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"Gheorghe Asachi" Technical University of Iasi, Romania

DEVELOPMENT AND PERFORMANCE EVALUATION OF BIOMASS PELLET MACHINE FOR ON-FARM SUSTAINABLE MANAGEMENT AND VALORIZATION OF PADDY STRAW

Sapna Birania[1], Yadvika[2], Mukesh Kumar Garg[1], Ravi Gupta[1], Ravi Kumar[1], Nitin Kumar[1*]

[1]*Department of Processing and Food Engineering, CCS Haryana Agricultural University, Hisar, 125004, India*
[2]*Department of Renewable & Bio-Energy Engineering, CCS Haryana Agricultural University, Hisar, 125004, India*

Abstract

The availability of an extremely limited window of 15 days between the harvesting of paddy and subsequent field bed preparation for the next crop, forces the farmers to adopt on-farm burning of paddy straw as an easy and economical approach for managing their huge straw stockpile. The unwarranted burning of straw prompts enormous soil and environmental pollution leading to numerous health hazards. The conversion of paddy straw into densified pellets can be an eco-friendly and economical alternative. Therefore, this study aims to develop a small-scale pellet-making machine suitable for on-farm sustainable management of residues and its utilization to convert paddy straw into pellets which can be used as an alternative source of fuel. Three different ratios of paddy straw to sawdust (100:0, 80:20, and 50:50) with an initial feed length of 4mm were tested for making pellets. At a feed rate of 24±0.5 kg/h, the output of the machine was 12.80±0.5 kg pellets/h at a 50:50 ratio of paddy straw and sawdust followed by 12.50±0.5 kg/h (100:0) and 12.60±0.5 kg/h (80:20). The average length of pellets ranged between 21.2-87.58 mm with a mean bulk density of 675kg/m^3. The maximum calorific value of pellets (14510±107.23 kJ/kg) was recorded at a feedstock ratio of 50:50 with 18% moisture content wet basis (wb) while the minimum (13366.67±112.98 kJ/kg) was in 100% paddy straw and at 14% moisture content wb. The economic feasibility of the machine was thus ascertained.

Key words: biofuels, characterization, paddy straw, pellet machine, palletization

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1. Introduction

The ever-growing global population demands a continuous supply of energy to lead a quality life. Largely, the fuels used for generating this energy had been fossil-based for decades. The unwarranted and unchecked usage of these fuels has caused serious environmental issues related to their combustion and sustainability (Razzak et al., 2013). The replacement of fossil fuels with renewable biofuels can be an environmentally sustainable solution. Biofuels are usually derived from bioresources like plant materials and other organic wastes and are classified based on phase in three categories namely, solid, liquid, and gas (Patil et al., 2008; Saini et al., 2020). Solid biofuels can be used either directly or may be converted into other forms by minimal physical processing before combustion (Birania et al., 2020; Enerdata, 2017). These include different types of wood chips, briquettes, cubes, pellets, etc. A challenge faced in this area is to use the biomass efficiently in a way that minimum cost of supply chain and other activities are required for transforming the biomass into a valuable energy source. There are several benefits of power

*Author to whom all correspondence should be addressed: e-mail: nitin@hau.ac.in

production from biomass and on the other side, several challenges are faced for its optimum utilization and effectiveness which include the quality, accessibility of the feedstock, cost, handling, stock, transportation cost, and logistic system (Zahraee et al., 2020). Presently, pellets are gaining importance among solid biofuels for energy production. Pellets are produced by densifying the dried and milled plant material into a cylindrical form of predetermined diameter and length. The commonly used biomasses for pelletization are wastes generated from the wood industries, crops, energy crops, and forest residues, etc. The pellets produced from these biomasses are highly densified and have little moisture content, usually, less than 10%, facilitates high energy conversion efficiency (Xiao et al., 2015). As compared to the original form of biomass fuels, biomass, when pelletized, generates less particulate matter emissions (Ghafghazi et al., 2011; Shen et al., 2012).

Wooden pellets are the most commonly used pellets for modern bioenergy. The worldwide market for wooden pellets is expected to expand at a CAGR (Compound Annual Growth Rate) of roughly 6.9% over the next five years and will reach 6150 million USD in 2024 from 4120 million USD in 2019 (Thrän et al., 2019). The ever-growing demand for wooden pellets has resulted in increased deforestation, which in turn has captivated the interest of environmentalists and researchers to find alternatives in the form of pellets from non-woody biomass.

Although, non-woody biomass is renewable and cheap but has issues related to availability, market demand, and supply chain logistics. De Mayer et al. (2014), explained the significance of all the operations including in the whole supply chain i.e., biomass production, harvesting, collection, pretreatment, storage, and conversion to bioenergy. The two major disadvantages of non-woody biomass for fuel purposes are lower bulk density and higher transportation and handling cost (Sid-Sahtout et al., 2020; Kumar et al., 2016; Pradhan et al., 2018; Rai et al., 2012).

The current need to increase the biomass utilization for palletization comes with new challenges for the palletization process and quality of pellets thus produced. Efforts are being made by many researchers for high-quality pellets production using different nonwoody biomass such as: switchgrass (Ciolkosz et al., 2015; Jackson et al., 2016), wheat straw (Agar et al., 2018; Jackson et al., 2016), barley straw (Serrano et al., 2011), paddy straw (Said et al., 2015) and corn stover (Jackson et al., 2016).

In India, paddy straw is produced in tremendous amount, but its use as animal fodder, animal bedding, and packaging material is minuscule as compared to its production, so farmers tend to burn it in the fields itself to facilitate the timely preparation of the seedbed for subsequent crops, usually wheat. The collection of paddy straw from the field requires a lot of time and labor, and also farmers have to pay extra costs for harvesting, transportation, and storage of paddy straw. Now a day, paddy straw is used in many industries for different purposes such as paper and cardboard industries, biofuels production, etc., but needs a lot of pretreatments which increases the cost of production.

Pelletization of loose paddy straw is an attractive option to produce renewable fuel. The pelletization process improves the handling characteristics, increases the volumetric calorific value, reduces transportation costs, and makes it available for a variety of applications (Purohit and Chaturvedi, 2018). Palletization of sawdust, cotton stalks, and dry leaves along with paddy straw is a good alternative for its sustainable management. Paddy straw pellets can be used as fuels at the household level to replace the LPG and other costly burning materials. Hence there is a need to develop a small-scale pellet machine for a farmer to manage the paddy straw at field level and production of pellets for household purposes.

Pellets making machine is a specialized machine for pelletizing the chopped biomass which can be paddy straw or any other crop residue/woody material. It works on the principle of compression and friction. The pellets can be produced using only biomass or a mixture of biomass with any binder or sawdust. Therefore, the present study was carried out to develop a small-scale biomass pellets machine especially for paddy straw which could be used in rural areas for on-farm management of paddy straw.

2. Material and methods

This study was carried out in the Renewable Energy Lab, Department of Renewable & Bio-Energy Engineering, CCS Haryana Agricultural University, India. Paddy straw in the form of cuboid bales (Fig. 1(a)) was procured from the farmer's field near village Kaimri (29.0811°N 75.7177°E) falling in the district Hisar. Straw bales were opened and chopped into a size of approximately 4 mm for desired pellets production using a power-operated leaf shredder (4 blades, 2800 rpm, and 1 hp motor; Fig. 1(b)) developed in the Department. Sawdust was procured from the local furniture shop and was pulverized in the leaf shredder. A Pellet machine (Fig. 1(c)) was fabricated for pellets production from paddy straw and other agri-residues/biomass.

2.1. Constructional details of pellet machine

The auto-CAD illustration of the pellet machine is shown in Fig. 2. The perusal depicts that it is comprised of different components such as hopper, pelleting chamber, die plate, pellet rolls, discharge cute, and frame. The machine was driven by a 7 hp electric motor. The pellet machine operated using a roll-type extrusion press, which forced down the expressed feed through the die plate (Kumar et al., 2017). When the vertically positioned shaft rotated, both the pellet rolls positioned on it revolved and compressed the feed for filling the holes of the die plate.

(a) (b) (c)

Fig. 1. Materials and machines used for the experiments: (a) represents cuboidal straw bales, (b) depicts the leaf shredder; (c) shows the pellet machine

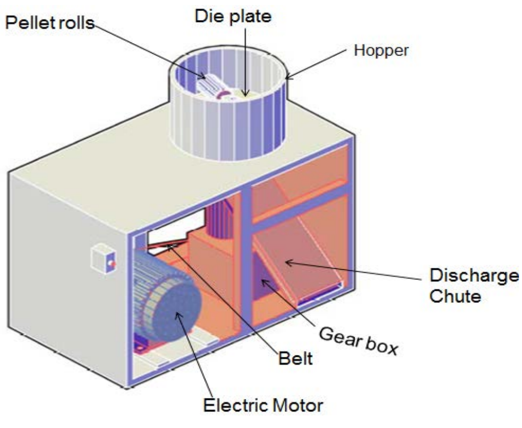


Fig. 2. Auto-CAD layout of pellet machine and its components

Pellet rolls revolved with continuous addition of feed to the chamber leading to increased compression in the die plate holes, resulting in the formation of pellets. Pellets coming out of the die were cut into the desired length by a rotating knife attached below it. The dimensional specifications of the machine are provided in Table 1.

2.1.1. Feed Hopper

The feed (either paddy straw or a mixture of paddy straw and sawdust) was fed through a feed hopper and eventually extruded by two revolving cylindrical pellet rolls fixed to the die plate in the form of pellets. Its shape was cylindrical with an average diameter of 300 mm and a length of 180 mm.

2.1.2. Pelleting chamber

It was used for feed mixing and extruding the chopped raw material before pushing to the holes of the die plate by revolving the pellet rolls. It was detachable from the mainframe of the machine. Its diameter was the same as that of the hopper (300 mm).

Table 1. Dimensional specifications of pellet machine

Parameters	***Units***	***Dimensions***
Diameter of hopper	cm	30.0
Height of hopper	cm	18.0
Diameter of holes	cm	1.0
No. of holes	-	206
Motor required	hp	7.0
The diameter of pellet rolls	cm	10.5
The diameter of the pelleting chamber	cm	30.0
Height of pelleting chamber	cm	10.5
Diameter of die plate	cm	30.0
The thickness of the die plate	cm	2.5
Length of the frame	cm	93.0
Width of the frame	cm	55.0
Height of the frame	cm	64.5

2.1.3. Pellet roll

It played a major role in the compression of the expressed feed before being extruded through the die plate. The machine consisted of two pellet rolls. The length of each pellet roll was 80 mm while the diameter was 105 mm. The distance between both the pellet rolls was 110 mm as shown in Fig. 3.

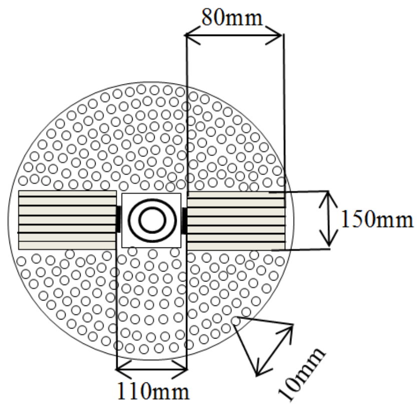


Fig. 3. Pellet die plate and Pellet rolls

2.1.4. Die plate

The function of the die plate was to convert formulated feeds into cylindrically shaped pellets. The die plate was fixed in the pelleting chamber while pellet rolls rotated on the die plate. The feed material was pushed in the holes of the die plate and compressed due to pressure and was subsequently converted into pellets. It consisted of 206 equally spaced holes; each having a diameter of 10 mm. The thickness of the plate was 25 mm.

2.1.5. Discharge chute

It was the outlet of the machine from where pellets were collected. The length and breadth of the discharge chute were 125 mm and 100 mm, respectively.

2.1.6. Electric motor

A 3-phase, capacitor start the electric motor of 7 hp was used which drove the pellet rolls at the desired speed of 40 rpm leading to the conversion of feed into pellets.

2.2. Experimental details

The Pellet machine was operated at different combinations or ratios of paddy straw and sawdust and moisture contents, details of which are provided in Table 2.

Table 2. Treatment details

Treatment no.	***Paddy straw: sawdust (PS: SD)***	***Moisture content (%)***
1	100:0	14
2	80:20	14
3	50:50	14
4	100:0	16
5	80:20	16
6	50:50	16
7	100:0	18
8	80:20	18
9	50:50	18

2.3. Experimental observations

The following observations of the machine, initial feed, and pellets were recorded:

- moisture content of feed and pellets (%);
- size of feed (mm);
- feed rate (kg/h);
- rotation speed of machine (rpm);
- the capacity of machine (kg/h);
- dimensions of pellets (mm);
- bulk density of feed and pellets (kg/m^3);
- pellet density (kg/m$^{3)}$;
- calorific value of pellets (kJ/kg).

2.4. Experimental analysis

The moisture content of the feed plays an important role in pelleting. Three varying moisture contents (14, 16, and 18% wb) were obtained by adding water and tempering the feed. The moisture content of feed and pellets was analyzed by the hot air oven method (Kargbo et al., 2016). The size of the feed was determined using sieve analysis (Ujam and Enebe, 2013), while the feed rate was observed manually. A known quantity of feed material was weighed and the pellet machine was operated for an hour. The remaining feed material was weighed and subtracted from the total feed taken initially. The result obtained was the feed rate per hour of the machine. The rotation speed of the machine was measured using a tachometer (Metravi DT- 2235). The capacity of the machine was assessed in terms of the quantity of pellets produced in an hour. It was calculated manually by operating the machine for one hour and weighing the pellets produced by the machine. Diameter and length of pellets were measured using a digital vernier caliper (Mitutoyo Absolute, having least count 0.01 mm).

The bulk density of feed and pellets was determined using weight by volume ratio. The calorific value of any fuel is one of its most important parameters. Bomb calorimeter was used for measuring the calorific value of pellets (Özçimen and Karaosmanoglu, 2004), according to ASTM D 3286 standard. A unit mass (1 g) of the pellet was placed in a closed bomb, filled with oxygen at 25 atmospheric pressure which was placed in the bucket filled with water. The bomb was ignited by supplying electricity to the nickel wire. The change in temperature of the water was recorded continuously for 20 minutes after every minute. The highest temperature rise was used for calculating heat energy of the sample, mathematically as given by Eq. (1):

$$H = W\ x\ \frac{t}{m} \tag{1}$$

where: W is water equivalent of calorimeter, cal/°C; t is rise in temperature, °C; H is calorific value of fuel (heat of combustion of material), cal/g; m is mass of sample burnt, g.

2.5. Experimental design and data analysis

Multivariate analysis is an important tool for obtaining valuable and statistically substantial models for any phenomenon by using a minimum set of well-selected experiments (Alam et al., 2018; Attkan et al., 2014). Using several analyses, analytical statistics can be achieved regarding the significance of each variable and the effect of the interaction of variables. Thus, a generalized linear model with the full factorial design was used to examine the effect of paddy straw percentage (PS %) on the characteristics of pellets produced from each moisture content of the feed (MCF 14, 16, and 18). A total of 9 experiments were run using SPSS software version 22 as shown in Table 2. Duncan's multiple range test was used as a post-hoc test.

3. Results and discussion

3.1. Performance evaluation of machine

The performance evaluation of the machine was carried out at three different ratios of paddy straw and sawdust. The perusal of Table 3 indicates that there was a constant feed rate of 24±0.5 kg/h. At this feed rate, the capacity of the machine was obtained maximum (12.80±0.5 kg/h) at 50:50 ratio of paddy straw and sawdust followed by 100:0 (12.50±0.5 kg/h) and 80:20 (12.60±0.5 kg/h), while operating at an average RPM of around 40. The capacity of the machine depended on the rpm, feed rate, and bulk density of the feed. The pellets made using different ratios of paddy straw (PS) and sawdust (SD) are depicted in Fig. 4.

Table 3. Parameters of the machine during pelleting

Parameters	***Units***	***Paddy straw: Sawdust (PS: SD)***		
		100:0	***80:20***	***50:50***
Feed Rate	kg/h	24.0±0.5	24.0±0.5	24.0±0.5
Rotation speed	rpm	40	40	40
Capacity	kg/h	12.50±0.5	12.60±0.5	12.80±0.5

n = 3; PS – Paddy Straw; SD – Saw Dust

(a) (b) (c)

Fig. 4. Pellets made using different ratio of PS and SD (a) 50:50 (b) 80:20 (c): 100:0

3.2. Characterization of pellets

The evaluation and assessment of different properties of the pellets for different experiments, as discussed in the previous section, are described in Table 4. All the experiments under different feeding conditions resulted in the production of pellets.

3.2.1. Pellet dimensions

The dimension of the pellets greatly determines the final strength of the pellet; correspondingly the increment in length reduces the strength of pellets, thus, resulting in breakage or cracks. The dimensions of the pellets are determinant for feeding properties of the fuel and combustion process.

The combustion rates of thinner pellets are more uniform than thicker ones. The easier continuous flow can be arranged for the shorter pellets if a pneumatic feeder is used for feeding (Obernberger and Thek, 2004).

The pellets produced from the developed machine indicated that the length of the pellets (Lp) varied between 39.12 to 40.68 mm, 64.06 to 66.11mm, and 81.49 to 86.95 mm respectively for moisture content of the feed (MCF) 14, 16, and 18%. However, the diameter of the pellets (Dp) varied between 9.52 to 9.54mm, 9.55 to 9.6 mm, and 9.44 to 9.51 mm respectively for the moisture content of the feed 14, 16, and 18 %. The effect of PS and MCF on the diameter and length of the pellets was highly significant (p=0.00; p=0.03 respectively) at a 5% level of significance as depicted in Table 5. There were slight variations for paddy straw percentage (PS %) and moisture content of the feed (MCF %) as depicted in Fig. 5(a) and (b). Despite the variations, all the values of dimensions obtained were within the established limits. The predicted and experimental values of various process parameters are presented in Fig. 6.

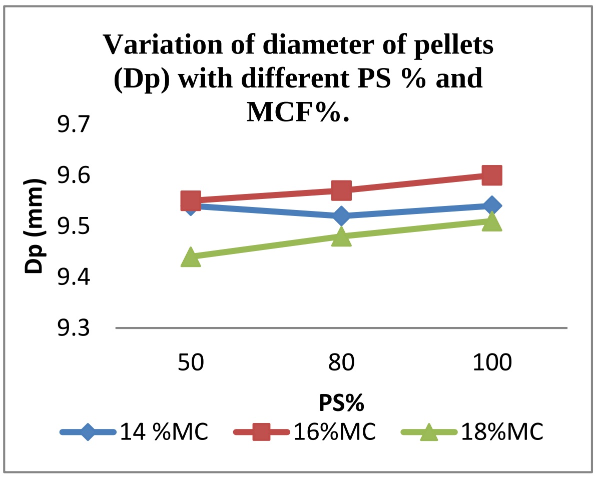
3.2.2. Bulk density of pellets (BDP)

The bulk density of the pellets is an imperative factor for storage and transportation as well as combustion efficiency (Gilbert et al., 2009). The bulk density of loose paddy straw ranges between 60 to 90 kg/m^3. The recommended bulk density range of pellets should be greater than 600 kg/m^3 (Alakangas et al., 2006). The bulk density of the pellets obtained by using pellet making machine varied between 673.33 to 686.67 kg/m^3, 668.33 to 685 kg/m^3, and 665 to 678.33 kg/m^3 respectively for the moisture content of the feed 14, 16, and 18% as depicted in Fig. 5(c).

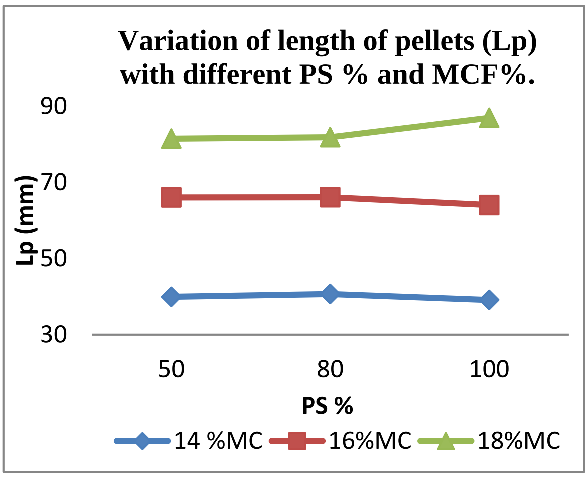
Table 4. Least square means of characterization parameters of pellets using Duncan's Multiple Range Test

MCF (%)	*PS (%)*	*Dp (mm)*	*Lp (mm)*	*BDP (kg/m^3)*	*PD(kg/m^3)*	*CV (kJ/kg)*	*MCP (%)*
14	100	9.54±0.01^{bcd}	39.12±0.64^{d}	686.67±5.77^{a}	1113.33±7.10^{e}	13366.67±112.98^{e}	13.22±0.11^{c}
14	80	9.52±0.00^{cd}	40.68±0.46^{d}	683.33±7.63^{ab}	1085.00±4.69^{f}	13760.00±63.89^{c}	13.32±0.09^{c}
14	50	9.54±0.02^{bc}	39.94±0.56^{d}	673.33±4.23^{cde}	1045.00±5.91^{g}	13937.66±101.20^{bc}	13.33±0.08^{c}
16	100	9.60±0.01^{a}	64.06±0.48^{c}	685.00±6.28^{ab}	1153.33±5.77^{d}	13933.33±91.52^{bc}	15.18±0.02^{b}
16	80	9.57±0.00^{ab}	66.11±1.27^{c}	680.00±3.88^{abc}	1120.00±5.74^{e}	13600.00±82.55^{d}	15.21±0.02^{b}
16	50	9.55±0.01^{bc}	66.05±1.67^{c}	668.33±1.73^{ef}	1161.67±2.88^{d}	14003.33±91.57^{b}	15.21±0.03^{b}
18	100	9.51±0.02^{de}	86.95±0.75^{a}	678.33±5.61^{bc}	1271.67±7.63^{c}	14266.67±72.93^{ab}	17.18±0.01^{a}
18	80	9.48±0.02^{e}	81.87±1.69^{b}	671.67±5.93^{def}	1313.33±4.10^{b}	14102.00±63.10^{b}	17.15±0.05^{a}
18	50	9.44±0.03^{f}	81.49±1.84^{b}	665.00±7.60^{f}	1355.00±6.12^{a}	14510.00±107.23^{a}	17.15±0.10^{a}
Mean sq. error		0.00	1.38	16.66	54.63	3407.74	0.05

Note: Means with the same letter are not significantly different. Reported values are expressed as mean ± standard deviation for n=3.



(a)



(b)

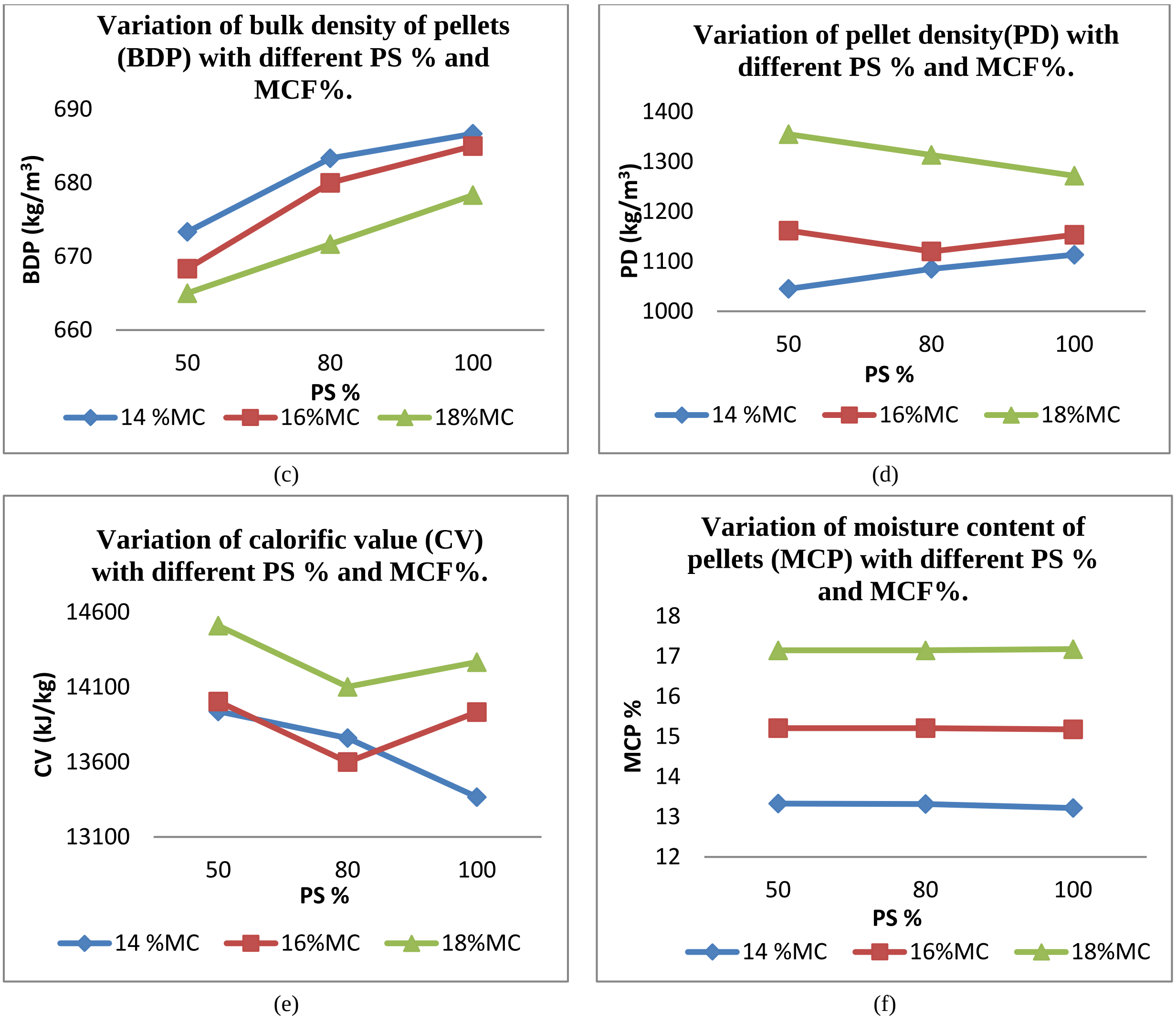


Fig. 5. Effect of PS and MCF on different characteristics of the pellets: (a) represents variation of diameter, (b) Variation of Length, (c) Variation of bulk density, (d) Variation of pellet density, (e) Variation of calorific value, (f) Variation of moisture content

The effect of PS and MCF on the bulk density of the pellets was highly significant (p=0.00) at a 5% level of significance as depicted in Table 5. These results indicate that the bulk density was slightly increasing with the increase in paddy straw percentage in the feed and the MCF 14% had the highest bulk density followed by 16 % and 18% respectively. Similar results were reported by Liu et al. (2013) in which the bulk density of straw pellets with a diameter of 6 mm, produced with the feed moisture content of 15% was 640 kg/m^3.

3.2.3. Pellet density (PD)

According to the limits described by German standards (DIN 51731, 1996 and DIN EN 15270, 2007) and previous studies' results, (Arshadi et al., 2008; Carone et al., 2011; Lehtikangas et al., 2001) the pellet density of paddy straw pellet or other materials may reach to 1500 kg/m^3; however, the ideal value of pellet density for best quality pellets is established as 1200 kg/m^3. A very high pellet density affects the combustion efficiency adversely because when the elements of pellets are tightly packed, the admission of the oxygen is prohibited. The effect of PS and MCF on pellet density was highly significant (p=0.00). The pellet density obtained, ranged from 1045 to 1113.33 kg/m^3, 1120 to 1161.67 kg/m^3, and 1271 to 1355 kg/m^3 respectively for the MCF 14, 16, and 18% as shown in Fig. 5(d). The highest pellet density was recorded for the pellets produced by MCF 18 % followed by 16% and 14% respectively. Comparing the density of feed, Rodriguez et al. (2016) observed that the pellet density of *H. pallens*, *A. Wrightii*, and *E. ebano* increased 93%, 30%, and 25%, respectively, which approve that pelletization increases the density.

3.2.4. Calorific value (CV)

Calorific value is yet another important factor to ascertain the combustibility of any material. Calorific value is defined as the energy produced by burning a unit mass of fuel. The calorific value of biomass can be described as higher heating value at constant volume (dry basis), Lower heating value at constant pressure (dry basis), and low heating value at constant pressure (wet basis or as received) (Chen et al., 2009).

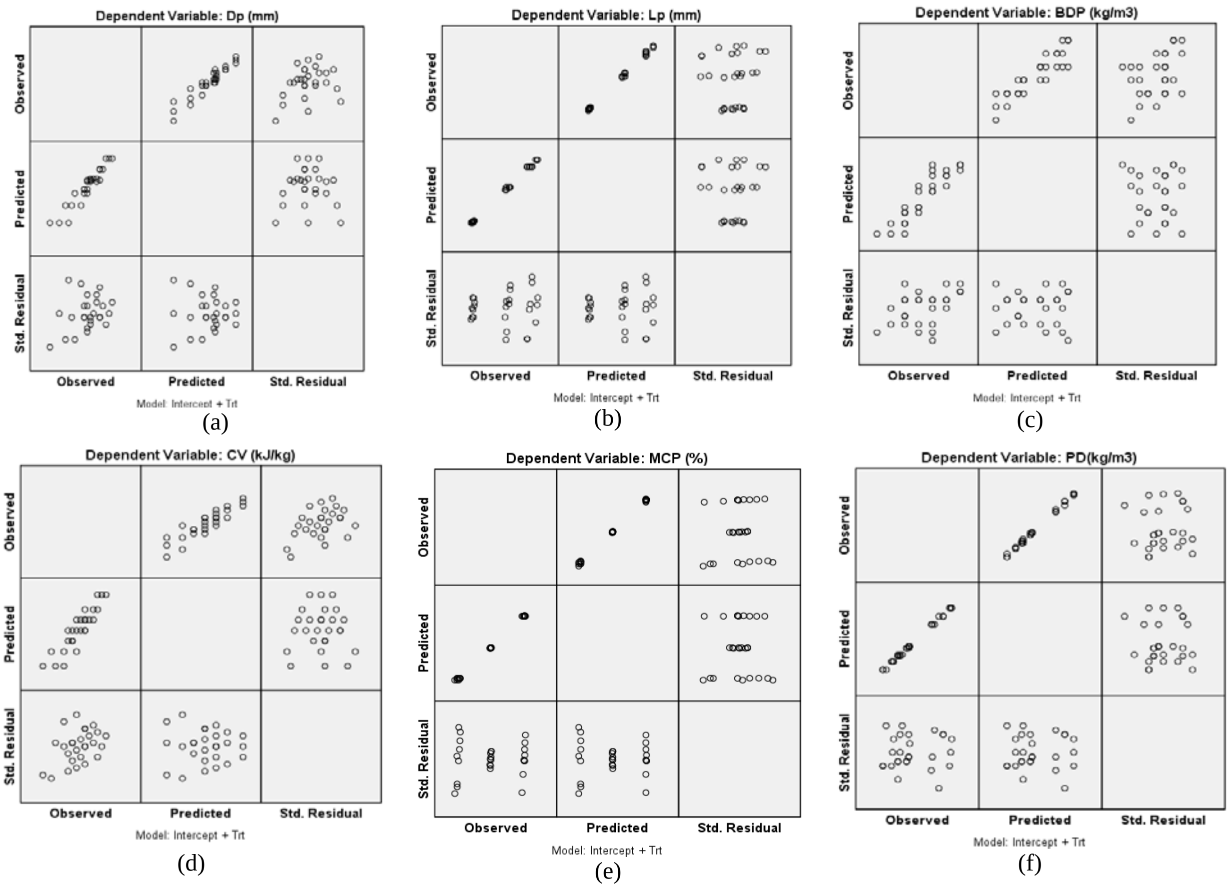


Fig. 6. Predicted and experimental values of various process parameters: (a) represents variation of diameter, (b) Variation of Length, (c) Variation of bulk density, (d) Variation of calorific value, (e) Variation of moisture content), (f) Variation of pellet density

Table 5. ANOVA table for tests of between-subjects effects

Source	***Dependent variable***	***Type III sum of squares***	***df***	***Mean square***	***F***	***p-value***
Corrected model	*Dp* (mm)	0.055[a]	8	0.007	21.218	0.000
	Lp (mm)	8675.203[b]	8	1084.400	783.837	0.03
	BDP (kg/m^3)	1407.407[c]	8	175.926	10.556	0.000
	PD (kg/m^3)	279440.741[d]	8	34930.093	639.398	0.000
	CV (kJ/kg)	2834074.074[e]	8	354259.259	10.397	0.000
	MCP (%)	67.469[f]	8	8.434	1700.574	0.04

a. R Squared = 0.904 (Adjusted R Squared = 0.862)
b. R Squared = 0.997 (Adjusted R Squared = 0.996)
c. R Squared = 0.824 (Adjusted R Squared = 0.746)
d. R Squared = 0.996 (Adjusted R Squared = 0.995)
e. R Squared = 0.822 (Adjusted R Squared = 0.743)
f. R Squared = 0.999 (Adjusted R Squared = 0.998)

The calorific value of the loose sawdust at 20% moisture content was 13250 kJ/kg. The calorific value of the sawdust depends on the type and conditions of the wood used (Shyamalee *et al.,* 2015). The effect of PS and MCF on the calorific value of the pellets was highly significant (p=0.00). The highest calorific values obtained were 14510 kJ/kg of the feed having 50 % PS and 18% MCF as described in Fig. 5(e), similar to reported by Telmo and Lousada (2011). The variations in the CV of the pellets varied according to the ratio of PS and MCF. High calorific values of the pellets indicate that biofuel produces a high amount of energy using a low amount of fuel (Boada and Vargas, 2015).

3.2.5. Moisture Content of Pellets (MCP)

The moisture content of the pellets largely depends on the moisture content of the feed. The effect of PS and MCF on the moisture content of the pellets was significant (p=0.04) at a 5% level of significance. The values of MCP % varied between 13.22 to 17.18 % as provided in Fig. 5(f). These values lied within the safe storage values of preventing material degradation, bacterial growth (Lehtikangas et al., 2001), and selfheating (Rhén et al., 2005) which cause the self-ignition of the pellets. The cooling of the pellets can be used to reduce the MCP by using the forced air (Zeng et al., 2007). The reasons for the high moisture content of the feed are the high relative humidity in the Asian and African countries; absence of an additional binder to the feed. The moisture content can be reduced by prolonged drying at high temperatures but this will increase the cost of pellet production.

3.3. *Cost-economics of pellet making machine*

The existing pellets-making machines are either highly expensive and large-capacity commercial-scale industrial machines that use multiple binders for producing the pellets or they are completely absent without any intermediate for small entrepreneurs/farmers. On the other hand, the machine developed in this research uses either paddy straw alone or a combination of sawdust and paddy straw for producing pellets without any binder with the sole purpose of waste management leading to the development of household fuel in the form of pellets. The farmers in developing nations usually tend to burn the paddy straw after harvest, thereby contributing to the carbon footprints. The pellets produced from the machine are comparable to the pellets produced by the commercial-scale machines. The machine can be used at the field level for producing pellets for domestic use of farmers or can be used for a small scale start-up business at the village level, which will help the farmers to earn extra income.

Other than paddy straw and sawdust, other available biomass, for example, cotton stalks, barley straw, paddy husk, dry leaves, etc., can be used in the machine for producing pellets, by conducting initial experiments to know the favorable conditions of different biomass, for producing pellets. The adoption of this machine at the farm level will lead to a reduction in straw burning cases and will help to reduce air pollution caused by the burning of paddy straw.

The manufacturing cost (fixed cost) of the machine was around 48000/- (INR) and the life of the system was considered as 8 years for calculating the economic feasibility of the machine. The details of fixed cost, operating cost, and other parameters used for calculating the pay-back period, benefit-cost ratio, and breakeven point are provided in Table 6. The pay-back period of the machine came out to be 2.5 years; while the benefit-cost ratio was around 2.84 with a break-even point of 0.31.

4. Conclusions

Pellet production from paddy straw is an economically feasible and eco-friendly approach for the management of paddy straw for energy production. This approach was used to develop a biomass pellet machine for on-farm sustainable management and valorization of paddy straw. Pellets can be produced with 100% paddy straw at a particle size of less than 4 mm and 14 to18% moisture content of the feed.

Table 6. Cost-economics of pellets making machine

Fixed cost	
Cost of the machine	₹48000
Life of the machine	8 Years
Cost of leaf Shredder	₹10000
Life of the Leaf Shredder	20 Years
Operating cost	
Labor charges	₹300/day
Cost of raw material (paddy straw)	₹2 /kg ₹3.50/ kg (sawdust)
The selling price of pellets	₹15/kg
Annual Fixed cost of the Leaf Shredder(A)	₹500
Annual fixed cost of machine/ yr. (B)	₹6000/year
Capacity of machine	12 kg/h
Operating time in a day	4 h
Labor charges @ Rs. 300/day (C)	₹90000/ year
Total paddy straw required	28800 kg/year
Electricity charges (D)	₹42000/year
Depreciation cost (maintenance and wear tear cost) (E)	₹1440/year
Total operating cost (A+B+C+D+E) = (F)	₹139440/year
Cost of paddy straw @ Rs. 2/kg (G)	₹57600/year
The total cost of production H= (F+G)	₹197040/year
The selling price of pellets @ Rs. 15/kg (I)	₹216000/year
Profit (I-H)	₹18060/year
Pay-back period	2.5 year
Benefit-cost ratio	2.84
Break-even point	0.31

Note: ₹ or INR stands for Indian National Rupee

The maximum calorific value of pellets (14510±107.23 kJ/kg) was recorded at a feedstock ratio of 50:50 with 18% moisture content wb, while minimum (13366.67±112.98 kJ/kg) was found in 100% paddy straw with 14% moisture content wb. The capacity of the pellet machine was approximately 12 kg/h at an RPM of 40.

The moisture content and size of the feed played a significant role in the formation and imparting strength to the pellets. Upon optimization of the process parameters, the best results were obtained at 18% moisture content of the feed (wet basis) with the paddy straw length of 4 mm approximately. The bulk density of the pellets was almost 10 times more than that of loose paddy straw. The economic analysis was carried out to ascertain the economic feasibility of the machine for adoption by the farmers. The payback period of the machine was 2.5 years while the benefit-cost ratio was 2.84.

The limitation of this machine is its limited capacity as it was designed especially for farmers with small to medium landholdings. One more challenge faced during the pelletization was that some loose feed material was obtained with the pellets from the outlet. For commercial usage, it'll require some modifications. The advantage of the machine over the existing pellets-making machines is that the machine is technically suitable from a farmer's point of view and is economically feasible for marginal and small farmers.

The findings of this research recommend the installation of an inbuilt heater to facilitate the torrefaction which can further increase the calorific value of the pellets. For further experiments, binders can be used for increasing the capacity of the machine and the strength of the pellets.

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