Chapter 19
Studies on Biomass Torrefaction for Energy Densification of the Fuel

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Abstract Torrefaction of selected biomass materials was successfully carried out using in-house developed indirectly heated fixed bed reactor (FBR) at varied temperature (200–300 °C) with a heating rate of 10 °C/min for 60 min. Commercially available sawdust pellets (6 mm diameter) were selected for preliminary studies for which the highest energy density around 12875 MJ/m^3 was obtained at 250 °C. For comparison, the torrefaction cum pelletization was further performed on powdered sawdust, rice straw, and cotton stalk biomass materials (0.6 mm). The maximum energy density was observed for the pelleted–torrefied sawdust which was 14080 MJ/m^3 followed by pelleted–torrefied cotton stalk which showed 9450 MJ/m^3 and then pelleted–torrefied rice straw of which 6545 MJ/m^3 energy density was obtained. Our preliminary observations indicate that torrefaction cum pelletization is the best way to improve the energy density of biomass materials than pelletization cum torrefaction.

Keywords Biomass · Fixed bed reactor · Torrefaction · Pelletization · Energy density

19.1 Introduction

Due to increasing concern over depleting fossil fuels (i.e., coal, petroleum, and natural gas), renewable energy resources have gained tremendous attention. Among various class renewable energy resources/carriers, the biomass has shown tremendous potential due to its easy availability, quick processibility, less cost, and zero emission as well as carbon neutrality [1]. Biomass, a promising renewable energy carrier, can be utilized via well-studied thermo-chemical and biological routes. Unfortunately, most of these technologies are still under development for worldwide commercialization for not meeting world energy demands. Moreover, handling, storage and processing of raw biomass feedstock is one of the major challenges among researchers. Some

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S. Singh and V. Ramadesigan (eds.), *Advances in Energy Research, Vol. 2*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-981-15-2662-6_19

of the inherent problems with biomass are their non-homogeneity, low bulk density, high tenacity of biomass that leads to inferior grindability, high moisture content, hydrophilic nature, and low calorific value [2]. All these problems limit its ease of wide application as well as result in low thermo-chemical conversion efficiency as well as difficulties in its collection, grinding, storage, and transportation.

Current bottlenecks led to the development of a novel methodology to enhance the basic fuel properties of biomass. Among the latest developments for improving the quality of raw biomass, the torrefaction is popularly being used worldwide [3]. In fact, torrefaction of the biomass fuel has gained tremendous attention in last few years and has been extensively carried out to get torrefied biofuel having improved fuel characteristics than conventional fuels (i.e., high energy density, materials' homogeneity, calorific value, hydrophobicity, etc.).

Torrefaction, a thermo-chemical route, is carried out at different temperatures (200–300 °C) under oxygen-free environment. During torrefaction, 70–80% of the mass is collected retaining 90% of the initial energy content. Compared to raw biomass, the carbon content and calorific value of torrefied biomass increase by 15–25% while the moisture content decrease to less than 3% [2].

Herein, we aim at biomass torrefaction of selected biomass samples (saw dust, rice straw, and cotton stalk) on our in-house designed and developed torrefaction reactor unit (indirectly heated type fixed reactor) of capacity ~1–5 kg/h to collect the torrefied biofuel of improved fuel characteristics compared to unprocessed biomass. To further improve the energy density of torrefied biofuel, pelletization technique will be employed. Our present work is, therefore, the upgradation of the selected biomass feedstock by torrefaction cum pelletization technology to produce improved biofuel and having potential applications in biomass gasification and pyrolysis further.

19.2 Experimental

The biomass samples selected for the torrefaction study includes wood (sawdust) and two different types of agricultural residues, i.e., rice straw and cotton stalk which are abundantly available in Gujarat. Agro-residues samples were chopped, pulverized, sieved, and separated into 0.6 mm particle size fractions. Preliminary trial runs were carried out with the commercially available fuel wood pellets of 6 mm diameter size. Torrefaction experiments were carried out in SPRERI fixed bed batch type S.S. reactor of 1 kg per batch capacity reactor. Torrefaction temperature was varied between 200 and 300 °C, and the heating rate was maintained constant at 10 °C/min. To increase the energy density of the powdered torrefied biomass samples, ring die type pellet machine of 25–50 kg/h capacity was used. Prior to the experiments, reactor was purged with N_2 gas to create the inert atmosphere. Thereafter, torrefaction temperature was raised by using electrically heated ceramic band heater of 3 kW capacity. This heater was insulated by ceramic wool and cladded with MS material sheet. Motor-driven agitator was used for proper mixing and to minimize the temperature gradients in the reactor during the torrefaction reaction. For

Fig. 19.1 Experimental setup to study the torrefaction of biomass at SPRERI

consistency in the reaction parametric studies, constant amount of biomass material (1 kg) was used for the experiments. Bio-char formed in the reactor was allowed to cool the room temperature. This bio-char was removed from the bottom of the reactor by manually operated slit-type valve. The slit-type valve was designed and fabricated to avoid the biomass material by sticking and obstruction of particles during the unloading of biomass. The vapors generated during the pyrolysis reactions were condensed in conical bottomed double-pipe heat exchanger at 6–8 °C followed by next level of condensation in the bottle at 2–4 °C using with ice chamber. Remaining non-condensable gases were scrubbed in wood shaving filter. These gases are sent to the burner which is attached to the end of the gas collection line to ensure generation of gas with sustained flame. Figure 19.1 shows the SPRERI experimental setup for torrefaction of biomass pellets. Product yields were determined on basis of mass balance of feed and torrefaction products. Proximate analysis, chemical analysis (cellulose, hemicelluloses, and lignin), and the calorific value of the raw and torrefied products were analyzed as per the ASTM standards. Torrefied biomass sample was pelletized using ring die type cattle feed pellet machine of 25–50 kg/h capacity. Torrefied sample was premixed with distilled water (5%) and fed manually into the pellet machine to get the proper pellets with good strength.

19.3 Results and Discussion

Preliminary, trial runs were carried out with 6 mm sawdust pellets at 150, 200, 250, and 300 °C reaction temperatures for a heating rate of 10 °C/min. Process conditions and the product yields for the experiment are given in Table 19.1. Proximate and chemical analyses of the fuel pellets after torrefaction are given in Table 19.2. Bio-

Table 19.1 Results of torrefaction of sawdust pellets (6 mm diameter) at different torrefaction temperatures

S. No.	Reaction temperature (°C)	Bio-coal yield (%)	Calorific value (MJ/kg)	Bulk density (kg/m^3)	Energy density (MJ/m^3)
	Raw pellets	100	18.0	716	12880.0
1	150	93.0	19.0	650	12350.0
2	200	82.3	21.1	571	12048.0
3	250	64.5	25.0	515	12875.0
4	300	52.7	27.0	460	12420.0

Table 19.2 Proximate and chemical analysis of torrefied sawdust pellets

Properties	Feedstock	Bio-char			
		150 °C	200 °C	250 °C	300 °C
Proximate analysis (wb %)					
Moisture content	7.2	6.5	2.4	1.9	1.2
Volatile matter	78.4	77.5	70.3	64.2	43.5
Ash content	0.5	0.6	0.8	1.3	1.8
Fixed carbon	13.8	15.3	26.5	32.5	53.5
Chemical analysis (%)					
Cellulose	41.6	34.9	22.0	15.2	9.2
Hemicellulose	13.0	10.3	9.0	4.7	1.7
Lignin	35.8	48.6	61.4	75.7	86.0
Minerals	9.5	6.2	7.5	4.4	3.0

coal yield was found reduced from 99 to 52.6% with increase in temperature from 150 to 300 °C while the calorific value increased from 18 to 29.6 MJ/kg. However, the bulk density of torrefied pellets was decreased from the 716 to 460 kg/m^3. The highest energy density of the fuel (12875 MJ/m^3) was found for 250 °C reaction temperature. For 150 °C reaction temperature, it may be seen that the lignin content increased by 35.8% and cellulosic and hemicellulosic contents reduced by 16.2 and 21%, respectively. Cellulose, hemicellulose, and mineral contents of the torrefied samples were found reducing with increase in temperature. Simultaneously, as the torrefication temperature was increased lignin content in the sample was increased due to degradation of hemicelluloses and cellulose [4, 5]. Figure 19.2 shows torrefied fuel pellet samples for different process temperatures. On increase in the temperature of the torrefied pellets, the heating value and energy density was increased. However, pellet stability decreased [6]. Pictorial view of the torrefied pellets shows the shrinking of the pellet diameter and swelling of few pellets. This results in decrease of pellet bulk density and mechanical durability of the pellet. So, the torrefied pellets during transportation and handling may result in the formation of dust and fines.

Fig. 19.2 Images of the sawdust pellets torrified at different torrefaction temperatures

This pathway of torrefication may be beneficial for the conventional coal mills while untreated pellets require high energy input [7]. Since biomass is generally flexible and tenacious, it is energy-intensive to reduce the particle size prior to the pelletization process or to use them in pulverized combustion systems. Torrefaction reduces the fibrous and tenacious nature of the biomass and results in a brittle material that can reduce the energy consumption for reducing into smaller particle size [8]. Significant increase in lignin (Table 19.2) was found in torrefied pellets, which can improve the binding property which is likely to improve the pellet strength [9]. So, work was further extended to the effect of torrefaction of biomass powder sample followed by its pelletization effect. For this study, two different agro-residues (rice straw and cotton stalk) are considered, which are most abundant in Gujarat region.

Torrefaction of powdered sawdust, rice straw, and cotton stalk were carried out at 200, 250, 275, and 300 °C reaction temperatures at constant heating rate of 10 °C/min and 60 min holding time. Process conditions and the product yields for the experiment are summarized in Table 19.3. With the increase in temperature from 200 to 300 °C, bio-char yield was reduced from 85.5 to 58%, 69 to 57.5%, and 94 to 44.1% for sawdust, rice straw, and cotton stalk, respectively. This may be due to the drying process and thermal degradation of low thermally stable biomass constituents [10, 11]. Bio-oil yield for sawdust gradually increases from 11.5 to 25% with an increase in temperature.

Optimum bio-oil yield of 19.4 and 23.5% was found at 250 °C for rice straw and cotton stalk, respectively. Torr-gas yield was found increasing with the increase in temperature. Proximate analysis along with bulk density and calorific values of the agro-residues before and after torrefaction is given in Table 19.4. With increasing

Table 19.3 Results of torrefaction of rice straw and cotton stalk agro-residues at different temperatures

Biomass type and size	Feed biomass moisture (%, wb)	Temperature (°C)	Torrefication product yields (%, db)		
			Bio-char	Liquids	Torr-gas
Saw dust 0.6 mm	8.2	200	85.5	11.5	3.0
	7.8	250	70.5	16.5	13.0
	8.0	275	64.0	21.0	15.0
	8.1	300	57.0	25.0	18.0
Rice straw 0.6 mm	6.2	200	69.0	17.0	14.0
	7.1	250	67.0	19.4	13.6
	6.8	275	64.0	14.4	21.6
	6.1	300	57.5	13.0	29.5
Cotton stalk 0.6 mm	4.5	200	88.0	7.5	4.5
	5.3	250	75.0	14.0	11.0
	4.2	275	48.5	15.5	36.0
	4.6	300	44.1	12.4	43.5

reaction temperature, the volatile matter, moisture content, and bulk density of the torrefied biomass were found reducing while the ash and fixed carbon contents were found increased. This results in an increase in calorific value of the torrefied sample for saw dust, rice straw, and cotton stalk. Figure 19.3 shows the images of torrefied biomass samples at different temperatures. Dark color of the torrefied sample was increased with the temperature due to the increase in fixed carbons (Table 19.4). Optimum torrefaction temperature for the biomass was selected based on the benefits of increasing the heating value with counterbalanced energy and mass loss [12]. Sawdust biomass torrefaction temperature at 250 °C shown the best energy yield with good heating value. Similarly, 275 and 250 °C for rice straw and cotton stalk were selected for optimum torrefaction temperature based on their calorific values and energy yield.

In order to further assess the effect of pelletization of torrefied biomass on fuel properties, the torrefied biomass materials were further densified by pelletization technique as discussed above in experimental section. Figure 19.4 shows the densified pellets (6 mm diameter) of the optimized torrefied biomass indicating good quality of pellets of torrefied biomass. Further, the calorific value, bulk density, and energy density of the pelleted–torrefied biomass were measured and compared with raw and optimized torrefied biomass. Table 19.5 shows the comparative fuel properties of the raw, optimized torrefied biomass and pelleted–torrefied biomass. It was noticed from the results that the torrefaction cum palletization led to a drastic increase in the energy density for all the biomass materials due to a synergistic effect. As per the results, the pelleted–torrefied sawdust (T-SD) showed highest energy density (14080 MJ/m^3) compared to pelleted–torrefied cotton stalk (T-CS) which showed

Table 19.4 Proximate analysis, bulk density, and calorific values of the raw and torrified agro-residues

Biomass type and size	Temperature (°C)	Moisture content (% wb)	Proximate analysis (%, db)			Bulk density (kg/m^3)	Calorific value (MJ/kg)	Energy yield (%)	Energy density(MJ/m^3)
			Volatile matter	Ash	Fixed carbon				
Saw dust, 0.6 mm	Raw	8.5	82.3	1.8	16.0	272.0	18.0	–	4896.0
	200	7.1	80.0	2.2	18.0	232.0	19.0	90.2	4408.0
	250	4.0	75.5	2.6	22.0	217.5	22.0	87.0	4785.0
	275	3.3	63.5	3.2	30.0	213.5	23.5	83.5	5124.0
	300	2.5	57.5	4.0	38.5	210.5	25.0	79.0	5410.0
Rice straw, 0.6 mm	Raw	6.0	75.5	15.4	8.9	167.0	14.0	–	2338.0
	200	2.4	64.5	17.0	18.4	136.1	16.5	80.7	2244.0
	250	1.5	59.0	19.3	21.5	132.1	17.6	83.6	2340.8
	275	1.2	54.7	20.4	24.8	128.0	18.7	85.0	2393.6
	300	1.1	40.5	23.5	36.0	118.0	19.3	78.7	2277.4
Cotton stalk, 0.6 mm	Raw	5.2	70.7	5.5	23.7	186.0	18.2	–	3385.2
	200	3.5	65.3	8.2	26.3	180.2	18.8	98.0	3658.0
	250	2.4	60.8	9.5	29.5	150.0	21.0	91.0	3150.0
	275	1.2	56.6	11.3	31.9	145.4	22.2	61.5	3736.8
	300	1.0	42.8	12.6	44.6	134.0	26.0	66.0	3457.2

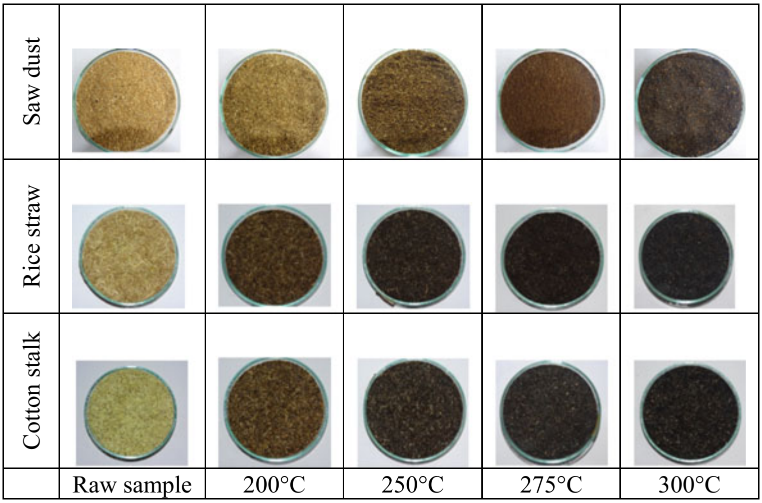

Fig. 19.3 Images of the torrified rice straw and cotton stalk at different reaction temperatures

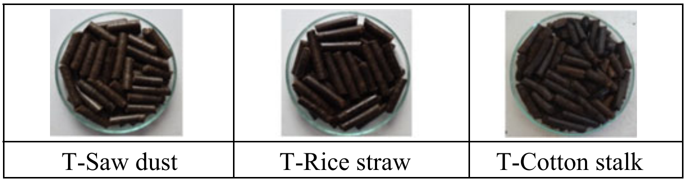

Fig. 19.4 Images of the 6 mm diameter pellets made from torrefied powered biomass materials at optimized conditions

Table 19.5 Comparative fuel properties of the raw, optimized torrefied biomass and pelleted–torrefied biomass

Biomass sample	Calorific value (MJ/kg)	Bulk density (kg/m^3)	Energy density (MJ/m^3)
Saw Dust (SD)			
Raw SD	18.0	272.0	4896
T-SD @250 °C	22.0	217.5	4785
Pelleted T-SD (6 mm)	22.0	640.0	14080
Rice Straw (RS)			
Raw RS	14.0	167.0	2338
T-RS @275 °C	18.7	128.0	2393
Pelleted T-RS (6 mm)	18.7	350.0	6545
Cotton Stalk (CS)			
Raw CS	18.2	186.0	3385
T-CS@250 °C	21.0	150.0	3150
Pelleted T-CS (6 mm)	21.0	450.0	9450

9450 MJ/m^3) and pelleted–torrfied rice straw (T-RS) for which 6545 MJ/m^3 energy density was obtained.

19.4 Conclusion

Biomass torrefaction of selected biomass samples (sawdust, rice straw, and cotton stalk) was successfully carried out using indirectly heated fixed bed reactor under controlled operating conditions. The highest energy density 12875 MJ/m^3 was found at 250 °C for commercially available sawdust pellets of diameter 6 mm mainly due to pelletizing effects. On the other hand, for the powdered sawdust, rice straw, and cotton stalk biomass samples (0.6 mm size), the maximum energy density was 4785, 2393 and 3150 MJ/m^3, respectively which is much lower than the pelletized sawdust samples. Interestingly, pelletization of torrefied biomass drastically improved the energy density. The pelleted–torrefied sawdust (T-SD) showed highest energy density (14080 MJ/m^3) compared to pelleted–torrefied cotton stalk (T-CS) which showed 9450 MJ/m^3) and pelleted–torrefied rice straw (T-RS) for which 6545 MJ/m^3 energy density was obtained indicating torrefaction cum pelletization is the best way to improve the energy yield and energy density of biomass materials.

Acknowledgements The authors gratefully acknowledge the financial support from Indian Council of Agriculture Research (ICAR), New Delhi, for carrying out the project successfully.

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