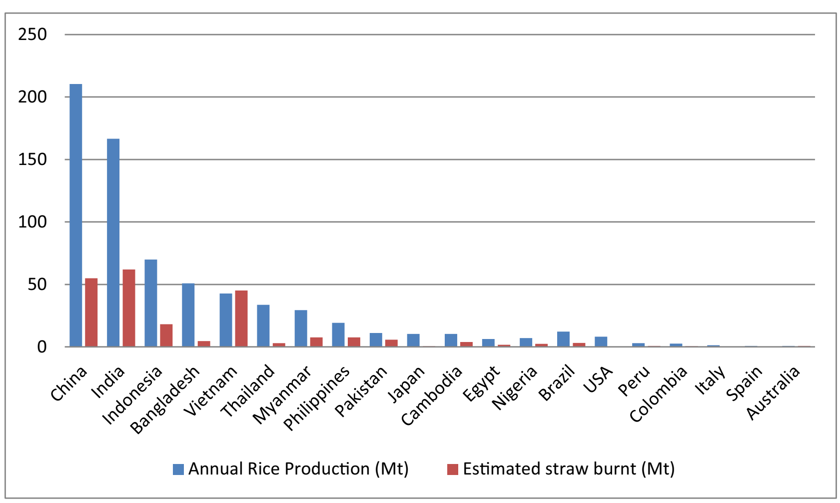

Fig. 9 Rice straw burning comparison among the leading global producers

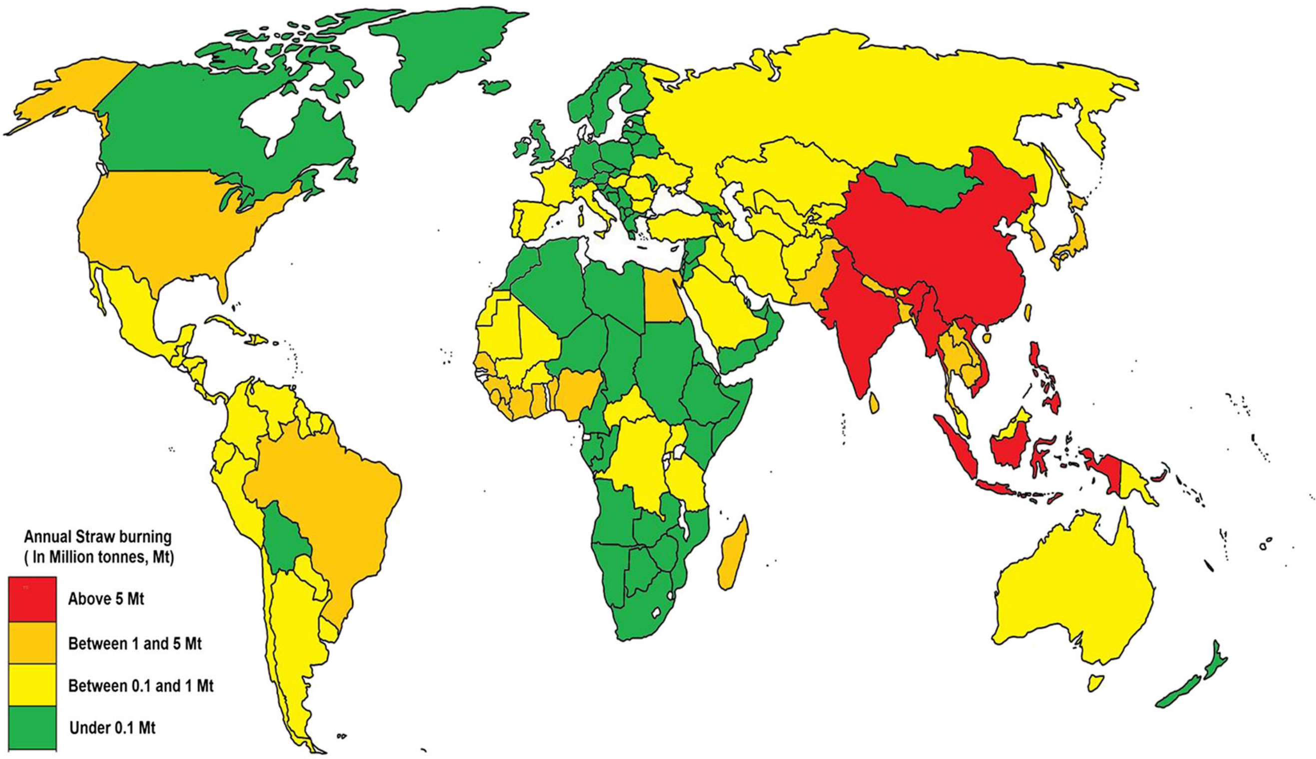

Fig. 10 Global rice straw burning zones

the manual cutting of the standing crop was highly convenient for the easier collection of the waste straw bundles and removing them from the fields. Contrarily, the combine harvesters tend to spread the waste straw randomly all over the field. This makes its collection highly tedious and expensive, thus motivating the farmer to burn it instead of collecting it (Gummert et al. 2020). This can be justified by linking the recent boom in the use of combine harvesters in countries like Vietnam, Thailand and Cambodia to the sudden increase in the straw burning tendency in these countries over the past few decades (Takeshima et al. 2018). Similar trends have also been witnessed in the northern plains of India, especially in the state of Punjab, which solitarily burns rice straw equivalent to the entire continent of South America. The state has emerged as a major hub for the manufacture of combine harvesters. Due to the shortage of agricultural labour, the use of combine harvesters has become indispensable for the timely harvest of the grain crops. Thus, the in-field techniques such as the mechanical collection of rice straw as well as the incorporation of straw into the soil have become very popular and are being promoted by the governments all over the world.

Mechanical collection

This is one of the major activities in the post-harvest management of rice straw. It is a primary procedure for majority of the in-field as well as the off-field techniques for straw management. The straw baling operation has emerged as a promising solution, where the scattered straw can be conveniently collected, compressed into specific shapes and finally packed as depicted in Fig. 11a. These densely packed straw bundles are much easier to stock and transport (Sandro 2016). A study conducted by Van Nguyen et al. (2016) clearly illustrated the feasibility of the mechanized collection of the rice straw and its further use in various in-field and off-field operations. The study was conducted in the Mekong River Delta of Vietnam by analysing the energy efficiency as well as the GHG emissions. Additionally, the cost comparison was also performed and it was concluded that, despite the GHG emissions, the technique added value to the rice production and also controlled the in-field burning (Van Nguyen et al. 2016). This technique is very famous in the European and the American countries, but is yet to gain popularity in the Asian countries, especially the Indian subcontinent due to the high cost of the baling equipment.

Incorporation into the soil: composting

The in-field straw incorporation is being professed as a better alternative to straw burning operation by the global community. The farmers' choices of burning, incorporation or removal are made on the basis of a mix of certain socio-economic factors (Launio et al. 2015). Incorporation is a much better technique as compared to burning due to a significant reduction in the GHG emissions. Although, it needs to be justified economically to the farmers due to the high cost of tillage

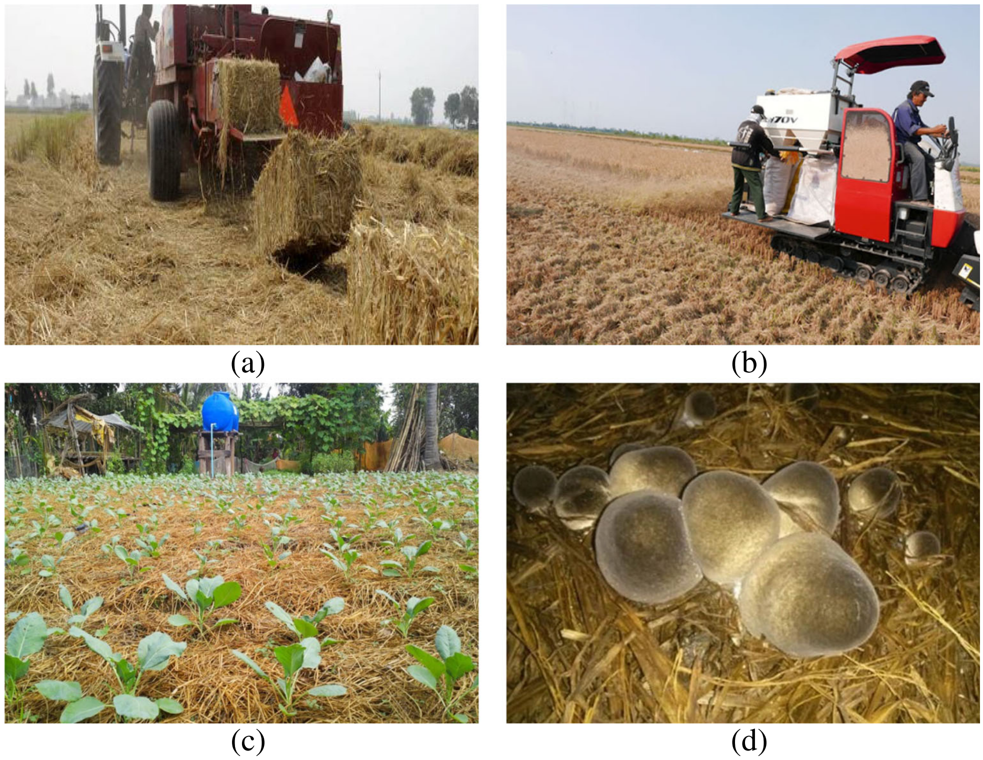

Fig. 11 **a** Straw baling (Courtesy: The Hindu, Business line). **b** Straw incorporation. **c** Straw mulching (The Horticulture Innovation Lab, the reagents of the University of California). **d** Mushroom production (Gummert et al. 2020)

including the fuel and equipment as well as the wear and tear costs. Moreover, there is a common misconception among farmers that the straw incorporation makes the soil less fertile. This is simply a myth and has been proven wrong by several studies conducted across the world. In a study by Kharub et al. (2004), long-term field experiments were performed in the northern plains of India, where it was concluded that the yield of wheat reduced in the field where incorporation was practiced for an initial period of 2 years. In the longer run of 5–7 years, the overall wheat yields improved (Kharub et al. 2004). In another study by Zhang et al. (2014) in Ningxia, China, it was concluded that the straw incorporation is of paramount importance for improving the soil stability as well as the soil aggregate structure (Zhang et al. 2014). In another recent study conducted in the Jiangsu province of China, Zhao et al. (2019) observed that the yields of wheat after immediate straw incorporation improved by as high as 58% to the fields where straw removal was practiced. It was also observed that the quantities of nitrogen and phosphorus as well as potassium increased by 15% as a result of the straw incorporation (Zhao et al. 2019). With the ever-increasing environmental awareness among farmers, the greater cost of straw incorporation when compared to burning may not hamper its adoption rates by the farmers if sufficient incentives are provided by the governments. Moreover, by reduction in the transporting and baling costs of straw, the opportunities related to the off-field processing of the excessive straw may experience an upsurge. Figure 11 b shows the incorporation process where the machine is harvesting and chopping the straw in the field, followed by spraying *Trichoderma* over it for increased decomposition rates.

Mulching

Another possible use of rice straw is in the regions with vegetable farming. Since the rice straw is light in weight and also has a neutral pH value, it can be extensively used for mulching purposes as shown in Fig. 11c. This activity is highly effective in controlling the weed growth as well as maintaining the soil moisture for longer durations. As a result, it prevents the use of chemical weedicides and also leads to less water utilization. After the crop, it can be easily tilled into the soil and may also be used in winters for covering the plants to protect them from the excessive cold weather. In a field study conducted by Rahman et al. (2005), the effectiveness of the rice straw mulching over the immediately next crop of wheat was evaluated. It was observed that the straw mulching had a positive effect on the water retention capacity of the soil and in controlling the weed growth. It was also noticed that the root development was much better in the wheat crop with mulching (Rahman et al. 2005). Besides the vegetables and grain crops, the rice straw is an excellent substrate for growing mushrooms as depicted in Fig. 11d. It is practiced both indoor and outdoors, though the indoor technique is considered more beneficial (Gummert et al. 2020). In a study conducted by Yang et al. (2013), it was observed that the use of rice and wheat straw acted as a perfect media for the growth and development of oyster mushrooms (Yang et al. 2013). To sum things up, mushroom farming can be promoted in the regions with larger generation of rice straw as it carries potential for sustainable management of rice straw as well as improving the farmer's income.

Power generation

The abovementioned methods are mostly related to the in-field straw management strategies. Nevertheless, the rice straw is known to have many off-field applications as well. It can be readily converted into different forms of energy like heat energy, through direct combustion process and ultimately used for production of electricity. This straw-based electricity generation is both economically and ecologically beneficial. One of the first straw-based power plants was based in Patiala district in the Punjab state of India in 2006. Similarly, China started its first straw-based power plant in 2006 as well and is currently running over 10 power plants which are directly fired using rice straw (Logeswaran et al. 2020). In a study conducted by Cheewaphongphan et al. (2018), the authors tried to evaluate the potential of rice straw for fuelling very small power plants in Thailand. It was observed that the demand and supply of rice straw residue in relation to the spatial analysis reached an efficiency up to 29% at a radius of 60 km (Cheewaphongphan et al. 2018). This efficiency may vary from region to region depending upon several parameters. One of the most important parameter could be the cropping patterns and the gradual changes experienced over time. For example, in relation to the Patiala-based power plant mentioned above, the Punjab state power corporation limited estimates an average requirement of 70,000 tonnes of straw each year. The problem becomes serious in the case of a cropping pattern change where large numbers of farmers may switch over to crops other than paddy. In such a scenario, the power plant may seize to operate due to lack of straw generated in the local area and the economical unviability of transporting straw from distant areas. Although there is a huge potential in such alternatives, there will have to be certain government backed assurances for the successful implementation of these steps towards a cleaner and more sustainable future.

Biogas production

Biogas comprises majorly CH_4 and CO_2 besides traces of other gases like H_2, NH_3, H_2S and H_2O as well. It is generated through the anaerobic digestion of different organic substances. This renewable energy source can be used as a fuel for domestic as well as commercial purposes. Rice straw serves as a perfect raw material for the production of biogas, thanks to its high cellulose (24–35%) and hemicellulose (32–37%) contents (Jin and Chen 2006). The process of biogas production takes place in different stages beginning with the pre-treatment phase where the chopping, the mixing and the fermentation of the straw are achieved. This is followed by the anaerobic digestion phase which produces biogas and the waste slurry as a by-product (Liu 2017). The waste slurry is also used as fertilizer in agricultural applications. Moreover, the anaerobic co-digestion of cow dung and rice straw has also attracted a lot of attention in the past couple of decades. In their study on the same, Haryanto et al. (2018) evaluated the effect of the addition of urea on the biogas yield through the co-digestion of cow dung and straw slurry. It was suggested that the addition of 0.25 g/L of urea to the slurry accounted for a much improved yield as well as quality of the biogas produced (Haryanto et al. 2018). Further improvements are being brought through rigorous research across the globe in terms of the quality and quantity of the biogas generated from the straw. In another study aiming to co-digest waste rice straw, domestic kitchen waste and pig manure, Ye et al. (2013) conducted multiple single-stage digestions in order to achieve the most optimum ratio of the three substances for best-quality biogas production. It was evaluated that a ratio of 0.4:1.6:1 for kitchen waste, pig manure and rice straw respectively gave the best results (Ye et al. 2013). This is a highly beneficial alternative for sustainable utilization of rice straw, where even the by-product may be used as a valuable farm input.

Ruminant feed

Rice straw has been used as cattle feed since a long time. Currently, a good percentage of the waste straw is used as cattle feed especially across Africa and the Indian subcontinent. Though it has limited nutritive value, yet instead of using it as a replacement feed, it is still used as a major component of feed despite its mixed results (Drake et al. 2002). Moreover, rice straw is known to have poor digestibility in ruminants in addition to its low protein contents. The daily amount of rice straw that an animal can consume can be as low as 2% of the animal's body weight. Additionally, a report mentioned the daily straw intake by ruminants to be as high as 1.2 kg (Dry matter) per 100 kg of live weight per day. The consumption patterns can, however, vary among animals. Additionally, it is treated with chemicals like sodium hydroxide, urea, ammonia or lime in order to improve its properties like intake, palatability and digestibility. These chemicals basically rupture the linkages among the lignin-cellulose structures of the straw, which are sensitive under alkaline or acidic conditions (Gummert et al. 2020).

Composite materials

Majority of the agricultural bio-wastes have a huge potential to be utilized in modern sustainable composite materials. This holds a humungous scope especially for the red zoned countries marked in Fig. 11. Rice straw along with other agricultural wastes like wheat straw, sugarcane bagasse and maize wastes can be used with both metals and polymers to manufacture green composites that have numerous industrial as well as domestic applications. The benefits of using such materials lie in the market appeal that they possess in addition to the environment friendliness of their constituents. To date, Jute, Flax and Coir are the most commonly used materials in composites although a lot of research and development are also being conducted on agricultural wastes like rice straw on a global platform (Taj et al. 2007). Rice straw and rice husk can also be used to manufacture particle boards with the assistance of suitable adhesives. In a related study, Pan et al. (2006) conducted extensive research on the fabrication of rice straw particle boards using polymeric methylene diphenyl diisocyanate (PMDI) as a binder. Furthermore, due to the high cost and toxicity of PMDI, natural rice bran adhesive was used in a ratio of 1:3 with PMDI to give similar binding results (Pan et al. 2006). Rice straw has also been extensively used for manufacturing composite materials with polymers such as polyvinyl chloride (PVC) and polypropylene (PP). It has been found that the pre-treatment of rice straw plays a highly important role in defining the properties of the manufactured composite (Kamel 2004). Besides polymers, wastes like rice straw are also used with metals and ceramics. The manufacturing of aluminium-based metal matric composites (MMCs) has been accomplished by adding agricultural biomass including rice straw ash in a few instances. It has been reported that the addition of rice husk and straw ash to metals like aluminium increases its properties like microhardness as well as the ultimate tensile strength. Moreover, the wear resistance also tends to improve as a result of the strain fields formed around the ash particle subjected to the difference in the coefficient of thermal expansion of the metal and the reinforcement material (Yadav et al. 2018). Due to the limited research, the area of green metal matrix composites using rice straw can be explored further. Besides polymers and metals, rice straw particles have also been blended with cement to study the properties of the material developed (Ataie 2018). Figure 12 displays some of the common composite materials fabricated from rice straw.

Life cycle assessment (LCA): in pursuit of finding the best alternatives to open burning

LCA is a powerful tool for the evaluation of the environmental impacts of a product system during its lifetime. It creates valuable opportunities for the improvement of the environmental aspects of products at discrete points in their lifetime. Besides its assistance in marketing of a product through certain environmental claims or eco-labelling schemes, it also helps in highlighting the most relevant indicators of the environmental performance of a product system. It is actively used by governments, industries and academia for its specific applications in these areas. There is a great scope of the use of LCA in evaluating the environmental impacts of straw burning in comparison to its numerous alternatives. Studies conducted for this purpose tend to give a bird's eye view of the relative advantages and disadvantages of the various alternatives in terms of various environmental modules. It is being used by researchers across the world, though the Asian countries tend to conduct a major portion of the research justified by their high straw burning rates. In a study conducted in China, Shang et al. (2020) compared scenarios where rice straw is used to manufacture particle boards, cement bonded particle boards and electricity generation through direct combustion. These scenarios were compared with the open burning of rice straw which is still prevalent all across the country. After a comprehensive inventory analysis of each of these scenarios, it was observed that the use of both types of particle boards slashed the environmental impact by 10% in comparison to the use of wood-based sources. Additionally, the electricity generation by combustion of straw cuts down the GHG emissions by as high as 30% when compared to the traditional coal burning thermal plants (Shang et al. 2020). Conclusively, it was suggested that the best alternative in terms of the environmental impact is the particle board making process, while the open burning is highly unadvisable due to its detrimental effects on the environment and human health. The viability of the chosen alternatives varies from country to country depending upon its socio-economic scenario. The manufacture of particle boards can be implemented in China due to its highly developed manufacturing industry boosted by the availability of cheap and trained labour.

In the case of developing economies like India, the choice of these alternatives is different from that of the developed nations. Soam et al. (2016) applied LCA for comparing the most suitable and viable straw utilization practices in India. The use of straw as fodder, biogas production, soil incorporation and electricity generation were comparatively analysed and further compared with the open burning process. The system boundaries have been depicted in Fig. 13. It was assumed that, when used in making animal fodder, rice straw shall replace wheat straw. Similarly, when used for generating electricity, it would replace the grid-generated electricity and the biogas would replace the liquefied petroleum gas (LPG) cylinders. It was noticed that, in terms of the global warming potential (GWP) and the acidification potential (AP), the use of rice straw in producing biogas and electricity has the maximum benefits, while in terms of the eutrophication potential (EP), the fodder making process gave the best benefits. It was further suggested to promote the rice straw–based electricity generation in the major rice growing areas of the country (Soam et al. 2016).

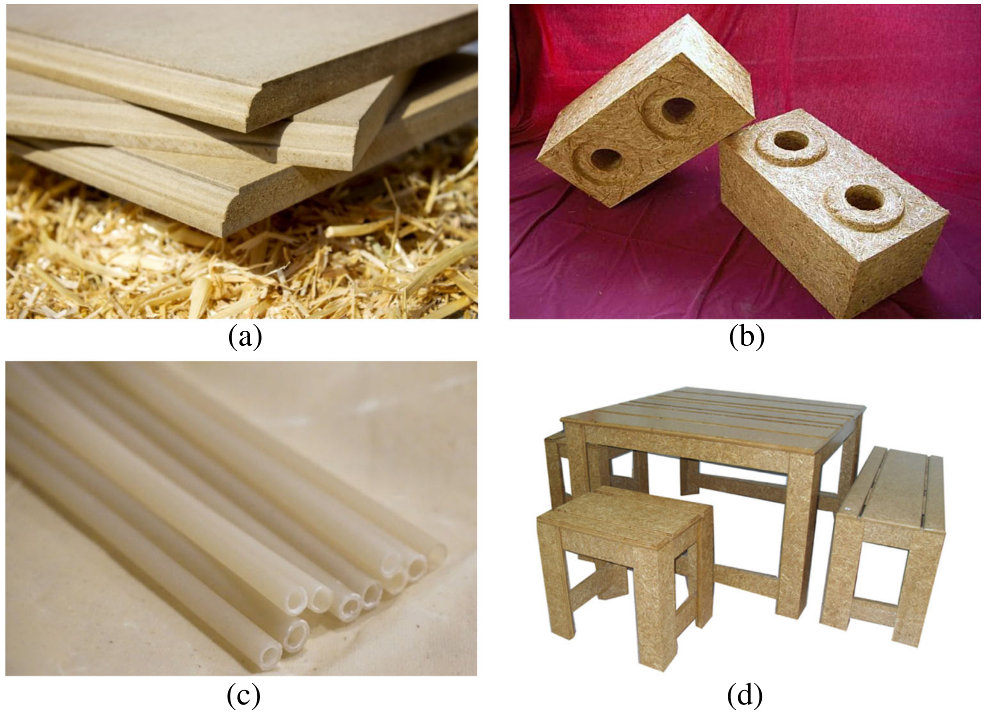

Fig. 12 Rice straw–based products. **a** Fibre boards (https://www.buildinggreen.com/product-review/mdf-made-rice-straw). **b** Bricks (https://greenbuildingelements.com/2015/01/16/building-rice-straw/). **c** Straws (https://www.piquenewsmagazine.com/food/could-rice-straws-kick-single-use-plastic-products-to-the-curb-for-good-2507235). **d** Furniture (http://www.kokoboard.com/en/service-oem-products/)

In another similar study based from the data collected from Maerim District, Chiang Mai province of Thailand, Yodkhum and Sampattagul (2018) performed LCA by comparing the open burning of rice straw with the alternative utilizations of power generation and soil incorporation. The data were collected on the basis of manual conversations and questionnaires. The base of the study was to compare the selected utilization strategies in terms of their GHG emissions, energy use and the particulate matter (PM_{10}) pollution. It was found out that, for every kilogram of rice produced, there was 0.64 kg CO_2-eq, 1.80 MJ of energy and 0.42 g of PM_{10} released. It was also observed that the field emissions contributed nearly 70% of the total emissions by

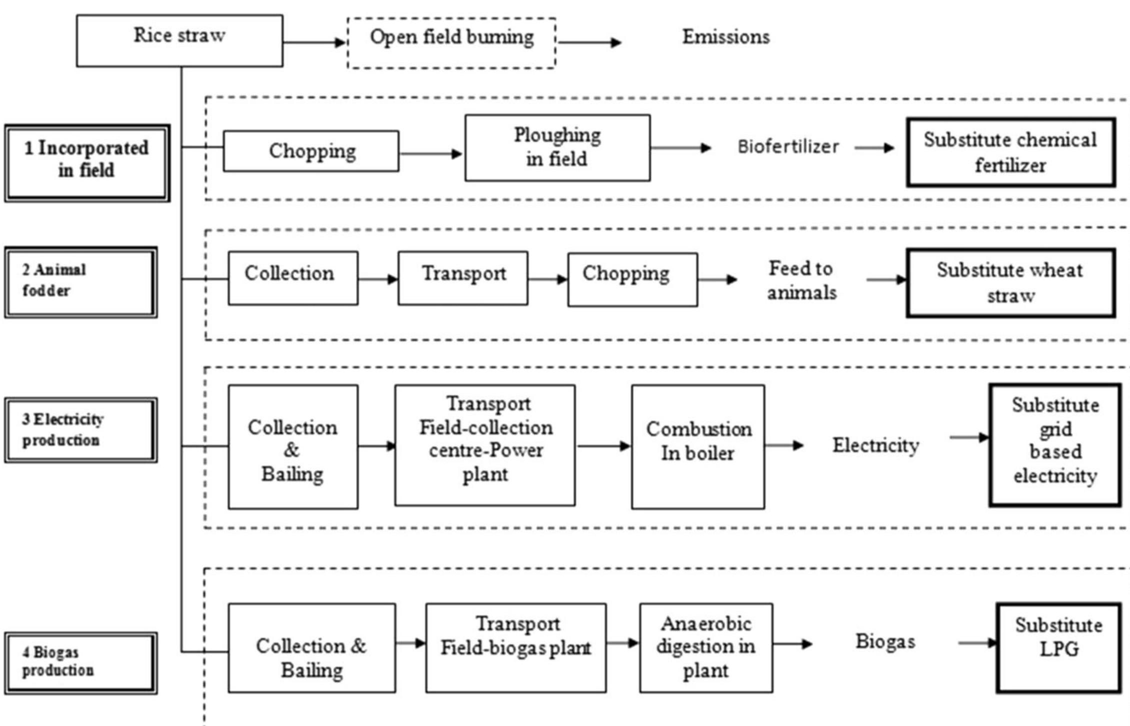

Fig. 13 System boundary of the utilization practices of rice straw (Soam et al. 2016)

Table 9 Environmental impact and energy consumption of the various straw utilization alternatives (Yodkhum and Sampattagul 2018)

	Open burning			Soil incorporation			Electricity generation		
	GHG (kg CO_2-eq)	En (MJ)	PM10 (g PM10-eq)	GHG (kg CO_2-eq)	En (MJ)	PM10 (g PM10-eq)	GHG (kg CO_2-eq)	En (MJ)	PM10 (g PM10-eq)
Rice straw cultivation				7.47	21.05	1.97	7.47	21.05	1.97
Open burning emission	1714		12,700						
Incorporation emission (fuel)				8.40	120	30.14			
Incorporation emission (soil)				1111					
Rice straw baling							13.8	262	43.2
Baled straw transportation							6.17	206.5	52.4
Electricity conversion							1312	− 2207	23585
Total balance	1714		12,700	1127	141	32.11	1339	− 1718	23,683

the rice crop (Yodkhum and Sampattagul 2018). The environmental impact and energy analysis of the three scenarios have been listed in Table 9. Furthermore, it was suggested that the alternatives of soil incorporation and electricity generation are both beneficial for sustainable utilization of rice straw. From the data presented in Table 9, it can be suggested that the process of straw incorporation into the soil is the best alternative in terms of the GHG emission as well as the PM_{10} particulate pollutants. The process of electricity generation also produces very less GHG emissions when compared to the open burning of straw but releases large amounts of PM_{10} particulates into the atmosphere. Nevertheless, it is beneficial on the energy saving front as it replaces the burning of fossil fuels for power generation. The selection of the best alternative therefore shall vary on the basis of a large number of factors which include the socio-economic conditions, the infrastructural and power requirements and also the environment-related policies of the government. For example, in the countries facing acute power shortages due to unavailability of hydro-power projects or thermal power plants, the use of rice straw subjected to its availability can act as an effective method of generating electricity.

The justification related to the use of rice straw for power generation can be further strengthened on the basis of the study by Shafie et al. (2014) based in Malaysia. The LCA-based data comparison study between rice straw, coal and natural gas was conducted. After a detailed analysis of the data obtained from all the three alternatives, it was concluded that rice straw–based power plants can save approximately 1.79 kg CO_2-eq for every kilowatt of energy generated when compared to coal-based plants while saving 1.05 kg CO_2-eq

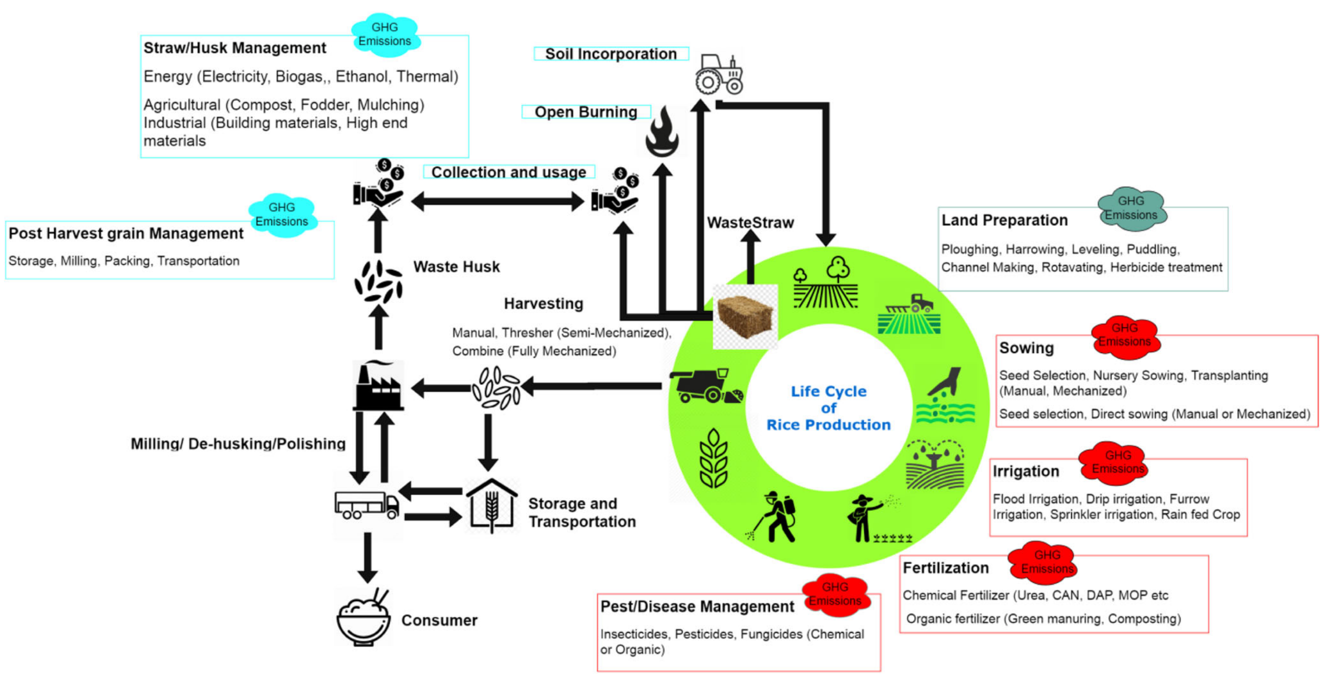

Fig. 14 General life cycle practices pertaining to rice crop

Table 10 Summary of the LCA-based alternative comparison

References	Country	Year	Alternatives compared
(Shang et al. 2020)	China	2020	• Particle boards, • Cement bonded particle boards, • Electricity generation, • Open burning
(Soam et al. 2016)	India	2016	• Soil incorporation, • Fodder, • Biogas, • Electricity generation, • Open burning
(Yodkhum and Sampattagul 2018)	Thailand	2018	• Soil incorporation, • Electricity generation, • Open burning
(Shafie et al. 2014)	Malaysia	2014	• Rice straw electricity generation, • Coal-based electricity generation, • Natural gas electricity generation
(Hung et al. 2019)	Philippines	2019	• Complete burning, • Complete incorporation, • Partial removal, • Complete removal
(Amarante et al. 2019)	Cuba	2019	• Soil incorporation, • Electricity generation from biogas

for each kilowatt of energy generated in comparison to the natural gas–based power plants. It was therefore concluded that the straw-based power plants not only prevented the open burning of the waste rice straw but additionally caused lesser GHG emissions in comparisons to the other fossil fuel–based power generation methods (Shafie et al. 2014).

Figure 14 gives a brief description of the life cycle and the related processes pertaining to the rice cropping systems. It clearly shows that every step of the crop system consumes a certain proportion of energy. Hung et al. (2019) in their study based in the Philippines compared the four different straw management scenarios of complete burning, complete straw retention, partial straw removal and full straw removal. It was suggested that the open burning of straw was the worst process in terms of GHG emissions while the partial and complete removal of straw reduced the GHG emissions by 30–40%. It was also concluded that the energy requirement in complete or partial removal of straw from the fields despite the additional collecting and transporting efforts resulted in a net energy increase of 10–15% as compared to the open burning (Hung et al. 2019). Table 10 displays a summary of a few LCA-based studies on the utilization of rice straw methodologies. These results provide a clear prediction of the ramifications related to the open burning of rice straw. Majority of the studies have discouraged the continuation of the burning process and professed the use of other sustainable alternatives.

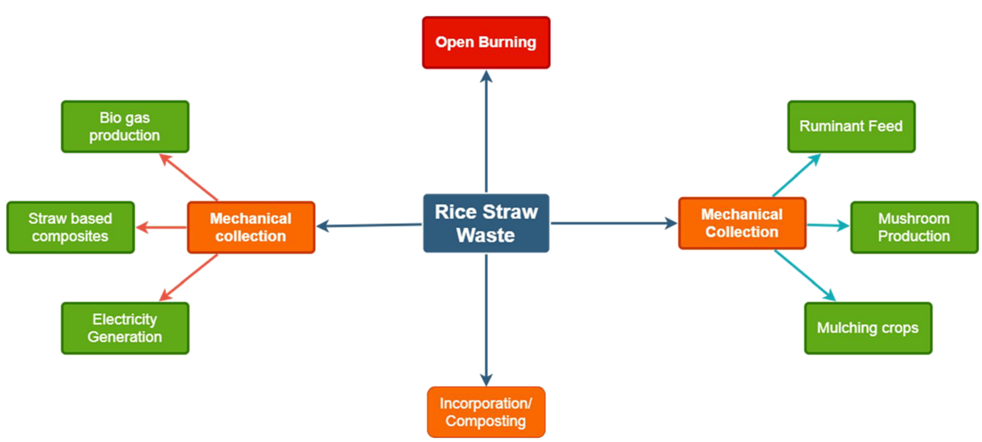

Fig. 15 Alternatives for utilizing waste rice straw

Figure 15 displays some of the most common and feasible alternatives for the sustainable utilization of rice straw.

Based on the studies, the incorporation of straw into the soil and the electricity generations are the most viably applicable straw management strategies. The major reason is the high quantity of straw that can be managed through these techniques. Other techniques like mushroom production or green composite manufacturing may be efficient, but are incapable of utilizing large quantities of waste straw. To sum things up, it would be fair to state that there is a vast scope of utilizing the wastes generated from rice all over the world. Depending upon the social and economic as well as the demographic constraints and opportunities, the sustainable utilization of rice straw wastes can be successfully implemented across the major rice growing regions.

Conclusions

Rice crop is expected to play a significant role in safeguarding the global food security. Although its per capita consumption varies from one area to another, it is considered a highly important crop across the globe. However, the effects of rice cultivation on the environment cannot be ignored. The contribution of rice production towards the global climatic change can be explained on the basis of its contribution towards the global GHG emissions. These emissions are already causing fluctuations in global temperatures and contributing towards the melting of the Arctic and Antarctic ice caps. The processes of water management, fertilizer application, cultivation techniques and waste straw burning are the key contributors in the rice production–related GHG emissions. It is obviously difficult to manage the irrigation or fertilizer-related emissions, but the GHG emissions due to the open burning of the waste straw can be termed as highly unnecessary as there are many methodologies to manage and utilize the generated waste straw from the harvested crop. Despite the available alternatives, farmers across the globe prefer to burn the waste straw, taking into account its economic viability, but ignoring the adverse effects it has on our environment. Every year, cases are reported from all continents related to the open burning of waste rice straw. The most important conclusions that can be drawn out of this study are as follows:

1. The problem of the open burning of rice straw is highly severe in Asia, which is the largest producer as well as the largest consumer of rice in the world. According to several studies across the globe and as described in Fig. 11, it can be concluded that the most sensitive areas in terms of the rice burning activities are the Northern plains of India (including the states of Punjab, Haryana, Uttarakhand and Uttar Pradesh), North-eastern and central regions of China (including the provinces of Heilongjiang, Shandong and Henan), the Mekong River Delta of Vietnam and the Indonesian islands of Sumatra, Papua and Kalimantan. According to Fig. 11, some areas of the Philippines, Bangladesh, Myanmar and Pakistan are also some significant contributors towards the global straw burning–related GHG emissions. Nevertheless, the burning activities in Africa (central and western coast), South and Central America (predominantly Brazil) or even Europe (cases in Spain and Italy) cannot be ignored. Therefore, the areas marked under the red and orange zones in Fig. 11 provide huge opportunities for the sustainable utilization of the rice straw and the development of related industries.
2. An important conclusion that may be drawn is the change in the method of harvesting of rice. The use of combine harvesters has improved the efficiency while reduced the labour requirements for harvesting rice, but has also played a promotional role in the open burning of straw by the farmers. This can be justified by the increasing trend in burning of straw with the increasing use of combine harvesting due to the uneven scattering of the straw making its collection costly for the farmer. As a result, it is concluded that an alternative mass harvesting technique may be developed that can simultaneously harvest and collect the rice straw in a more organized way.
3. Based upon the LCA results, there is a huge potential for the utilization of the waste rice straw in both off-field and in-field applications. The soil incorporation of the rice straw is the most useful in-field management technique despite a noticeable amount of GHG emissions. In the case of the off-field utilization, the electricity generation is the most common technique while the generation of biogas and use as fodder are also highly popular. Moreover, there is a colossal potential in the use of rice straw for making newer materials. Newer rice straw composites with both metals and polymers may be developed and marketed under the eco-materials tag. This can open up new domains for the development of manufacturing industry in the major rice-producing regions of the developing world.
4. Eventually, it is suggested that efficient policy-making from the governments and farmer education concerning the alternative options for disposing or utilizing the residues are the most vital contributors that can assist in controlling this avoidable menace. In the absence of such measures, especially in Asia and Africa, the vicious circle repetitively moves on where rice production is becoming both a victim of and a contributor towards climate change.

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Data Availability Not applicable.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication The copyright permissions have been taken and consent to submit has been received explicitly from all co-authors.

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