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Assessment of Densified Fuel Quality Parameters: A Case Study for Wheat Straw Pellet

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Abstract: An investigation was conducted to examine the impact of additive mixing with wheat straw (WS) for pellet making. This study manufactured seven types of pellets with different additive combinations to evaluate pellet quality characteristics and their relationships. A laboratory-type hammer mill and a pellet mill were used for feedstock preparation and pellet production. Experimental investigations showed that the lignin content increased from 7.0% to 13.1%, which was a primary need for pelletization. Also, the heating value rose from 17.02 to 20.36 MJ/kg. However, the ash content also increased from 7.09% to 16.2%. Results showed that dimension (length and diameter), durability, and tensile strength increased significantly with additives while the fines content decreased. The fines content had an inverse relationship with durability and strength. Wheat straw (60%), together with 10% sawdust (SD), 10% corn starch (CS), 10% bentonite clay (BC), and 10% biochar (BiC), was optimal with good pellet performance (T7). In addition, both the T5 pellets (70% WS, 10% SD, 10% BiC, and 10% BC) and the T6 pellets (70% WS, 10% SD, 10% BiC, and 10% CS) provide suitable quality according to EN plus 2015 standard requirements. The ash content of produced pellet was higher than the recommended value, which suggests that further research onto the alternative additive use for ash reduction is needed.

Keywords: biomass; wheat straw; pellet quality; properties relationship; additive/binding material

1. Introduction

There is currently significant attention being given to biomass densified fuels, like pellets or briquettes, to replace traditional (fossil) fuels in developing countries, particularly Bangladesh. However, biomass's high moisture content, variable shape or size, and poor bulk density are common features (Kaliyan and Vance Morey, 2009; Carroll and Finnan, 2012). Therefore, biomass management, transport, and storage are challenging in their original form (Kaliyan and Vance Morey, 2009). However, the bulk density of the pellet also affects transporting and handling effectiveness and storage space (Nunes, et al., 2014). For example, Fasina (2008) reported that the pelletization of peanut hulls could save four times storage space. Furthermore, densification raises biomass bulk density from its initial density, resulting in a consistent

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shape and size of products (Mani et al., 2004). Therefore, the pellets or briquettes demand for a home or combined heating and power generation has predominantly increased.

Forest and agricultural waste are the primary biofuel sources in most developing countries. A developing nation like Bangladesh is one of the intensive agro-based economic countries with year-round crop cultivation, producing massive agricultural waste, including crop waste. Agricultural waste accounts for more than 3.648×10^7 t annually (Halder et al., 2014). The general use of agricultural residues is cooking (57.06%) (Islam et al., 2021), heating, fertilizer, animal feeding, bedding, and burning in situ after harvest, etc. (Karim et al., 2019). Since they are extensively available, representing a management problem, this waste is not used to produce a product with added value in some cases. In addition, each year burned many crop residues due to a lack of management practice, triggering extreme particulate emissions and air pollution, and wasting valuable resources (El-Sobky, 2017). Besides, crop waste burning has become a obviously environmental issue, posing health risks and consequences of global warming (Romasanta et al., 2017). Therefore, developing densified biofuel is an effective and sustainable way to manage multi-crop and multi-character agricultural straws.

Only agricultural residues contribute 48% of Bangladesh's total biomass energy consumption. Moreover, biomass was estimated 70% of total primary energy consumption in rural areas of Bangladesh (Masud et al., 2019). In addition, globally, agricultural waste resources (straw) are abundant and have excellent potential as bioenergy resources. Also, the valuable biomass (straw) resources to bioenergy through the pelleting aim to archive high-quality solid fuel (Järvinen and Agar, 2014). Therefore, with the growing demand for biomass fuel (solid), the idea of making biomass pellets from straw has recently resurfaced. Thus, the global pellet market reached 6.87 billion in 2018 (Khan et al., 2021).

Information on agricultural straw pellets is also available now, such as wheat straw (El-Sayed and Elsaid Mohamed, 2018), barley straw (Iroba et al., 2014), wheat straw and peat (Demirbas, 2004), wheat straw and rice husk (Ríos-Badrán et al., 2020), agricultural straw (Emami et al., 2014), and cereal straw (Carroll and Finnan, 2012; Niedziółka et al., 2015), among others. Moreover, the available literature has primarily focused on the implication of variables and binding materials' pellet properties. Shaw et al. (2009) used poplar wood (untreated and steam-exploded) with wheat straw grinds to densify and determine physicochemical characteristics. The particle size, moisture content, and pine sawdust addition on barley straw affected the pellet quality (Serrano et al., 2011). Theerarattananoon et al. (2012) considered pellet production from corn stover, wheat straw, and sorghum stalk and reported the effects of pelleting and chemical composition. Ishii and Furuichi (2014) studied rice straw pellet productivity and quality concerning moisture content, particle size, and forming temperature. Gil et al. (2010) considered biomass blend pellets' physical properties (durability) and combustion features. Nilsson et al. (2011) conducted an empirical experiment to make pellets from agricultural waste such as salix, reed canary-grass, hemp, straw, screenings, rape-seed meal, rape cake, and distiller's waste. They also estimated the pelleting costs and energy necessities. Alternatively, Kashaninejad et al. (2014) produced pellets from wheat straw, while moisture content was 9% and ground materials particle sizes were 1.6 and 3.2 mm. They found durability resistance increased from 65% to 90% with the decrease of the ground material particle size. Thus, most of the available works on pellet properties relation and the pellet quality and properties relation are not fully understood. In addition, there is limited study on pellet properties concerning each other, which urges new research on pellet quality parameters relationship. However, little is known about the systematic pellet making from herbaceous wheat straw considering all quality evaluation parameters.

Furthermore, material, procedure, consideration, the effect, and the relationship of physical-chemical characteristics on quality are needed to investigate suitable pellet making. Therefore, the preliminary work on wheat straw pellet development and quality improvement was completed and compared with the European Pellet Standard (ENplus) (Table 1). In addition, the study on biomass and pellet fuels characteristics is noteworthy due to its development, deployment, quality improvement, and marketing. The objective of this research is to investigate binding materials' effect on pellet properties. Moreover, this study considered the relationship between the physical characteristics as well as combustion properties.

Alternatively, the findings of this study are instrumental in selecting process parameters for producing pellets from agricultural straw and providing guidelines for future research.

Table 1 European Pellet Standard (ENplus) for pellet quality

Particular	ENplus A1	ENplus A2	ENplus B
Diameter (mm)	6–8		
Length (mm, *L*)	3.15 < *L* ≤ 40		
Moisture content (%, ar)	≤ 10		
Ash content (%, db)	≤ 0.7	≤ 1.2	≤ 2.0
Mechanical durability (%, ar)	≥ 98.0	≥ 97.5	
Fines (< 3.15 mm) (%, ar)	≤ 1.0		
Heating value (MJ/kg, ar)	≥ 16.5		
Bulk density (kg/m^3)	≥ 600		

Note: ar, as received; db, dry basis.

Source: ENplus. Quality Certification Scheme for Wood Pellets. 2015. Available at: https://enplus-pellets.eu/en-.

2. Materials and Methods

Pelleting research described herein was at the P3 laboratory of the University of Southern Queensland, Toowoomba, Queensland, Australia.

2.1. Materials collection

In this study, feedstock was wheat straw (WS). The straw was collected from the Center for Agricultural Engineering (CAE) Farm Field, the University of Southern Queensland, Toowoomba, Australia. In addition, five different additive materials (bentonite clay, coconut sells biochar, starch (corn), glycerol, and sawdust) were used. Besides, the bentonite clay, biochar, corn starch, and glycerol were collected from Queensland commercial re-seller. Moreover, radiate pine sawdust (*Pinus radiata*) was sourced from Pollards Sawdust Suppliers, 130 Yan Yean Road, Plenty Victoria, Australia.

2.2. Size reduction

Densification needs different types of pre-treatments. This study considered the physical pe-treatment techniques as size reduction, additives mixing, and condition for 72 h at room temperature.

The wheat straw is irregular in size and shape. For palletization, wheat straw needs to be nearly the same size as other materials. Therefore, the WS was chopped and ground by a hammermill (4.0 kW electric motor) with a 3.2 mm circular sieve. A sieve with openings (size) of 4.75, 2.36, 1.80, and 0.70 mm was used to analyze the ground materials. For this experiment, wheat straws with particle size less than 2 mm were chosen to adjust the likely uniform mixture with additives. Each feedstock lot was kept in a plastic container, sealed, and labeled.

2.3. Experiment design

This study considered seven treatments with different binder combinations and additives (Table 2). Moreover, we followed the published data such as used additives' proportion, moisture content, particle size, etc. According to Pradhan et al. (2018), the moisture range was 15%−23%, and particle size was less than 6.5 mm for perfect pellet processing. In addition, Kaliyan and Vance Morey (2009) suggested that 20% of sawdust with wheat straw enhanced pellet strength. Also, pellet quality could be improved by adding additives in the range of 0.5%–5.0% (fraction of total mass basis) (Tabil, 1996). Therefore, the present research considered the moisture content of raw material to be around 20%, particle size less than 2 mm. Besides, the bentonite clay, sawdust, starch, glycerol, and biochar ratio were all 10%.

Table 2 Feedstock (wheat straw) and additives used in combinations for pellet production

Treatment	Material composition
T1	Wheat straw (100%)
T2	Wheat straw (80%):sawdust (10%):bentonite clay (10%)
T3	Wheat straw (80%):sawdust (10%):corn starch (10%)
T4	Wheat straw (70%):sawdust (10%):bentonite clay (10 %):glycerol (10%)
T5	Wheat straw (70%):sawdust (10%):bentonite clay (10%):biochar (10%)
T6	Wheat straw (70%):sawdust (10%):corn starch (10%):biochar (10%)
T7	Wheat straw (60%):sawdust (10%):corn starch (10%):bentonite clay (10%):biochar (10%)

Note: %, fraction of total mass basis.

2.4. Materials preparation

Homogenization (uniform mixing of additives and feedstock materials) and conditioning (weathering) of feedstock materials are vital in pre-treatment for pellet production. First, prepare all materials according to the experimental design for suitable pellet production. Then around 10 kg of mixtures in each treatment were conditioned, and adjusting the desired sample moisture content by about 20% (wet basis) by adding a prearranged amount of water (Ríos-Badrán et al., 2020). Then, to enable uniform moisture distribution, the materials were placed in a room for 72 h with a temperature of ~27 ℃ and humidity of ~65%. Afterward, all materials were mixed every 12 h to achieve uniform distribution and equilibrium moisture content (Emami, et al., 2014). The final average moisture content of the mixture was 18.87%.

2.5. Pelleting mill

The pelleting study was conducted by using a 7.5 kW Roller-Turned Flat Die pellet mill (GEMCO, ZLSP200B R-Type, China). The pellet press is made up of a feeding hopper, barrel, a cylindrical steel roller, and a plate-type flat die with a hole. The pellet ejection hole's internal length and diameter were 40 and 8 mm, respectively. The mill had one roller operating at a frequency of 50 Hz. The principle of pellet production is producing friction (roller weight), compressing the feedstock, and feeding it through a die. In addition, the roller is slipped on the die plate surface, which helps to densify the materials and discharge.

A hand-held infrared thermometer (IR160_industrial Infra-Red, USA) was used to measure the temperature of the extruded pellets from the die. Making good quality pellets needs a pelleting temperature of around 90 °C. However, the used pellet mill has no heating facilities. Hence, a heat resistance blanket was used to enhance the pellet chamber temperature. As a result, due to the friction between rollers and feedstock materials, the pellet production temperature was higher than 80 ℃.

2.6. Pellet production process

All materials, including wheat straw ground particles, were kept in a dry place and protected until the day of pelleting upon receiving. Figure 1 presents the pellet-making process. To maintain a stable pellet production rate, the manufacturing capacity was determined by collecting and weighing produced pellets over a set time, using extra materials. All treatments followed the same systematic process for pellet production. The pellet production mill was first primed with a wood sawdust mixture starter to stabilize the die temperature, which took about 30–40 min. Once the production rate and die temperature were stable, the sample was fed into the pellet mill for experimental pellet production. The produced pellet sample was collected, weighed, labeled, and lay down on a large plastic sheet to cool. All sample batches were left overnight to cool down to room temperature. To measure density and initial dimension (after one day), 33 pellets data were recorded. In addition, the pellet was dried at room temperature until moisture content reached less than 10%. The dried pellet was kept in an air-tight plastic bucket to measure physical and chemical properties after 14 d. Overall, under seven treatments, 231 pellets data were produced and characterized.

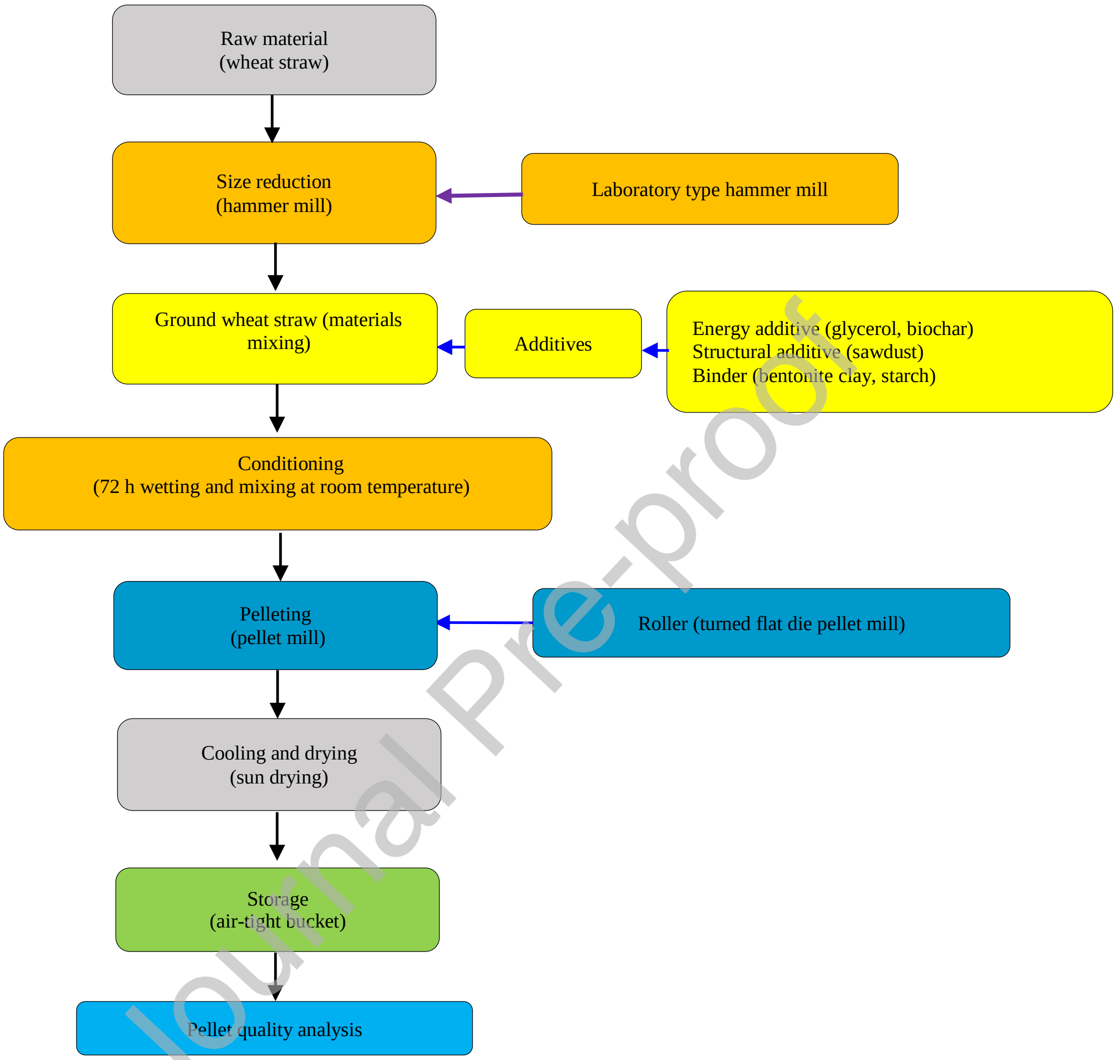

Fig. 1 Flow diagram of pellet production

2.7. Feedstock and pellets characterization

2.7.1. Measurement of elemental composition

The chemical analysis of wheat straw, sawdust, biochar, bentonite clay, and produced pellets was performed in the Feed Central Laboratory, Toowoomba, Queensland, Australia. Each sample was analyzed three times. The ultimate, proximate, and compositional analyses followed the standard protocol and were listed in Table 3. Information on raw materials, including their proximate and ultimate analysis, compositional elements, and density, was presented in Table 4.

Table 3 Raw materials and pellets properties characterization methods

Particular	Standard procedure	Reference
Moisture content Volatile compounds	Hach methods	a
Fixed carbon	ASTM Standards D 3173-87	b
Total organic carbon (TOC) and nitrogen	AOAC 990.03	c
Gross and net calorific value	ASTM D5865-03	d
Ash	AOAC standard method 942.05	e
Particle size distribution	ASTM E 828-81: designating the size of refuse-derived fuel-3	f
Bulk density	ASTM E 873-82	g
Durability test	ASTM D3038	g
Fines quantity	ISO 17827-2	h

Sources: a, Association of Official Analytical Chemists (AOAC), 2002. Official Methods of Analysis of AOAC International. In: Water Analysis Handbook. Loveland: Hach Company; b, American Society for Testing and Materials (ASTM), 1998. Standard test method for moisture in the analysis sample of coal and coke (ASTM Standards D 3173-87). West Conshohocken: American Society for Testing and Materials; c, AOAC, 2006. Official Method 990.03, Protein (Crude) in Animal Feed, Combustion Method, in Official Methods of Analysis of AOAC International. Gaithersbur: AOAC International; d, ASTM, 2003. Standard test method for gross calorific value of coal and coke (D5865-03). In: Annual book of ASTM standards. West Conshohocken: American Society for Testing and Materials; e, AOAC, 1990. Ash in animal feeds. In official method of analysis of the association of official analytical chemists (AOAC Method 942.05). Gaithersburg: Association of Official Analytic Chemists; f, ASTM, 2004. Standard Test Method for Designating the Size of RDF-3 From its Sieve Analysis. West Conshohocken: American Society for Testing and Materials; g. ASTM, 2013. Standard Test Method For Bulk Density Of Densified Particulate Biomass Fuels (ASTM E873-82). West Conshohocken: American

Society for Testing and Materials; h, ISO/TS, 2016. 17225-8: Solid biofuels—Fuel specifications and classes—Part 8: Graded thermally treated and densified biomass fuels. Available at: https://www.iso.org/standard/71915.html.

Table 4 Physiochemical analysis of used raw materials for pellet production

Sample	Proximate analysis					Ultimate analysis					Density	Composition		
	MC (%, wb)	VMC (%, db)	FCC (%, db)	AC (%, db, ar)	HV (MJ/kg)	C (%)	H (%)	N (%)	S (%)	O[a] (%)	BD (MJ/m^3)	HC (%)	C (%)	L (%)
Wheat starw	9.62	72.78	10.30	7.30	17.60	46.06	5.00	0.53	0.11	48.30	107.26	23.00	40.5	7.30
Sawdust	6.60	76.80	16.27	0.33	20.95	51.8	6.14	0.26	0.02	41.78	208.09	13.66	45.38	26.66
Coconut Shell biochar	7.40	7.40	81.30	3.90	30.75	83.8	0.90	0.50	0.10	14.70	583.48	–	–	–
Bentonite clay	7.30	–	–	89.63	0.00	–	–	–	–	–	890.00	–	–	–

Notes: MC, moisture content; VMC, volatile matter content, FCC, fixed carbon content; AC, ash content; HV, heating value; C, carbon; H, hydrogen; N, nitrogen; S, sulfur; O, oxygen; BD, bulk density; HC, hemicellulose; C, cellulose; L, lignin; wb, wet basis; ar, as received; db, dry basis; a, determined by a difference.

2.7.2. Component analysis

The primary component of biomass is lignin, cellulose, and hemicellulose. These were determined from acid detergent fibre (ADF) and neutral detergent fibre (NDF). Lignin and ADF were determined by the Association of Official Analytical Chemists (AOAC) standard method 973.18 (AOAC, 1990. Fiber (acid detergent) and lignin in animal feeds (AOAC method 973.18). In: Helrick, K. Official Method Of Analysis of the Association of Official Analytical Chemists. Arlington: Association of Official Analytical Chemists.), and NDF was determined by AOAC standard method 992.16 (AOAC, 1990. Total dietary fiber: enzymatic gravimetric method (AOAC method 992.16). In: Helrick, K. Official Method Of Analysis of the Association of Official Analytical Chemists. Arlington: Association of Official Analytical Chemists.). Cellulose and Hemicellulose percentage was calculated indirectly from the percentage of ADF and lignin as (Mani et al., 2006):

Percentage of hemicellulose = Percentage of acid detergent fibre – Percentage of neutral detergent fibre (1)

Percentage of cellulose = Percentage of acid detergent fibre – Percentage of acid detergent lignin (2)

2.7.3. Proximate analysis

Proximate analysis is a broad measurement to determine the moisture content, volatile matter content (VMC), fixed carbon content (FCC), and ash content (AC). These are all typically done on a mass basis. Moisture is driven off at 105–110 °C (just above the boiling point of water), representing physically bound water only. In contrast, volatile compounds are driven off in an inert atmosphere at 950 °C, using a slow heating rate. First, moisture content and volatile compound were determined using the reported Hach methods (Association of Official Analytical Chemists (AOAC), 2002. Official Methods of Analysis of AOAC International. In: Water Analysis Handbook. Loveland: Hach Company.). Next, the total ash content was determined using the AOAC standard method 942.05, where 2–3 g sample was burnt in a furnace at above 700 °C in oxygen (AOAC, 1990. Ash in animal feeds. In official method of analysis of the association of official analytical chemists. Gaithersburg: Association of Official Analytic Chemists.). Next, the remaining material (after VMC loss) was taken. Finally, the FCC was calculated from 100% reduced by moisture, ash, and volatile matter (American Society for Testing and Materials (ASTM), 1998.

Standard test method for moisture in the analysis sample of coal and coke (ASTM Standards D 3173-87). West Conshohocken: American Society for Testing and Materials.).

2.7.4. Ultimate analysis

Total organic carbon (TOC) and nitrogen content were determined by CN628 Carbon/Nitrogen Determinator followed by AOAC 990.03 (AOAC, 2006. Protein (Crude) in Animal Feed, Combustion Method, in Official Methods of Analysis of AOAC International. Gaithersbur: AOAC International.). In addition, the sulfur was determined by the categorization-elaboration model (CEM) Application Notes for the Acid Digestion method (ASTM, 2008). Standard Test Methods for Instrumental Determination of Carbon, Hydrogen, and Nitrogen in Laboratory Samples of Coal (Standard D5373). West Conshohocken: American Society for Testing and Materials.). Finally, the difference of elements decided was oxygen.

2.7.5. Heating value

Gross energy of solid materials (gross heating value) is expressed as calories per gram (Cal/g). The heating value was determined using an IKA C2000 basic oxygen bomb calorimeter using ASTM D5865-03 standard (ASTM, 2003. Standard test method for gross calorific value of coal and coke (D5865-03). In: Annual book of ASTM standards. West Conshohocken: American Society for Testing and Materials.). The instrument was set to IKA's dynamic mode with an outer vessel temperature of 25 °C. The calorimeter was standardized using 1 g Parr standard benzoic acid. About 0.5 g sample was put in the metal combustion capsule and placed in the sample holder in the bomb head for gross energy determination.

2.7.6. Measurement of physical characteristics

The pellet quality was assessed and compared with the commercially prescribed level (EnPlus). The density, durability, water absorption index, and fines are evaluating factors of pellet fuel (Zafari and Kianmehr, 2014). Therefore, a specific qualitative analysis on seven different types of pellets (treatments) was carried out (Fig. 2). First, all samples were handled and chosen to ensure a certain homogeneity of the samplings. Then, weight, diameter, length, bulk density, water absorption, and dust content were tested in the lab for the selected samples (Mani et al., 2006; Jiang et al., 2016; Pampuro et al., 2018).

Treatment

T1 T2 T3 T4 T5 T6 T7

The meanings of T1–T7 are shown in Table 1.

Fig. 2 Pellets produced with different additives blends containing wheat straw

This study used 33 pellets from each treatment to measure physical properties, including pellet diameter, length, weight, and densities (individual and bulk). Two data sets were used to calculate and compare the density of each pellet (apparent and relaxed). The first set of data measurements was recorded after one day of pellet extrusion, while the second set was taken on the 14th day of storage. A digital caliper measured length and diameter while measuring the pellet weight by digital balance.

The bulk density was determined by the ASTM E 873-82 (Table 3). The impact resistance study measured the durability (14 d storage) of the pellets using the single drop test method (Al-Widyan and Al-Jalil, 2001; Iroba et al., 2014; Tilay et al., 2015). For the test, drop a pellet onto a stainless pan from 1.85 m. The durability is distinct from the final weight of pellets (large fragments) to the percentage of initial weight. The practice was repeated four times. Thirty-three replicates were made for each treatment.

The ENplus technique determined the fines quantity of pellets for solid biofuels (ENplus. Quality Certification Scheme for Wood Pellets. 2015. Available at: https://enplus-pellets.eu/en-.). This method used a vibrating sieve set, where a screen with square holes was 1 mm in size. Three times repeater, the particle quantity estimation technique was used.

The pellet diametric compression test represents the tensile strength. First, using a diamond cutter, cut the pellets into around 2 mm thick diametrically tablets (Shaw, et al., 2009). Then, the pellet tablets were put lengthwise in the centre of the base plate and pushed at a 1 mm/min speed by the plunger Instron. After that, force-displacement information and the fracture load of the pellet tablet (at the point of failure) were recorded. Next, the tensile strength of the pellet was calculated by using the tensile strength equation (Shaw et al., 2009). Finally, for each sample, replicated the test 10 times.

2.8. Statistical analysis

We used the IBM SPSS software version 27 (IBM crop., Armonk, New York) for data analysis. One-way ANOVA was also used for the statical analysis, and the significant level was set at 95% (P = 0.05).

3. Results and Discussion

3.1. Influence of additives blend on pellet component

Biomass and produced products are principally composed of lignin, cellulose, and hemicellulose (Liu et al., 2013), while the component's contents of these are dissimilar. Figure 3 shows major compositional elements of the pellet. Generally, the cellulose content in biomass is higher among the elements; however, external factors (temperature, softening, pressure, etc.) could change the amount. It was observed that pellets, combined with additives, increased the lignin percentage, which acted as a function of binders. In addition, the hemicellulose and cellulose content also changed their respective treatments.

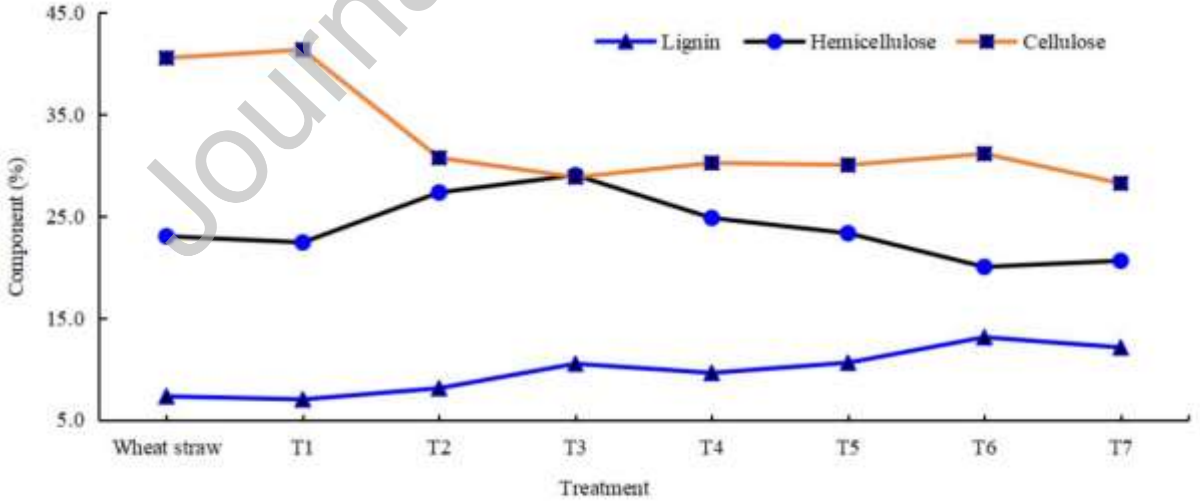

Fig. 3 Composition of pellet

Holt et al. (2006) noted that densification and pelleting were created due to the solid bonding between the particles through attractive, adhesive, cohesive forces, and mechanical interlocking. However, the disparity in pelletization process, particle bonding, and physical traits might be affected by the component percentage variation. Hence, additive mixing with wheat straw altered the elemental composition (Brand et al., 2017) and positively enhanced lignin content.

In the pelletization process, conditioning is vital, where softening of natural binder happens. In addition, for durable particle bonding, a suitable temperature (glass transition) is needed. The lignin and hemicellulose have glass-transition temperatures of 60–120 ℃ and –23–200 ℃, respectively, based on moisture content and measurement technology (Olsson and Salmén, 1997). Therefore, the varied element content might influence the lignin glass transition in the pelletization technique (Fig. 3). However, the pellet formation temperature was lower than 80 ℃ because of particle friction between the die and roller. Stelte et al. (2011) noted that the glass-transition temperature of wheat straw was around 53 ℃, which helped to soften lignin and result in durable particle-particle bonding.

3.2. Pellet dimensional relationship

The pellet dimension is significant for combustion and fuel-feeding properties (small burner) (Núñez-Retana et al., 2020). Figure 4 illustrates the diameter and length relationship of the pellet. For each treatment, mean diameter and length were calculated using 33 pellets. All pellets production had an average diameter of ~8.2 mm, while the die (pellet mill) internal hole was 8.0 mm. The similar diameter could be due to the same average moisture for all produced pellets (Mahapatra et al., 2010).

In Fig. 4, the length of pellets without additives (T1) was the lowest (around 6.35 mm) and the highest for T7 (40 mm). However, the result observed from the figure indicated the pellet length varied remarkably with additives combination, and all pellets showed a relatively high length. Therefore, the additives might be formed a durable bond in the pelletization process (Mahapatra, et al., 2010). Thus, an additive could improve the pellet length, fulfilling the hypothesis.

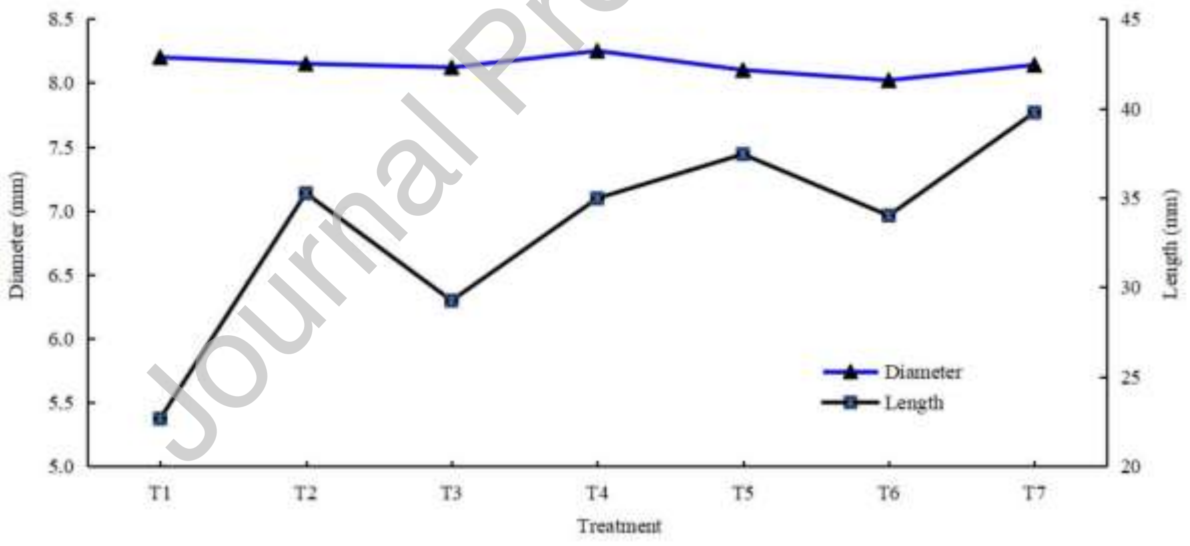

Fig. 4 Length and diameter of pellets

3.3. Relation of combustion properties (*ash content and heating value*)

Figure 5 displays the inorganic ash concentration and heating value of the pellets. The result represents that the combustion parameters of various pellets varied with different additive combinations. However, it was observed from the figure that there had no affiliation between the inorganic ash percentage and heating value (Fig. 5).

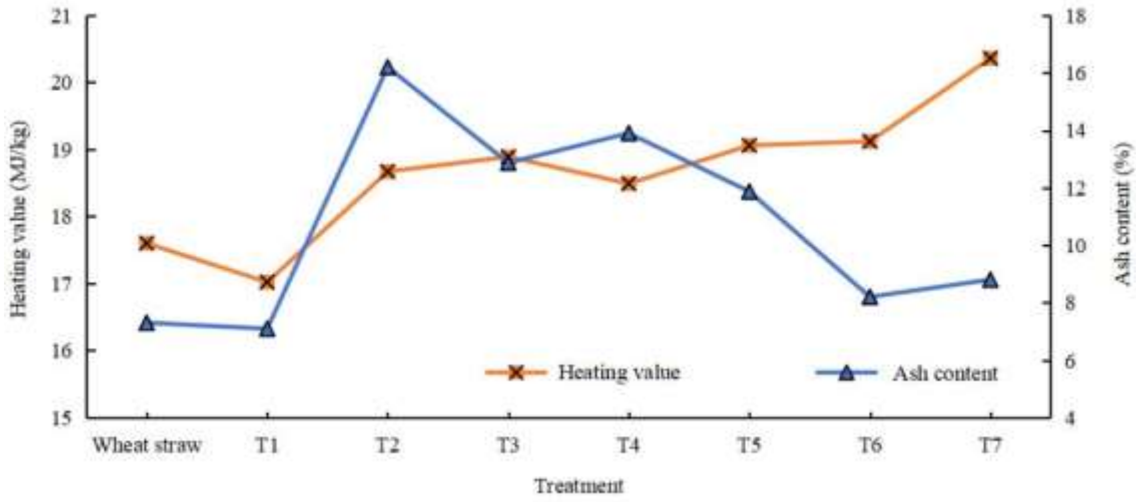

Fig. 5 Combustion properties of pellet

Ash is in an inorganic form in biomass and produces pellets. Therefore, the pellets ash depends on the feedstock's mineral composition or fuel source (Assi et al., 2020). According to the results of this research, wheat straw had a 7.30% ash content, which was higher than the T1 pellets (7.09%). In addition, the lowest and highest inorganic ash contents of the pellet were 16.20% (T2) and 7.09% (T1), respectively. Moreover, the additive blend pellets (T2–T7) contained more ash than the wheat straw and T1 pellets. Therefore, the higher ash content could result from these pellets, which were made for a combination of bentonite and had the highest ash content (89.63%) (Table 4). Overall, the pellet ash content did not decrease with the mixing with wheat straw, in most cases even significantly higher.

The amount of energy released while burning a unit quantity of fuel is known as the heating value (Telmo and Lousada, 2011), which varies from 16.0 to 23.0 MJ/kg for biomass (Sadaka and Negi, 2009). On the other hand, heating value is an essential combustion characteristic of biomass or substance (Liu et al., 2013). The numerous compositions of the biomass led to the heating value/energy variation. The lowest energy content (17.02 MJ/kg) was in pellets for wheat straw without additives (T1). In addition, this value was lower than feedstock materials (wheat straw). Moreover, with pellets from additive combination with wheat straw, the heating value positively increased and ranged from 18.49 to 20.36 MJ/kg (Fig. 5). Thus, it was valuable information that additives could enhance the pellet heating value (Telmo and Lousada, 2011), which meets the hypothesis in this study.

3.4. Relationship between pellet apparent and bulk density

This study produced seven types of pellets from wheat straw with additives (T2–T7) and wheat straw without additives (T1). Generally, the length, diameter, and weight were used to calculate the density. Fig. 6 shows the pellet density pattern, where experiences no relationship between the apparent and bulk density.

The additives did not influence the apparent density as shown in Fig. 6. The T5 pellets had a lower apparent density (713 kg/m^3), and the higher was T4 (1 266 kg/m^3). The average apparent density was comparatively higher than bulk density (Liu et al., 2013). The apparent density counted after one day of pellet extrusion from the machine; there could be more moisture. However, additives combination positively impacted bulk density, which meant additives improved the bulk density. For instance, the bulk density variation ranged from 204 to 665 kg/m^3. Liu et al. (2013) noted that pellet bulk density increased with the additive mixture. Therefore, the binder addition is vital to improve physical quality as bulk density.

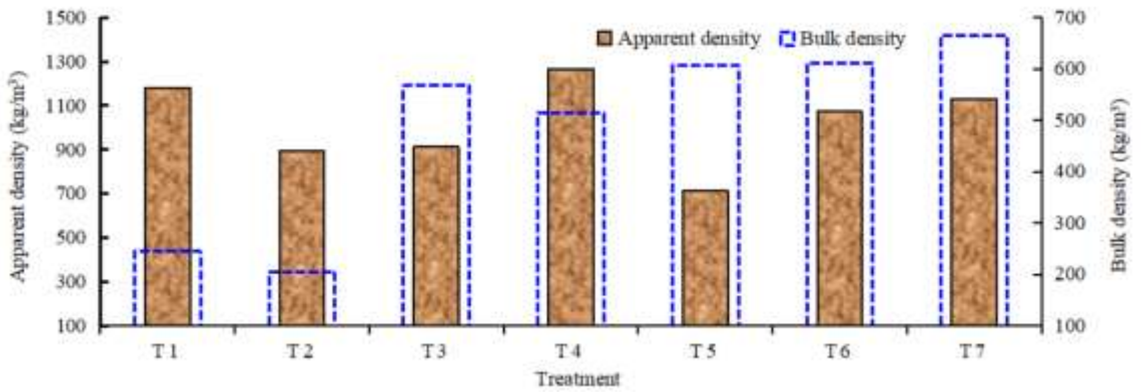

Fig. 6 Bulk density and unit density of pellets

3.5. Relationship between pellet strength, fines content, and durability

This study measured pellet strength using three parameters: durability, tensile strength, and fines content, as shown in Figs. 7 and 8. Figure 7 shows the fines content and durability value of the pellet. The results indicate that the durability of pellets without additive (T1) was 85.22%, which was the lowest among the pellets. The lower durability could be due to the poor bond between the particles. At the same time, the durability of the additive blend pellet increased significantly and ranged from 92.20% to 97.20%. Hence, adding additives confirmed the durability of the pellet was mainly improved. Furthermore, Pokhrel et al. (2021) found that pellet durability increased by adding binding materials (wood residues). Overall, the fines content and durability were recommended to have an inverse relationship.

The amount of dust, fines, or small particles is a significant evaluating factor for quality pellets. In addition, handling, transportation, and storage implied fines or small particle production from a pellet. The highest amount (8.58%) of fines was observed in wheat straw pellets without additives (T1), and the second-highest (5.13%) was in T2 pellets. The smaller particles could result from loose bonding among the particles. In contrast, the fines content dramatically decreased for the T_3–T_7 pellets, and the value was lower than 2%; the binding additives such as bentonite clay and starch might be used. Therefore, it was noted that suitable bindings material could reduce small particle generation.

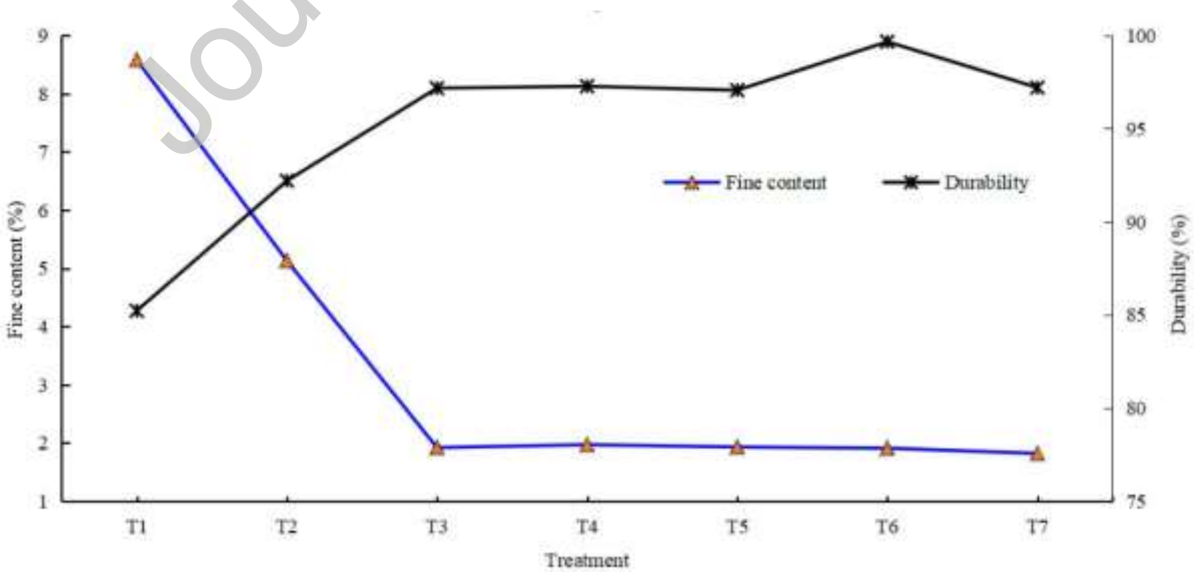

Fig. 7 Durability and fines contents of pellets

The relationships of fines content and tensile strength for the pellet were shown in Fig. 8. Tensile strength implies pellet quality regarding pellet strength and hardness. In addition, it resisted breaking and dust generation through transportation and handling. According to the results from Fig. 8, pellets without additives (T1) had lower tensile strength (0.36 MPa), probably due to the poor particle bonding. The wheat straw additives significantly improved the pellet's tensile strength (T_2–T_7). As a result, tensile strength increased from 0.36 to 2.09 MPa. Kashaninejad and Tabil (2011) noted that wheat straw pellets had a tensile strength of 0.81 MPa, which supported the results of this study. It was also confirmed that additive addition was an efficient method to improve the strength of pellets. Additionally, the additive mixing rate increased the tensile strength of the pellets and decreased the fines content. Overall, additive mixing enriched the durability and tensile strength while reducing the fines generation from pellets.

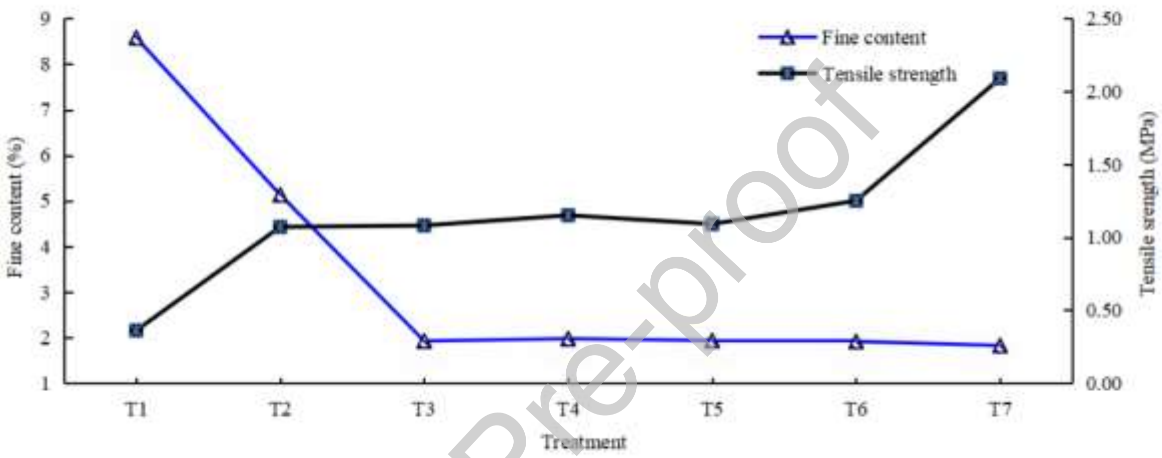

Fig. 8 Fines content and tensile strength

3.6. Relationship between moisture content, durability, and bulk density

During solid fuel burning, the moisture content of the pellet directly affected the combustion efficiency (Huangfu et al., 2014), which was related to bulk density and durability. The relationship between durability and moisture percentage were shown in Fig. 9a, while the relationship between moisture content and bulk density were depicted in Fig. 9b. A non-linear relationship was observed between pellet durability and bulk density for all pellet types based on moisture content (Fig. 9). From the experience of the study, moisture content did not affect pellet durability improvement. Samuelsson et al. (2012) informed that the optimal moisture level of feedstock influenced durability but had no positive relationship with pellet moisture. However, Agar et al. (2018) studied pellet raw material and agri-pellet physical parameters. They noted that the durability and moisture content had opposite relations, contrasting the present study results.

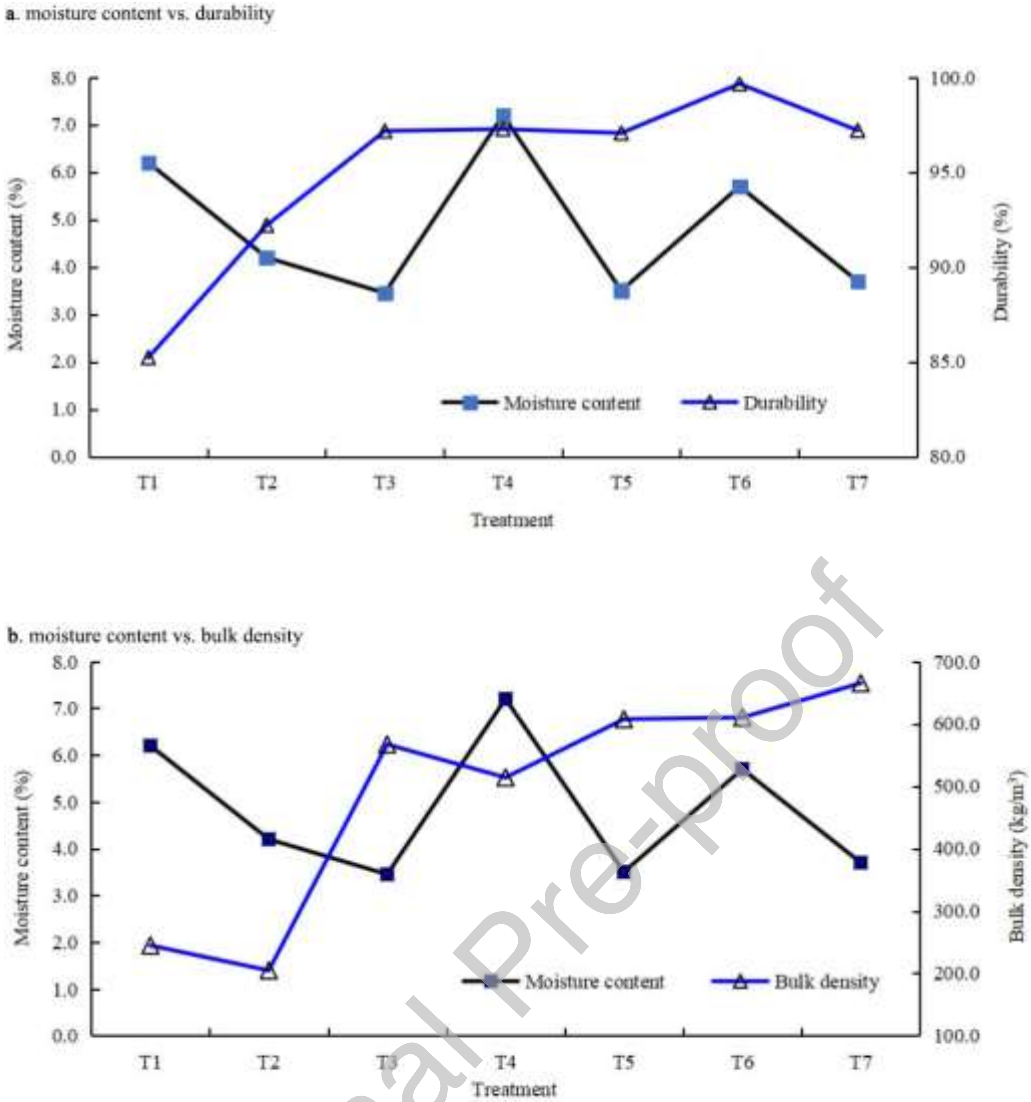

Fig. 9 Relationship moisture content with durability and bulk density

In the pelleting process, water acts as a lubricant, resulting in the particle bonding mechanism and enhancing the compression force in the pellet production channel. Generally, the moisture content of feedstock (about 20%) was higher than that of the produced pellet (less than 10%) (Yılmaz et al., 2021). Hence, the moisture content of the produced pellet was markedly lower than pelletizing moisture. Overall, the optimum humidity is needed for pelletization. The moisture content of wheat straw-based pellet fluctuated from 3.5% to 7.2%, while the bulk density increased with the additive combination, and density ranged from 204.69 to 665.21 kg/m^3. Although the result observed in Fig. 9b, the moisture content and bulk density had no linear relationship. Nguyen et al. (2017) stated that the optimum moisture level reduced friction during compression, subsequent in high pellet density. Similarly, Ungureanu et al. (2018) reported that the pelleting process with low moisture content required high compressive pressure consequences with greater bulk density. Nevertheless, Agar et al. (2018) observed that the bulk density and moisture percentage had an inverse relation, opposing the present study results. The different results might be due to the different types of raw materials used in the study.

3.7. Pellet quality assessment and comparison

This study determined several physical properties of pellet, such as length, diameter, apparent density, bulk density, durability, and fines percentage, for evaluating pellet standards. In addition, the European Pellet

Council (EPC) recommended guidelines (ENplus) were followed to assess physiochemical pellet traits. Most materials (wheat straw and additives) produced relatively good pellet quality. However, none of the pellets matched the A1, A2, and B standards compared to the ENplus quality standard (Table 1). Table 5 lists the quality shortages in ENplus standards as shown in the rightmost column.

Table 5 Comparison of pellet quality and ENplus deficiencies

Treatment	MC (%)	AC (%)	HV (MJ/Kg)	BD (kg/m^3)	DU (%)	FC (%)	ENplus deficiency
T1	6.20[a]	7.09[a]	17.02[a]	244.79[a]	85.22[a]	8.58[a]	AC, BD, DU, FC
T2	4.20[b]	16.20[b]	18.67[b]	204.69[b]	92.20[bg]	5.13[b]	AC, BD, DU, FC
T3	3.45[c]	12.87[c]	18.89[c]	567.04[c]	97.17[b]	1.92[c]	AC, BD
T4	7.20[d]	13.90[d]	18.49[d]	513.97[d]	97.27[cf]	1.97[c]	AC, BD
T5	3.50[c]	11.87[e]	19.06[e]	607.40[e]	97.06b[efg]	1.93[c]	AC
T6	5.70[e]	8.20[f]	19.12[f]	610.12[f]	99.66b[g]	1.91[c]	AC
T7	3.70[f]	8.80[g]	20.36[g]	665.21[g]	97.20[d]	1.82[c]	AC

Notes: MC, moisture content; AC, ash content; HV, heating value; BD, bulk density; DU, durability; FC: fines content. Superscript letters of alphabets indicated that means followed by the same letter did not significantly differ at $P = 0.05$.

The produced wheat straw pellets with pelletising moisture lower than 10% complied with ENplus standard (A1, A2, and B) classes. In this study, the pellet moisture content was statistically dissimilar after pelletization, while the moisture content of raw materials was about 20%. The moisture content and heating value of all pellet fulfilled the ENplus required value. Generally, durability describes pellets' physical distortion during transportation and storage. Based on European Pellet Council standards (Table 1), the pellet durability in the ENplusA1 and ENplusA2 quality categories would not be less than 98%, and ENplusB type pellets should not be less than 97.5% (ENplus. Quality Certification Scheme for Wood Pellets. 2015. Available at: https://enplus-pellets.eu/en-.). The pellets T1 and T2 did not fit the mechanical durability, while others fulfilled that quality. Rendering to the pellet durability tests, the influence of additives on the durability was significant ($P < 0.05$).

The bulk density of the pellet was directly associated with transport, handling, and storage efficacies (Liu et al. 2016). The European Pellet Council recommends that pellets have a bulk density of 600 kg/m^3 (ENplus. Quality Certification Scheme for Wood Pellets. 2015. Available at: https://enplus-pellets.eu/en-.). The bulk density values of the wheat straw pellet need to fulfill the ENplus standards, while the T1–T4 pellets did not meet, and the T5–T7 pellets fulfilled the standard requirement. It was also confirmed that adding the additives improved the bulk density, and the highest density was in T7. Hence, the experimental outcome complied with the study hypothesis.

When the EnPlus requirements were used to assess the pellet characters, most physical properties of the wheat straw pellets were satisfactory, except for ash content. Agar et al. (2018) noted that the ash content and heating value for various agro-pellets were 0.50%–9.36% and 15.18–18.7 MJ/kg, respectively (Carvalho et al., 2013). In this study, the straw pellets had ash content ranging from 7.09% to 16.20%, and a heating value varied from 17.02 to 20.23 MJ/kg, similar to agricultural waste pellets and wood pellets. While all wheat straw pellets meet the ENplus standard of heating value, the highest heating value was obtained in T7. Moreover, additives addition with wheat straw for pellet production was statistically significant regarding the calorific value and ash percentage.

According to the physical analyses, the bonding composition influenced the fines content of the pellets. For instance, the highest fines was found in a non-additive mixed pellet (T1), which might due to the loose bonding, while the second-highest was observed in T2. On the other hand, the pellets made from additive mixed (T3–T7) had similar levels of fines (lowest). Hence, adding additives with wheat straw decreased the fines content of the pellets.

The information was important that all pellets contained a higher ash level than the ENplus standard (maximum level: 2%). Hence, there is a potential research area to minimize the ash content in the pellet.

4. Conclusions

This study produced seven types of wheat straw pellets with different additives: biochar, bentonite clay, sawdust, corn starch, and glycerol. From this investigation, two major conclusions can be made. Firstly, in the comparison of the properties, the moisture content did not influence the durability and bulk density. However, the fines content had an inverse relationship with tensile strength and durability, which meant if tensile strength and durability increased, the contents of the fines decreased. Moreover, there was no relationship between bulk and apparent density, as well as between the diameter and length. Secondly, when considering the physical properties (moisture content, bulk density, durability, and fines content) and combustion characteristics (gross heating value), better-quality pellets could be produced with wheat straw, biochar, bentonite clay, and sawdust. The results showed that biochar mixed pellets had a relatively high heating value, as biochar had a synergistic effect on ash melting and reduction. Apart from the ash content, most pellets fulfilled the ENplus Standard requirements. Therefore, it was concluded that adding binding materials with biomass effectively optimized the properties of densified fuel and could have potential at the industrial-scale commercial level.

Conflict of Interest

There are no conflicts to declare.

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