Production of Biomass Pellets from Sawdust to Enhance Fuel Efficiency

Mohammad Mostafizur Rahman
Jagannath University
Md. Aminul Haque
Jagannath University
Nargis Akter
Jagannath University
Mohammad Shah Jamal
Bangladesh Council of Scientific and Industrial Research
Mosharof Hossain (mosharof@bcsir.gov.bd)
Bangladesh Council of Scientific and Industrial Research https://orcid.org/0000-0003-0834-4740

Research Article

Keywords: Sawdust, Biomass, Pellets, Heating value

Posted Date: August 8th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1903314/v1

Abstract

Providing energy security for sustainable rural development biomass pellets are the major contributor to the bioenergy sector. The higher heating value of woody biomass pellets has encouraged much commercial utilization in the present rapidly growing industrial-economic world. Commercially available biomass sawdust-like Gurjan Balsam (*Dipterocarpus turbinatus* Gaertn.), White Siris (*Albizia lucida*), Cadamba (*Neolamarckia cadamba*), Tamarind (*Tatoul markarian*), Blackberry (*Acacia acuminate*), Mango (*Mangifera indica*), Raintree (*Samanea saman*), and Lambu (*Swietenia hybrida*) are opened up huge opportunities in the bioenergy sector. Eight wood sawdust samples investigated the heating value with the increasing pressure in the range of 6 kN to 20 kN. The height heating value was achieved at the pressure for Tamarind sawdust (14221.66 kJ/kg ± 0.84%) which possesses 6.53 ± 0.23% of moisture content. Gurjan Balsam with the highest moisture content (32.28 ± 0.14%) produced the lowest heating value (11260.09 kJ/kg ± 0.32%).

Introduction

The growing energy crisis is the prime concern around the globe. Fossil fuels are the main attractive sources of energy at present due to their worldwide availability, relative inexpensiveness, established economic extraction procedure, and easy utilization process. The greenhouse gas (GHG) emissions due to the consumption of fossil fuels as energy sources have induced global warming-like adverse effects on the environment. In 2019, global GHG emissions by fuel combustion were 34.2 $GtCO_{2eq}$ [1]. Because of the non-renewable nature and growing consumption rate, the fossil fuel stock will be declined within the century. Efforts are continuing to find environmentally-friendly alternative energy sources. As a substitution for fossil fuels, renewable bioenergy (biomass derived energy) sources could play an important role in the global energy systems by reducing GHG emissions [2]. Albeit the chemical constituents and moisture content of biomass materials fluctuate, they all contain low proportions of polluting agents and ash content. As a ‘carbon lean’ fuel biomass produces a fraction of the carbon emission of fossil fuels. Biofuels have the potential to fulfill at least 25% of the expected world’s energy demand (approximately 623 exajoules) by 2035 [3]. Biomass in the form of wood chips and wood pellets is used for the production of power and heat in temperate and boreal countries. The pelletization process produces low moisture content uniform shaped biomass fuel [4]. Wood pellets are advantageous over wood chips owing to their increased energy density and higher mass density. These characteristics make them easier to store, handle, and transport [5, 6]. Pellet density has remarkable importance among other mechanical factors and is the prime indicator of pellet grade [7]. Pellet density could be affected by several factors such as particle size, moisture content, and compressive force. To produce densified products, the optimum moisture content was recommended to be approximately 8% [8]. The studies showed that the density of the product decreases with increasing moisture content [9]. During the densification process, smaller particles yield greater surface area and thus generally, pellet density inversely varies with its particle size. It was reported that biomass in the form of fine grinding could generate high density pellets [10]. A study revealed that applied pressure had the most influence (60.4%)

on the pellet density [11]. Although the little study has been performed to evaluate the obtainable energy from biomass pellets, a significant linear correlation was found between higher extractive and lignin contents with higher heating values from biomass pellets [12, 13]. Softwoods are considered to contain greater amounts of extractives than hardwoods [14]. Thus, softwoods usually have higher heating values in contrast to hardwoods. Variations in energy content were noticed among different plant organs. Root and main stem derived biomass samples exhibit higher heating values than the leaves derived biomass. When the raw biomass is dried to produce refined pellets, its heating value decreases [15]. It presumably happens because of the loss of volatiles thorough the drying process. Wood and straw based pellets commonly produce heating values ranges from 17 to 18 MJ/kg [16, 17]. A few extractives like resins and tannins have adverse effects on combustion of pellets and their heating values as they generate relatively excessive amount of ash and dust [18]. Considering the necessity (or demand) of renewable energy sources, the present study was aimed (1) to utilize the sawdust (a wood residue produced from wood sawing process) for the preparation of biomass pellets to improve the fuel efficiency, (2) to investigate the impact of pelletizing pressure on pellet density, (3) to examine the variation of calorific value with increasing pressure, and (4) to determine the optimum pressure required to prepare pellets with highest heating value. The findings presented in this paper would be supportive in developing a clean and renewable energy source based on wood sawdust.

Materials And Methods

Raw materials

Eight wood sawdust samples: Gurjan Balsam (*Dipterocarpus turbinatus* Gaertn.), White Siris (*Albizia lucida*), Cadamba (*Neolamarckia cadamba*), Tamarind (*Tatoul markarian*), Blackberry (*Acacia acuminate*), Mango (*Mangifera indica*), Raintree (*Samanea saman*), and Lambu (*Swietenia hybrida*) were used in this study. All the wood species were collected from the local wood sawmill in the second half of July. Among the wood species, Gurjan Balsam were collected from Chandpur, Bangladesh, Raintree and Lambu were collected from Pabna, Banglades, Other samples were collected from Narayanganj, Bangladesh, respectively. All the samples were grinded in the planetary mill (Ball mill) with 400 rpm and rotating was done for 6 minutes to obtain a fixed particle size. Collected sawdust were then stored in plastic bottles prior to further analysis.

Methods

Proximate analysis

Moisture content of each raw material was measured by drying the samples (about 2 g each) in an oven at 105 °C ± 2 °C for 3 h, according to the ASTM Standard D4442-07 for wood and wood-base materials [19]. The oven-dried samples were heated in a muffle furnace for the determination of ash content according to a standard procedure for biomass described in ASTM E1755-01 [20].

Volatile matter was determined using the standard ASTM D271-48 procedure used for coal. Raw materials (about 12. to 1.4 g) were kept in a furnace and heated at 950 °C ± 20 °C for 7 min. Volatile matter was then calculated by weighing the weight loss, excluding the moisture weight expelled at 105 °C.

The percentage of fixed carbon was determined by subtracting the sum of the volatile matter, moisture and ash content from 100.

Ultimate analysis

Organic elemental analyzer (Thermo Scientific™ FLASH 2000, USA) was employed for ultimate analysis of the samples (Reactor temp. 900 °C, He: 2.5 bar, O_2: 2.5 bar, column: TCD, PTFE) according to the standard procedure described in ASTM D5291-02 [21].

Heating value

Oxygen bomb calorimeter (Julius Peters, Berlin-NW 21) was used to determine the gross calorific value (heating value) of raw sawdust samples according to ASTM D5865 Standard [22]. The temperature was increased by the liberated heat when the samples were burned. The heating value of the samples was calculated using the following (**Eq. 1**)

$$Heating\ value\ (kJ/kg) = \frac{W \times (T_1 - T_2)}{X} \quad \text{(Eq. 1)}$$

Here, W represent the energy equivalent of the calorimeter, $T_1 - T_2$ is the difference between initial and final temperature of the calorimeter, and X is the weight of the sample. The energy equivalent (W) was obtained 10027.42 kJ/°C when standard benzoic acid was used.

Pellet preparation

Universal Testing Machine–UTM (FS300 kN, The Testometric Co. Ltd., England) was used for the preparation of pellets from raw sawdust samples at 25 °C which has cylindrical die made of carbon steel (10 mm diameter). The sample was put into the cylinder in between two carbon steel pellets each time. Pelletizing pressure was exerted by a second steel pellet, a piston made of metal and crosshead of the machine (UTM). The compression force was estimated using a 450 kN load cell, connected to a meter. The die was rinsed with acetone and mopped clean with tissue paper prior to each use and when changing sawdust samples. Usually, less than 0.25 g of sawdust was loaded into the die and compressed by hydraulic press at a rate of 2 mm/min until the desired pelletizing pressure was gained. The pressure was released after 3 mins and the piston was removed. The pellets were brought out from the die by applying pressure at a compression rate of 2 mm/min and the removal of backstop. Four different pelletizing pressures (6 kN, 12 kN, 16 kN, and 20 kN) were used in this study.

Pellet density

The dimensions of pelletized pellet at various pressures (6 kN, 12 kN, 16 kN, and 20 kN) were measured using Vernier or slide calipers. The weight of the pellets was estimated by an analytical balance up to four decimal places with an accuracy of 1.0 mg. The pellet density at various pressures was then calculated by taking the ratio of weight to volume of pellets.

Scanning electron microscope

Scanning electron microscope (SEM) was used to study the morphology of the prepared biomass pellets' surface. The scanning electron microscope (SEM) uses a focused beam of high-energy electrons to generate a variety of signals at the surface of solid specimens. The signals that derive from electron-sample interaction reveal information about the sample including external morphology (texture), chemical composition, crystalline structure, and orientation of materials making up the sample. To determine the surface morphology of the prepared pellet of saw dust SEM (SEM; JSM-7610F, JEOL, Japan) (accelerating voltage: 15 kV, magnification: 25000X) was used to take images.

Results And Discussion

Proximate analysis

The proximate analysis results (percentage of moisture content, ash content, volatile matter, and fixed carbon) of raw biomass samples are illustrated in Fig. 1. Proximate analysis gives preliminary results in evaluation of fuel quality. Moisture content has significant consequences on fuel quality of sawdust samples. It inversely affects the heating value as high moisture content reduce the liberated heat of combustion. This happens because the produced energy is greatly absorbed to evaporate water during combustion [23, 24]. High level of moisture content causes difficulty in biomass processing and hamper the formation of durable densified product. Moreover, high percentage of moisture in biomass sample might decompose the product by mold formation during storage. The recommended optimal moisture content for the formation of pellets is 5% to 15% on a wet basis [25, 26]. The raw materials exhibited the moisture content in between the recommended limit (4.57 ± 0.06% to 6.91 ± 0.10%) except Gurjan Balsam (32.28 ± 0.14%) (Fig. 1A). Biomass obtained from mango tree have had the lowest percentage of moisture content. Ash is measure of non-combustible inorganic impurities in biomass. Although the consequences of ash content on heating value is not understood yet, it is presumed that the heating value is reduced with higher ash content [27]. The impact of ash content is a significant issue when maintenance and emissions are concerned. The slagging and fouling problems causing by ash fusion resulted corrosion and lowering in combustion efficiency. Biomass obtained from Tamarind had the lowest ash content whereas Gurjan Balsam had the highest ash content among the examined raw materials in this study (Fig. 1B). High volatile matter of biomass usually has a positive impact on the sustainability of combustion which transforms the biomass in a highly reactive fuel with rapid combustion rate in the devolatisation stage [28]. The percentage of volatile matter of biomass samples were 79.37 ± 0.43% to 86.22 ± 0.02% in which Gurjan Balsam had the highest whereas Mango had the lowest percentage of volatile matter (Fig. 1C). Fixed carbon the available carbon portion for char combustion by removal of all volatile matter in a biomass which perform as the major energy generator in combustion process [29]. Fixed carbon content of the biomass samples studied were ranges between 11.91 ± 0.01% to 19.33 ± 0.34%, in which Mango has the maximum amount of fixed carbon whereas Gurjan Balsam possesses the lowest amount of fixed carbon (Fig. 1D).

Ultimate analysis

The ultimate analysis revealed the elemental composition (carbon, oxygen, hydrogen, nitrogen, and sulfur) of biomass sample and assist in determining the requisite amount of air for complete combustion, composition and the volume of combustion gases, and biomass heat of combustion. Carbon, oxygen, and hydrogen are the major constituents among the elemental compositions in ultimate analysis. Usually, carbon exists as partially oxidized form that demonstrate the low heating value of biomass in contrast to coal. The hydrogen content substantially contributes to the heating value. The organically bound oxygen in biomass which is liberated by the thermal decomposition, partially satisfy the oxygen requirement for combustion reaction and the remaining part is provided by air injection. However, nitrogen and sulfur mostly contribute in evolution of hazardous emissions. The ultimate analysis of biomass samples *via* gas-analysis processes revealed that carbon, oxygen, and hydrogen are the three main constituents which comprise between 30 to 60%, 30 to 40%, and 5 to 6%, respectively of dry biomass samples. Nitrogen and sulfur (and chlorine) generally make up 1% of dry biomass [30]. The investigation of chemical compositions in biomass samples revealed that carbon content was in between the ranges except Lambu biomass (82.28%), oxygen content was beyond limit in the most cases, although it was much less (11.71%) in Lambu. The excessive amount of nitrogen and sulfur contents were found in several biomasses. This might arise due to high nitrogen and sulfur content in the respective soil from where the wood was collected (Fig. 2).

Higher heating value of biomass samples

The energy content of biomass depends on its chemical compositions as well as moisture content. Sometimes, the combustion volume may also be affected by ash content. The variation of higher heating values with moisture and ash content of biomass samples has been evaluated and results are summarized in Table 1. Biomass sample from Mango with the lowest moisture content (4.57 ± 0.06%) generated the second highest heating values whereas Gurjan Balsam with the highest moisture content (32.28 ± 0.14%) produced the lowest heating value (11260.09 kJ/kg ± 0.32%) in this study (Table 1). Biomass from Tamarind has the highest heat of combustion (14221.66 kJ/kg ± 0.84%) which possesses 6.53 ± 0.23% of moisture content. Biomass from Tamarind having 0.71 ± 0.01% of ash content has the highest gross heat of combustion whereas Gurjan Balsam has the lowest heat of combustion and it possesses the highest ash content (1.87 ± 0.02%) albeit an obscure relationship prevails between ash content and heating values of biomass samples.

Table 1 Variation of higher heating values with moisture content and ash content of sawdust biomass samples. Data are means ± relative SD of three experiments

Name of sample	Moisture content (%)	Ash content (%)	Higher heating value (kJ/kg)
Gurjan Balsam	32.28 ± 0.14	1.87 ± 0.02	11260.09 ± 0.32%
Cadamba	6.90 ± 0.17	0.88 ± 0.07	12320.19 ± 0.58%
Raintree	6.91 ± 0.10	1.16 ± 0.09	13512.32 ± 0.58%
Lambu	6.90 ± 0.01	1.51 ± 0.08	13518.54 ± 0.70%
Blackberry	6.59 ± 0.61	0.98 ± 0.02	13733.52 ± 0.63%
White Siris	6.01 ± 0.35	1.02 ± 0.06	13789.48 ± 0.72%
Mango	4.57 ± 0.06	1.30 ± 0.10	14069.79 ± 0.54%
Tamarind	6.53 ± 0.23	0.71 ± 0.01	14221.66 ± 0.84%

Effect of pelletizing pressure on pellet density

Fig. 3 shows the effect of pressure on pellet density, showing that the pellet density gradually increased for a biomass species with gradually increasing pellet pressure and then decreasing in the range of 6-20 kN. Fig. 3 shows that the pellets have expanded after being released from the mold. It is also reported that the pellet height decreases with increasing pressure in the White siris, Cadamba, Mango, Raintree and Lambu experimental samples presented in Table 2. But another pattern was found in Tamarind and Blackberry; first decrease and then increase the height of the pellets. The diameters of all samples tested in the same experiments were slightly changed.

Table 2 Measurement of the dimension of pellets at various pressures

Name of sample	Dimensions	Pellete dimensions at pelletizing pressures (cm)			
		6 kN	12 kN	16 kN	20 kN
Gurjan Balsam	*h*[a]	0.201	0.201	0.201	0.201
White Siris		0.209	0.207	0.205	0.205
Cadamba		0.208	0.206	0.205	0.205
Tamarind		0.207	0.205	0.204	0.205
Blackberry		0.205	0.204	0.203	0.204
Mango		0.208	0.207	0.206	0.204
Raintree		0.209	0.206	0.206	0.206
Lambu		0.209	0.207	0.206	0.206
Gurjan Balsam	*D*[a]	1.001	1.001	1.001	1.001
White Siris		1.001	1.001	1.001	1.001
Cadamba		1.001	1.001	1.001	1.001
Tamarind		1.001	1.001	1.000	1.000
Blackberry		1.000	1.000	1.000	0.910
Mango		1.001	1.001	1.001	1.001
Raintree		1.001	1.001	1.001	1.001
Lambu		1.002	1.002	1.002	1.002

[a] *h* and *D* denote height and diameter, respectively

Since there is no external heat effect during the production of the pellets, the pellets become loose and expand when the pressure is removed. Increasing pressure reduces moisture content and particle size, which contributes to a decrease in total pellet weight. This occurs mainly due to the interaction between humidity and temperature due to applied pressure [31]. In the case of unheated biomass, heat is generated during pelleting due to friction between the biomass particles and the pressing channel of the die hole. The increase in friction and temperature inside the substrate due to the increase in pressure causes the expulsion of moisture from the biomass. As a result, the mass of the particle decreases. The higher the moisture content of the untreated sample, the greater this mass loss due to the higher moisture extrusion. Natural binders such as lignin, protein, and starch in the biomass contribute to the formation of pellets [31,32]. The extent of these natural binders varies between biomass species and since no binder is used in the pelleting process, the weight of pellets prepared at a given pressure has been determined. There is a difference between the raw materials.

Effect of pelletizing pressure on the higher heating value

The higher heating value of most of the tested samples is increasing with the increasing pelletizing pressure in the range of 6 to 16 kN from the die. Then decreasing the measured value in 20 kN pressure. The nature of the higher heating value of the experimental samples is illustrated in Fig 4.

Gurjan Balsam, possessing the highest moisture content, showed a sharp increase in calorific value during granulation at 6 kN. This is due to the removal of moisture, which results in its low calorific value in its uncompressed form. The initial part of the envelope obtained between the pressures of 6 kN and 20 kN can be explained by the observation by Mani et al. [33]. After the evaporation of moisture, the biomass particles first rearrange to fill this space, and air is removed from the pores. No appreciable amount of intergranular bonding develops at this stage other than the natural binding force that binds the particles into pellets at low pressure. Further compression brings the particles together and binding forces such as hydrogen bonding and van der Waals forces develop, which stick to the particles quite tightly. Mechanical nesting and mutual diffusion mainly come into play when biomass components such as lignin and proteins tend to flow. With increasing pressure, that flow capacity increases. At lower pressures, pelletizing conditions are not always favorable for the flow of lignin and the formation of solid bridges due to mutual diffusion. Migration of lignin results in strong cohesive forces and this increases the calorific value at higher pressures. This explains the trend of increasing thermal value in this region.

In the case of Cadamba pellets, increasing pressure contributes to the improvement of calorific value (Fig. 4). At low pressures, hydrogen bonding, van der Waals forces and some mechanical bonds are the main binding mechanisms. The formation of stiff bridges is the main reason for the maximum calorific value at high pressure to be achieved at 16 kN. Further increase in granulation pressure will reduce the energy obtained from the particles due to the growth of weak boundary layer or gaps and voids between particles. A weak boundary layer is formed due to the migration of some extracts to the surface of the grain and this tendency increases at high pressure and temperature. At high pressure, the collapse of the cell structure can create voids and voids between particles. Another factor is repulsive force was arising when high pressure is applied to biomass pellet. This repulsive also causes some void and crack in the interparticle surface. These factors eventually decline the heating value at elevated pressure.

The calorific values of Raintree, Lambu, Mango, and Blackberry pellets gradually increase up to pelletizing pressure of 12 kN (Fig.4). Afterward, these values decrease at 16 kN. Tamarind pellets show an abrupt increase in calorific values at 20 kN pressure and the very close result are shown in Cadamba in this pressure range.

SEM analysis

About 0.2gm samples were prepared for SEM analysis (Table 3). SEM image of Cadamba clearly shows that the internal surface morphology where lignocellulosic biomass is closely binding pattern in the various pressure range (Fig.5). The binding pattern is increasing with the increasing pressure shown in Fig. 2(A), 2(B), 2(C), and 2(D) for Cadamba sawdust pellets. From Fig.6, very similar results were found in the SEM image of Blackberry except in 20kN pressure, some big voids and cracks were found due to intermolecular repulsive force.

Table 3 Measurement of pellet weight for SEM study

Name of sample	Pellet weight at different pelletizing pressure (gram)			
	6 kN	12 kN	16 kN	20 kN
Cadamba	0.2158	0.2172	0.2164	0.2144
Blackberry	0.2168	0.2161	0.2152	0.2194

Conclusion

The higher volatiles of biomass generally has a positive effect on combustion sustainability, turning biomass into a highly reactive fuel with a fast combustion rate in the decomposition step. The percentage of volatiles in the biomass samples ranged from 79.37 ± 0.43% to 86.22 ± 0.02%, with Gurjan Balsam having the highest percentage while Mango had a low percentage of volatiles. best. It is assumed that the calorific value is reduced with higher ash content. The final analysis of biomass samples through gas analysis revealed that carbon, oxygen, and hydrogen were the three main components accounting for 30-60%, 30-40%, and 5-6% of the samples, respectively. dry biomass. The heating values of the Raintree, Lambu, Mango, and Blackberry pellets gradually increased to a pelletizing pressure of 12 kN. These values are then reduced to 16 kN. Tamarind pellets show a height calorific value of 14221.66 kJ/kg without any pressure. But give an abrupt increase in calorific values at 20 kN pressure. On the other hand, Cadamba showed a height calorific value at the pressure of 16 kN.

Declarations

Acknowledgements

The authors would like to thank Dr. Abdul Gafur of Pilot Plant and Process Development Center (PP&PDC), BCSIR, Dhaka-1205, Bangladesh, for his help with pellets preparation. The authors gratefully acknowledge the research facilities provided by Institute of Fuel Research and Development (IFRD), BCSIR, Dhaka-1205, Bangladesh.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Availability of data and material

Not applicable

Code availability

Not applicable

Authors' contributions

Mohammad Mostafizur Rahman: Methodology, Software, Formal analysis, Investigation, & Writing. **Md. Aminul Haque**: Validation, Writing - Original Draft, Visualization. **Nargis Akter**: Writing - Original Draft & Formal analysis. **Mohammad Shah Jamal**: Writing - Review & Editing, Visualization. **Mosharof Hossain:** Conceptualization, Writing - Original Draft, Software, Resources & Supervision.

References

1. Greenhouse Gas Emissions from Energy Overview (2021) https://www.iea.org/reports/greenhouse-gas-emissions-from-energy-overview/global-ghg-emissions
2. Chum H, Faaij A, Moreira J, Berndes G, Dhamija P, Dong H, Ribeiro SK (2011) Renewable Energy Sources and Climate Change Mitigation: Bioenergy. *Special Report of the Intergovernmental Panel on Climate Change*. Camb Univ Press 209–332. https://doi.org/10.1017/CBO9781139151153.006
3. Kopetz H (2013) Build a biomass energy market. Nature 494:29–31. https://doi.org/10.1038/494029a
4. Lam PY, Lam PS, Sokhansanj S, Bi XT, Lim CJ, Melin S (2014) Effects of pelletization conditions on breaking strength and dimensional stability of Douglas fir pellet. Fuel 117:1085–1092. https://doi.org/10.1016/j.fuel.2013.10.033
5. Hamelinck CN, Suurs RAA, Faaij APC (2005) International bioenergy transport costs and energy balance. Biomass Bioenergy 29:114–134. https://doi.org/10.1016/j.biombioe.2005.04.002
6. Sultana A, Kumar A (2012) Ranking of biomass pellets by integration of economic, environmental and technical factors. Biomass Bioenergy 39:344–355. https://doi.org/10.1016/j.biombioe.2012.01.027
7. Mani S, Tabil LG, Sokhansanj S (2006) Effects of compression force, particle size and moisture content on mechanical properties of biomass pellets from grasses. Biomass Bioenergy 30:648–654. http://dx.doi.org/10.1016/j.biombioe.2005.01.004

8. Li Y, Liu H (2000) High pressure densification of wood residues to form an upgraded fuel. Biomass Bioenergy 19:177–186. https://doi.org/10.1016/S0961-9534(00)00026-X
9. Rehkugler GE, Buchele WF (1969) Biomechanics of forage wafering. Trans Am Soc Agric Eng 12:1–8. https://doi.org/10.13031/2013.38747
10. Dobie JB (1959) Engineering appraisal of hay pelleting. Agric Eng 40:76–77
11. Adapa PK, Tabil LG, Schoenau GJ (2013) Factors affecting the quality of biomass pellet for biofuel and energy analysis of pelleting process. Int J Agric & Biol Eng 6:1–12. https://doi.org/10.3965/j.ijabe.20130602.001
12. White RH (1987) Effect of lignin content and extractives on the higher heating value of wood. Wood Fiber Sci 19:446–452
13. Demirbas A (2001) Relationship between lignin contents and heating values of biomass. Energy Energy Convers Manage 42:183–188. https://doi.org/10.1016/S0196-8904(00)00050-9
14. Finell M, Arshadi M, Gref R, Scherzer T, Knolle W, Lestander T (2009) Laboratory-scale production of biofuel pellets from electron beam treated Scots pine (*Pinus silvestris* L.) sawdust. Radiat Phys Chem 78:281–287. https://doi.org/10.1016/j.radphyschem.2008.12.002
15. Lehtikangas P (2001) Quality properties of pelletised sawdust, logging residues and bark. Biomass Bioenerg 20:351–360. https://doi.org/10.1016/S0961-9534(00)00092-1
16. Tumuluru JS, Sokhansanj S, Lim CJ, Bi T, Lau A, Melin S, Sowlati T, Oveisi E (2010) Quality of wood pellets produced in British Columbia. Appl Eng Agric 26:1013–1020
17. Narra S, Tao Y, Glaser C, Gusovius HJ, Ay P (2010) Increasing the calorific value of rye straw pellets with biogenous and fossil additives. Energy Fuels 24:5228–5234
18. Relova I, Vignote S, Leon MA, Ambrosio Y (2009) Optimisation of the manufacturing variables of sawdust pellets from the bark of Pinus Caribaea morelet: particle size, moisture and pressure. Biomass Bioenerg 33:1351–1357
19. ASTM D4442-07 (2007) Standard Test Methods for Direct Moisture Content Measurement of Wood and Wood-Base Materials. ASTM International, West Conshohocken. https://doi.org/10.1520/D4442-07. PA
20. ASTM E1755-01 (2001) Standard Test Method for Ash in Biomass. ASTM International, West Conshohocken. PA. https://doi.org/10.1520/E1755-01
21. ASTM D5291-02 (2002) Standard Test Methods for Instrumental Determination of Carbon, Hydrogen, and Nitrogen in Petroleum Products and Lubricants. ASTM International, West Conshohocken. PA. https://doi.org/10.1520/D5291-02
22. ASTM D5865-10a (2010) Standard Test Method for Gross Calorific Value of Coal and Coke. ASTM International, West Conshohocken. PA. https://doi.org/10.1520/D5865-10A
23. Demirbas A (2007) Effects of Moisture and Hydrogen Content on the Heating Value of Fuels. Energ sources part A 29:649–655

24. Sunardi, Djuanda, Mandra MAS (2019) Characteristics of Charcoal Briquettes from Agricultural Waste with Compaction Pressure and Particle Size Variation as Alternative Fuel. Int Energy J 19:139–148
25. Demirbas A, Sahin-Demirbas A (2010) Briquetting Properties of Biomass Waste Materials. Energ sources 26:83–91. http://dx.doi.org/10.1080/00908310490251918
26. Stelte W, Holm JK, Sanadi AR, Barsberg S, Ahrenfeldt J, Henriksen UB (2011) Fuel pellets from biomass: The importance of the pelletizing pressure and its dependency on the processing conditions. Fuel 90:3285–3290. https://doi.org/10.1016/j.fuel.2011.05.011
27. Sun S, Zhao Y, Ling F, Su F(2009) Experimental research on air staged cyclone gasification of rice husk. Fuel Process Technol 90: 465–471. https://doi.org/10.1016/j.fuproc.2009.02.003
28. Koppejan J, Loo SV (2007) The Handbook of Biomass Combustion and Co-firing. Routledge, London. https://doi.org/10.4324/9781849773041
29. Akowuah JO, Kemausuor F, Mitchual SJ (2012) Physico-chemical characteristics and market potential of sawdust charcoal briquette. Int J Energy Environ Eng 20:1–6. https://doi.org/10.1186/2251-6832-3-20
30. Chaney J(2010) Combustion characteristics of biomass briquettes. Ph.D. Thesis, University of Nottingham, Nottingham. United Kingdom
31. Mani S, Tabil LG, Sokhansanj S (2006) Effects of compressive force, particle size and moisture content on mechanical properties of biomass pellets from grasses. Biomass Bioenergy 30(7):648–654
32. Carone MT, Pantaleo A, Pellerano A (2011) Influence of process parameters and biomass characteristics on the durability of pellets from the pruning residues of Olea europaea L. Biomass Bioenergy 35(1):402–410
33. Mani S, Tabil LG, Sokhansanj S (2004) Evaluation of compaction equations applied to four biomass species. Can Biosyst Eng 46(3):55–61

Figures

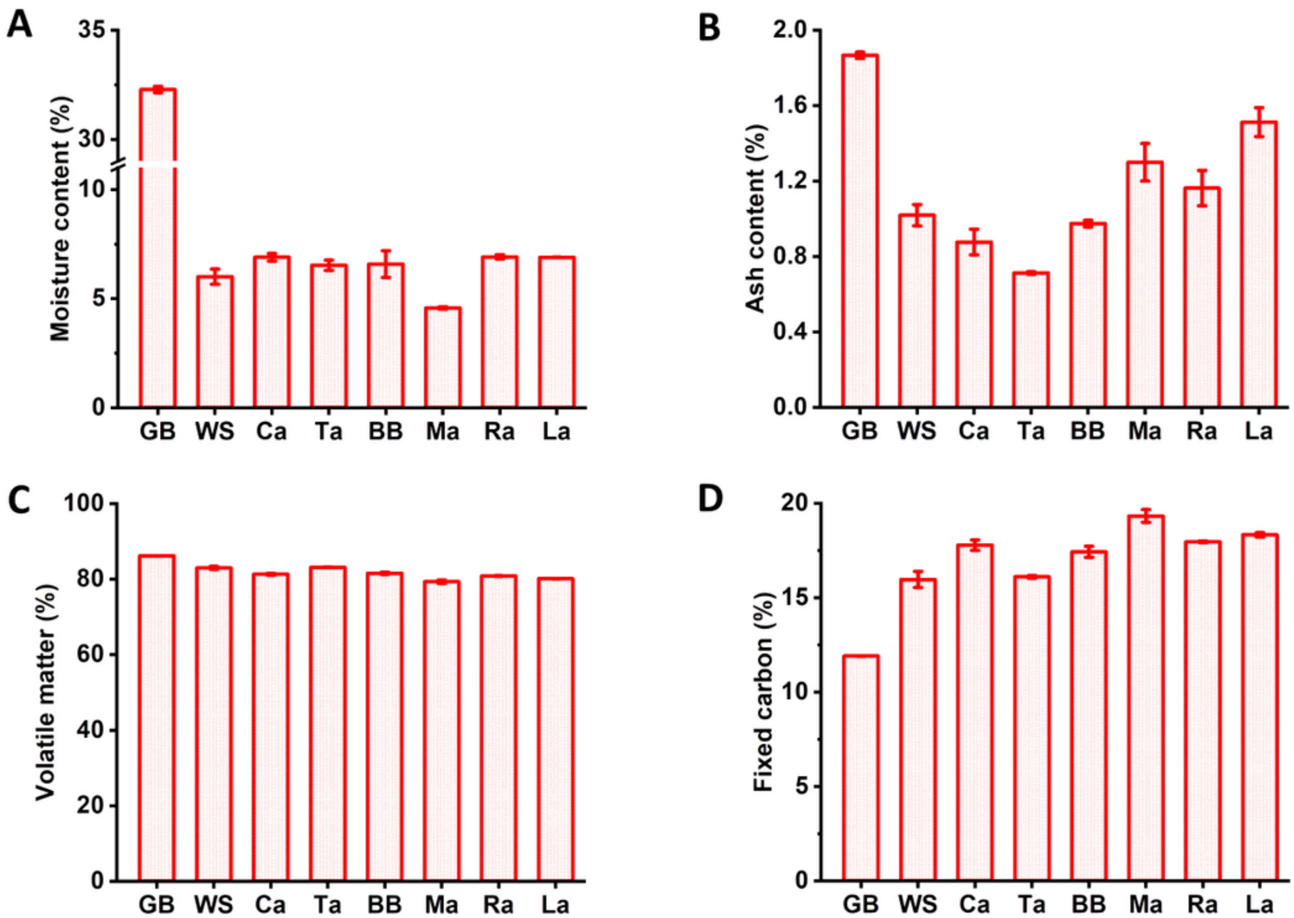

Figure 1

Proximate analysis of raw sawdust. Data are means ± SD (standard deviations) of three experiments. Percentage of (**A**) Moisture content, (**B**) Ash content, (**C**) Volatile matter, and (**D**) Fixed carbon of Gurjan Balsam (**GB**), White Siris (**WS**), Cadamba (**Ca**), Tamarind (**Ta**), Blackberry (**BB**), Mango (**Ma**), Raintree (**Ra**), and Lambu (**La**) sawdust, respectively

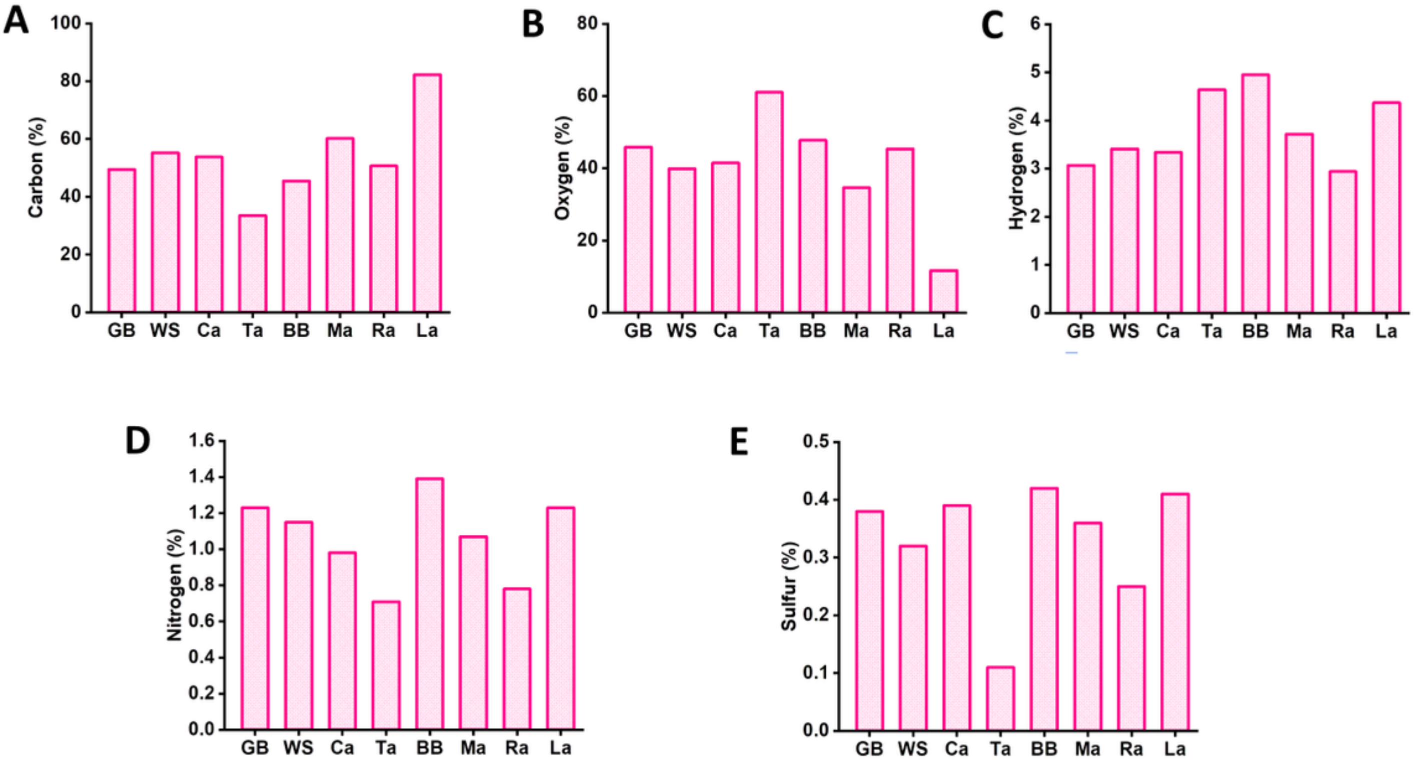

Figure 2

Ultimate analysis of raw sawdust. Data are means ± SD (standard deviations) of three experiments. Percentage of (**A**) Carbon, (**B**) Oxygen, (**C**) Hydrogen, (**D**) Nitrogen, and (**E**) Sulfur of Gurjan Balsam (**GB**), White Siris (**WS**), Cadamba (**Ca**), Tamarind (**Ta**), Blackberry (**BB**), Mango (**Ma**), Raintree (**Ra**), and Lambu (**La**) sawdust, respectively

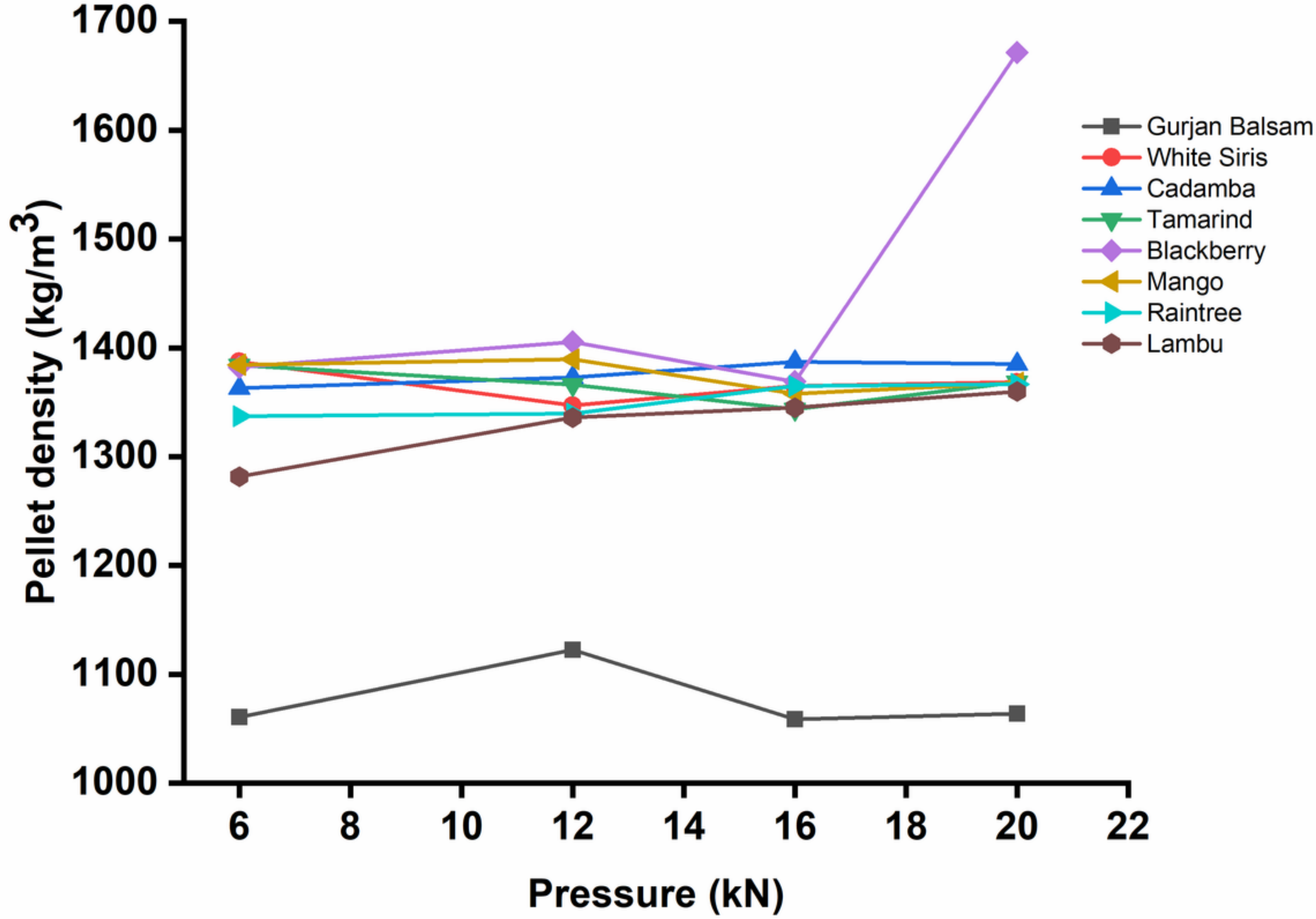

Figure 3

Variation of pellet density with different pelletizing pressure

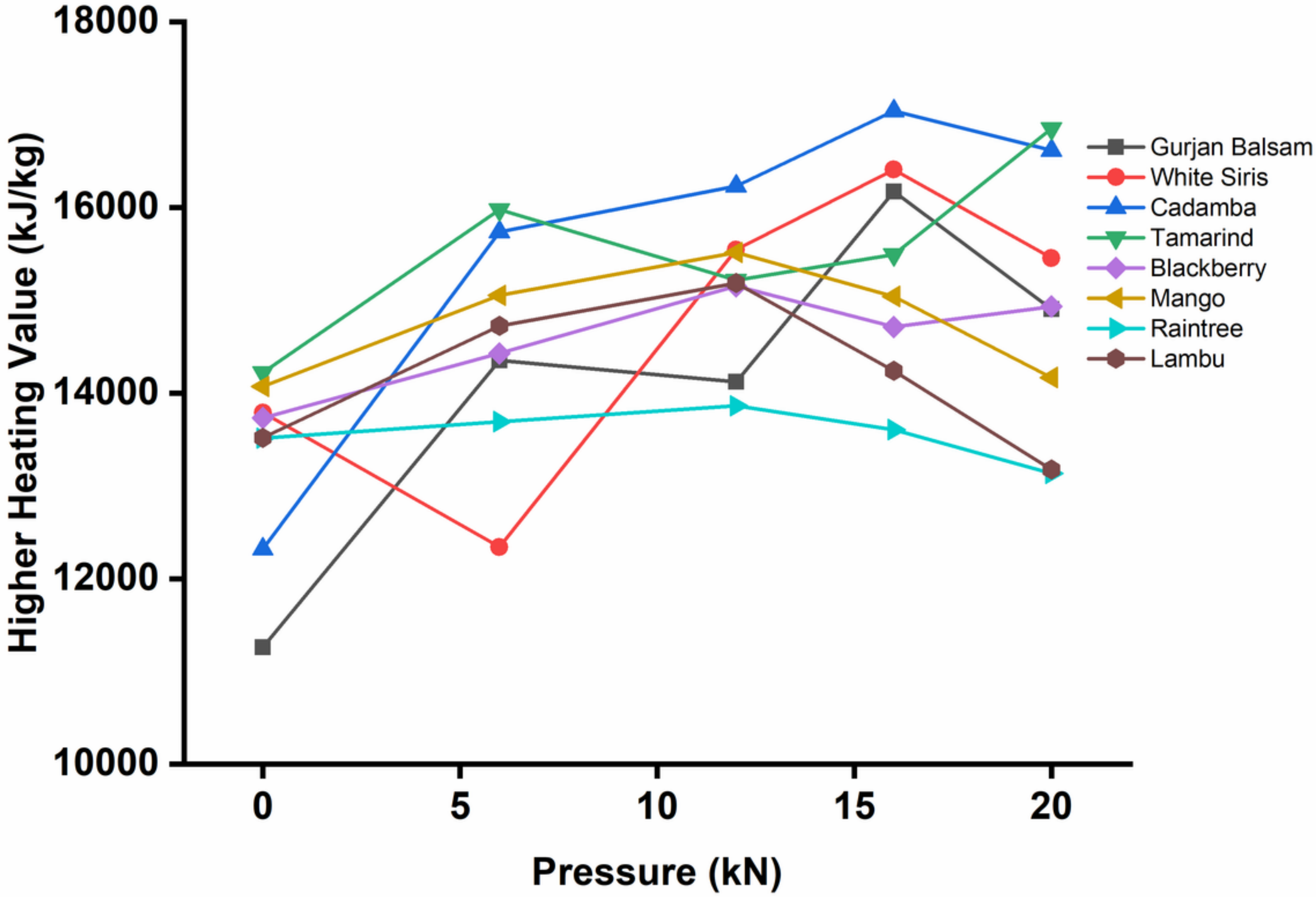

Figure 4

Variation of higher heating values with increasing pelletizing pressure of pellets prepared from raw sawdust

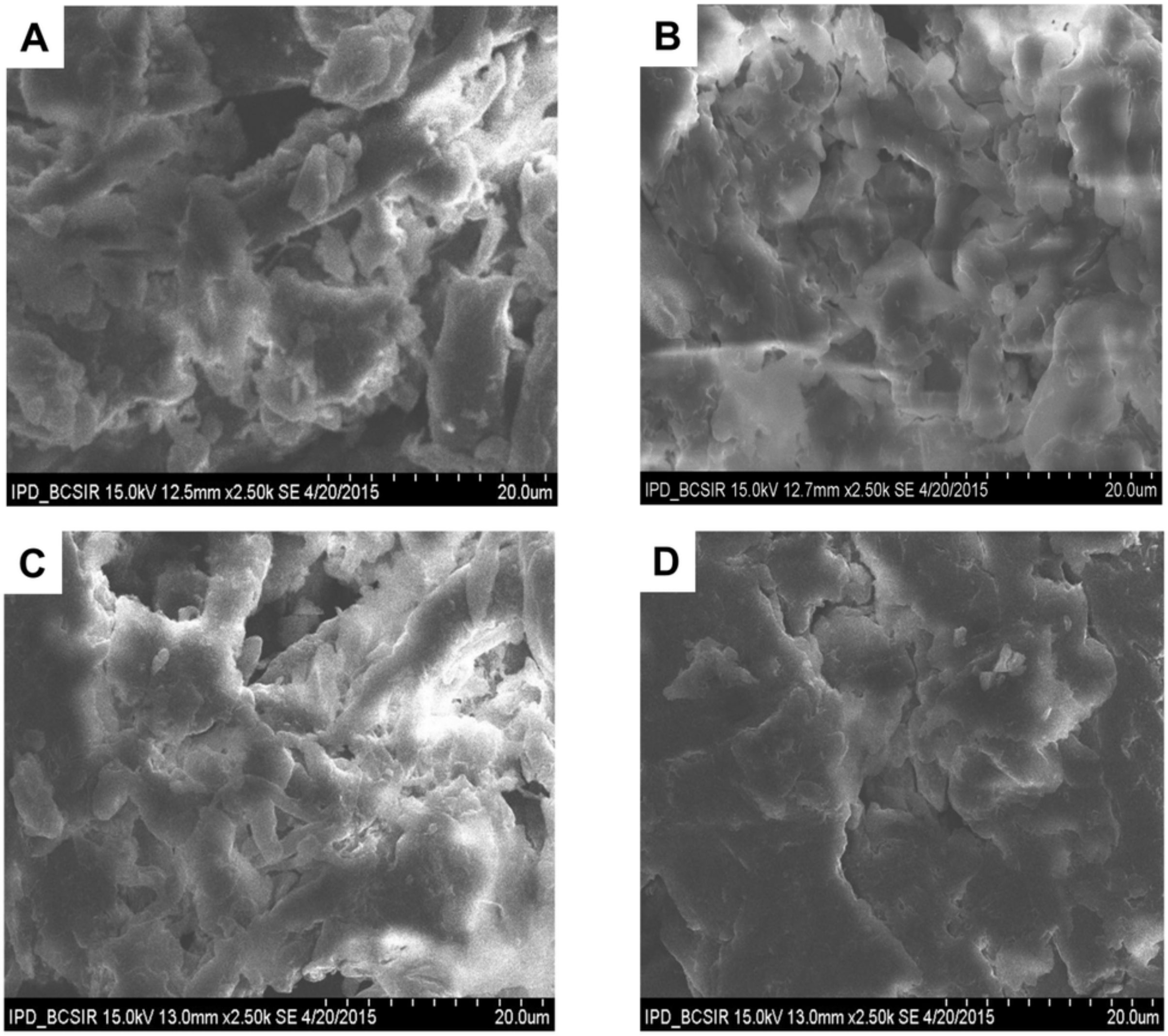

Figure 5

SEM images of Cadamba (softwood) pellets. (**A**) 6 kN. (**B**) 12 kN. (**C**) 16 kN. (**D**) 20 kN

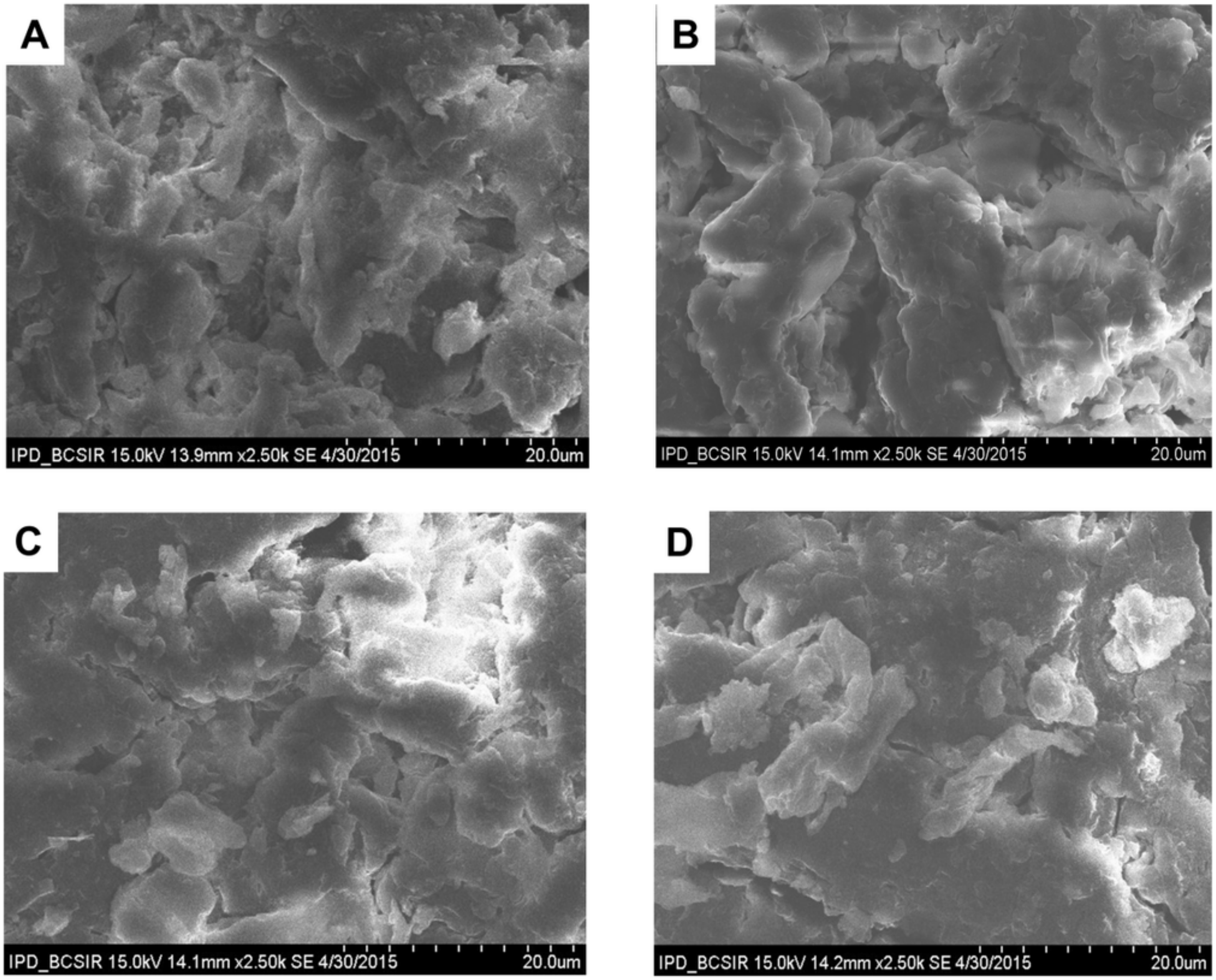

Figure 6

SEM images of Blackberry (hardwood) pellets. (**A**) 6 kN. (**B**) 12 kN. (**C**) 16 kN. (**D**) 20 kN

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Onlinefloatimage1.png