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Review

Potential of Rice Industry Biomass as a Renewable Energy Source

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Abstract: Fossil fuel depletion, along with its ever-increasing price and detrimental impact on the environment, has urged researchers to look for alternative renewable energy. Of all the options available, biomass presents a very reliable source due to its never-ending supply. As research on various biomasses has grown in recent years, waste from these biomasses has also increased, and it is now time to shift the focus to utilizing these wastes for energy. The current waste management system mainly focuses on open burning and soil incorporation as it is cost-effective; however, these affect the environment. There must be an alternative way, such as to use it for power generation. Rice straw and rice husk are examples of such potential biomass waste. Rice is the main food source for the world, mostly in Asian regions, as most people consume rice daily. This paper reviews factors that impact the implementation of rice-straw-based power plants. Ash content and moisture content are important properties that govern combustion, and these vary with location. Logistical improvements are required to reduce the transport cost of rice husk and rice straw, which is higher than the transportation cost of coal.

Keywords: rice straw; rice husk; power generation; gasification; alternative fuel

1. Introduction

The usage of fossil fuels has increased rapidly since the 19th century due to the increased population and technological development in many countries; neither the population nor the technological development are able to be controlled, and the development of technology is important for sustaining society and the economy [1]. Many scientists are worried that due to their limited reserves, fossil fuels will become incapable of supporting global energy needs in the coming years [2–4]. The increasing price of fossil fuels is due to the high market demand, excessive use, and phasing out of fossil fuel based technologies which have caused climate change over a period of years [5–8]. It has been reported that global carbon dioxide (CO_2) emissions increased from 30,295 million metric tons in 2008 to 33,234.8 million metric tons in 2018. In 2018, the largest CO_2 emitter globally is the Asia Pacific region (16.27 billion metric tons of CO_2 emissions, and China alone contributed 27% of the world total fossil fuel CO_2 emissions) [9]. Currently, the coal industry dominates the Chinese power generation industry, especially in electricity production [10,11]. Malaysian power generation industries generally rely on fossil fuels. High consumption of fossil fuels for combustion processes in power generation increases the emissions of carbon dioxide (CO_2) [12]. During the year 1990, there was an emission of 3.1 metric tons of CO_2 per capita, whereas in 2011, it was 7.8 metric tons per capita, representing an increase of 155% in emission rate [13]. The major environmental and health issues of fossil fuels and increasing energy requirements have drawn attention from all over the world to the search for renewable fuels as these fuels are assumed to be neutral, as shown in Figure 1. During their development cycle, plants use photosynthesis to retain and change sunlight and carbon dioxide from the atmosphere into nutrients and energy. Therefore, when biomass is combusted as a power generation fuel, it does produce carbon, but the carbon dioxide is again absorbed by plants during the next crop cycle [14].

It is crucial to maintain energy usage and find a more sustainable source of energy, such as renewable energy, to fulfil global needs [15–17]. Most countries have come up with policies which offer benefits and funding to companies that seek to develop the renewable energy technology and eliminate fossil-fuel-based technologies [8]. For example, the European Union has set the target for its energy distribution to have a 20% contribution from renewable energies by the year 2020 [18]. The government in Spain has pushed the deployment of renewable energy to lower the impacts of pollution on the environment [19]. In Denmark, Spain, and Germany, innovations and inventions related to renewable energy and the production of energy at lower cost have been highly welcomed and appreciated. In Taiwan, many energy conservation patents have been established to lead the country towards the use of renewable energy sources [20]. In Indonesia, renewable energy has been widely used for biofuel and power generation. Renewable energy is going to be the main alternative energy source in Africa to overcome hydra-headed problems such as climate change and the lack of energy access in certain secluded areas [21]. There is a clear understanding that energy is the need and pivot upon which society turns.

There are various types of renewable energy source, such as biomass, hydro, wind, solar photovoltaic, and solar thermal, which have been implemented in many countries around the world [22–26]. However, some of renewable energy, like wind and solar, is not continuously available, and energy storage devices are therefore required [27]. To date, batteries are the only energy storage equipment available commercially. Hence, many researchers have attempted to find a material that stores energy in significant amounts to be used when necessary [28–30]. For this reason, researchers and the private sector still interested in deriving biofuel from biomass [31–35]. Biomass is classified into two types: waste biomass and energy crops [36]. Harvesting energy from biomass also depends on its fuel capacity and availability. It is only wise for a country to invest in biomass if the supply is abundant and able to be sustained continuously in future years [36]. In recent decades, the application of agricultural residues such as rice husk and rice straw has gained much more attention than other energy crops, as they are cheaper in cost and do not affect the food price, and circumvent the food versus fuel controversy. In addition, both rice husk and rice straw are the main residues from the most essential foods crop: rice. Both the abundant availability of agricultural residues and the technological development of biomass conversion techniques have enabled the biomasses from the rice industry to be converted into an important source of renewable power.

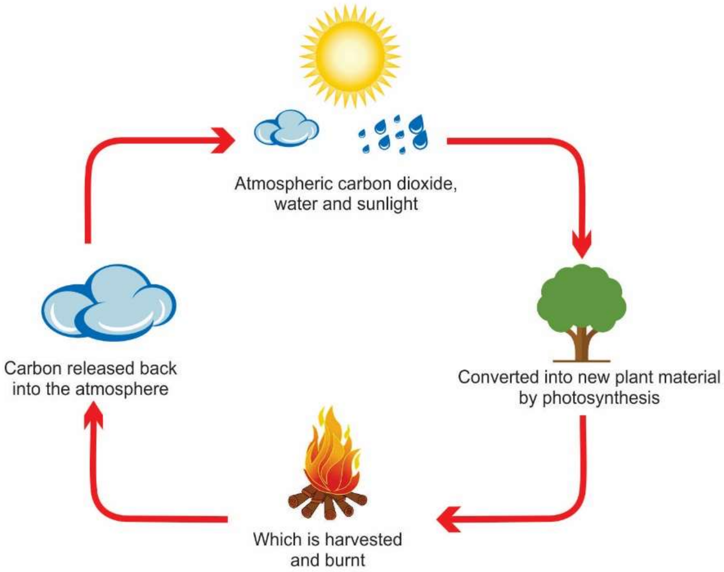


Figure 1. Illustration of the carbon-neutral cycle [37].

It is predicted that the consumption of rice will continue in coming decades due to the increasing population and economic development in Africa and Asia especially. It has been predicted that the total global rice consumption will be 450 million tons by 2020; the rice industry will be sustained long terms and the availability of its agricultural waste will remain high [38]. The development of rice husk and straw utilization for energy purposes has been seriously researched and studied worldwide for years, but few researchers have reviewed and analyzed these works. This paper provides a comprehensive review of the technology available for the production of renewable energy from rice crops and their residues.

2. Advantages of Biomass

There are many agricultural waste products classified under energy crops, such as rice straw, rice husk, wheat, potatoes, and residues from processing fruits [39]. The Association of Southeast Asian Nations (ASEAN) countries have an abundant supply of biomass, but it is unevenly distributed. Malaysia, as one of the top palm oil producers, could be a major contributor to renewable energy from biomass [40,41]. Other countries rich in biomass are Cambodia, Myanmar, and Laos. Due to a lack of financial means and slow progression of technology, agricultural residues are normally disposed of in these countries by open burning, where their energy potential is not being utilized [42].

Biomass offers some benefits compared to other sources of power generation. The advantages of biomass are [43–46] as follows:

(i) Renewable energy source
This source of biomass will never run out as crops, manure, and garbage are continuously produced by human activities.

(ii) Carbon-neutral
Utilizing biomass in the power generation industry basically follows the principle of the carbon-neutral cycle. Therefore, there is no contribution to greenhouse gas emissions when biomass-based fuel is burnt in power plants.

(iii) Cost-effective
Biomass energy is cheaper compared to other forms of renewable energy generation. It has been reported that utilization of 70% of rice husk residues could contribute 1328 GWh electricity production annually, and the cost of per unit electricity generated using rice husk is 47.36 cents/kWh, compared to 55.22 cents/kWh of electricity generated by coal [47].

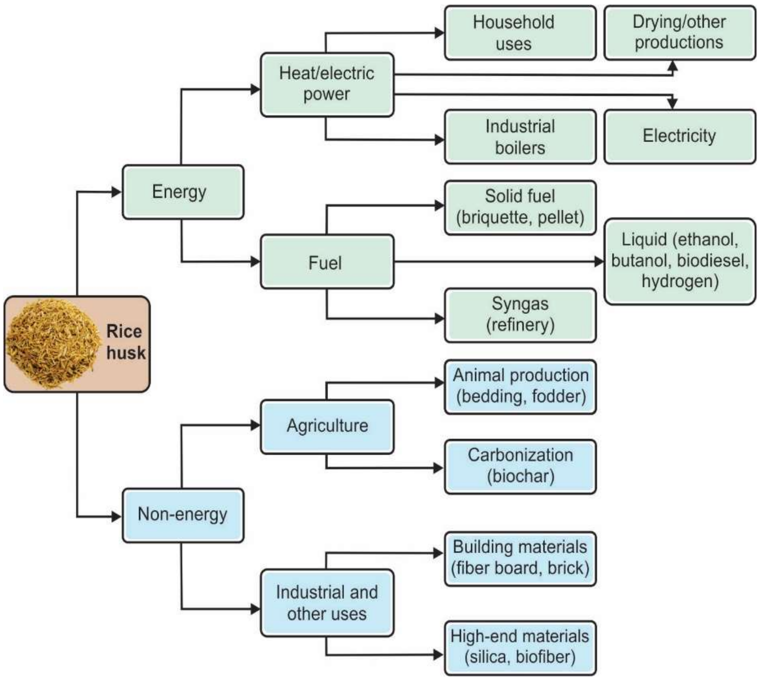
(iv) Ability to have small scale power production
By using the gasification method, power production can be done on a small scale, especially in rural areas.

(v) The large variety of feedstock
Biomass power is capable of incorporating a variety of feedstock, such as rice straw, rice husk, wood pellets, bagasse, etc.

(vi) Reduces methane gas
The decomposition process of organic matter indirectly releases methane gas; combustion of the biomass to produce energy could control the release of methane gas.

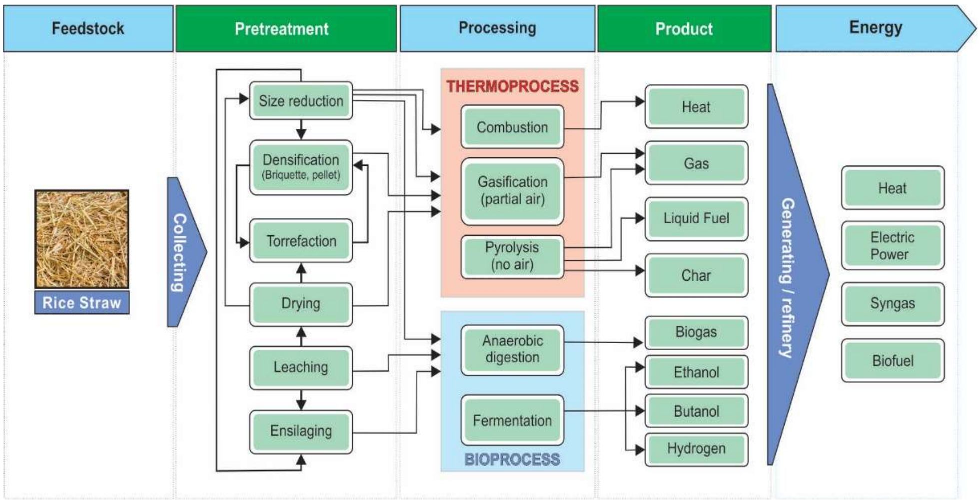
3. Agricultural Residues from Rice Crops

In general, agricultural wastes are biomass residues that can be divided into two categories, namely the crop residues and the agro-industrial residues. Crop residues can be further divided into different sub-groups, such as rice straw and rice husk. Rice husk is the outer layer of a rice seed. Rice husk is removed from the rice seed as a byproduct during the milling process. Rice straw is the stalk of the rice plant, which is left in the field as a waste product upon harvesting of the rice grain (i.e., the seeds of rice). Rice straw is produced when the paddy plant is cut at grain during harvest [48]. Rice straw actually makes up almost 50% of the clean weight of rice plants, and this may vary in the range of 40–60% depending on the method used during cultivation. Therefore, it is clear that almost half of the weight of the plant is contributed by the straw. Figure 2a,b shows the potential application of rice husk and rice straw for power generation.



(**a**)

Figure 2. *Cont.*



(**b**)

Figure 2. The potential application of (**a**) rice husk and (**b**) rice straw for fuel and power generation.

Kadam et al. [49] stated that for every ton of rice grain obtained, there is at least 1.35 tons of rice straw residue remaining in the fields. Therefore, looking at the paddy production reported in previous studies, it becomes clear that the amount of agricultural rice straw residue produced is extremely high. According to Zhiqiang Liu [50], rice straw waste represents about 62% of the rice production in China, and it is not utilized properly for energy generation. In Taiwan, during 2007, based on the paddy field area of 9375 ha, around 0.0563 million tons of wet and fresh rice straw remained at farms following the rice harvest. The total planted area was 38,862 ha, producing up to 0.233 million tons of rice straw [51]. Different researchers have reported different residue ratios of rice straw and rice husk, varying from 1.0 to 3.96 and 0.2 to 0.33, respectively. Table 1 shows the rice crop, rice straw, and rice husk production of the top 20 rice-producing countries. Globally, 769.75 million tons of rice straw and 153.95 million tons of rice husk was produced in 2017, which could have been used to produce 638.03 PJ of energy [38].

Table 1. Rice crop, rice straw, and rice husk production in the top 20 rice-producing countries in 2017 [52].

Countries	Rice Crop (million tons)	Predicted Rice Husk [a]	Predicted Rice Straw [b]	Energy Potential (PJ)
China, mainland	212.68	42.54	212.68	638.03
India	168.50	33.70	168.50	505.50
Indonesia	81.38	16.28	81.38	244.15
Bangladesh	48.98	9.80	48.98	146.94
Vietnam	42.76	8.55	42.76	128.29
Thailand	33.38	6.68	33.38	100.15
Myanmar	25.62	5.12	25.62	76.87
Philippines	19.28	3.86	19.28	57.83
Brazil	12.47	2.49	12.47	37.41
Pakistan	11.17	2.23	11.17	33.52
Cambodia	10.35	2.07	10.35	31.05
Nigeria	9.86	1.97	9.86	29.59
Japan	9.78	1.96	9.78	29.34
USA	8.08	1.62	8.08	24.25
Egypt	6.38	1.28	6.38	19.14
Republic of Korea	5.28	1.06	5.28	15.85
Nepal	5.23	1.05	5.23	15.69
Lao People's Democratic Republic	4.04	0.81	4.04	12.12
Madagascar	3.10	0.62	3.10	9.30
World total	**769.75**	**153.95**	**769.75**	**638.03**

[a] Predicted residue ratio of 0.2 and [b] predicted residue ratio of 1.0.

4. Characteristics of Rice Crop Residues

The size of rice husks is normally uniform, similar to the size of grain, and they are normally very dry with a very low moisture content. Husks are normally collected at the factory level where grain is processed. Rice husk has good market access and can be traded, because there are already established rice husk power plants (e.g., the 2.5 MW rice-husk-based cogeneration plant at Hanuman Agro Industries Limited), and it can also be used in the co-firing process. Husks do not require preprocessing due to their low moisture content and high ash content, and so can be directly used for heat generation or energy generation in power plants [18,53,54]. Rice straw is usually very bulky and it is normally dry, although under circumstances of the rainy season, it is normally wet. It is a field-based resource that most farmers do not collect from the field after the harvesting process. However, both rice straw and rice husk are composed of hemicellulose (35.7% and 28.6%), cellulose (32% and 28.6%), lignin (22.3% and 24.3%), and extractive matter (10% and 18.4%), respectively.

In addition, rice crop residues have several properties which can be determined through proximity analysis, ultimate analysis, and elemental analysis. Both residues of rice crops also have high heating values of 15.84 MJ/kg and 15.09 MJ/kg, respectively, which indicates their energy content and potential as a source of power generation. Table 2 lists the important properties of rice crop residues [38,55,56]. The properties of crop residues affect combustion performance during power generation. For example, extractive content characteristics play a role in higher heating values (HHV) and lower ash contents. The presence of Na, K, and P also lowers the melting point of rice husk and rice straw, which may cause fouling and corrosion.

Table 2. Properties of rice crop residues.

Analysis	Properties	Rice Husk	Rice Straw	References
Constant volume	HHV MJ/kg	15.84	15.09	[38]
Proximate analysis (% dry fuel)	FC	16.22	15.86	[55]
	VM	63.52	65.47	
	AC	20.26	18.67	
Ultimate analysis (% dry fuel)	C	38.83	38.24	[55]
	H	4.75	5.20	
	O_2	35.47	36.26	
	N	0.52	0.87	
	S	0.05	0.18	
	Cl	0.12	0.58	
	AC	20.26	18.67	
Elemental analysis of ash (%)	SiO_2	91.42	74.67	[55,56]
	Al_2O3	0.78	1.04	
	TiO_2	0.02	0.09	
	Fe_2O_3	0.14	0.85	
	CaO	3.21	3.01	
	MgO	<0.01	1.75	
	Na_2O	0.21	0.96	
	K_2O	3.71	12.30	
	SO_3	0.72	1.24	
	P_2O_5	0.43	1.41	

5. The Conversion Process of Rice Crop Residues into Power

Rice straw has three key elements: silica, high cellulose, and a long decomposition period. Rice straw is widely used, including as animal feed and to produce non-wood fibers for newsprint production and corrugated mediums. Rice straw can be converted into bioethanol, a clean-burning fuel [57]; however, this requires a costly chemical conversion process. Rice straw can also be used as a fuel source in a combustor or utility boiler. It is necessary to avoid slagging and fouling during the boiling and combustion processes. There are two processes for harvesting energy from rice straw [58]: thermochemical and biochemical processes. The choice of conversion process depends upon the type and quantity of biomass feedstock; the desired form of the energy, i.e., end-user requirements; environmental standards; economic conditions; and project-specific factors. Figure 3 shows a typical rice husk power plant. The details of both thermochemical and biochemical processes are discussed in the following sections.

5.1. Thermochemical Processes

The thermochemical conversion processes can be classified into two categories: direct conversion of biomass to energy products, and conversion of biomass into another form which can be used later to produce energy. The thermochemical processes include direct combustion, gasification, and pyrolysis.

5.1.1. Direct Combustion

In this process, the chemical energy stored into the biomass is converted into heat, electricity, or mechanical power by burning the biomass in the presence of air. For feasible energy production, the biomass should have a moisture content of less than 50%. This process has some disadvantages. In most cases, pretreatment of biomass is important before burning. Some pretreatment processes include drying, chopping, grinding, etc. Pretreatment processes increase financial costs and energy expenditure [59,60]. Combustion is the most widely used thermochemical process, especially in developing countries, accounting for some 97% of the bioenergy obtained worldwide [61,62]. Indirect combustion processes refer to the use of biomass as a source of fuel in a boiler, contributing to the production of steam in the presence of oxygen in the boiler. The steam is used to generate heat and electricity concurrently using a turbine.

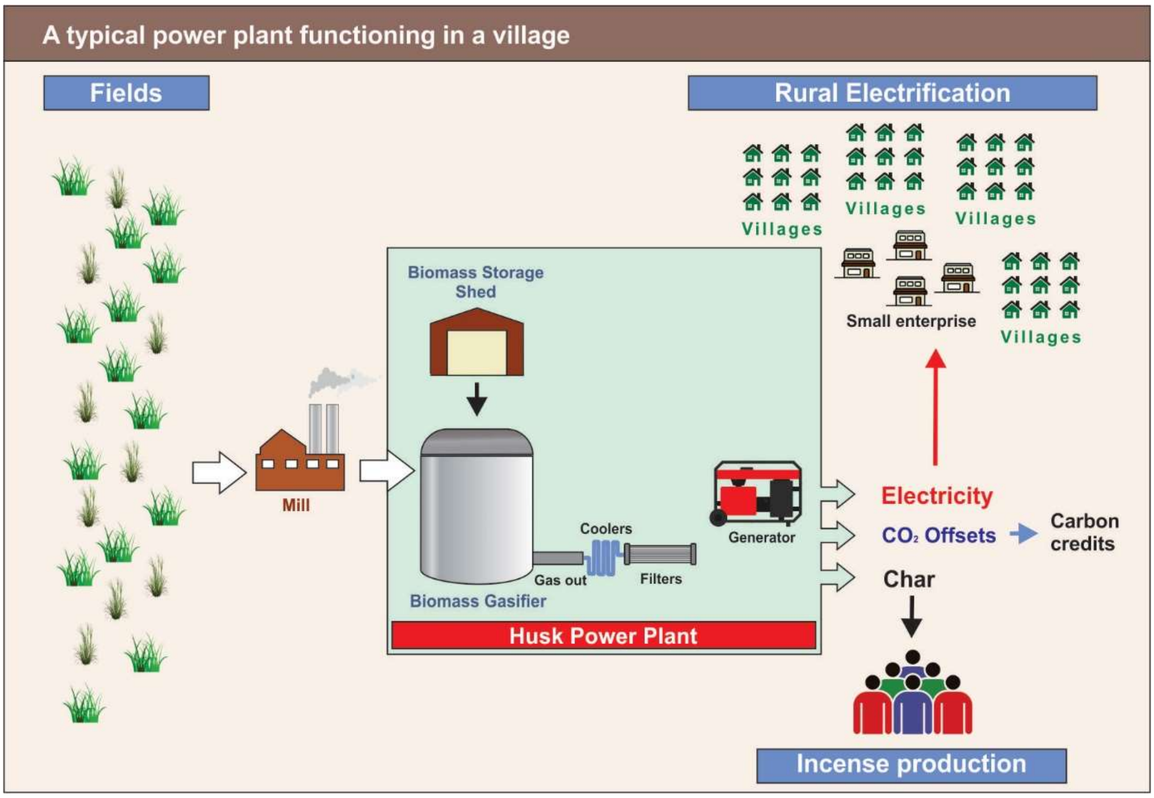


Figure 3. A typical rice husk power plant.

5.1.2. Gasification

The biomass is heated at high temperatures (800–900 °C) with an insufficient supply of air (partial oxidation); as a result, a combustible gas mixture is produced. Rice husk gasification power generation has become very popular in many Asian countries like China, Indonesia, India, Thailand, Cambodia, and the Philippines. The advantages of gasification are that the gas produced can be used in gas engines, gas turbines, and fuel cells for electricity generation at higher efficiency. Pode et al. [63] mentioned that one ton of rice husk can produce 800 kWh of electric power and can save about 1 ton of CO_2 emissions compared to current uses. Prasara et al. [64] mentioned that an ideal gasification process yields only non-condensable gas and ash residue. Susastriawan et al. [65] investigated the compatibility of a downdraft gasifier using different feedstocks such as rice husk, sawdust, and their mixture, and found that the optimum equivalence ratios of the producer gas were 3.13, 2.69, and 0.35 MJ/Nm^3, respectively. The potential of rural electricity generation using biomass gasification system was discussed by Abe et al. [66]. However, tree farming is required to provide a long-term biomass supply for gasification.

5.1.3. Pyrolysis

Pyrolysis occurs at high temperatures and in the absence of air with biomass decomposition. The nominal operating temperature range is 350–550 °C. The ratio of the products from pyrolysis, gas-, liquid-, and carbon-rich residues, depends on the operating conditions of the process. Bridgwater et al. [67] indicated that a fast pyrolysis process is very important and consists of the principal reaction systems and processes along with the resulting liquid products. Depending on the temperature, heating rate, and residence time, there are three main types of pyrolysis process found: namely, slow, fast, and flash. The main product of slow pyrolysis process is char, with a small amount of oil and gas. The fast pyrolysis process produces mainly pyrolysis oil, whereas the main product of flash pyrolysis is gas. Fukuda et al. [68] found that a maximum 50% wt. pyrolysis oil yield could be achieved through a fast pyrolysis process using rice husk. Another study showed that about 75% wt. pyrolysis oil can be obtained on a dry feed basis using a fast pyrolysis process [69].

5.2. Biochemical Processes

Different useful products can be obtained through the conversion of biomass using the following bio-chemical processes.

5.2.1. Anaerobic Digestion

An anaerobic digestion process refers to the conversion of biomass into biogas by microorganisms (the combination of carbon dioxide and methane) in the absence of oxygen. This biogas is an excellent source of fuel for the generation of heat and energy. Anaerobic digestion of rice straw is not a new concept; however, its renewable energy potential has barely been analyzed. Mussoline et al. [70] mentioned that optimum digestion conditions of pH (6.5–8.0), temperature (35–40 °C), and nutrients (C:N ratio of 25–35) could produce methane yields of 92–280 l/kg of volatile solids. Matin et al. [71] investigated the development of biogas production from rice husk by solid-state anaerobic digestion (SSAD) and found that lignin content was very difficult to degrade using microbes. They also found that a better biogas yield was produced by using the SSAD method compared with liquid anaerobic digestion (LAD). Haryanto et al. [72] investigated the effect of urea addition on the biogas yield from co-digestion of rice straw and cow dung using a semi-continuous anaerobic digester, and concluded that urea addition positively influenced the biogas yield and its quality.

5.2.2. Fermentation

Bioethanol produced from lignocellulose biomass generally involves three main steps: (i) pretreatment, (ii) enzymatic hydrolysis, and (iii) fermentation. The first step involves sieving and pelletizing which is very important for reduction of transportation expenses and handling fees. The second step involves the transformation of cellulose and hemicellulose biomass into glucose, pentoses, and hexoses [73]. In the third step, glucose is fermented into ethanol by a chosen microorganism. However, the conversion of rice straw and rice husk is possible through the different simultaneous processes, including saccharification and fermentation (SF) and separate enzymatic hydrolysis and fermentation processes. An overview of the fermentation process of biomass to produce ethanol was provided by Binod et al. [74]. They mentioned that the high ash and silica content in rice straw made it an inferior feedstock for bioethanol production. Swain et al. [75] used rice straw and wheat straw for bioethanol production and found some challenges, such as the lignin, ash, and silica content of rice straw, which required an appropriate pretreatment process. However, other researchers found that ethanol production from rice straw could be achieved up to 83.1% [76]. A summary of rice crop residue research in recent years is presented in Table 3.

Table 3. Summary of recent research in agricultural residues.

Technology	Details	Year	References
Gasification	Experimental investigation on the role of operating conditions on gas and tar composition and product distribution of rice husk gasification in the existence of dolomite.	2019	[77]
	Described the repossession of hydrogen gas from rice husk aided by nanoparticles.	2019	[78]
	Presented an investigational reference for biomass gasifier design and operation.	2016	[79]
	Investigated the feasibility of enhanced energy yield in gasification of rice straw by using a prepared iron-based catalyst.	2016	[80]
	Investigated the characteristics of rice husk from varieties of rice and the benefits of power generation using rice husk compared to a diesel generator.	2016	[81]
	Investigated the experimental statistics of air-staged cyclone gasification of rice crops.	2009	[82]
	Studied the role of different parameters on the gasification performance using rice husk biomass in power generation plant.	2009	[83]
	Studied the role of equivalence ratio on the performance of two-stage gasifier using rice straw.	2009	[84]
Pyrolysis	The physicochemical and toxicological characteristics of rice husk (RH) and rice husk ash (RHA) pyrolysis were investigated.	2019	[85]
	Bio-oil made from rice husk by a commercial-scale biomass fast pyrolysis plant was utilized to investigate the effects of long-period storage (two years) under three different conditions.	2019	[86]
	Investigated the potential tertiary treatment of wastewater by adsorption using rice husk biochar (RHC) obtained from microwave pyrolysis of rice husk.	2019	[87]
	Focused on liquid fuel production through co-pyrolysis of polythene waste and rice straw in varying compositions and characterized the liquid products.	2019	[88]
	Evaluated the effects of different demineralization processes on the pyrolysis behaviour and pyrolysis product properties of raw/terrified rice straw.	2018	[89]
	Investigated the pyrolysis process in a fluidized-bed reactor using rice husk biomass under different operating conditions.	2010	[90]
	Studied the effect of pyrolysis of rice straw biomass in a microwave-induced reactor for the production of hydrogen gas.	2010	[91]
	Produced bio-oil through fast pyrolysis using rice husk biomass in a fluidized-bed reactor.	2011	[92]

Table 3. *Cont.*

Technology	Details	Year	References
Anaerobic digestion	Evaluated the effect of pretreated rice straw on high-solid anaerobic co-digestion with swine manure, focusing on biogas production and kinetics.	2019	[93]
	Investigated rice straw physicochemical characteristics and anaerobic digestion (AD) performance via ammonia pretreatment.	2019	[94]
	Analyzed anaerobic digestion of heavy-metal-contaminated rice straw inoculated with waste-activated sludge.	2018	[95]
	Provided useful parameters to evaluate biogas production via anaerobic digestion of rice straw	2018	[96]
	Investigated the effect of trace element (TE) addition and NaOH pretreatment on the anaerobic digestion of rice straw.	2018	[97]
	Studied the role of sodium hydroxide composition and extractives on the improvement of biogas yield through anaerobic digestion.	2009	[98]
	Studied the influence of different operating condition and method on the production of biogas using rice straw through anaerobic digestion.	2009	[99]
	Studied the use of rice straw and swine feces for anaerobic co-digestion in a fed-batch single-phase reactor.	2009	[100]
	Investigated the co-digestion process for biogas production using cow dung and rice husk.	2009	[101]
	Studied anaerobic digestion performance using rice straw with acclimated sludge and phosphate at room temperature.	2010	[102]
	Reported on the variation of efficiency of anaerobic digestion using rice straw with the variation of solid concentration at different temperatures.	2010	[103]
Fermentation	Studied the ethanol production process through the synchronized saccharification and co-fermentation of rice straw biomass with *Candida tropicalis*.	2010	[104]
Direct combustion	Reported on the performance of rice husk combustion with bituminous coal in a cyclonic fluidized-bed reactor.	2009	[105]
	Investigated the co-firing performance of rice husk with coal in a fluidized-bed reactor with a small combustion chamber.	2009	[106]

6. Current Rice Crop Residue Management

Rice straw is the waste product of paddy production. It comprises up to 50–60% of the paddy itself, and is produced during every harvesting process. There must be a way to manage all the resulting waste. The current methods used by most farmers include open burning, soil incorporation, animal feed, and removal from the field. There is no productive method used due to the cost issues and lack of development in rural areas. Each method has different impacts on the environment and on the nutrient balance and long-term soil fertility due to continuous plantation activities [107].

The straw removal method is used widely in India, Bangladesh, and Nepal. The repeated process of straw removal has resulted in field soils with low potassium (K) and silicon (S), which will present a major problem in the coming years. Apart from that, the removed straw also serves different purposes, such as fuel for cooking in rural areas, ruminant fodder, and stable bedding. It could also be used in the papermaking industry. Most rice straw removal involves loose straw racking, baling it in small bales, and road-siding the bales. Processed rice straw is normally baled and hauled. The baling format, e.g., round, square, large, or small, mostly depends on the farmer and what method is preferable for disposal [108]. If the paddy field is small, straw removal will not be sufficient due to the lack of cost-effectiveness in using vehicle to remove straw from the field. Compared to other management methods, straw removal is the best choice for reducing pollutants; the only setback is the emissions caused by the use of the vehicles transporting the rice straw [109].

The most common method of rice straw disposal is burning. It is the easiest method, involves no additional management cost, and is one of the fastest ways to dispose of all rice straw during harvesting time. This method might be helpful for farmers and paddy field operators but it has a major effect on the environment. According to Dobermann, the burning disposal method ignites atmospheric pollution which also results in nutrient loss, but is the most cost-effective method and has the capability to reduce pests and diseases [107].

Normally, during combustion, very high amounts of CO_2 are released along with carbon monoxide (CO), methane, nitrogen oxides, sulfur dioxide, etc. Some of these gases are classified as toxic and may be human carcinogens. There have been medical issues faced by communities in Japan, India, and California due to continuous exposure to open burning, mainly asthma and pulmonary morbidity. This practice has been banned in several paddy-producing countries, including California. It is still widespread in Asian countries due to the lack of rules regulating open burning enforced by the government. Not only does open burning cause air pollution, but there are also high nutrient and energy losses. Most importantly, it is a clear waste of potential energy where straw energy could be dissipated into heat [110–112].

An alternative to open burning is soil incorporation, which is widely practiced among farmers to re-fertilize the soil. The nutrients can be recycled for the next crop cycle and the waste is turned to good use and helps to maintain soil quality. The incorporation method mostly uses rice straw and stubble by ploughing (wet soil during land preparation or dry soil during fallow periods). This particular method has caused a serious increase in methane gas emissions [108,110]. Table 4 shows the greenhouse gas (GHG) emission factor for different rice straw management.

Table 4. GHG emission factor (EF) for different rice straw management practices [113].

Rice Straw Management Practice	Name of Pollutant	Emission Factor
Open burning	CH_4 (methane)	1.2 g/kg (dry fuel)
	N_2O (nitrogen dioxide)	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 EF for continuously flooded fields without organic amendment	1.3
	Conversion factor for rice straw amendment	1.0 for straw incorporated <30 days before cultivation 0.39 for straw incorporated >30 days before cultivation
	Scaling factor to account for differences in water regime during the cultivation period	0.78 for irrigated
	Scaling factor to account for differences in water regime in the pre-season before the cultivation period	1 for irrigated (<180 days); 1.22 for rain-fed
Composting and incorporation	CH_4 (wet soil)	13.37 kg/ton yield
	CH_4 (dry soil)	2.1 kg/ton yield
Rice straw used as animal feed	CH_4	10,000–20,000 gCH_4/ton dry weight
Rice straw for mushroom production	CH_4	7.27 gCH_4/ton dry weight

7. Challenges in Rice-Crop-Residue-Based Power Generation

The concept rice-crop-residue-based power generation represents an effective method of converting waste into electricity. The first ever rice-crop-based power plant was built in Jai Kheri village in the Patiala district of Punjab in 2006, with a capacity of 10 MW. In China, the first power plant based on rice straw was built, also in 2006, and since then, straw-based power generation has been developing in a remarkable way. The demand for straw in China is roughly 2.13 million tons/year, with 10 direct-fired power plants, one gasification plant, and other mixed-fired plants [114]. However, some challenges still exist in the establishment of rice-crop-based power plants. There are still high chances that these plants could face major problems due to ongoing changes in the state's agricultural and industrial activities. If there is any diversion in agricultural activity, such as from rice paddy to higher-value crops, then the amount of rice straw will drop, causing the plant to fail [115–117]. Zhiqiang [50] explained the challenges for the combustion of rice straw in China; the main challenges are harvesting issues, process and system considerations, technical improvement, and policy support. The details of the challenges are as follows.

7.1. High Ash Content

The main challenge is managing the high ash content of in rice straw, and also the alkali metals such as sodium and potassium that are present. During the combustion process, these chemicals could cause slagging, fouling, and corrosion in superheaters. Slagging refers to deposits of slag material and fouling is accumulation of unwanted particles on solid surfaces. In addition, there is the deterioration of catalysts for nitrogen oxide reduction. Ash from coal has properties useful for cement production, whereas ash from straw cannot be used for any other industries; therefore, it becomes an unmanaged waste [118].

7.2. Harvesting Issues

The collection of rice straw brings up several concerns. First, pests and disease infecting the rice straw could reduce the quality of it. The timeliness of operation has to be short to avoid high expenditures on labour cost; therefore, a system has to be developed to make the collection time just sufficient. Continuous removal of rice straw from paddy fields could cause loss of soil nutrients in the field, and extra fertilizer will be required to restore the minerals lost. However, the addition of fertilizer will have some negative impacts on the soil and may result in increased emissions. The usability of the machines in the field is also an important consideration. The machines should be capable of operating all conditions including muddy fields, and the field should be able to withstand the weight of the machinery used during the harvesting process. Grower attitudes mainly concern farmers' understanding of the collection system, for which the best way forward is to offer incentives to the farmers that provide rice straw.

7.3. Process and System Consideration

There must be a system established for each process, including collection, processing, and transportation of rice straw to the power plant. These systems could ensure that the cost of using machinery for harvesting and the quantity of rice straw could be determined. Drying is definitely required to reduce the moisture content in wet rice straw from 60–70%. It is necessary to wait for the moisture content to drop to 25% for complete combustion to be achieved. Apart from that, if the straw retains a high moisture content, the chance of fermentation increases, which would lessen the quality of the straw. It is more costly to transport wet rice straw compared to dry rice straw; this represents another reason that the drying process is necessary. Besides drying, rice straw should go through densification to increase the bulk density, which will reduce the logistical costs. Moisture content plays an important role in power generation; baled straw has a moisture content of 10–18%, and when the moisture content exceeds 13%, the power output is reduced by 2% for the same feedstock amount [119].

8. Logistical Analysis

Logistics practically describe a distributed flow of things from one point to another. Logistical analysis is very important due to the effect of the cost of transportation, which is relatively high due to the bulk density of rice straw [120]. In this case, we are referring to rice straw transportation from the paddy field to the power plant. Before being transported to the power plant, there are several pit stops it has to go through for processing and collection purposes. The four main processes are harvesting, collection, storage, and transportation. The main concern in harvesting would be increased speed and efficiency of harvesting, instead of focusing on increasing the straw yield. The current rice straw storage facilities in California are suitable, but there are several drawbacks in maintaining the quality of the rice straw.

Many end-users prefer good quality straws with low moisture content and low contamination. These end-users mostly use the straw for power generation purpose. When harvesting, collection, and storage activities increase, the transportation of rice straw to the corresponding end-user will eventually increase as well. Therefore, suitable transportation infrastructure should be established to make sure that sufficient quantities of rice straw can be distributed in an acceptable time [121].

Due to the bulk density discussed earlier, the use of rice straw for power generation has issues related to transportation cost. It is very expensive to transport rice straw compared to coal [122–129]. Besides rice straw, there are many other logistical impacts related to transportation, as discussed in Table 5. The cost of operating a rice straw power plant depends solely on the harvesting, processing, and transporting cost. The use of machinery in forming bales of rice straw is normally powered by diesel, where the cost of bales varies in different countries according to their operating cost. Forming rice straw into bales is very important due to the resulting size reduction and increase in bulk density. Much space is saved by compacting the rice straw into bale form before transporting.

The power requirement for a tractor is about 30 kW, which increases if a higher number of bales need to be produced in a short period of time. The authors mainly focused on the work rate, power requirement, size, quality and mass of bale on a small area of 50 ha of paddy production to determine the techno-economic analysis [130–133].

Table 5. Main parameters impacting logistical costs [134].

Parameter	Impact on Cost	Type of Biomass	Country
Distribution of efficient biomass management	Minimizing transportation cost	Any type	Spain
Effective and efficient planning of logistical operations	Minimizing transportation cost	Agricultural crop	Canada
Increased transport vehicle capacities	The minimum cost of transportation	Cotton plant stalks	Greece and Europe
Maximized truck utilization factor	Minimizing transportation cost	Herbaceous biomass	United States
Increased size of power plants	Logistical constraints on economic performance became less restrictive	Agricultural crop, agro-industrial, and wood waste	Italy
Biomass storage	Has a significant role in biomass logistics	Cotton stalk and almond tree pruning	Greece
Site productivity	A high productivity plantation would reduce the transportation cost	Eucalyptus	United States
Increased bulk density	The minimum cost of transportation	Agricultural and woody biomass	Canada
Development of more efficient collection and transport systems	The minimum cost of transportation	Corn stover	United States

On top of that, the most crucial criterion in baling is that the moisture content of the particular rice straw has to be below 20%. The best method by which to achieve this is to carry out the baling process 2–3 days after harvesting. There are two main baling techniques: small rectangular bales and big rectangular bales. Small rectangular bales are already being implemented in Thailand, whereas study has focused more on big rectangular bales for their higher density. Bales have to be dense to ease the transportation cost [135]. Figure 4 shows an overview of the logistical model. It explains how rice straw is transported to a power plant [134].

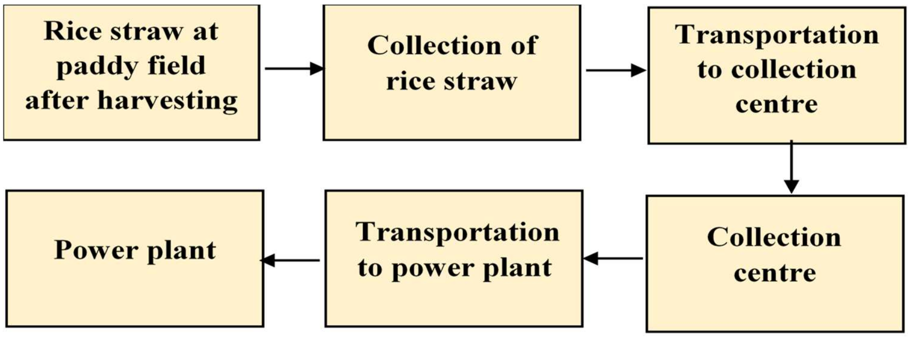


Figure 4. Overview of the logistical model [134].

The first process involved is rice straw being left to sun dry after harvesting; it is then baled in a rectangular form to ease transportation. Secondly, all rice straw in a particular field is collected and transported to a collection center, where all other straw bale from other paddies are also collected. Once the capacity of the collection center is almost reached, the rice straw is checked for quality and moisture content before being transported to a power plant for energy generation purposes. The quality and moisture content are checked to avoid any drop in power plant efficiency. Therefore, the collection center has to have equipment able to check the quality of rice straw, and also equipment to dry bales of rice straw if their moisture content exceeds the required limit.

9. Conclusions

The paper reviewed the possibility of power generation using rice husk and rice straw, and the various factors that impact their production. Based on the literature, the following can be concluded:

- Rice straw has very high potential for power generation; however, sustainable energy production depends on the availability of rice straw.
- Properties of rice straw vary between countries due to relative humidity and the use of different types of fertilizer.
- Though rice straw power plants are eco-friendly, the major problems preventing wide implementation are logistical issues, which contribute to about 35–50% of the total operation cost. Therefore, a detailed cost–benefit study must be conducted to avoid losses and make sure the power plants are sustainable in the future.

There are few things to be considered in the establishment of rice-crop-based power plants:

- The amount of rice straw available in an area, because it is the main supply of feedstock for the plant. A simple method could be used to determine the straw amount in an area, namely the straw to grain ratio. In most studies a ratio of 0.75 is used.
- Ash content and alkali metal contents affect the combustion process.
- The supply of rice straw should have a low moisture content to enable complete combustion and increase efficiency. If the moisture content exceeds 13%, the power output is reduced by 2%.

Before rice straw is fed into a power plant, it has to undergo preprocessing to reduce the moisture content, and the easiest method for this is open sun drying before collection. The next step is to have a decent rice straw supply chain to the power plant. Therefore, the power plant should be located in a strategic location. Finally, it can be concluded that rice husk and rice straw could be a potential source of renewable energy if various factors such as straw properties and logistics can be improved.

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