Energy harnessing routes of rice straw

Rice is one of the most important food grains of India in terms of area, production and consumer preference. India produced about 105 MMT of rice in 2015–16 accounting for 23% of global production, becoming the largest producer in the world after China[1]. Rice–wheat cropping system is a widely practised cropping system in India covering about 9.5 m ha. Wheat is sown immediately after rice and there is little time available between harvesting of rice and planting of wheat which compelled farmers to adopt mechanized harvesting of rice. In rice–wheat cropping system, combine harvester is the most common machine for mechanized harvesting. Combine harvesters leave all straws and chaffs on the field which create hindrance while sowing the next crop. Collection, transportation and storage of straw are energy and cost-intensive. For this reason, farmers burn them in the field which is the easiest way to get rid of the straw. Burning of rice and wheat straw causes emission of gases like CO, CO_2, CH_4, N_2O, NO_x, NMHCs (non-methane hydrocarbons) and aerosols which pollute the local environment[2]. In 2009, the estimated emission of CO_2, CH_4, N_2O, CO, NMHCs, NO_x and SO_2 from burning of rice straw alone was 16.253, 13, 1, 386, 45, 35 and 22 MMT, respectively[3]. Further, burning also causes residual nitrogen loss of 40–80% and residual sulphur loss of 40–60%. The heat of burning also kills the beneficial microbes at the top layer of soil[2].

The estimated production of rice straw in India was about 157 MMT in 2015–16. This huge quantity of straw can be utilized as means of bio-energy production to replace fossil fuel. But, to be a viable substitute of fossil fuels, it should be environmentally beneficial when compared to fossil fuel, economically competitive and should be available in sufficient quantities. While there is no doubt regarding availability and environmental superiority, technical and economic viability is a major concern[4]. Hence, the efficient energy conversion route should be selected carefully.

The major constituent of rice straw is hemicelluloses (30–35%) followed by cellulose (21–31%) and lignin (4–19%). Calorific value (15–17 MJ/kg) is also lower when compared to other fuel biomass (Table 1). Bulk density of loose straw is approximately 75 kg/m^3 which is the reason for higher energy input in handling and storage. There have been many ways by which rice straw can be converted to energy in the form of steam[5], briquettes[6], pellets, biogas[7], producer gas[4], bio-oil, bio-char and ethanol[8]. Among these routes of energy conversion, hydrogen and bio-oil production are still in laboratory scale. The other five ways which may have commercial viability are discussed here in brief in terms of energy efficiency and energy productivity (Table 2).

As seen in Table 3, basic operations such as collection, transportation, conveying, drying, elevating and lighting are the same for all routes. For collection, a baler having 0.26 ha/h capacity has been considered as it is the most common baler used in the country. With a straw productivity of about 6 t/ha and single bale of 25 kg with density of 150 kg/m^3, time requirement for 40 bales will be 0.64 h. Fuel consumption will be approximately 3.20 l. In the case of transportation, for a distance of 20 km a trolley of two tonne capacity attached with a tractor will consume 4.50 l of fuel and 4 human-hours. For conveying, drying, elevating of bales and lighting of farm house, manpower, diesel and electricity requirements are 2 human-hours, 6 l and 12.8 kWh respectively. So, altogether to bring and store rice straw in the form of bales we need approximately 840 MJ/t of energy.

To generate steam by direct combustion the total energy input is 900 MJ. The only addition in energy need is to operate the air blower for burning them in the gasifier after the basic operation of collection, transportation and storage. For production of biogas, paddy straws are finely chopped. Long straws clog the digester causing less flow or no flow of slurry out of it which ultimately stops production of gas. Feeding of chopped straws to digester requires lot of manual hands which may result in higher cost but lesser energy requirement. Digesters also need to be kept warm during winter to achieve mesophilic temperature range in which methanogenic bacteria are most active. This helps in producing more gas[9]. For chopping and feeding, manual and electrical input energy was found to be 35.28 and 57.6 MJ/t respectively. For heating of digesters hot water is necessary and for this, the energy need was approximately 900 MJ which may be supplied by burning the straw itself. Therefore, total energy input in biogas production was to the tune of 2700 MJ/t.

Rice straw can be fed to gasifiers as whole bale or by chopping it to small pieces. For gasification alone, an electrical energy need of 16.9 kWh/t was observed[10,11]. As seen in Table 4, higher electrical energy (76.5 kWh/t) is required in the process of briquetting for chopping, grinding and compressing. For ethanol fermentation, chopping, grinding and pre-treatment are basic need. Steam explosion process was considered as the pre-treatment process for rice straw as it gave higher ethanol productivity. Steam explosion is a heat treatment process in which very high pressure steam is induced to the biomass in a closed container. Then it is suddenly exposed to a lower pressure vessel. Due to sudden change in pressure the high pressure water droplets inside the tiny pores of biomass explode causing minute breakdown of lignin and cellulose bonds[8]. Pre-treatment needs heat which can be provided by directly burning the straw. In ethanol fermentation, there are number of refining processes to increase the concentration of ethanol in brewed solution. Most of the processes are distillation which also need heat energy. A total of 12,917 MJ/t of input energy was required in ethanol fermentation process.

If we compare total energy input in different routes, ethanol fermentation needed the highest and direct combustion needed lowest. If we compare sector-wise, it gives an important observation.

Table 1. Properties of rice straw[4]

Properties	Value
Heating value, MJ/kg (dry basis)	17.14
Proximate analysis (wet basis, wt.%)	
Moisture	8.25
Ash	12.26
Volatiles	66.24
Fixed carbon	13.21
Thermogravimetrical analysis, wt.%	
Hemicellulose	30–35
Cellulose	21–31
Lignin	4–9

Table 2. Energy conversion routes of rice straw

Name of the process	Process conditions	Product	Output/t of straw	Energy in unit product	Total energy output, MJ/t	Reference
Direct combustion	Direct burning inside furnaces with ample supply of air to generate steam.	Steam	640 kg	3.33 MJ/kg	2131	5
Anaerobic digestion and biogas production	Digestion of straw inside an anaerobic digester in absence of air and production of methane enriched biogas.	Biogas	376 Nm^3	20 MJ/Nm^3	7520	7
Gasification and power generation	Conversion of straw using single stage or double stage gasifier and production of producer gas and char.	Producer gas enriched by CO, H_2 and CH_4	1840 Nm^3	5.1 MJ/Nm^3	9384	11
Densification and briquette production	Densification of smashed rice straw using piston mould at 85 kg/cm^2 pressure and 150 °C temperature.	Briquette	950 kg	17.3 MJ/kg	16,435	6
Acid hydrolysis and ethanol fermentation	Ethanol production from pre-treated rice straw by simultaneous saccharification and fermentation.	Ethanol	208 l or 164 kg	30 MJ/kg	4920	8

Table 3. Forms of energy input per tonne in conversion of rice straw in different routes

Operations	Human (Man-h)	Electricity (kW-h)	Diesel (l)	Heat (MJ)
Direct combustion				
Collection	4	0	3.2	0
Transportation	4	0	4.5	0
Conveying, drying, elevating, lighting	2	12.8	6	0
Combustion	1	16.9	0	0
Total	11	29.7	13.7	0
Anaerobic digestion				
Collection	4	0	3.2	0
Transportation	4	0	4.5	0
Elevating and lighting	2	5	6	0
Chopping	6	10	0	0
Digester feeding and fermentation	12	6	0	900
Total	28	21	13.7	900
Gasification				
Collection	4	0	3.2	0
Transportation	4	0	4.5	0
Conveying, drying, elevating, lighting	2	12.8	6	0
Chopping	6	5	0	0
Gasification	1	16.9	0	0
Total	17	34.7	13.7	0
Briquetting				
Collection	4	0	3.2	0
Transportation	4	0	4.5	0
Conveying, drying, elevating, lighting	2	12.8	12.8	0
Chopping	6	5	0	0
Grinding	1	19	0	0
Briquetting	2	52.5	0	0
Total	19	89.3	20.5	0
Ethanol fermentation				
Collection	4	0	3.2	0
Transportation	4	0	4.5	0
Conveying, drying, elevating, lighting	2	12.8	12.8	0
Chopping	6	5	0	0
Grinding	1	19	0	0
Pre-treatment	1	1.5	0	900
Processing and refinement	6	5	0	3952
Total	24	43.3	20.5	4852

Table 4. Different forms of energy input (MJ/t) in conversion of rice straw in different routes

Conversion routes	Human	Electricity	Diesel	Heat	Total
Direct combustion	21.56	106.92	771.45	0.00	899.93
Anaerobic digestion	54.88	75.60	771.45	900.00	1801.93
Gasification	33.32	124.92	771.45	0.00	929.69
Briquetting	37.24	321.48	1154.36	0.00	1513.08
Ethanol fermentation	47.04	155.88	1154.36	4852.00	6209.28

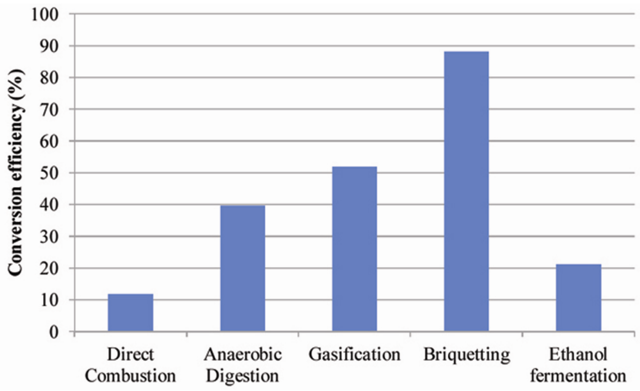

Figure 1. Conversion efficiency of different routes.

As electricity is non-renewable and is scarce, electrical energy need may draw a boundary in adopting some routes like briquetting which needs the highest electrical energy. In comparison, anaerobic digestion for biogas production was found to be very environment-friendly consuming the lowest electrical energy. Although muscle power was negligible in terms of energy value, it might be significant in terms of cost. Anaerobic digestion required highest human involvement. Diesel requirement in briquetting and ethanol production was higher due to greater numbers of handling operations.

Conversion efficiency of different routes is depicted in Figure 1. To calculate conversion efficiency in the input energy calculation, energy contained by the rice straw was also counted with addition to the process energy need. Figure 1 shows that briquetting was the most efficient process. It was due to the fact that the end product briquette had almost the same energy value and the output was also almost equal. There was only 5% mass loss. Least efficient was found to be steam generation. Gasification of rice straw was found to be a good alternative with a conversion efficiency of 52% but is associated with problems of high ash deposition. Bio-gas production had a conversion efficiency of about 40% when only bio-gas energy is considered. This route gives clean energy with least pollution and as by-product manure is produced. This process has practical limitation of digester feeding and decanting. It also needs a specially designed reactor. High acid accumulation during digestion process is another reported problem[9].

All the routes have their own merits and demerits. The above brief analysis of the energy conversion routes shows anaerobic digestion and ethanol fermentation as promising processes. Briquetting is a good alternative when storability is concerned as it takes up very little space. A detailed site-specific field study can give better understanding of the efficient process. The indirect energy expenditure in terms of machinery and material involvement in the process is needed to be included in further studies.

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