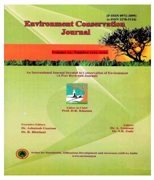
Environment Conservation Journal 24 (2):236-243, 2023

Journal homepage:https://www.environcj.in/



Environment Conservation Journal

ISSN 0972-3099 (Print) 2278-5124 (Online)

Production and characterization of briquettes made from rice straw and sawdust under high pressure and high temperature conditions

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ARTICLE INFO

Received : 20 May 2022
Revised : 18 October 2022
Accepted : 28 October 2022

Available online: 07 March 2023

Key Words:
Bio-energy
Biomass
Briquetting
Energy densification
Paddy straw
Sawdust

ABSTRACT

Briquettes offer good value in terms of energy density. Briquetting of sawdust with paddy straw is a ray of hope for paddy straw waste utilization, which has been a burning issue in India for a long time. A commercial briquetting machine was used to make briquettes of sawdust with paddy straw in two different forms—shredded and chopped, in different ratios, separately. The ratio of paddy straw in briquettes was increased until the produced briquettes had an acceptable firmness. The maximum ratio of shredded paddy straw for which briquetting was possible was 40:60 with sawdust, whereas for chopped paddy straw it was 60:40 with sawdust. The briquettes were then analysed for different properties to assess their quality and durability. The shatter index of shredded straw briquettes and chopped straw briquettes varied from 0.10–10.12% and 0.26–4.54%, respectively. The friability index of shredded straw briquettes was in the range of 93.54-99.85%, whereas for chopped straw briquettes it was in the range of 89.89-99.90%. The volatile matter of shredded straw briquettes ranged from 79.60-83.89%, whereas for chopped straw briquettes it ranged from 76.69-86.07 %. The ash content of shredded straw briquettes was in the range of 9.83-13.07%, whereas for chopped straw briquettes, it was in the range of 6.60-16.44%. The fixed carbon content of shredded straw briquettes varied from 0.09 to 0.87%, whereas for chopped straw briquettes it varied from 0.11 to 0.59%. The results suggested that the densification experiments were successful and the briquettes produced were of good quality.

Introduction

There are increasing concerns about pollution and climate change through the use of fossil fuels. Coupled with their exhaustible nature, there is a pressing need to shift focus towards renewable sources of energy. A study has estimated that the reserves of coal, oil, and gas will be depleted by 2112, with coal remaining as the sole fossil fuel source after 2042 (Shafiee & Topal, 2009). Fossil fuels contribute heavily to air pollution, leading to increased mortality risks. It is estimated that fossil fuel-related emissions account for 65% of excess mortality. They are also shown to contribute to 70% of climate cooling (Lelieveld *et al.*, 2019). Biomass energy is seen as an alternative and is an attractive renewable resource. Currently, it contributes to 10–14% of the world's primary energy needs, with the potential to contribute up to 30-40% by 2050 (Rosillo-Calle, 2016). Agricultural residues are a major source of energy production. On a global scale, residue production of the six most important crops—barley, maize, rice, soybean, sugarcane, and wheat—is estimated to be 3.7 Pg. dry matter y^{-1}. The theoretical energy production from this amount is estimated to be 65 EJ y^{-1}(Bentsen *et al.*, 2014). In

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Doi:https://doi.org/10.36953/ECJ.12992370

India itself, the potential for the utilisation of agricultural residues is huge. The Ministry of New and Renewable Energy estimates that India generates 500 million tonnes of crop residue per year, of which 92 million tonnes are burned (NPMCR, 2014). Currently, a lot of agricultural residue produced goes to waste, and farmers find burning the residue a convenient method to deal with it.

Stubble burning is a major problem in India as it is a significant source of gaseous pollutants like CO_2, CO, NO_x, SO_x, methane and particulate matter (Sain, 2020). This causes all sorts of health hazards, such as chronic obstructive pulmonary disease (COPD), bronchitis, cancer, etc. Utilizing this waste residue effectively is essential towards alleviating these problems (Anonymous, 2019). There are myriad ways to develop fuels from this waste, including the production of bioethanol, biodiesel (liquid fuels), bio-methane (gaseous fuel) and pellets and briquettes (solid fuels). Biomass densification into pellets or briquettes is used for improved utilisation of agri-residue waste. Densification confers multiple advantages such as improved handling, storage, and lower cost of transportation along with a reduction in particulate matter emission, higher calorific value, and uniform rate of combustion (Kaliyan & Vance Morey, 2009; Purohit *et al.*, 2006). Thus, briquettes are an attractive fuel source for the utilisation of agri-residue. Considering these advantages, this study aims to produce briquettes from paddy straw and analyses the properties to determine their attractiveness as alternative sources of fuel.

Material and Methods

The briquettes were prepared from sawdust in different combinations with paddy straw in different forms. Sawdust was procured from a local market and cleaned via sieving (sieve pore size of 1 mm) before making briquettes. The paddy straw was selected in two forms: shredded straw and chopped straw. The shredded straw had a thread-like structure. The chopped straw was prepared from full-sized paddy straw. The whole paddy straw was cut into smaller pieces by a regular chaff cutter. The briquettes were prepared in a commercially available briquetting machine (Model: EcoStan 40; Fig. 2). Briquettes were produced using this machine (Fig. 2) using rice straw (shredded and chopped) separately (Fig. 1.a & 1.b) with sawdust in various combination ratios (Table 3 and 4). The die temperature, an important parameter in briquetting, is also recorded. The proportion of straw is increased until the briquettes are made. The briquettes were analysed preliminarily for their firmness by hand. The following tests on briquettes samples were performed:

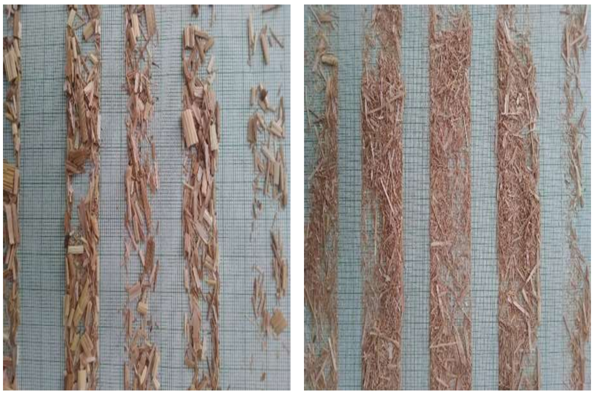

Figure 1a: Raw Material for Briquettes- Chopped Straw
Figure 1b: Raw Material for Briquettes- Shredded Straw).
Note:The smallest graph paper square size- 1mm x 1mm.

Figure 2: Briquetting machine

Moisture content: The briquette samples were powdered, and 1 g of each was baked for 1 hour at 105 °C in a hot air oven (ASTM D3173). Moisture content was calculated by a formula:

$$\text{Moisture content, \%} = 100 * (W_1 - W_2) / W_1$$

where,
W_1= weight of sample before placing into the oven
W_2= weight of sample after placing into the oven

True density: The briquettes were weighed and dipped into the distilled water contained in a graduated cylinder (Stamm, 1928). The increase in volume (ΔV) was immediately noted. The true density was measured by the following formula:

$$\text{True density} = 100 * W / \Delta V$$

where, W= weight of briquette sample before dipping into water

Shatter index: The Shatter Index is used to assess the hardness and friability of the briquettes. The briquette samples were dropped on a concrete floor from a height of one meter. The weight of the largest portion of the briquette after chipping out of material due to impact was noted. The percentage loss of material is calculated by formula (Rajaseenivasan *et al.*, 2018):

$$\text{Shatter index} = 100 * (W_1 - W_2) / W_1$$

Where,
W_1, W_2 = weight of briquette before and after shattering, respectively, g.

Friability index: The Friability index is a drop test for assessing the durability of the briquettes. The Friability index test is used for determining the strength and hardness of briquettes. Briquette samples were dropped from a height of 1.86 m onto a concrete floor, and the weight of the largest piece of briquettes remaining was recorded (Henning *et al.,* 2018).

$$\text{Friability index} = 100 * W_2 / W_1$$

where, W_2= weight of largest piece of briquette after impact, g
W_1 = weight of briquette before impact, g

Water resistance: To measure water resistance, the briquette samples were immersed in water maintained at the atmospheric temperature for 30 s to determine the percentage of water resistance to penetration (Davies & Davies, 2013). The water resistance indicates how the briquettes will respond with respect to moisture absorption. Water resistance was calculated with the formula:

$$\text{Water resistance} = 100 - \{(M_2 / M_1) * 100\}$$

where, M_2= Mass of briquette after 30 s water dip, g
M_1= Mass of briquette before 30 s water dip, g

Volatile matter: The powdered 1 g fresh sample of briquettes in a crucible was placed in a muffle furnace for 950±20 °C for 7 minutes (ASTM D3175-07). The volatile matter was calculated from the formula:

$$\text{Volatile matter} = \{100 * (W_2 - W_1 / W_1)\} - MC\ (\%)$$

where,
W_2= weight of briquette sample before placing into furnace, g
W_1 = weight of briquette sample after placing into furnace, g

Ash Content: The powdered 1 g fresh sample of briquettes in a crucible was placed in a muffle furnace for 950±20 °C for 2 hours (ASTM D3174-02). The samples were then taken out and placed into the desiccator to cool down. The volatile matter was calculated from the formula:

$$\text{Ash content} = 100 * (W_2 - W_1 / W_1)$$

where, W_2= weight of briquette sample before placing into furnace, g
W_1= weight of briquette sample after placing into furnace, g

Fixed Carbon: Fixed carbon is calculated by formula (ASTM D3172-07a):

Fixed Carbon, % = 100 – (Moisture content, % + Ash Content, % + Volatile matter, %)

Results and Discussion

Physical properties of the raw material

The physical properties of the raw material were studied and presented in Table 1. Chopped paddy straw has a higher bulk density than shredded straw due to its better uniformity in particle size. Saw dust has a bulk density similar to the research reported by Retana *et al.* (2019) but less than reported by Stasiak *et al.* (2019) and Trzciski *et al.,* (2021). It is quite obvious that sawdust made from different woods has a different bulk density. The paddy straw in shredded and chopped form has a maximum ash content of 14.8%. Similar results were also reported by El-Sayed and El-Samni, 2006 (15%); Ngi *et al.*, 2006 (18.1%); and Sarnklong *et al.*, 2010 (12.1%). As ash content is a material property, it is not affected by different sizes of paddy straw. The end results of different combinations are presented in Table 2 (sawdust + shredded paddy straw) and in Table 3 (sawdust + chopped paddy straw). It can be concluded from Tables 2 and 3 that paddy straw in chopped form can easily be blended with sawdust up to a 60% concentration, which offers good utilisation of paddy straw with sawdust. Similar results were reported by Alo *et al.* (2017) for sawdust with bagasse mixture. Shredded straw could be added in a 40% concentration to sawdust for the preparation of acceptably firm briquettes. The briquettes made were analysed for their different properties. The end results of the experiments are discussed below:

Table 1: Physical properties of raw material

	Shredded straw	**Chopped straw**	**Sawdust**
Bulk density, g/cc	0.04-0.05 ± 0.4	0.06-0.07 ± 0.4	0.24-0.27 ± 0.4
Moisture content, %	8.3-8.7 ± 0.1	7.0-7.3 ± 0.1	8.5-8.8 ± 0.1
Ash content, %	11.8-14.8 ± 0.1	13.0-14.2 ± 0.1	10.7-11.7 ± 0.1

Table 2: Output of different combinations of shredded straw and sawdust

Sr. No.	**Sawdust, %**	**Shredded Rice Straw, %**	**Die temperature, °C**	**Result of the manual inspection for produced briquettes**
1.	100	0	105	Acceptable firmness
2.	90	10	104	Acceptable firmness
3.	80	20	102	Acceptable firmness
4.	70	30	104	Acceptable firmness
5.	60	40	104	Acceptable firmness
6.	50	50	103	Acceptable firmness

Table 3: Output of different combinations of chopped straw and sawdust

Sr. No.	**Sawdust, %**	**Chopped Rice Straw, %**	**Die temperature, °C**	**Result of the manual inspection for produced briquettes**
1.	100	0	105	Acceptable firmness
2.	90	10	101	Acceptable firmness
3.	80	20	101	Acceptable firmness
4.	70	30	104	Acceptable firmness
5.	60	40	103	Acceptable firmness
6.	50	50	102	Acceptable firmness
7.	40	60	103	Acceptable firmness
8.	30	70	104	Not Good. Got crumbled when taken into hand (fluffy nature)

Moisture content

The moisture content of different types of briquettes made is given in Table 4 and 5. The comparison of the average moisture contents of shredded straw + sawdust and chopped straw + sawdust briquettes is given in Fig. 3. The moisture content of briquettes made from shredded material plus sawdust had a lower moisture content than the chopped straw plus sawdust combinations. It is due to the structure of the paddy straw in two forms. The chopped straw retained more moisture due to its open pore structure (Mesa & Arenghi, 2019). The shredded straw had thread-like filaments and hence offered little moisture-holding capability. The little higher moisture content of some of the briquettes than raw material can be attributed to the humidity of the environment during experiments as the briquetting machine was placed in an open area. The pure sawdust briquettes are more affected due to this effect (Glass *et al.,* 2010).

True density

The true density of different types of briquette samples is given in Table 4 and 5. The comparison of the average true density of shredded straw +

sawdust and chopped straw + sawdust briquettes is given in Fig. 4. The true density of briquettes made from shredded straw was greater than those made from chopped straw. This can be attributed to the threaded structure of the shredded straw. In the case of chopped straw briquettes, the density first decreases and then increases. The first decrease might be due to the decrease in the proportion of the sawdust, and the second increase is due to the better embodiment of chopped straw in the sawdust. In comparison to pure sawdust, the density was on the higher side due to the better packing of paddy straw in sawdust.

Based on the experimental results, it can be easily interpreted that the density of all briquettes lay between 0.79 and 1.35 g/cc, which is much denser than raw materials. Jittabut (2015) found the density of briquettes made from rice straw and sugarcane leaves with molasses as the binding agent in the range of 0.53-0.58 g/cc, whereas Urbanoviová *et al.* (2017) found the density of briquettes produced from energy plants in the range of 0.80-0.90 g/cc. The higher density of the briquettes in the present study may be attributed to the high pressure applied by the machine (Mani *et al.,* 2006). Also, the briquettes prepared were about 6–9 times denser than

Table 4: Properties of briquettes made from Shredded Paddy Straw + Sawdust

SN	Shredded straw, %	Sawdust, %	Shatter index, %	Friability Index, %	True Density, (g/cc)	Water resistance, %	Moisture content (%)
1	0	100	0.16-0.68	98.76-99.32	0.89-1.14	83.96-87.45	8.75-9.26
2	10	90	0.13-0.20	99.54-99.66	1.27-1.35	85.18-93.43	4.60-6.56
3	20	80	0.41-2.04	99.63-99.80	1.05-1.06	76.39-84.09	5.64-7.33
4	30	70	0.10-0.45	94.78-99.36	1.14-1.16	78.10-89.18	3.40-6.34
5	40	60	0.13-10.12	93.54-99.85	0.75-0.98	71.46-87.30	5.34-7.36

Table 5: Properties of briquettes made from Chopped Paddy Straw + Sawdust

SN	Shredded straw, %	Sawdust, %	Shatter index, %	Friability Index, %	True Density, (g/cc)	Water resistance, %	Moisture content (%)
1	10	90	0.26-1.22	97.89-99.66	1.09-1.21	88.51-92.50	5.27-6.55
2	20	80	0.47-0.73	97.89-99.18	0.79-1.00	76.34-83.40	6.27-7.57
3	30	70	0.21-0.49	99.04-99.90	0.77-0.85	76.37-78.44	8.67-8.73
4	40	60	0.85-4.54	96.64-99.61	0.80-0.96	89.62-93.51	6.86-8.37
5	50	50	0.63-0.76	89.89-99.34	0.86-1.02	85.44-87.73	7.15-8.42

Table 6: Proximate analysis of briquettes made from Shredded Paddy Straw + Sawdust

SN	Shredded straw, %	Sawdust, %	Volatile Matter, %	Ash Content, %	Fixed Carbon, %
1.	0	100	86.34	4.39	0.11
2.	10	90	80.92	13.39	0.11
3.	20	80	82.73	10.51	0.28
4.	30	70	82.32	12.00	0.81
5.	40	60	82.10	10.96	0.60

Table 7: Proximate analysis of briquettes made from Shredded Paddy Straw + Sawdust

SN	Shredded straw, %	Sawdust, %	Volatile Matter, %	Ash Content, %	Fixed Carbon, %
1.	10	90	78.89	15.04	0.16
2.	20	80	82.77	10.00	0.31
3.	30	70	83.75	7.26	0.30
4.	40	60	84.23	7.76	0.40
5.	50	50	84.92	6.94	0.36
6.	60	40	82.94	10.52	0.57

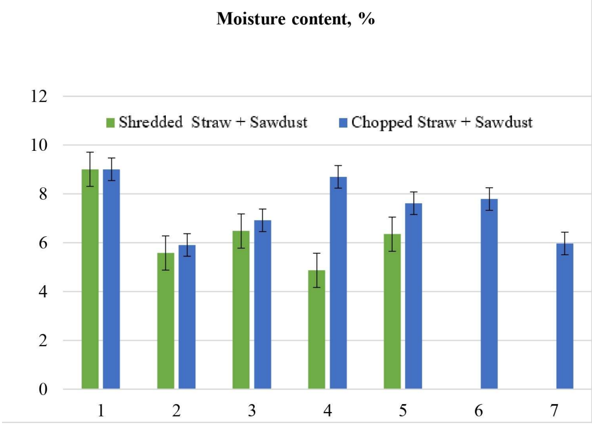

Fig. 3: Moisture content variation of different briquettes samples

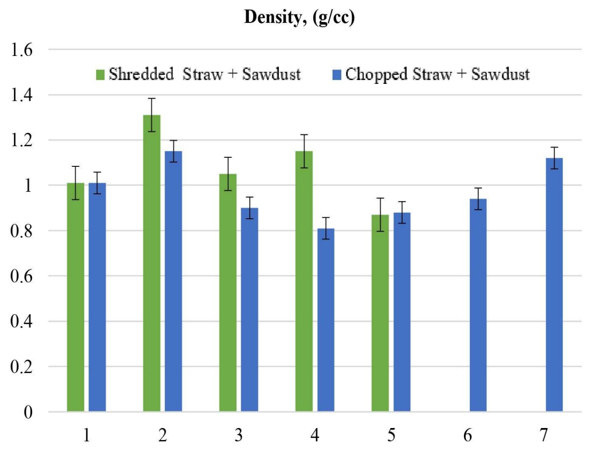

Fig. 4: Density variation of different briquettes samples

sawdust; 19–29 times denser than shredded paddy straw; and 14–18 times denser than chopped paddy straw, all three of which were used as raw materials.

Shatter Index

The shatter index of different briquette samples is given in Table 4 and 5. The comparison of the average shatter index of shredded straw + sawdust and chopped straw + sawdust briquettes is given in Fig. 5. The shatter index of different briquettes doesn't depict any definitive trend. The shatter index of the briquettes of all combinations was in the range of 0.21-1.26, which was better than that found for sawdust and rice husk combinations, having a 9.6-27.6 (Tembe *et al.,* 2014). The shatter index of the 40:60 combination of both forms of paddy straw showed a high shatter index. It might be due to the looseness caused by the paddy straw in the briquette structure.

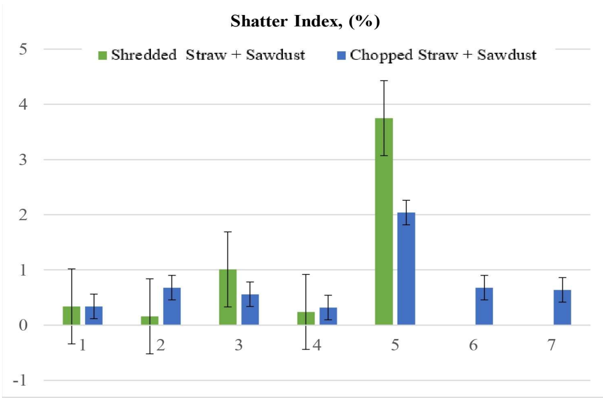

Fig. 5: Shatter index variation of different briquettes samples

Friability index

The friability index of different briquette samples is presented in Tables 4 and 5. The comparison of the average friability index of shredded straw + sawdust and chopped straw + sawdust briquettes is given in Fig. 6. The friability index of all samples was above the recommended minimum threshold friability index value of 80% (Richards, 1990). This demonstrated the good durability of the briquettes. The friability index of all briquettes decreased as the proportion of straw increased. This could be due to the looseness of paddy straw in comparison to sawdust. The decrease is more pronounced in comparison to chopped straw briquettes.

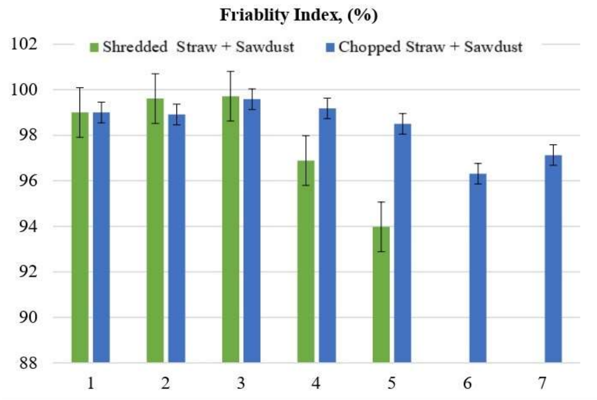

Fig. 6: Friability index variation of different briquettes samples

Water resistance

The water resistance of different briquette samples is shown in Table 4 and 5. The comparison of the average water resistance of shredded straw + sawdust and chopped straw + sawdust briquettes is given in Fig. 7. The water resistance of all briquette samples was below the recommended minimum water resistance of 95% (Richards, 1990) but similar to values obtained by Rajaseenivasan *et al.*, 2018.

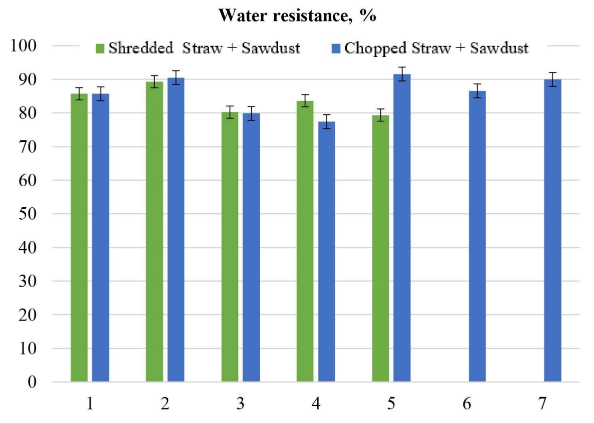

Fig. 7: Water resistance of different briquettes samples

Volatile matter, ash content and fixed carbon content

The average values of volatile matter, ash content, and fixed carbon content of different briquettes samples are shown in Tables 6 and 7P. The volatile matter of shredded straw briquettes ranged from 79.60-83.89%, whereas for chopped straw briquettes, it ranged from 76.69-86.07%. The ash content of shredded straw briquettes ranged from 9.83-13.07%, whereas for chopped straw briquettes it ranged from 6.60-16.44%. The increased ash content is due to the increased proportion of the paddy straw, which contains higher inorganic matter (El-Sayed *et al.,* 2006). The fixed carbon content of shredded straw briquettes ranged from 0.09-0.87%, whereas for chopped straw briquettes it ranged from 0.11-0.59%.

Conclusion

The briquettes formed by the commercial briquetting machines had a density of between 0.87 and 1.31 g/cc, which is much denser than raw material and hence offers a good method for energy densification of biomass. Due to the lower moisture content of the briquettes formed in comparison to raw material, they offered improved net heat content. Briquettes also had good strength and durability, as evidenced by their low shatter index and high friability index. Water resistance of most of the briquettes from different combinations was also in an acceptable range but showed scope for improvement. Tests on compressive strength, calorific value, and emission characteristics will be needed to characterize the briquettes further and determine their suitability in commercial combustion operations as a replacement for traditional fuel.

Acknowledgement

We would like to thank CCS HAU, Hisar for funding this project and providing research facilities.

Conflict of interest

The authors declare that they have no conflict of interest.

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