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Effects of Feeding Speed and Temperature on Properties of Briquettes from Poplar Wood Using a Hydraulic Briquetting Press

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Abstract: Biomass has a high potential to contribute towards resolving the energy deficit. Processing biomass into solid fuels enhances its use in various bioenergy conversion technologies. The quality of densified biomass depends on several variables. The investigation of the effect of densification parameters on briquette quality is necessary for process optimization. This study investigates the influence of die temperature (100, 120, 140 °C) and feeding speed (2.4, 2.9, 3.3 mm s^{-1}) on the quality of briquettes produced from poplar using a hydraulic biomass briquetting machine. The density of the briquettes ranged between 746.7 and 916.8 kg m^{-3}, the mechanical durability ranged from 97.4 to 98.4%, and the water resistance index was between 91.6 and 96.1%. The results show that the temperature was statistically significant ($p < 0.05$) on the density, mechanical durability and water resistance of biomass briquettes. The feeding speed was statistically significant ($p < 0.05$) on the density and water resistance. The interaction of temperature and feeding speed was statistically significant ($p < 0.05$) on all properties considered. The results obtained in this study are useful for optimizing the quality of briquettes produced using the hydraulic piston press.

Keywords: biomass; briquettes; temperature; poplar wood; bioenergy

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1. Introduction

Globally, there is a lot of effort to promote renewable energy by increasing its share in the energy mix. Taking into account a variety of alternative energy sources, biomass energy has been an indispensable part of the energy discussions with regards to framework policy [1,2]. Various estimations [3–10] have shown that biomass has huge regional and global potential for the production of biofuels and bioenergy. For instance, Jekayinfa et al. [5] estimated that the technical energy potential of biomass resources in Nigeria was approximately 2.33 EJ. From the review by Long et al. [6], bioenergy production in 2050 from agricultural and forestry residues and wastes will range between 76 and 96 EJ and up to 96 EJ could be obtained from energy crops. Stecher et al. [7] noted that optimistic estimations indicate that the global potential of energy crops could reach 1272 EJ yr^{-1} by 2050, whilst global potential of forest residues could reach 150 EJ yr^{-1}. Bioenergy potentials for sub-Saharan Africa were estimated to be 4 EJ yr^{-1}, whilst for Europe, it was up to 12.8 EJ yr^{-1}, 3.9 EJ yr^{-1} and 5.4 EJ yr^{-1} for dedicated bioenergy crops, agricultural residues and forestry residues, respectively [6]. Ojolo and Orisaleye [8] and Jekayinfa and Scholz [10] opined that the persisting energy deficit could be solved to a large extent if bioenergy is effectively utilized. Searle and Malins [9] emphasized the sustainable utilization of the projected global bioenergy potentials, which were up to 20 EJ yr^{-1} for biofuel, 40 EJ yr^{-1} for electricity and 30 EJ yr^{-1} for heating in 2050. Despite this huge potential, biomass has yet to gain extensive application for energy and power generation because it is not as efficient as fossil fuels. It has, however, been established that agriculture-based rural communities of developing countries could benefit greatly from the utilization of biomass for heat and power applications [11].

There are several means for converting biomass into efficient energy carriers, which are classified into thermochemical, biochemical and physical/mechanical conversion processes. Thermochemical conversion of biomass involves the utilization of heat to initiate and sustain chemical reactions that transform biomass into energetic products. Thermochemical conversion processes include gasification [12–14] and pyrolysis [15–17]. Biochemical conversion involves the use of micro-organisms and enzymes to breakdown biomass into liquid or gaseous fuels. The fuels obtained from the biochemical conversion methods include biogas [18,19], bioethanol [20] and biodiesel [21,22].

Physical or mechanical conversion of biomass requires the modification of biomass; it involves pre-processing activities, including size reduction/comminution, drying and densification [23–27]. Mechanical conversion of biomass is required to transform biomass into forms that have better properties than raw biomass, such as higher bulk density, higher energy density and hydrophobicity. Densification of biomass is considered a viable option to impact these properties whilst it improves the handling properties.

Densification technologies have been classified into low pressure (<5 MPa), medium pressure (5–100 MPa) and high pressure (>100 MPa). High-pressure technologies utilize equipment, such as the screw press/extruder briquetting machine, mechanical piston presses, hydraulic piston presses, roller presses and pelleting machines [27]. Theoretical studies [28–34] have been carried out on some high-pressure densification technologies to understand the effect of design parameters on the operational performance of equipment. Similarly, empirical investigations have been carried out on some densification technologies using different biomass materials. Jekayinfa et al. [35] utilized a full factorial design of experiment (DOE) to investigate and model the effect of densification variables on the density and water resistance of corncob briquettes produced with a uniaxial press. Temperature and particle size along with their interaction was significant ($p < 0.05$) to the water resistance whilst pressure, temperature and particle size were significant to the density of the corncob briquettes. Using a uniaxial press, Orisaleye et al. [36] utilized response surface methodology (RSM) to investigate the physical properties of Abura sawdust briquettes. From the study, temperature, hold time and pressure were significant ($p < 0.05$) for the briquette density.

Cabrales et al. [37] carried out an investigation on the densification process of oil palm empty fruit bunches using an experimental hydraulic press. From the study, it was found that moisture content had a great influence on the briquette density. It was also found that short fibres were preferred for high density. Fibre length and moisture content greatly influenced the durability index and compressive strength. Compaction time was also found to influence the compressive strength, along with interactions between compaction time and fibre length, and compaction time and moisture content. Low-pressure densification using binder was carried out by Essien and Oke [38] using sawdust, rice husk and palm kernel shell. The study found that the material type was a key factor in influencing the briquettes produced. The study also found that compaction pressure has a great influence on the quality of briquettes. Lai et al. [39] investigated the influence of processing and storage parameters on the strength of oil palm kernel shell pellets. It was observed that the strength of the pellets increased with compaction pressure, but pressures above 188 MPa had little effect on the strength. The pellet strengths were also found to increase with longer hold times.

A laboratory hydraulic press was used by Mitchual et al. [40] to produce briquettes from different biomass species by applying pressures between 10 and 50 MPa. The study showed that the particle size of sawdust had a significant effect ($p < 0.05$) on the relaxed density and compressive strength of the briquettes produced. Regression models developed in the study indicated that species density, particle size and compacting pressure were good predictors of relaxed density and compressive strength. Muntean et al. [41] investigated the influence of raw material properties on the quality of solid biofuel produced using a hydraulic piston briquetting press. It was observed that the bulk density of the initial materials, along with the temperature, influenced the quality of the briquettes produced. The study also found that the utilisation of raw materials with smaller fraction sizes positively influenced the mechanical durability of the briquettes.

It is important to develop a wide knowledge base in order to understand how densification factors influence different product quality parameters based on the various densification technologies and in dependence on the biomass processed [26]. In particular, controllable machine variables, such as feeding speed, which measures the rate at which biomass is fed into the briquetting press, are expected to affect the quality of briquettes [41–43]; however, this has received little attention in the literature. An understanding of the interaction between feed rate and other process variables will be useful in optimising the briquetting process for high-quality briquettes using briquetting equipment.

In this study, an investigation is carried out to determine the effect of feeding speed (2.4, 2.9, 3.3 mm s^{-1}) and die temperature (100, 120, 140 °C) in a hydraulic briquetting machine on the density, durability and water resistance of biomass briquettes created from softwood (poplar wood).

2. Materials and Methods

2.1. Production of Fibres as Raw Material for Briquettes

Poplar wood (clone Max-4 *Populus maximowiczii* Henry × *Populus nigra* L.) was obtained from the short rotation coppice plantation at the Leibniz Institute of Agricultural Engineering and Bioeconomy, Potsdam, Germany. The 4-year-old trees, with an average stem diameter of 6 cm at cutting height were harvested with a tractor-mounted mower-chipper [44] in the winter, stored, and dried until June as wood chips in an outdoor pile (Figure 1).

(**a**)  (**b**) 

Figure 1. (**a**) Harvest of poplar with a mower-chipper. (**b**) Wood chips produced at harvest.

Due to microbiological activity, the wood chip pile heats up to approximately 60 °C. This increase in temperature dried the wood chips to a moisture content of approx. 30% (wet based, w.b.) for storage until further processing [45]. Before milling, the wood chips were pretreated with water and brought to a 55% moisture content (w.b.) using barrels and a barrel tumbling machine. The wet wood chips were then milled to fibre using a small industrial-scale twin-screw extruder (P = 90 kW, Model MSZK B90e, Lehman Maschinenbau GmbH, Jocketa, Germany) at an aperture opening of 20 mm [46]. The produced poplar fibre was subsequently passed through a flash dryer to reduce the moisture content from approx. 55% to 10% (w.b.). The fibres were collected and stored in big bags before further processing into briquettes. Particle size analysis was carried out on fibre samples collected from the big bags according to standard EN ISO 17827-2 [47] in quadruplicate using a sieving tower with different sieve mesh widths. The bulk density of the fibre was determined using EN DIN 17828 standard test methods, based on a test volume of 10 L in a threefold repetition [48].

The moisture content of the fibres was determined using the oven-dry method outlined in standard EN ISO 18134-2 [49].

2.2. Operation of the Hydraulic Briquetting Press

A hydraulic-powered biomass densification machine (D-89231, RSN Maschinenbau GmbH/Germany, power 5 kW), shown in Figure 2a, was used to produce the briquettes from poplar wood fibre without the use of a binding agent. Before briquetting, the die was heated to the required temperature with three 200-W temperature sensor-controlled heating mats covering the press channel (Pt 100 temperature sensor, total heating power 600 W).

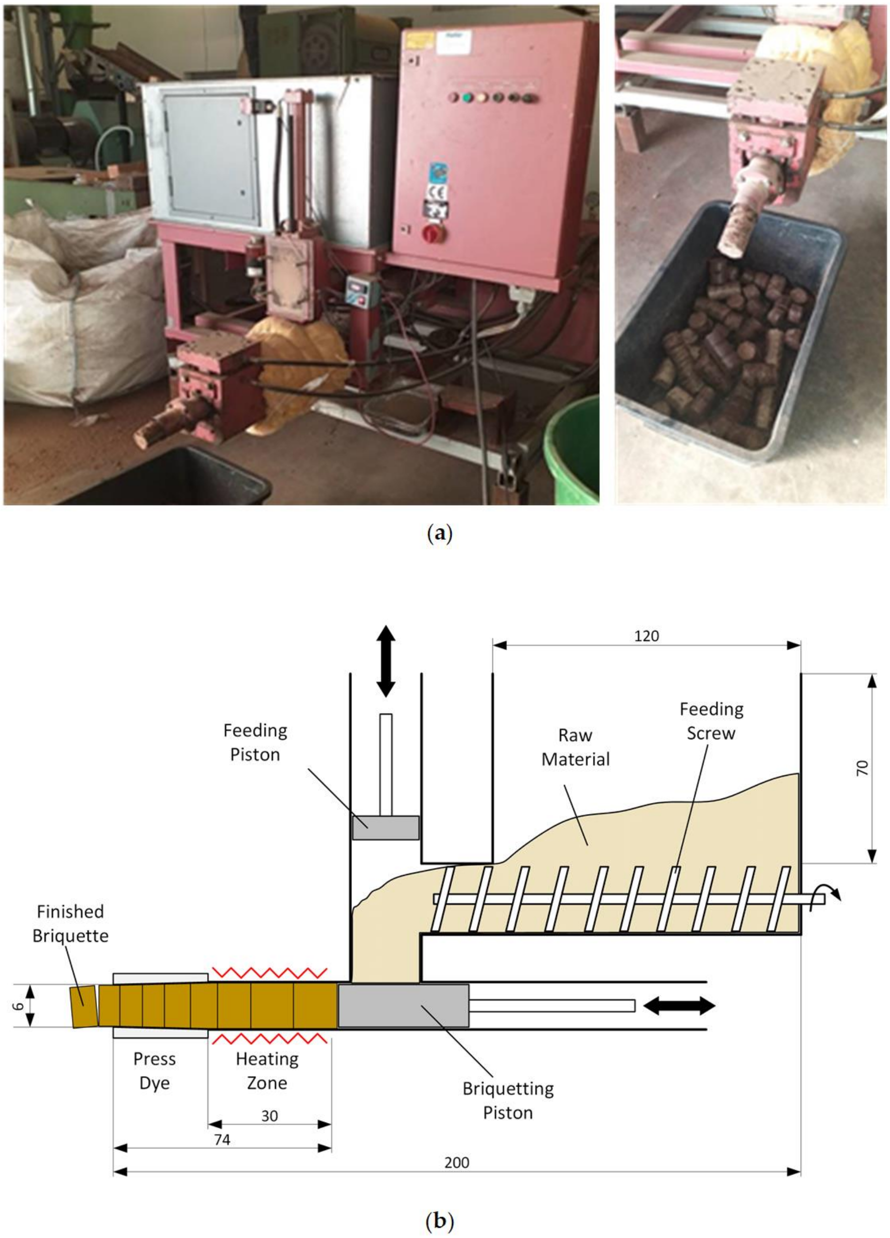

Figure 2. (**a**) Hydraulic piston press for biomass briquetting and briquettes; (**b**) schematic diagram showing the principle of operation of the hydraulic piston press (dimensions in cm).

Additionally, the heating mats were insulated with mineral wool to minimise heat losses to the ambient temperature. After the die had reached the desired temperature, the required feeding speed was selected. Feeding speed was determined by the rotational speed of the feeding screw and varied for the trials in the range from 2.4 to 3.3 mm s^{-1} (horizontal speed of the screw). Fibres from the poplar wood were fed into the machine to produce briquettes. The feeding screw transports the material from the hopper to a vertical piston, which precompresses the material by forcing the material into the moulding chamber (Figure 2b). A horizontal piston then forces the material through the heated die, where it takes the shape of the die. Figure 3 shows an example of the produced briquettes and their dimensions (diameter approx. 6 cm, height approx. 5 cm). The temperature and feeding speed were varied during the experiment using an experimental design.

Figure 3. Dimensions of the briquettes produced from poplar fibre.

2.3. Experimental Design

For the investigation of the influence of the feeding screw speed and the temperature on briquette properties, a full factorial experimental design was used. Three levels, each, of die temperature and screw speeds were utilised. The die temperatures used were 100, 120 and 140 °C. The feeding screw operated at speed levels 5, 6 and 7 set at the control cabinet, which correspond to feeding speeds of 2.4, 2.9 and 3.3 mm s^{-1}. The levels of temperature and speeds used are presented in Table 1. The full factorial experimental design used for the study is presented in Table 2. Three replicates of the experimental design were used for the statistical analysis of the responses by randomly selecting samples from each experimental run for each response (density, durability and water resistance) considered.

Table 1. Levels of variables used for the experimental design.

Factor	Low Level	Medium Level	High Level
Temperature (°C)	100	120	140
Feeding speed (mm s^{-1})	2.4	2.9	3.3

Table 2. Full factorial design of experiments.

Experiment Number	Temperature (°C)	Feeding Speed (mm s^{-1})
1	100	2.4
2	100	2.9
3	100	3.3
4	120	2.4
5	120	2.9
6	120	3.3
7	140	2.4
8	140	2.9
9	140	3.3

2.4. Determination of Density of Briquettes

The masses of the briquettes were measured using an electronic mass balance with an accuracy of 0.01 g (Sartorius TE3102S, Göttingen, Germany). Due to cracks on the surface of briquettes, the dimensions of fairly cylindrical briquettes were measured using a vernier calliper, with an accuracy of 0.1 mm. The dimensions were utilised in the determination of the volume of the briquettes. The densities of the briquettes produced were determined from the ratio of the mass to the volume of the briquettes [35,36]. The determination of density was conducted in triplicates.

2.5. Determination of Durability of Briquettes

The durability of the briquettes was determined using the tumbling method. The tumbling machine (Feed and Biofuel Pellet Tester, Andritz Feed Technologies, Esbjerg/Denmark) used is shown in Figure 4. Briquettes with a mass of approximately 1500 g were weighed and loaded into the tumbling machine. The number of rotations was set to 150 at a speed of 50 rpm. After the tumbling operation, the mass of whole briquettes was measured to determine the mass loss due to abrasion. The mechanical durability (*MD*) was determined from the ratio of the mass of whole briquettes after tumbling to the initial mass of briquettes, as shown in Equation (1). The durability of the briquettes was also determined in triplicate.

$$MD = \frac{m_u}{m_i} \times 100\% \tag{1}$$

Figure 4. Tumbling machine for durability test.

MD: Mechanical durability [%]; m_u: Mass of unabraded/intact briquettes [g]; m_i: Initial mass of briquettes [g].

2.6. Determination of Water Resistance of Briquettes

Water resistance of the briquettes was determined using procedures used by Orisaleye et al. [25], Birwatkar et al. [50], Sengar et al. [51] and Saha et al. [52]. Individual samples of briquettes were weighed using an electronic mass balance before they were immersed completely in water for 120 s at room temperature. The mass of each briquette after immersion was determined. The water absorption was determined from the percentage change in mass of the briquettes after immersion in water using Equation (2). The water resistance of the briquettes was analysed in triplicate.

$$WR = 100\% - \left[\frac{m_w - m_i}{m_i} \times 100\%\right] \tag{2}$$

WR: Water resistance [%]; m_w: Mass of wet briquette [g]; m_i: Initial mass of briquette [g].

2.7. Statistical Analysis

The ANOVA for the density, durability and water resistance indexes was carried out using data obtained from the multiple experiments. The significance level was 5%. Parameters which were statistically significant to the density, durability and water resistance were determined. The statistical analysis was carried out using Minitab 19 software.

3. Results and Discussion

The density, durability and water resistance of the briquettes produced from poplar wood fibres using a hydraulic briquetting machine were determined under different conditions. The temperature and feeding speed were varied, as specified in the experimental design, during densification to determine their effects on the quality of the briquettes. Since the degree of comminution of the raw material used also has a significant influence on the briquette properties, this was investigated in more detail first.

3.1. Properties of Poplar Fibre

The bulk density of the fibre after drying was 87.7 kg m^{-3} (moisture content 10%, wet based). The result of the particle size analysis is shown in Figure 5. According to this analysis, the raw material for briquetting had an average particle length (X_{50}) of 0.55 mm and a content of fines (particles smaller than 0.5 mm) of 47%.

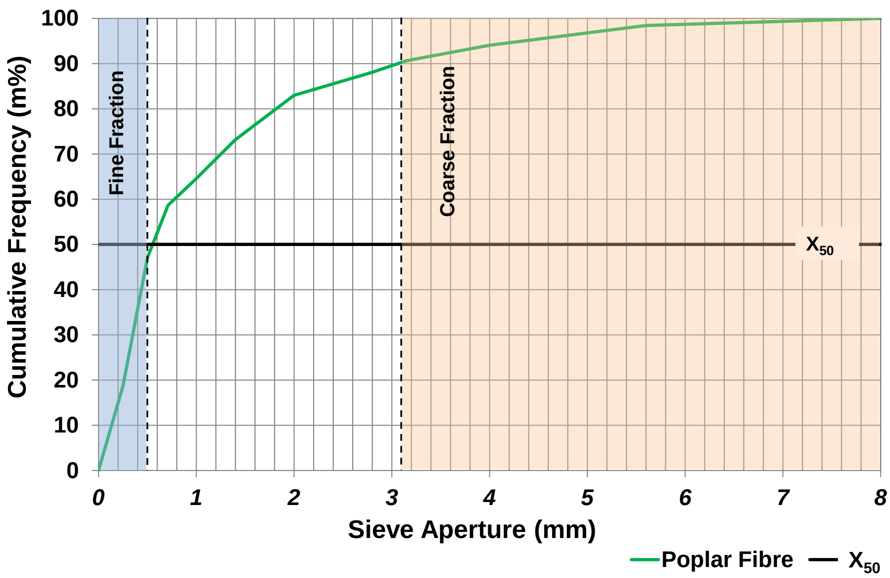

Figure 5. Particle size distribution of the raw material (poplar fibre) used for briquetting.

3.2. Effect of Temperature and Feeding Speed on Briquette Density

Table 3 shows the effects of the variables on density. From the table, the highest value for briquette density is 916.82 kg m^{-3}, obtained at a feeding speed of 3.3 mm s^{-1} and a temperature of 140 °C. The lowest value was obtained at a temperature of 100 °C and a feeding speed of 2.4 mm s^{-1}. Lindley and Vossoughi [42] noted that, irrespective of the material type, the biomass feeding rate affects the density of the resulting briquettes. Coşereanu et al. [53] used a hydraulic briquetting machine to densify corn stalks, corn cobs, staghorn sumac, apple tree pruning, vineyard pruning and pine cores. The densities obtained from the study by Coşereanu et al. [53] were in the range of densities obtained in the present study for poplar wood.

For the statistical analysis, Figure 6 shows the residual plots for density. The plots show that the assumptions of ANOVA are met. These include the normal distribution of the population from which data samples are drawn, constant variance, and independence of cases. Table 4 presents the ANOVA for the density of the briquettes from poplar wood fibres. The table shows that the die temperature and feeding speed were statistically significant ($p < 0.05$) in determining the density. The interaction between the temperature and feeding speed on the density is also statistically significant ($p < 0.05$). This is in line with the study by [35], who noted that the combined effect of higher temperature and higher feeding rate results in higher briquette density. Figure 7 presents the main effects plot for density, which shows that density increases with increasing temperature from 100 to 120 °C, but remains almost constant for temperatures between 120 and 140 °C. For the speed, however, the density increases as the feeding speed is increased.

Table 3. Results for average density (and standard deviation) of briquettes in kg m^{-3}.

Temperature	**Feeding Speed (mm s^{-1})**		
	2.4	**2.9**	**3.3**
°C	**kg m^{-3}**	**kg m^{-3}**	**kg m^{-3}**
100	746.74 (10.88)	822.72 (49.66)	837.03 (29.40)
120	897.81 (55.40)	848.81 (51.98)	847.48 (12.40)
140	838.41 (25.26)	838.19 (13.10)	916.82 (28.58)

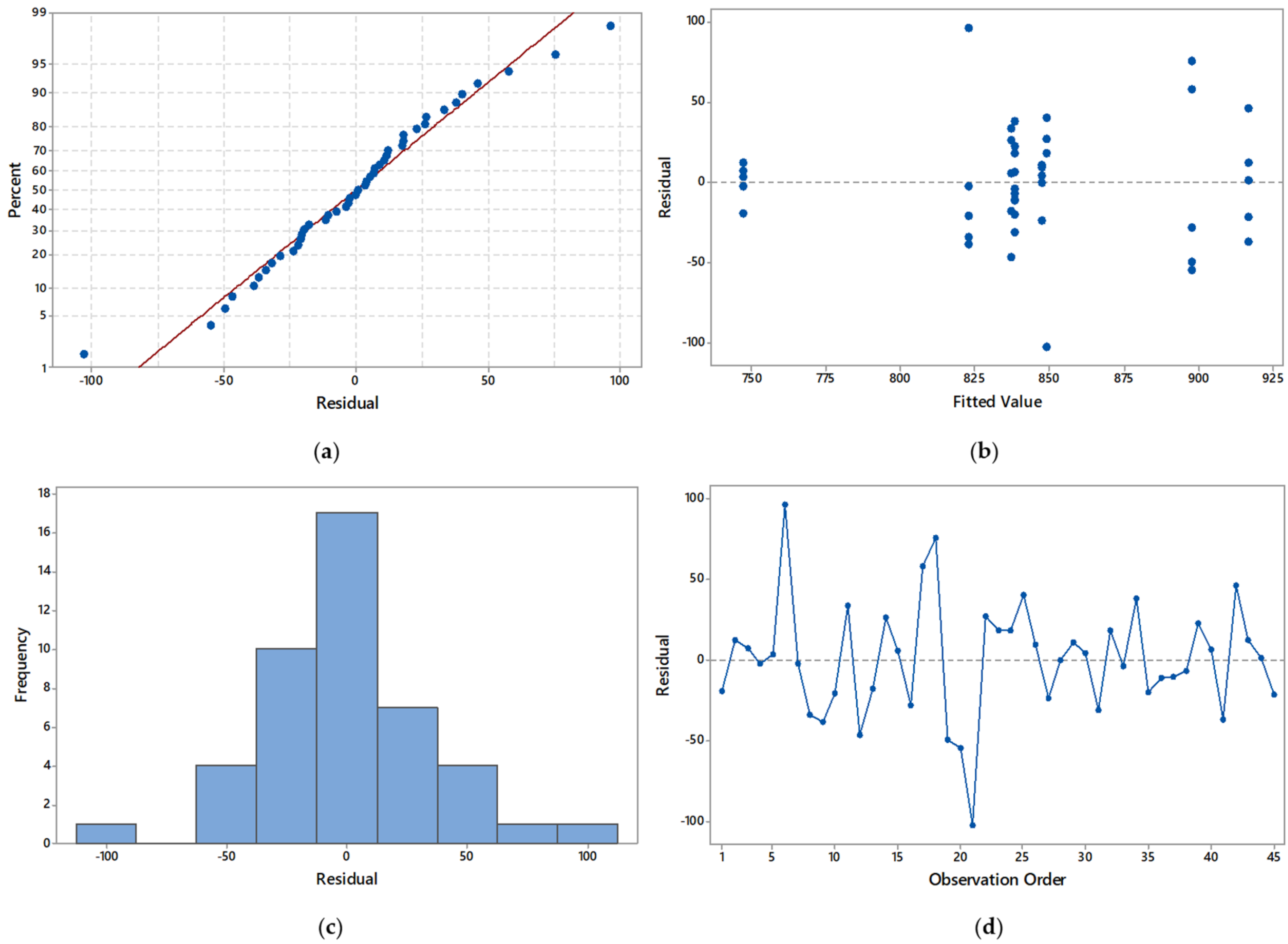

Figure 6. Residual plots for density: (**a**) normal probability plot; (**b**) versus fits; (**c**) histogram; (**d**) versus order.

Table 4. ANOVA for density.

Source	DF	Adj SS	Adj MS	*F*-Value	*p*-Value
Model	8	91,297	11,412	7.47	0.000
Linear	4	51,815	12,954	8.48	0.000
Temperature	2	38,970	19,485	12.75	0.000
Feeding Speed	2	12,845	6423	4.20	0.023
2-Way Interactions	4	39,482	9870	6.46	0.001
Temperature × Feeding Speed	4	39,482	9870	6.46	0.001
Error	36	55,004	1528		
Total	44	146,301			

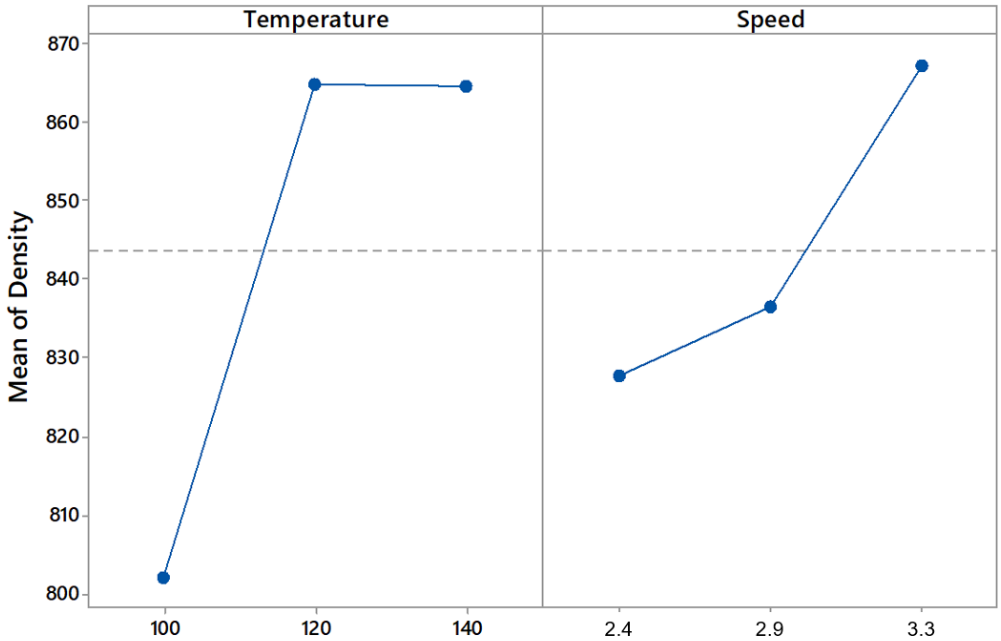

Figure 7. Main effects plot for density.

Although the effects of feeding speed and piston speed on briquette quality can be different, Voicea et al. [54] stated that the density of briquettes varies almost linearly with piston displacement speed. It was also noted that piston displacement speed is a weak parameter related to quality parameters but is, nevertheless, significant. Li and Liu [55] found that increasing compaction speed up to 3 MPa s^{-1} decreased densities of briquettes beyond which the effect becomes negligible. Zafari et al. [56] found that piston speed had significant effects on the pellet density, but there was a negative correlation between piston speed and the density for compost samples. The temperature was found to be statistically significant on density in studies by Orisaleye et al. [24,36], Jekayinfa et al. [35], Zhang et al. [57]. Lisowski et al. [58], however, found that temperature did not have a statistically significant effect on the variations in the density of briquettes produced from walnut shells.

3.3. Effect of Temperature and Feeding Speed on Mechanical Durability

From Table 5, it is shown that the lowest mechanical durability is obtained at 2.4 mm s^{-1} and 100 °C and the highest at 3.3 mm s^{-1} and 140 °C. It is observed from the table that the mechanical durability increases with increasing temperature. This could be linked to the earlier reported higher density associated with a higher feeding rate and temperature. The average mechanical durability ranges between 97.4 and 98.43%.

Table 5. Results for average mechanical durability (and standard deviation) of briquettes in percentage.

Temperature	**Feeding Speed (mm s^{-1})**		
	2.4	**2.9**	**3.3**
°C	**%**	**%**	**%**
100	97.40 (0.07)	97.88 (0.04)	97.86 (0.11)
120	98.14 (0.26)	98.10 (0.20)	97.99 (0.13)
140	98.36 (0.09)	98.38 (0.17)	98.43 (0.48)

Figure 8 shows that the assumptions of normal distribution of the population from which data samples are drawn, constant variance and independence of cases for ANOVA are met. The ANOVA for mechanical durability is given in Table 6. It is observed from the table that the temperature is statistically significant (p < 0.05) in the determination of the mechanical durability. Although the feeding speed is not statistically significant, the interaction of the temperature with the feeding speed is shown to be statistically significant in determining the mechanical durability. This agrees with [42], who observed that the strength of wheat straw and flax straw briquettes was not significantly affected by temperature or feeding rate. The main effects plot in Figure 9 shows that varying the temperature between 100 and 140 °C has a greater effect on the mechanical durability than the feeding speed. It is also shown that increasing the temperature increases the mechanical durability of the briquettes from poplar wood fibre.

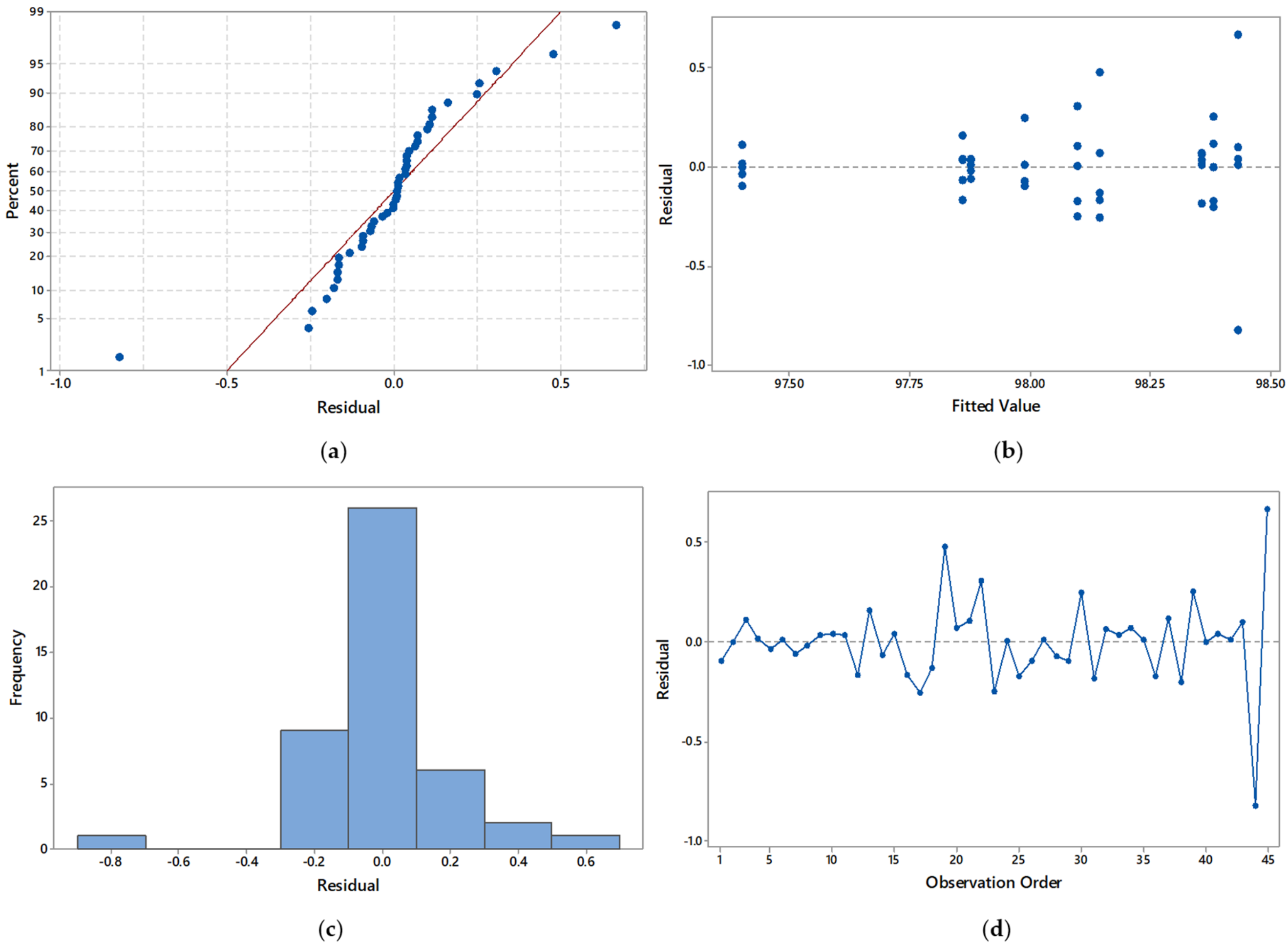

Figure 8. Residual plots for mechanical durability: (**a**) normal probability plot; (**b**) versus fits; (**c**) histogram; (**d**) versus order.

Table 6. ANOVA for mechanical durability.

Source	DF	Adj SS	Adj MS	*F*-Value	*p*-Value
Model	8	4.2609	0.53261	9.41	0.000
Linear	4	3.6532	0.91331	16.13	0.000
Temperature	2	3.4576	1.72882	30.54	0.000
Feeding Speed	2	0.1956	0.09780	1.73	0.192
2-Way Interactions	4	0.6076	0.15191	2.68	0.047
Temperature × Feeding Speed	4	0.6076	0.15191	2.68	0.047
Error	36	2.0382	0.05662		
Total	44	6.2990			

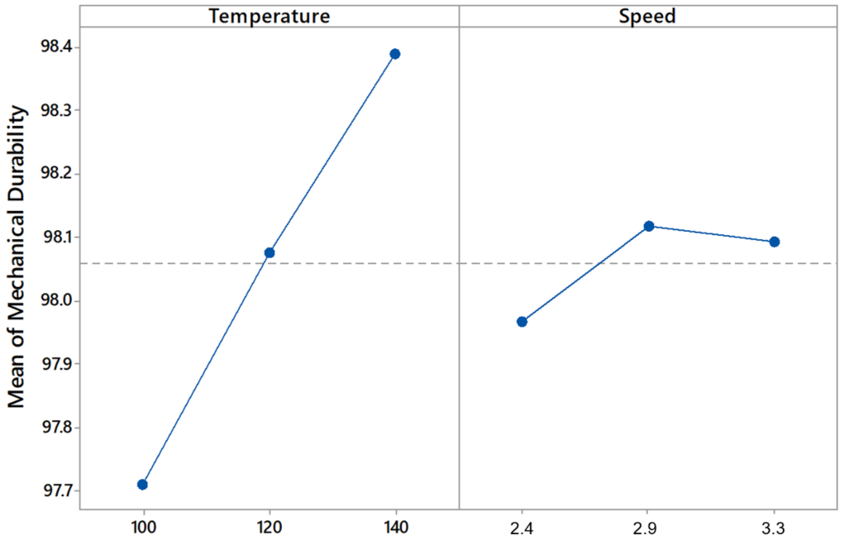

Figure 9. Main effects plot for mechanical durability.

According to Gilvari et al. [59], some research has shown that a compression temperature higher than room temperature is crucial for making pellets with high durability. In line with the findings in this study, Nurek et al. [60] stated that an increase in temperature improves the durability of briquettes from shredded logging residues. Other studies with similar results on the significant effect of temperature on briquette durability include Zhang et al. [57] and Zafari and Kianmehr [61]. Zafari and Kianmehr [62] noted that low piston speed had a significant effect on increasing pellet durability. From Figure 6, however, no particular trend in briquette durability with the feeding speed was observed in this study. The mean durability increases from a feeding speed of 2.4 to 2.9 mm s^{-1} but begins to reduce afterwards. Contrary to the observations in this study, Voicea et al. [63] noted that piston speed is significant to the durability of briquettes.

3.4. Effect of Temperature and Feeding Speed on Water Resistance

Results presented in Table 7 show that the water resistance of the briquettes ranged between 91.60 and 96.12%. The mean water resistance was highest at temperature of 120 °C and at feeding speed of 5 mm s^{-1}. Figure 10 shows that the assumptions of ANOVA have been met, whilst Table 8 shows the ANOVA for water resistance. From Table 8, it is observed that temperature and feeding speed were statistically significant ($p < 0.05$) in determining the water resistance. The interaction between the temperature and feeding speed in determining the water resistance was also statistically significant ($p < 0.05$). While temperature and feeding rate were observed to significantly affect the water resistance of poplar wood briquettes, [42] reported a significant effect on flax straw briquettes, but no effect on the water resistance of sunflower stalk briquettes. Orisaleye et al. [25,36] and Jekayinfa et al. [35] have shown that die temperature is significant to the water resistance with higher temperature resulting in better water resistance of briquettes. Figure 11 shows the main effects plot for water resistance.

Table 7. Results for average water resistance (and standard deviation) of briquettes in percentage.

Temperature	Feeding Speed (mm s^{-1})		
	2.4	2.9	3.3
°C	%	%	%
100	91.60 (1.50)	93.08 (0.69)	94.86 (0.40)
120	96.12 (0.08)	94.97 (0.63)	95.13 (0.58)
140	94.92 (0.31)	93.51 (0.50)	95.94 (0.30)

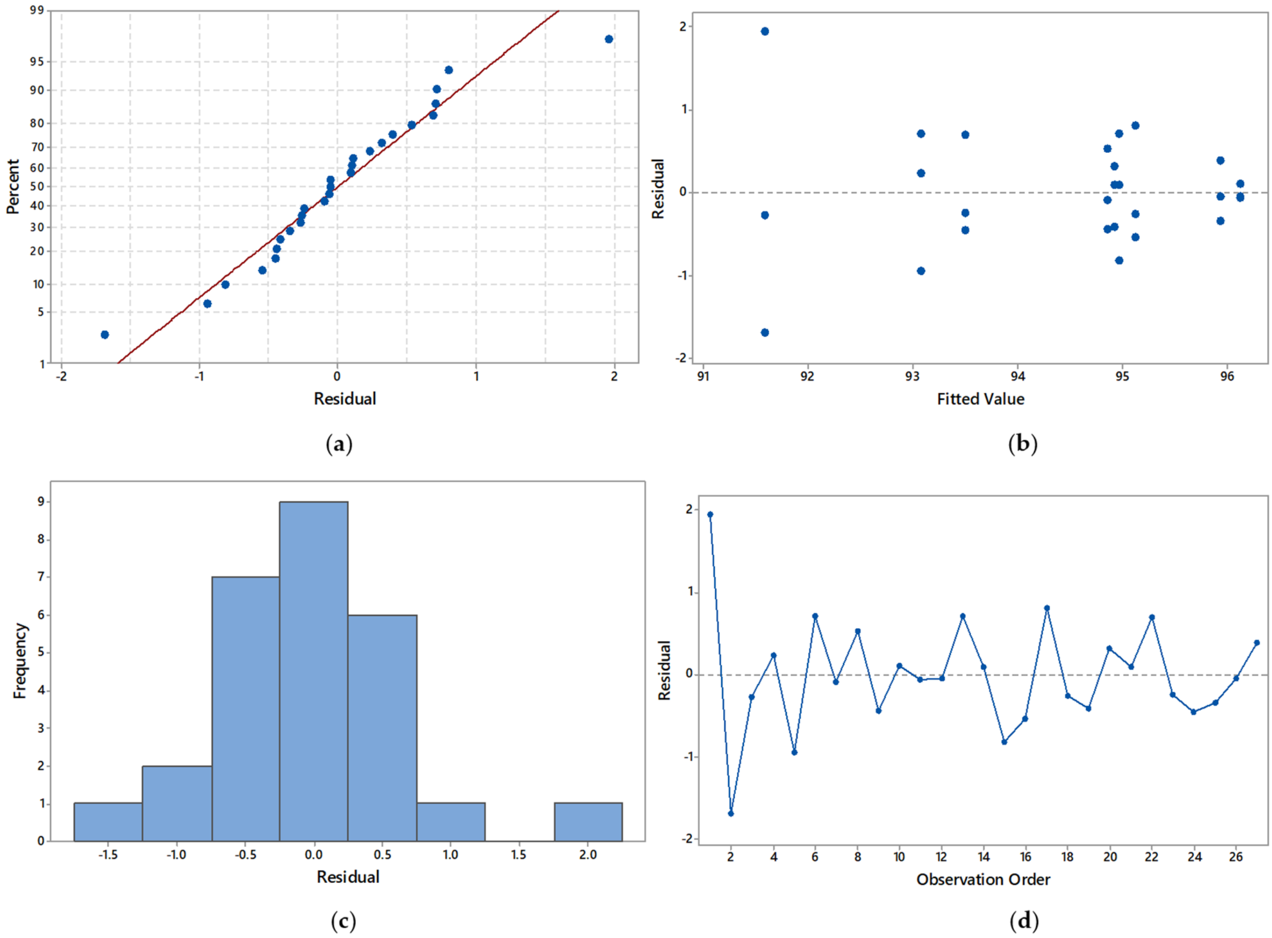

Figure 10. Residual plots for water resistance: (**a**) normal probability plot; (**b**) versus fits; (**c**) histogram; (**d**) versus order.

Table 8. ANOVA for water resistance.

Source	DF	Adj SS	Adj MS	*F*-Value	*p*-Value
Model	8	51.09	6.3864	9.42	0.000
Linear	4	34.20	8.5488	12.61	0.000
Temperature	2	23.84	11.9207	17.59	0.000
Feeding Speed	2	10.35	5.1769	7.64	0.004
2-Way Interactions	4	16.90	4.2239	6.23	0.002
Temperature × Feeding Speed	4	16.90	4.2239	6.23	0.002
Error	18	12.20	0.6777		
Total	26	63.29			

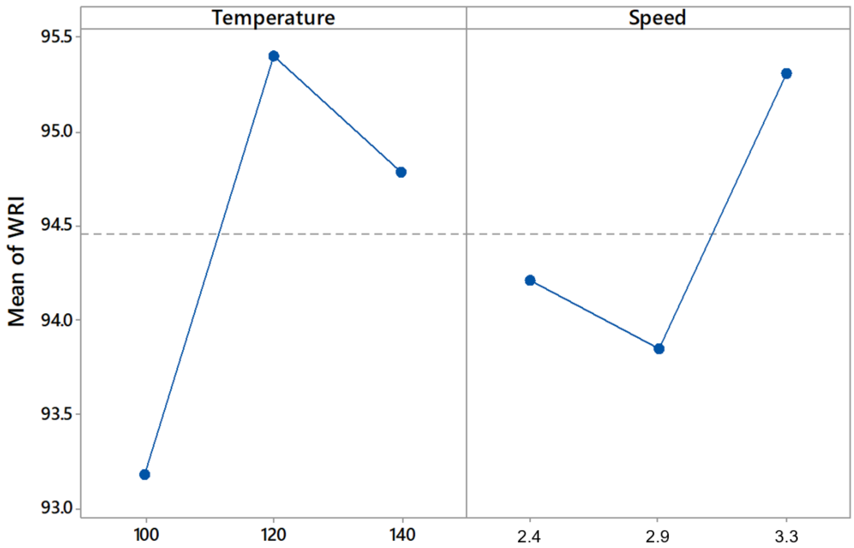

Figure 11. Main effects plot for water resistance index.

4. Conclusions

In this study, the effects of die temperature and feeding speed of a hydraulic biomass briquette machine on the quality of briquettes from poplar wood were determined. The temperatures considered were 100, 120 and 140°C. The feeding speed was varied to 2.4, 2.9 and 3.3 mm s^{-1}. The density of briquettes ranged from 746.7 to 916.8 kg m^{-3}. The mechanical durability ranged from 97.4 to 98.4%. The water resistance index was between 91.6 and 96.1%. The temperature was statistically significant ($p < 0.05$) on all investigated quality parameters and briquette quality increased with rising die temperature. The feeding speed was statistically significant ($p < 0.05$) on the density and water resistance. The interaction of temperature and feeding speed was statistically significant ($p < 0.05$) on the density, mechanical durability and water resistance of biomass briquettes.

This study particularly established that high feeding rates and high die temperatures were beneficial to enhancing the physical and mechanical properties of the briquette. Subsequent studies could expand the work to optimise the biomass properties by including other machine parameters, such as the geometry of the die, and biomass material variables, such as particle size, moisture content and biomass type. In addition to this, the effects of the variables on the thermal properties also need to be investigated.

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