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REVIEW ARTICLE

Prospect of using rice straw for power generation: a review

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Abstract

With the ever-increasing energy demands, fossil fuels are gradually depleting and eventually, these nonrenewable sources of energy will be exhausted. Hence, there is an urgent need to formulate alternative fuels that are both renewable and sustainable. Biomass is one of the reliable sources of energy because it is replenishable. Rice is the staple food in many countries, particularly in Asia. The number of paddy fields has increased tremendously over the years and is expected to increase in the future in response to the growing world population. This will lead to significant amounts of agricultural wastes annually, particularly rice straw. In some countries, open burning and soil incorporation are used to manage agricultural wastes. Open burning is the preferred method because it is inexpensive. However, this method is highly undesirable because of its detrimental impact on the environment resulting from the release of carbon dioxide and methane gas. Hence, it is important to develop an energy-harvesting method from rice straw for power generation. More studies need to be carried out on the availability and characteristics of rice straw as well as logistic analysis to assess the potential of rice straw for power generation. This paper is focused on reviewing studies pertaining to the characteristics and potential of rice straw for power generation, current rice straw management practices, and logistic analysis in order to develop a suitable energy-harvesting method from rice straw in Malaysia.

Keywords Rice straw · Rice residue · Paddy · Power plant · Alternative fuel · Environmentally friendly

Introduction

Biomass is one of the most cost-effective, renewable, and sustainable sources of energy. Studies have shown that biomass-generated electricity is substantially cheaper compared with other renewable energy sources. However, coal is still the cheapest source of energy while biomass is slightly more expensive than coal by 10–15%. Biomass is a sustainable alternative fuel compared with fossil fuels. Biomass is versatile because it is not only used to produce energy, but it can also be used to produce biomethane gas, which can replace natural gas (Mahlia et al. 2020; Masjuki et al. 2002; Milano et al. 2018; Viaspace 2015).

The global paddy production reached its peak in 2015 with 749.8 million tons of rice. The increasing demands for rice have led many associations to venture into more agricultural activities dealing with paddy production in order to fulfill the needs of the population (Food and Agriculture Organization of the United Nations 2014). In the nineteenth century, Asian countries contribute ~ 92% of the total rice production worldwide, where the main suppliers are China and India (Kadam et al. 2000).

At the turn of the twentieth century, there was only about 50 million ha of irrigated farmlands. This value increased to 270 million ha by the end of the twentieth century, where most of the irrigated farmlands are found in Asian countries. Asian countries dominate paddy production because 23.5% of the land area on Earth is in Asia. In addition, Asia is the largest continent, constituting 60.7% of the global population. Moreover, the rate of paddy production increases drastically owing to the sufficient rainwater supply for paddy cultivation (Taniyama 2002). Figure 1 shows the trend of paddy production in the world and in Southeast Asia from 1920 to 1999. The trend clearly indicates that paddy production has increased rapidly over the years (van der Eng 2004).

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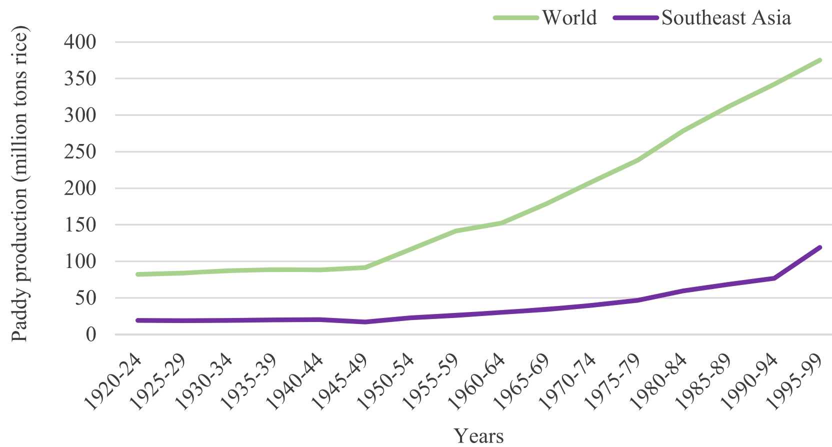

Fig. 1 Paddy production in the world and in Southeast Asia (Food and Agriculture Organization of the United Nations 2015)

Paddy production has skyrocketed in Asia from 2011 to 2015 and currently, the four major producers are China, India, Indonesia, and Bangladesh. China is the leading producer of rice among these countries, with an average of 200 million tons per year, followed by India (~ 150 million tons per year), Indonesia (90–100 million tons per year), and Bangladesh (~ 40–50 million tons per year) (Food and Agriculture Organization of the United Nations 2015).

Malaysia is also a rice-producing country; however, owing to the size of the country and land allocation for paddy plantation, paddy production is relatively small compared with that in other countries. The paddy production in Malaysia is able to sustain 65% of the staple food in this country. After 1957, Malaysia has inherited an economy that is largely dependent on rubber and palm oil exports. Paddy and rice production have received considerable attention from the Government of Malaysia because this sector sustains the staple food for the country. Paddy and rice production are agricultural activities that are a major contributor to the nation's revenue. In 2000, the generated revenue was MYR 590 million and this value increased to MYR 632 million in 2005. The generated revenue further increased to MYR 988 million in 2010, which is a significant increase in revenue. The land allocated for paddy plantation is estimated to be ~ 671,000 ha, with an average paddy production of 3.660 metric tons per hectare (Fahmi et al. 2013).

Hence, it is expected that paddy production will increase rapidly in the future because of technological developments as well as the strategic location of the country. Figure 2 shows the trend of paddy production in Malaysia from 1961 to 2013 (Fact Fish 2015). The paddy production increased from 1,000,000 tons in 1961 to ~ 2,500,000 tons in 2013. However, the escalating global paddy production is also disadvantageous because of the significant amounts of agricultural wastes left behind after harvesting. Thus, there is a serious need to handle the wastes produced from paddy cultivation. In this regard, the agricultural wastes can be used as a source of biomass energy, which eliminates the need for clearing new lands to plant alternative energy crops (Yukihiko et al. 2005).

Rice straw as agriculture wastes

Rice straw is produced when the paddy plant is cut at the grains during harvesting. Rice straw constitutes ~ 50% of the gross weight of the paddy plant and this value varies within a range of 40–60%, depending on the method used for cultivation. This indicates that almost half of the weight of the paddy plant is contributed by rice straw. According to Kadam et al. (2000), there are at least 1.35 tons of rice straw remaining in the fields for each ton of grains obtained. Based on the amount of paddy production in earlier studies, it is evident that amount of rice straw produced is extremely high. According to Liu et al. (2011), rice straw wastes constitute ~ 62% of the rice production in China and these wastes are not utilized properly for power generation. In Taiwan, based on a paddy field area of 9375 ha, there were around 0.0563 million tons of rice straw in the field before harvest in 2007. The total planted area was 38,862 ha, which produces up to 0.233 million tons of rice straw (Shie et al. 2014).

The amounts of rice straw in different countries are presented in Table 1. It shall be noted that these values are provided for China, Vietnam, Thailand, and India, which are the leading paddy producers in the world. The theoretical potential and estimated surplus of values of the rice straw are provided (Hiloidhari and Baruah 2011, Silalertruksa et al. 2013; Taniyama 2002; Zeng et al. 2007).

Characteristics of rice straw

Rice straw is typically very bulky and dry; however, these wastes are usually wet during the rainy season. Rice straw is typically left behind in the paddy fields by most farmers after harvesting. Most of the time, rice straw is only available in the local market because of its sheer size and transportation cost.

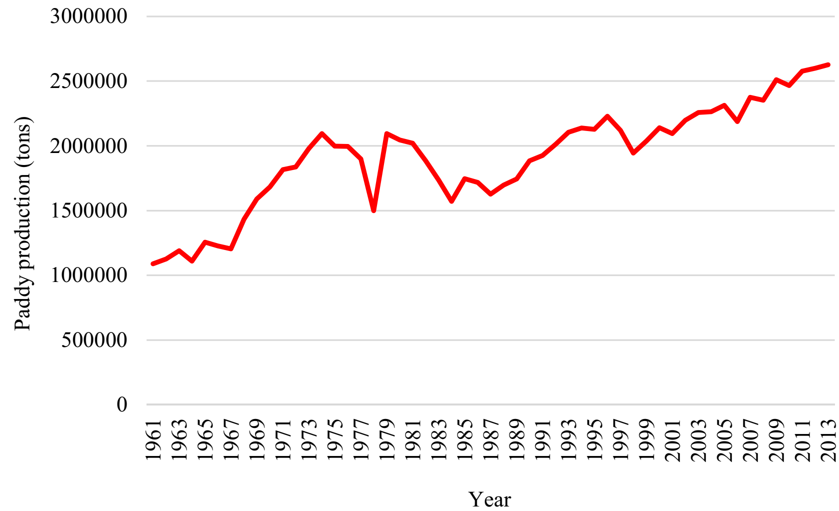

Fig. 2 Paddy production in Malaysia from 1961 to 2013 (Fact Fish 2015)

The price of rice straw varies from one location to another, depending on the transportation distance. Rice straw needs to be pre-processed in order to harness energy. These wastes have high ash content (Siemers 2011). For these reasons, rice straw will have greater potential as biomass if it can be pre-processed and transported at a cheaper cost. The moisture content, bulk density, ash content, pollutant emissions, volatile matter, and calorific value are the important properties of rice straw. In general, the moisture content of rice straw is roughly 10–20% during the dry season, and this value may be higher during the wet season. Higher moisture content is undesirable because this will reduce the combustion temperature in boilers, which will degrade the quality and efficiency of the combustor. This will reduce the generated power (Kumar et al. 2016; Oanh et al. 2011).

Flue gas will likely form if the rice straw is combusted without reducing its moisture content to an acceptable level. In such cases, equipment is needed to manage the release of flue gas. Despite its bulkiness, rice straw has a low mass and density. For example, the density of chopped rice straw is 50–120 kg/m^3 whereas the density of coal is significantly higher, with a value of 560–600 kg/m^3. Therefore, to attain the same amount of generated power as coal, the amount of rice straw needs to be increased by more than tenfold, which complicates the transportation and storage of this feedstock (Kadam et al. 2000). The properties of rice straw need to be analyzed in order to assess its quality. These properties are crucial to determine the direction of the future processes of rice straw as a renewable feedstock. The methods used to assess the composition of rice straw are listed as follows:

(a) Moisture content analysis (constant drying in the oven)
(b) Proximate analysis

- The thermal behavior of the rice straw is studied by measuring the rate of weight loss of the sample as a function of time and temperature (thermogravimetric analysis). The size and density of the sample are also analyzed.

(c) Ultimate analysis

- This analysis provides the elements (carbon, hydrogen, nitrogen, sulfur, and oxygen) contained in the sample based on the difference in solid fuel.

(d) Structural analysis

- This analysis is performed to determine whether the chemical composition of rice straw is lignocellulosic

Table 1 Theoretical potential and estimated surplus values of rice straw (Hiloidhari and Baruah 2011; Silalertruksa et al. 2013; Taniyama 2002; Zeng et al. 2007)

Value (million tons)	Country			
	China (Zeng et al. 2007)	Vietnam (Taniyama 2002)	Thailand (Silalertruksa et al. 2013)	India (Hiloidhari and Baruah 2011)
Theoretical potential value	200.0	21.5	22.0	100.0
Estimated surplus value	37–150	6.0	11.0	22.0

or herbaceous. The cellulose, hemicellulose, and lignin components of the rice straw are analyzed.

(e) Heating value (higher heating value (HHV) and lower heating value (LHV)

- HHV represents the heat of combustion of the sample relative to that of liquid water.
- LHV represents the heat of combustion of the sample relative to that of water vapor.
- The gross heating value of most lignocellulose biomasses is 15–19 MJ/kg.

(f) Ash content

- The ash content represents the inorganic content of the rice straw.

The ash content of rice straw differs, depending on the location where the biomass is obtained. The silicon dioxide content of dry rice straw is very high (0.1–0.7%), depending on the harvesting method (Jenkins et al. 1998). There are also other chemical elements in rice straw, as shown in Table 2 (Danish et al. 2015; Jeng Shiun et al. 2012; Jenkins et al. 1998; Kaur et al. 2014; Liu et al. 2011; Sadh et al. 2018).

In general, rice straw has a very high volatile matter content, depending on its dryness. Hence, rice straw burns easily with a rapid combustion rate. Rice straw is more volatile compared with coal and thus, this biomass has great potential for power generation. The volatile matter significantly affects the combustion rate and this needs to be taken into account. It is vital to achieve complete combustion in order to minimize carbon monoxide emissions and enhance the efficiency of the power generation (Oanh et al. 2011). Pollutant emissions are also important in determining the characteristics of rice straw. Combustion of rice straw produces pollutants such as sulfur, nitrogen, and chlorine, which need to be analyzed to prevent the detrimental effects of these gasses on the environment (Engling et al. 2009; Irfan et al. 2015).

Table 2 Proximate and ultimate analyses of rice straw (Danish et al. 2015; Jeng Shiun et al. 2012; Jenkins et al. 1998; Kaur et al. 2014, Liu et al. 2011; Sadh et al. 2018)

	Rice straw
Proximate analysis (wt%, dry basis)	
Moisture content	10–20
Volatile matter	75–85
Fixed carbon	15–25
Ash content	0.1–0.7
Higher heating value (MJ/kg)	18
Ultimate analysis (wt%, dry basis)	
C	47–52
H	6.1–6.3
O	38–45
N	< 0.2
S	< 0.1
Cl	< 0.02
K	0.036–0.055

Rice straw is a fibrous lignocellulose, which mostly exists in agricultural wastes. However, there is a slight difference in the lignocellulose content of rice straw because of the high concentrations of silicon dioxide. The chemical composition of rice straw in California is shown in Table 3, which was determined using the National Renewable Energy Laboratory (NREL) method of biomass compositional analysis. The HHV is 17.8 MJ/kg, indicating that rice straw has good potential for power generation in California (Danish et al. 2015, Kaur et al. 2014, Sadh et al. 2018; Sopian et al. 2005). The estimated heating values of rice straw obtained from ultimate and proximate analyses in different countries are tabulated in Table 4 (Caijin et al. 2008; Kargbo et al. 2009; Liu et al. 2011; Patel and Sahu 2018; Shafie et al. 2013a; Shafie et al. 2014; Suramaythangkoor and Gheewala 2010).

It can be seen that the heating values of rice straw in China obtained from the experiments are almost similar. The HHV of rice straw in China is 18 MJ/kg on a dry basis. It can be reasonably assumed that the HHV will be the same or similar for rice straw in other countries. Based on the HHV, the rice straw has great potential for power generation.

Potential of rice straw

Rice straw has high silica and cellulose content and therefore, it requires long periods of natural decomposition. Owing to the long decomposition process, rice straw is typically stacked in the farm area and managed through open burning. Open burning is the primary method used to prepare the field for the next cultivation season. In addition, rice straw is used as a domestic heating source by households in rural areas. Open burning of rice straw has been practiced by many farmers in most countries, which contribute to air pollution, global warming, and energy wastage. To overcome these issues and promote a more environmentally friendly approach, the rice straw can be recycled and used as biomass. Rice straw is a potential alternative source that can be exploited to replace or reduce the dependency on fossil fuels.

Rice straw has been used as compost, animal feed, erosion control materials, biofuel, biogas, fertilizer, papermaking materials, and growth medium in many Asian countries (Rosmiza et al. 2014). China is one of the countries that use most of the rice straw collected from paddy fields for biomass energy in rural areas. Rice straw is a renewable energy source,

Table 3 Rice straw composition

Feedstock component (wt%, dry basis)	Kadam et al. (2000)	Kaur et al. (2014)	Sadh et al. (2018)	Danish et al. (2015)
Glucan	38.9	—	—	—
Mannan	0	—	—	—
Galactan	0.5	—	—	—
Xylan	20.4	—	—	—
Arabinan	3.4	—	—	—
Cellulose	—	36.2	39.2	—
Hemicellulose	—	19	23.5	—
Lignin	13.5	9.9	36.1	—
Extractives	5.3	—	—	—
Ash	18	—	12.4	20.02
Moisture	—	—	6.58	6.96
Total solid	—	—	98.62	—
Fixed carbon	—	—	—	14.77
Volatile matter	—	—	—	58.25

where the energy can be obtained by chemical conversion processes such as pyrolysis, gasification, and combustion (Jinje et al. 2014).

To utilize rice straw for power generation, the basic method is direct combustion, which is a thermochemical method that produces steam from the combustion of biomass. This is a promising approach of disposing rice straw and the useful heat is used for power generation. Another alternative is the cofiring method, where rice straw is used as a partial fuel in high-efficiency coal boilers, which eliminates the need to build a dedicated plant to harvest energy from rice straw (Eisentraut and Brown 2012).

The average efficiency of a coal power plant is ~ 32–42%, depending on the superheat and reheat steam temperatures and pressures. The power output of the power plant is within a range of 100–1500 MW, which is extremely high. The main drawback of the cofiring method is that this process is not carbon neutral because it produces high greenhouse gas emissions (Bright Hub Engineering 2010). In contrast, a biomass power plant has an efficiency of 20% if the biomass is used for combustion. For example, because dry rice straw has a very low moisture content, the efficiency of the power plant can be increased up to 40% if dry rice straw is used the feedstock. The capacity of the biomass power plant typically falls within a range of 20–50 MW (Boundy et al. 2011). Even though coal-based power generation is still the preferred method, biomass-based power generation has greater potential because it is a renewable and sustainable method of power generation in the future with lower environmental impact.

According to Sopian et al. (2005), the productivity energy for paddy plant production in Malaysia is ~ 11.54 (boe/ha/year). This yields significant amounts of unused rice straw. This rice straw can be used to produce 2.541 million boe of energy. The annual production of energy from rice straw may be currently small; however, this value can be increased with technological developments, which can contribute to the national energy grid. Rice straw has a high potential for power generation because of the continuous paddy production for human consumption (Sopian et al. 2005).

There are several methods used to harvest energy from rice straw other than open straw burning practiced by local farmers, which are listed as follows:

Table 4 Estimated heating values of rice straw in different countries

Researchers	Estimated heating value of rice straw (MJ/kg)		
	Thailand	China	India
Shafie et al. (2013a); Shafie et al. (2014)	10.24	14.97	14
Liu et al. (2011),	—	18.0	—
Patel and Sahu (2018)	—	—	5.5
Suramaythangkoor and Gheewala (2010)	12.33	—	—
Caijin et al. (2008)	11	—	—
Kargbo et al. (2009)	—	15	—

- Direct combustion heating
- Direct combustion power generation
- Gasification
- Methanol production
- Flash pyrolysis
- Cofiring
- Acid hydrolysis

The only method that is currently implemented in certain countries for power generation is direct combustion because of its cost-effectiveness. In Japan, there are ideas on powering boilers for schools and hospitals using 400 kg/h of steam with 90% efficiency, where rice straw with a moisture content of 15% is used as the fuel. Rice straw also has the potential for other uses such as:

(a) Feeds

Rice straw can be used to replace or compete with other cereal grains such as barley and wheat. The digestion rate can be increased if proper treatment is carried out using sodium hydroxide. Rice straw can also be used as animal feeds. In addition, rice straw can be used as a growth medium for mushrooms as well as compost and vermicompost. Compost and vermicompost are natural decomposition processes that return nutrients to the soil; however, these methods are more time-consuming compared with open burning.

(b) Fibers

Rice straw can be used to produce non-wood fibers for newsprint and corrugated media. The current use of fibers is only emphasized by major paddy developing countries such as China and India. These straw fibers can be used for papermaking, food packaging, and thermal insulation, as well as building construction materials.

(c) Fuel

Rice straw can be converted into ethanol, which is a fuel. However, the chemical conversion process is rather costly. Biodiesel and bioethanol are transportation fuel with lower exhaust emissions (Ong et al. 2014; Ong et al. 2019; Silitonga et al. 2020; Silitonga et al. 2013). Direct combustion can be used, where the rice straw is used as the fuel for the combustor or utility boiler in order to generate power. However, it is crucial to avoid slagging and fouling during the boiling and combustion processes (Jenkins et al. 1998). Besides fuel and electricity, the biogas produced from rice straw after decomposition can be used as a source of energy.

The paddy production in East Malaysia, especially Sarawak, is estimated to be 280,000 tons over a 5-year period. This implies there will be about 350,000 tons of rice straw that can be procured by the paddy industry in this state. If all of the rice straw can be used in the gasification and combustion processes, the energy potential is estimated to be ~ 592,013 MWh of electricity with an efficiency of 32% using only agricultural wastes. It is clear that rice straw has a strong potential as an alternative source of energy in the future (Sarawak Energy 2013).

Current rice straw management practices

Rice straw is a waste product of paddy production, comprising up to 50–60% of the paddy itself. Rice straw is produced during the harvesting process and hence, it is important to manage this agricultural waste. The current methods used by most farmers are open burning, soil incorporation, animal feed, and removal from the field. At present, there are no useful methods owing to the lack of development in rural areas and cost issues. Each method has a different impact on the environment and nutrient balance, which will affect the soil fertility in the long term because of ongoing plantation activities (Dobermann and Fairhust 2002; Shuai et al. 2015).

The straw removal method is widely used in India, Bangladesh, and Nepal. The repeated straw removal process has caused the field soil to have low potassium (K) and silicon (S), which will be a major problem in the near future. In addition, rice straw is used for different purposes such as fuel for cooking in rural areas as well as ruminant fodder and stable bedding. Rice straw can also be used in the papermaking and packaging industry. Rice straw removal involves racking loose straw, baling the straw into small bales, and road siding the bales. The processed rice straw is typically normally bailed and hauled.

There are various bailing formats such as round, square, large, and small, which is primarily dependent on the farmer's preferred method (Steven et al. 1993). If the paddy field is small, straw removal is not suitable because of the lack of cost-effectiveness in using vehicles to remove the rice straw from the paddy fields. Compared with other management methods, straw removal is the best choice to reduce pollutants; however, the main drawback is the release of greenhouse gas emissions because vehicles are used to transport the rice straw (Massimo et al. 2015).

The most common rice straw management method is to burn the rice straw. This method is the easiest and it does not incur additional cost for rice straw management. Hence, it is one of the fastest ways to dispose rice straw during the harvesting period. Even though this method is helpful for farmers and paddy field operators, it is highly detrimental to the environment. According to Dobermann and Fairhust (2002), this method ignites atmospheric pollution and leads to nutrient losses from the soil. Despite these disadvantages, open burning is a cost-effective method and it can help reduce pests and diseases.

During combustion, high amounts of carbon dioxide (CO_2) are released, along with carbon monoxide (CO), methane, nitrogen oxides (NO_x), and sulfur dioxide (SO_2). Some of these gasses are toxic and they may be carcinogenic. There were several medical issues faced by the communities in Japan, India, and California such as asthma and pulmonary morbidity owing to continuous exposure to open burning. This practice has been banned in several paddy-producing countries including California. However, open burning is still widespread in Asian countries owing to a lack of regulations and enforcement from the authorities on open burning. Open burning does not only lead to air pollution but also to high nutrient and energy losses. Most importantly, this practice is a clear wastage of potential energy feedstock since the rice straw can be used to harness energy, which can be dissipated into heat (Escriba and Porcar 2010; Hironori et al. 2015; Kumar et al. 2015).

Composting and vermicomposting processes are other effective alternative methods to decompose rice straw, which eliminates the need for open burning. However, the natural decomposition of rice straw is a long process, which will take up to three months to complete. The products of these processes are compost, which is full of beneficial nutrients needed by the soil. Vermicomposting is a decomposition process in which various species of worms are used to create a mixture of decomposing media (organic fertilizer). Vermicomposting can be performed in large-scale vermicultures, which are suitable for small-scale farmers. This is an environmentally friendly waste management approach, which eliminates wastes and the need for burning.

Another alternative method is soil incorporation, which is widely practiced among farmers to refertilize the soil. The nutrients can be recycled for the next crop cycle and the waste is converted to good use, which helps maintain the soil quality. Soil incorporation typically involves the use of rice straw and stubble by plowing wet soil during land preparation or by plowing dry soil during fallow periods. However, this method results in a significant increase in methane gas emissions (Escriba and Porcar 2010). Methane gas is a good source of energy and therefore, a suitable facility can be built at the

Table 5 Greenhouse gas emission factors for different rice straw management practices (Launio et al. 2013)

Rice straw management practice	Pollutant	Emission factor	Unit
Open burning	Methane (CH_4)	1.2	g/kg (dry fuel)
	Nitrogen dioxide (NO_2)	0.07	g/kg (dry fuel)
	Combustion factor	0.8	
Scattering and incorporation of rice stubble and straw in the soil (wet condition)	CH_4 (wet soil)	129.77	kg/ton yield
	CH_4 (dry soil)	36.99	kg/ton yield
	Baseline emission factor for continuously flooded fields without organic amendments	1.3	
	Conversion factor for rice straw amendment	1.0 for straw incorporated less than 30 days before cultivation	
		0.39 for straw incorporated more than 30 days before cultivation	
	Scaling factor to account for differences in the water regime during the cultivation period	0.78 for irrigated	
		0.27 for rain-fed	
	Scaling factor to account for differences in the water regime during pre-season before the cultivation period	1 for irrigated (< 180 days);	
		1.22 for rain-fed	
Composting and soil incorporation	CH_4 (wet soil)	13.37	kg/ton yield
	CH_4 (dry soil)	2.1	kg/ton yield
	Conversion factor for rice straw compost amendment	0.05	
Rice straw used as animal feeds	CH_4	10,000–20,000	gCH_4/ton dry weight
Rice straw used for mushroom production	CH_4	7.27	gCH_4/ton dry weight
Compost and vermicompost	NH_3	—	

plantation to collect the methane gas. This provides renewable energy and reduces the harmful effects of methane gas on the environment. At present, 70% of the rice plantations in California are produced in the same land repeatedly and most of the farmers use the soil incorporation method. These farmers seem to face some difficulties in covering the cost of soil incorporation owing to factors such as wet soil, short seasons, high volumes, and low-intensity crops. According to Steven et al. (1993), crop rotation is a better method, which provides an economically viable and flexible method of managing rice. Table 5 shows the greenhouse gas emission factors for different rice straw management practices.

Converting rice straw into usable biomass is another common practice in China especially in rural areas, where ~ 55% of the rice straw produced is used as an energy source (Wang and Feng 2004). Rice straw is currently used for electricity generation in China. Japan, Korea, and India have also developed biofuels and biogasses for electricity production using agricultural residues. India uses straw for biogas production (~ 28%) while South Korea and Taiwan emphasized on the use of straw for biofuel production, with a value of ~ 20% and ~ 5.1%, respectively. These values can be further improved in line with technological developments to secure sustainable power generation in the future.

Rice straw–based power generation

To use rice straw for power generation, it is first important to determine the amount of available rice straw in an area because the rice straw is the main feedstock for a particular power plant. It is crucial to ensure a continuous supply of rice straw. Therefore, a simple method (straw-to-grain ratio) can be used to determine the amount of rice straw in an area. In most studies, a straw-to-grain ratio of 0.75 is used.

Second, it is important to ensure that the rice straw has a low moisture content to achieve complete combustion and improve the efficiency of power generation. Even a slight increase in the moisture content can reduce the efficiency. For this reason, rice straw is pre-processed before it is fed to the power plant. The easiest method to reduce the moisture content is to dry the rice straw under the sun before collection. Next, it is crucial to ensure that there is a reliable supply chain of rice straw to the power plant and therefore, the power plant should be located in a strategic location. This step is important to minimize transportation costs, which can be very high because of the bulk density of rice straw (Gupta et al. 2015).

The first rice straw–based power plant was built in Jai Kheri Village in the Patiala district of Punjab in 2006. The capacity of the power plant is 10 MW and it is the first of its kind in the world. The power plant is operated based on an effective method of converting waste into electricity. According to the Punjab State Electricity Board, 70,000 tons/year of rice straw is required to sustain the power plant. There is still a high possibility that the power plant will face major problems when there are continuous changes in the state's agricultural and industrial activities. If there is any diversion in agricultural activities (e.g., from paddy to crops of higher value), then the amount of rice straw will significantly decrease in the future, resulting in failure of the power plant (Cherail 1992; Renewable Energy World 2006, 2012; Singh 2015).

In China, the first rice straw–based power plant was built in 2006 and ever since its establishment, rice straw–based power generation has been developing in a remarkable way. The demand for rice straw in China is roughly 2.13 million tons/year where 10 plants are direct-fired whereas others are mixed-fired (Qin et al. 2013). According to Sansiribhan et al. (2014), the central province in Thailand can produce 2–4 times of crops annually and therefore, this province will be a strategic location to establish a small-scale rice straw–based power plant. They assumed that the power plant will have a capacity of 9.5 MW and they calculated that the required amount of rice straw supply will be up to 67,620 tons/year for rice straw with moisture content and LHV of 12% and 14 MJ/kg, respectively (Sansiribhan et al. 2014). The moisture content plays a vital role in power generation, where baled straw has a moisture content of 10–18%. When the moisture content exceeds 13%, the power output is reduced by 2% for the same amount of feedstock (Suramaythangkoor and Gheewala 2010).

Challenges and solutions of rice straw–based power generation

The main challenge is to manage the high ash content of rice straw as well as alkali metals such as sodium and potassium. During the combustion process, these materials can cause corrosion in super heaters as well as slagging and fouling. Slagging refers to the deposition of slag material while fouling is the accumulation of unwanted particles on solid surfaces. In addition, the presence of catalysts can deteriorate nitrogen oxide reduction.

Ash from coal has the properties suitable for cement production whereas ash from a straw cannot be used for other industries. Hence, the ash produced from straw becomes unmanaged waste (Wirseniues 2003). Liu et al. (2011) has stated the challenges of rice straw combustion in China. The main challenges are harvesting issues, processes and systems, technical improvements, policies, and techno-economic analysis, which will be described below. These challenges arise because of the characteristics of rice straw.

Harvesting issues

The collection of rice straw involves several things. First, the presence of pests and diseases affecting the paddy can degrade the quality of rice straw. Second, the operation needs to be conducted in a timely manner (as short as possible) to avoid incurring labor costs. Therefore, a system is required to ensure that the rice straw is collected in a timely manner. Third, the continuous removal of rice straw from the paddy field can reduce nutrients in the soil and thus, fertilizer is required to replenish the minerals lost in the soil. The loss of minerals in the soil can be restored by composting and vermicomposting methods. Both of these are reuse and recycle methods, where the rice straw is used for composting and the end products can be used to enrich the soil as well as suppress plant diseases and pests. This natural way of decomposing will reduce the need of chemical fertilizers and reduce methane emissions and carbon footprint. Fourth, the machine used for rice straw collection should be capable of operating in all conditions including muddy fields and the field must be able to withstand the weight of the machinery used during the harvesting process. Lastly, there is a need to promote awareness on the collection system to farmers and this can be done by offering incentives to the farmers who provide rice straw.

Process and system considerations

There is a need to establish a system for each process: (1) collection, (2) processing, and (3) transportation of rice straw to the power plant. These systems can help determine the cost of using machinery during the harvesting process as well as determine the amount of rice straw. Drying is required to reduce the moisture content of rice straw (60–70%, wet basis). It is essential to reduce the moisture content to 25% to achieve complete combustion. Improving the drying system is the first step for power generation. Technological improvements on the shape of the combustion chamber, and the size of the feeding door, grate, and ash pit can help improve the combustion of rice straw. This will enhance direct combustion in the boilers in order to generate electricity and supply heat. The heat supplied can be recycled to dry wet or semi-wet rice straw transported from the paddy field. In addition, if the rice straw has high moisture content, fermentation will likely occur, which will reduce the quality of the rice straw. Transporting wet rice straw is more expensive compared with transporting dry rice straw, which necessitates the drying process. Besides drying, densification is needed to increase the bulk density of rice straw, which will help reduce the logistic cost.

Moreover, it is important to improve the gasification system for gas supply. Hence, studies should be conducted to improve the efficiency of gasification systems and their applications. In addition, briquette-making machines and biocoal molding machines can be developed to enhance the quality of briquette sand functions. This will reduce the transportation cost and time for post-making of rice straw products.

Policies and techno-economic analysis

In 2017, China is one of the largest energy consumers followed by the USA and India for world primary energy (Qiang et al. 2020). The Chinese government has emphasized the need to develop and utilize biomass as an alternative energy source. The National Program for Key Science and Technology project began in the 1950s to research and source the latest biomass energy conversion technologies. In this project, much effort has been made to convert biomass into useful energy by the following: (1) direct combustion, (2) biochemical, and (3) physicochemical conversion. These technologies are already established in China and the use of this technology has helped reduce the emission of greenhouse gases. The energy consumption in China is dependent on coal, fuel oil, and liquid petroleum gas, electricity, straw, stalk, and least of all, firewood (Wang and Feng 2004). The rapid growth of the family income in China has turned the domestic energy consumption from non-commercial energy to commercial energy as their main source of energy. This indicates that there are more sources of straw available now than before. In the past, people used straw and firewood as their primary sources of energy. After the country was developed, people switched to liquefied petroleum gas or electricity. Therefore, straw is now a sustainable source for power generation. At the same time, this will reduce the dependency on traditional coal consumption, especially in the power generation sector.

In the USA, oil consumption is the second dominant energy consumption and thus, shifting to oil consumption has changed the trend of the rate of energy consumption. In India, coal consumption is significantly high because coal is the main source of energy. The trend of coal consumption in India is very similar to that in China, where coal consumption increases over the years. The growth of energy consumption in China and India increases each year because these countries are developing countries, which intensifies coal consumption. By mixing coal with renewable energy source, this will create a low carbon economy and promote the use of renewable energy, which will boost low-carbon footprint.

In Ghana, rice residue is used for the second generation of bioenergy where 72% of capital costs of combustion plant is due to the rice straw supply, while the cost of straw logistic is dependent on the baling processing cost which is approximately 50% of the total logistic cost (Ramamurthi et al. 2014). In Vietnam, the techno-economic analysis of rice straw industry was investigated by Nguyen et al. Rice straw is commonly used for biogas and mushroom production. The collection of the rice straw is a crucial part of the analysis; labor cost normally accounted approximately 48% of the cost of mushroom production industry. The collection of rice straw is roughly less than USD 18 per ton, which is proximately 10 to 20% of total investment cost of biogas or mushroom production. Net profit of the mushroom production was USD 123 per ton of straw used (Nguyen et al. 2016).

Besides, Thailand investigates direct combustion of rice straw to generate electricity. During crop season in 2015/2016, there are about 26 Mt if rice straws generated after harvesting process, 15 % of the total rice straws were used for heat and electricity production. The result shows that 3.9 Mt of rice straw would produce heat and electricity that are equivalent to 1331 ktoe of oil or 457 MWe. Cheewaphongphan et al. (2018) reported the energy target to be produced by year 2026 is 5570 MWe. The power plant required about 1428 Mt of rice straw to be used as fuel and this amount of rice straw is equivalent to 1925 Mtoe of oil that used for energy production. Hence, by using 1428 Mt of rice straw or other waste biomass materials which is discarded by most farmer instead of using coal or oil as a source of energy produces the same amount of electricity output. This indicated that rice straw is a more reliable, affordable, and efficient energy with lower environmental impact while improving the overall economics (Cheewaphongphan et al. 2018). The government can switch to a more sustainable energy consumption development gradually, which will be beneficial in the long term. At the same time, the implementation of renewable energy systems, especially in the energy industry, requires more in-depth research to boost their efficiency and assess their feasibility, which will offer more job opportunities.

Logistic analysis

Logistics is a distributed flow of things from one point to another. In this case, logistics refers to the transportation of rice straw from the paddy field to the power plant. Before the rice straw is transported to the power plant, the rice straw will pass through several stations for processing and collection purposes. The main processes of rice straw are harvesting, collecting, storing, and transporting. The main concern in harvesting is increasing the speed and efficiency of harvesting rather than increasing the rice straw yield. The current rice straw storage facilities in California are suitable; however, there are several drawbacks in maintaining the quality of rice straw.

Many end-users prefer rice straw of good quality, i.e., rice straw with low moisture content and minimum contamination. Most end-users use rice straw for power generation. Collection and storage activities will increase during the harvesting period, which will increase the transportation of rice straw to the respective end-users. For this reason, a suitable transportation infrastructure needs to be established to ensure that sufficient amounts of rice straw can be distributed in a timely manner (Kenny 2001).

Owing to the bulk density of rice straw, there are issues with the cost of transporting rice straw for power generation. It is relatively costly to transport rice straw compared with coal. Besides rice straw, there are many other parameters that can affect the logistic cost, as shown in Table 6 (Caputo et al. 2005; Ebadian et al. 2011; Gonzaleza et al. 2011; Perpina et al. 2009; Ravula et al. 2008; Rentizelas et al. 2009; Sokhansanja et al. 2010; Sultana and Kumar 2011). The cost of operating a rice straw power plant is dependent on the harvesting, processing, and transportation costs. The machinery used to form bales of rice straw is typically powered by diesel and therefore, the cost of rice straw bales varies from one country to another, depending on the operating cost. In addition, it is crucial to form rice straw into bales in order to reduce its size and increase its bulk density. Much space is saved by compacting the rice straw into bales before transporting.

Table 6 Impacts of different parameters on the logistic cost of various biomasses (Caputo et al. 2005; Ebadian et al. 2011; Gonzaleza et al. 2011; Perpina et al. 2009; Ravula et al. 2008; Rentizelas et al. 2009; Sokhansanja et al. 2010; Sultana and Kumar 2011)

Parameter	Impact on cost	Type of biomass	Country
Distribution of efficient biomass management	Minimize the transportation cost	Any type	Spain
Effective and efficient planning of logistic operation	Minimize the transportation cost	Agricultural crops	Canada
Increase in the transport vehicle capacity	Minimize the transportation cost	Cotton plant stalks	Greece and Europe
Maximized truck utilization factor	Minimize the transportation cost	Herbaceous biomasses	USA
Increased size of power plants	Logistic constraints on the economic performance become less restrictive	Agricultural crops, agro-industrial, and wood wastes	Italy
Biomass storage	Plays a significant role in the logistics of biomass	Cotton stalks and almond tree pruning	Greece
Site productivity	A high productivity plantation would reduce the transportation cost	Eucalyptus	USA
Increase in bulk density	Minimum cost of transportation	Agricultural and woody biomasses	Canada
More efficient collection and transport system	Minimum cost of transportation	Corn stover	USA

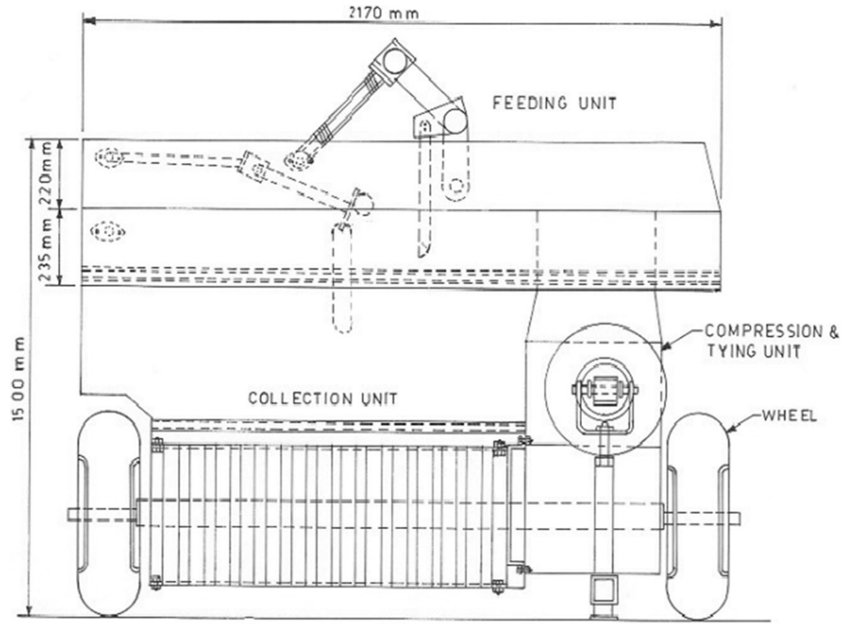

Fig. 3 Mechanism of commercial straw gatherers (Mangaraj and Kulkarni 2010)

Commercial straw gatherers cum balers (Class Markant 55) are used in Punjab, as shown in Figs. 3 and 4. The tractor has a power requirement of ~ 30 kW and the power required increases if more bales need to be produced within a short period. A number of researchers (Gupta et al. 1994; Indian Agricultural Statistical Research Institute 2010; Mangaraj and Kulkarni 2010; Yiljep et al. 1993) have focused on the work rate, power requirement, size, quality, and mass of bales on a small area for paddy production (50 ha) in order to perform techno-economic analysis.

The most important criterion in baling is ensuring that the moisture content of the rice straw is less than 20%. The baling process should be carried out after 2–3 days of harvesting. There are two types of balers: (1) small rectangular balers and (2) large rectangular balers. Small rectangular balers are already implemented in Thailand. This review is focused more on large rectangular balers because these pieces of equipment produce rice straw bales with higher density. It is crucial to produce bales with a higher density in order to minimize transportation costs (Delivand et al. 2011). Figure 5 shows an overview of the logistic model, which depicts how the rice straw is transported to the power plant (Shafie et al. 2013b).

Fig. 4 Operation of a baler in the paddy field (Mangaraj and Kulkarni 2010)

In this logistic model, the rice straw is first dried in the sun after harvesting. Next, the rice straw is baled into rectangular bales to facilitate the transportation process. Second, the rice straw is collected from the paddy field and transported to the collection center, where rice straw bales from other paddy fields are also collected. Once the capacity of the collection center is nearly full, the rice straw is checked for its quality and moisture content before it is transported to the power plant for power generation. The quality and moisture content are checked to prevent drop in the power plant efficiency. Therefore, it is important for the collection center to have the equipment to check quality of rice straw and equipment to dry the bales of rice straw if the moisture content exceeds the required limit.

Conclusion

Based on the literature review, it is evident that rice straw has great potential for power generation; however, there are some key areas that need to be focused. First, it is essential to ensure a continuous supply of rice straw based on the yearly paddy production. The amount of rice straw produced can be estimated using the simple straw-to-grain ratio method. Second, the properties of rice straw will vary from one country to another because of the relative humidity and the different types of fertilizers used for paddy cultivation. Hence, by using

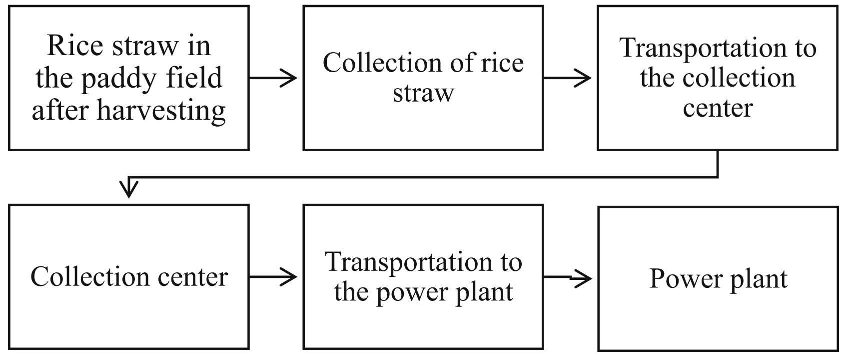

Fig. 5 Overview of the logistic model (Shafie et al. 2013b)

ASTM standards, it is possible to calculate the calorific value of the rice straw which can be used to determine the maximum capacity of the power plant. Although the maximum capacity of the rice straw power plant will be lower than that of a coal power plant, the former is more environmentally friendly. Rice straw is a sustainable source of energy for a power plant, considering that the annual output of straw and stalks in the world is in the order of billion tons. The use of rice straw for power generation promotes zero waste and minimizes open burning of rice straw after harvesting. However, the main problem of establishing a rice straw power plant is logistics. Logistic cost contributes 35–50% of the total operation cost for rice straw–based power generation. The high logistic cost translates to high usage of fossil fuels for rice straw transportation. Moreover, the use of rice straw or other agriculture wastes for power generation will reduce the dependency on coal, which will reduce the cost of the power plant. This approach is more environmentally friendly because farmers will no longer need to practice open burning to discard the rice straw. The use of existing sources (rice straw) for power generation will gradually reduce the import of coal in the long term. However, a detailed techno-economic study needs to conduct to assess the feasibility of rice straw power plants in the future and minimize economic losses associated with this approach.

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