Journal of the Air & Waste Management Association

ISSN: 1096-2247 (Print) 2162-2906 (Online) Journal homepage: www.tandfonline.com/journals/uawm20

Enhancement of wheat straw pellet quality for bioenergy through additive blending

Bidhan Nath, Guangnan Chen, Les Bowtell & Thong Nguyen-Huy

To cite this article: Bidhan Nath, Guangnan Chen, Les Bowtell & Thong Nguyen-Huy (2025) Enhancement of wheat straw pellet quality for bioenergy through additive blending, Journal of the Air & Waste Management Association, 75:5, 387-404, DOI: 10.1080/10962247.2024.2447480

To link to this article: https://doi.org/10.1080/10962247.2024.2447480

JOURNAL OF THE AIR & WASTE MANAGEMENT ASSOCIATION
2025, VOL. 75, NO. 5, 387–404
https://doi.org/10.1080/10962247.2024.2447480

Taylor & Francis
Taylor & Francis Group

TECHNICAL PAPER

Enhancement of wheat straw pellet quality for bioenergy through additive blending

Bidhan Nath[a], Guangnan Chen[a], Les Bowtell[b], and Thong Nguyen-Huy[c,*]

[a]School of Agriculture and Environmental Science, University of Southern Queensland, Toowoomba, Australia; [b]School of Engineering, University of Southern Queensland, Toowoomba, Australia; [c]Center for Applied Climate Sciences, University of Southern Queensland, Toowoomba, Australia

ABSTRACT

Densification of biomass through pelletizing offers a promising approach to producing clean biofuels from renewable resources. This study, which investigates the impact of additive blends on wheat straw pellet making and upgrading the physiochemical properties, has revealed exciting possibilities. Five additives, including sawdust (SD), bentonite clay (BC), corn starch (S), crude glycerol (CG), and biochar (BioC), were chosen for this study. Pellets were made from seven different combinations using a laboratory-scale pellet mill. The resulting pellets' physical and elemental properties were assessed against ISO 17,225-8 standards. Compared to control pellets, additive blends (T_3-T_7) exhibited significant improvements in mechanical durability (80% to 99%), tensile strength (0.36 MPa to 2.09 MPa), and bulk density (244 kg/m^3 to 665.21 kg/m^3), all meeting ISO standards. Additionally, these blends maintained low fines content (<2%) and water absorption capacity (<2%, except T_1 and T_5). Furthermore, fixed carbon content increased from 11.1% to 30.90%, and energy content rose from 17.02 MJ/kg to 20.36 MJ/kg, which showed a significant synergistic effect of blending additives. These findings underscore the potential of wheat straw as a viable biomass source for bioenergy production through pelletization, offering a hopeful outlook for the future of renewable energy. However, further research is necessary to optimize additive mixing ratios for even greater pellet quality.

Implications: The study successfully demonstrated that adding specific materials during wheat straw pelletizing significantly improves the quality of the pellets as a biofuel. Here are the key implications of the statement.

- Wheat straw is a promising biofuel source: Densification through pelletizing makes wheat straw a viable option for renewable energy production.
- Additives enhance pellet quality: Sawdust, bentonite clay, corn starch, crude glycerol, and biochar improve the pellets' durability, strength, density, and energy content.
- Improved pellet properties meet industry standards: The resulting pellets meet ISO standards for mechanical strength, bulk density, and fines content.
- Synergistic effect of blending: Combining different additives leads to a greater improvement than using them individually.
- Need for further research: Optimizing the ratios of these additives can potentially create even better biofuel pellets.

Overall, the study highlights the potential of wheat straw pelletizing with specific additives as a sustainable and efficient biofuel option. There's room for further improvement, but the initial findings are promising.

PAPER HISTORY
Received May 26, 2024
Revised October 27, 2024
Accepted December 2, 2024

Introduction

Global energy demand has continuously increased due to both population and industrial growth. It is foreseen that there will be a 30% increase in energy demand between now and 2040 (Kamruzzaman et al. 2024; OECD 2016). A total of 32,294 million tonnes of CO_2 will also be released into the earth to generate this large amount of energy (Ríos-Badrán et al. 2020; Nath, Bowtell, Chen, et al. 2024). Consequently, new alternative renewable energy generation with minimum environmental impact is gaining popularity daily and must be developed.

Renewable energy options include biomass, solar, wind, and hydropower (Nanda et al. 2018). Solid biomass is the most demanding and promising renewable energy alternative to fossil fuels (Rajmohan, Ramya, and Varjani 2021; Nath 2023). Solid biomass is less location- and climate-dependent, inexpensive, abundant, and also globally available (Ribeiro and Junior

---

CONTACT Bidhan Nath bidhanbrri@gmail.com School of Agriculture and Environmental Science, University of Southern Queensland, 7 Whitley Court, Glenvale, Toowoomba, QLD 4350, Australia.

*Secondary affiliation: Faculty of Information Technology, Thanh Do University, Kim Chung, Hoai Duc, Ha Noi, Vietnam

2023). Moreover, biomass is often emission-negative (Quan, Jia, and Gao 2020). Agricultural waste is the world's largest solid biomass by mass (Sarkar et al. 2012). This plentiful agro-waste is often highly accessible, representing both a management problem and a fossil-fuel-free alternative (Lu et al. 2014). In addition, several technical hurdles are limiting the production of bioenergy from biomass on a larger scale (Sarwer et al. 2022). These barriers are connected to the physicochemical properties of biomass, such as low energy density, hydrophilicity, etc. (Yu et al. 2019; Nath et al. 2024a). The densification process (pelleting) is often essential to overcoming the agro-residue management problem and upgrading the quality of raw materials (Nath et al. 2024b).

The interest in agricultural residues from straw (corn, sorghum, barley, wheat, rice, etc.) has recently increased, especially for wheat and rice straw, because both crops are widely grown globally (Singh et al. 2021; Nath, Chen, Bowtell et al. 2024). Worldwide total wheat and rice grain production in 2022/23 was 1286.78 million metric tonnes (https://www.statista.com/statistics/263977/world-grain-production-by-type/), which also produced approximately 1673.0 million metric tonnes of straw (grain and straw ration = 1:1.3). Therefore, managing this massive amount of straw is often quite challenging. To date, developing countries like India and Bangladesh typically burn straws on the field, resulting in raw material losses, energy waste, and pollution (Singh et al. 2021). However, direct use of straws as well as heating and cooking are often unjustified and impractical because of low energy density, unpredictable burning, and hurdles in storage and transportation (Jian et al. 2019). In this situation, raw straw processing, like pelleting, is necessary for easy management (handling, storage, transportation, and combustion) and obtaining sustainable combustion characteristics (High calorific value) (Guo et al. 2022).

Up to now, the majority of pellets are made from woody biomass because of their low ash contents (Mansuy et al. 2015). However, pellet production from wood-based biomass materials cannot meet market demand. Also, some countries like Australia stopped pellet-making from forest biomass (https://happyeconews.com/australia-rejects-forest-biomass-in-first-blow-to-wood-pellet-industry/). On the other hand, Australia produced 45.0 million tonnes of wheat residue as crop waste. Therefore, wheat straw biomass could be a significant source for pellet making because of its low price and wide availability. Compared to woody pellets, agro-pellets, especially wheat straw pellets, are often regarded as low-grade pellet fuel, typically having a lower calorific value, a lower density, and a higher ash content (Yu et al. 2019). Shahram Emami et al. (2014) Stated that making standard-quality wheat straw pellets is challenging without additives. Moreover, manufacturing agricultural straw pellets is often more difficult due to lower lignin content (Brand et al. 2021; Liu et al. 2013). Therefore, improved methods are needed to increase the quality of wheat straw pellets, which may be done by mixing different additives (Mehdi et al. 2021).

The volumetric densities, energy efficiency, and mechanical qualities of agro-pellets are often incomparable with coal or wood (Guo et al. 2022). However, agro-pellet quality improvement could be possible through suitable treatment and pre-processing (Ashokkumar et al. 2022). However, pre-treatment often involves significant energy requirements (Nath et al. 2023). Complex and sophisticated steps involved in pre-treatment methods could increase the pellet production cost. For example, stream exploration needs a temperature of 180 ~ 230°C for 2 ~ 10 minutes (Harmsen et al. 2010). This may not be realistic for farm-level pellet production, which should involve a relatively simple process and less cost. Therefore, this study is focused only on additive/biomass mixing and size reduction of wheat straw by milling machine for pellet production.

Several investigations have used various methods and considered different types of blending or additive materials for straw or non-weedy (herbaceous biomass) pellet production and their quality improvement. For example, Park et al. (2020) and Ríos-Badrán et al. (2020) have used a wood/agricultural residue mixture for pellet production. Siyal et al. (2021) and Jiang et al. (2016) have blended agro-waste with other residues, such as sewage sludge, pyrolysis oil, and hydrolysis lignin for co-pelleting. Previous research has demonstrated that biomass mixing can considerably enhance the physiochemical character by mechanical interlocking among the particles (Li et al. 2015), ultimately improving pelleting performance. For instance, mixing spruce wood with corn stover increases their pellet mechanical qualities (Stasiak et al. 2017; Yub Harun, Parvez, and Afzal 2018). Also added pine sawdust (high calorific value) with wheat straw to boost the heating value by 15% García et al. (2019). Additionally, energy additives like glycerol, molasses, coal, biochar, and rapeseed cake help reduce the ash percentage and increase the pellet heating value (Kaliyan and Vance Morey 2009; Yang, Hanna, and Sun 2012). Furthermore, lubricant oil can improve the biomass pellet's bulk density and flowability (Adapa et al. 2007). The sawdust and biomass mixtures are usually structural additives that are environmentally friendly (Ståhl and Berghel 2011). Therefore, the present study considered sawdust (which works as structural formation), glycerol and biochar (which act as energy additives), corn starch, and bentonite (which are binding agents) as additive/blending materials.

It is noted that previous work mainly focused on pellet fuel properties (Kaliyan and Vance Morey 2009), for different combinations of biomass (Bilal et al. 2017), varied binders use (Shahram Emami et al. 2014), and pellet durabilities (Kumar, Jones, and Hanna 2009; Shaw 2008; Nath, Bowtell, Chen, et al. 2024), among others (Table 1). Until now, less attention has been paid to the quality improvement of wheat straw pellets. An attempt has been made to quantify oat, wheat straw, barley, and canola straw's densification properties (Adapa, Tabil, and Schoenau 2009). Lu et al. (2014) investigated the additives admixing and densification load for wheat straw pelletization. They found that binding materials and compact load (4000 N) positively impacted density and tensile strength. However, as noted previously, the improvement in the quality of wheat straw pellets has only been limited. In addition, there have only been limited studies that attempt to manufacture pellets in on-farm conditions.

The objective of this work was to make quality fuel pellets using several additive combinations for the upgradation of chemical and physical characteristics. In addition, the impact of additives on fuel properties (calorific values, strength, durability, fines content, and wettability index) was explored in this research. Finally, the fuel properties were compared with the standard value specified by ISO 17,225–8 (ISO/TS 2016).

Materials and methods

Materials

The study was conducted at the University of Southern Queensland, Toowoomba, Australia. It used wheat (*Triticum aestivum* L.) straw to produce pellets. Five different additives/binding materials—sawdust

Table 1. List of different biomass blends/additives for wheat straw pellet production.

Material	Objectives	Analysis/Outcomes	References
Rice husk and wheat straw pellets and their blends	Physicochemical and energetic characterization	• Rice husk exhibits lower calorific value and higher ash content • Moisture, ashes, and nitrogen content did not match ISO 17,225–6 standard, but diameter, length, and durability were compiled	Ríos-Badrán et al. (2020)
Wheat straw pellet blended with wood residues, pre-treated wood residues, lignosulfonate, glycerol, and bentonite clay	• Investigate the binder effects on pellet quality • Study of specific energy consumption and pellet properties	• Binders significantly decrease the specific energy consumption • Additives increase the tensile strength, higher heating value, and reduce the ash content	Lu, Tabil, Wang et al. (2014), Nath et al. (2023)
Wheat straw pellet	Effect of pelletization process and densification parameters on the properties of the wheat straw powder and 40% epoxy 1092 mixture	• Increase the fixed carbon and heating value, bulk density • Improved combustion characteristic	EL-SAYED and Elsaid Mohamed (2018)
Wheat straw pellet-making	Identification of the key factors affecting the pelletizing pressure in biomass pelletization processes	• Pelletizing pressure increased the pellet length • Increasing the temperature resulted in a decrease in the pelletizing pressure	Stelte et al. (2011)
Pine sawdust and wheat/rapeseed straw blends and pellet production	Mechanical and combustion properties of pellets made of pine sawdust mixed with straws	• Pellet density, strength and calorific capacity increased with the addition of pine sawdust	Stasiak et al. (2017)
Wheat straw pellet manufacturing	Investigation of the effects of molasses on wheat straw pellet physical quality	• Temperature is a key factor for good pellet quality • Exceeding the lignin glass transition temperature leads to better pellet quality • Molasses strengthens pellet production at temperatures below the lignin glass transition	MIŠLJENOVIĆ et al. (2016)
Wheat straw pellet	Investigation of biological pre-treatment to improve the pellet quality	• Temperature and biological pre-treatment could improve the physical quality	Gao et al. (2017)
Pellet from torrefied and raw wheat straw	Thermo kinetic properties study	• The bulk density is higher in brown torrefied pellets • Pellet properties satisfy the ISO 17,225–6 standards • Temperature is the potential pre-treatment application	Azocar et al. (2019)

(pinewood organic biomass), bentonite clay, glycerol, corn starch, and activated carbon/biochar (coconut nutshell)—were used in this study.

Chopping and milling of wheat straw

Wheat straw is uneven in shape and size. Furthermore, wheat straw needs to be mixed with other materials to produce a uniform dimension for pelletization. For size reduction, wheat straw was chopped and ground by a hammermill with an electric motor power of 4.0 kW (MKHM 198, Meelko CO-United States, Agricultural Machinery, China). Sixteen swinging knives were used for chopping purposes, and the blade rotational speed was 1500 rpm. An exchangeable screen (3.2 mm) was used for milling the straw. The sample was milled to less than 7 mm ground particles (Figure 1). However, fine powders were also produced in this process.

The ground materials' particle size distribution was determined using a sieve analysis with the opening (sizes) of 4.75, 2.36, 1.8, and 0.7 mm. The particle size distribution of ground raw materials is presented in Table 2. All blending materials' particle size was less than 1.8 mm.

Blending material selection and proportion

Different combinations of blenders or additives were used to develop a suitable wheat straw (WS) pellet (Table 3). This work used seven different types (treatments) of pellets for qualitative analyses. This research followed the published paper regarding the proportion of blenders used and their material characteristics (moisture content and particle size). According to Pradhan, Mahajani, and Arora (2018), the moisture range is 15 to 23%, and a particle size of less than 6.5 mm is required for pellet processing. In addition, Nazemi et al. (2022) suggested that 20% of sawdust with wheat straw can enhance pellet strength. Also, additives proportion of 0.5 to 5% (total mass fraction) can improve pellet quality (Tabil 1996). During mixing, water was added to increase moisture content even though the initial moisture of wheat straw was around 10%. Therefore, the present research considered the raw material moisture content to be around 20%, with particle size not bigger than 2 mm. Moreover, the bentonite clay, sawdust, starch, glycerol, and biochar ratio were all set at a 10% (weight basis) level.

The research aim was pellet production at the farm level. Based on this objective, locally available and less costly additives were considered for pellet making. Therefore, this research selects additives from bentonite clay, sawdust, starch, glycerol, and biochar. During the pellet production, it was found that the (pure) wheat straw pellet (without additive) production capacity was shallow. However, the other pellets (T_2~T_7) production rate was satisfactory.

Pelleting process and pellet production

The wheat straw pellet production method involves collecting raw materials, reducing wheat straw size, mixing additives with ground wheat straw, homogenizing (mixing all materials), pelleting, and drying. The pelleting process adopted in this research is presented as a block diagram in Figure 2. A HOMMAK Y-HM200 homogenizer was used to mix the pellet-making ingredients properly.

A Roller-Turned Flat Die pellet mill (*GEMCO-China, Model: ZLSP200B R-Type*) was used for pelleting, with a production capacity (wood pellet) of 80 ~ 220 kg/hour. This pellet mill consisted of a feeding hopper, a barrel, a cylindrical steel roller, a plate-type flat die with a hole, and an electrical motor (3-phase, 7.5 kW). The pellet ejection hole's inner length and diameter were 40 and 8 mm, respectively.

The rotating (50 rpm) roller's weight produces friction, compresses the biomass sample, and feeds it through a die. The roller slipped on the die plate surface, which helped to discharge the densified sample. In this study, the produced pellets were allowed to cool and dry

Figure 1. Size reduction of wheat straw for pelletizing.

Table 2. Particle size (%) distribution of raw materials.

Raw materials	≥6.7 mm	≥4.75 mm	≥2.36 mm	≥1.8 mm	≥0.7 mm	<0.7 mm
Wheat straw	13.40	12.60	27.20	16.70	7.80	22.30
Sawdust	0.00	0.00	0.00	16.50	22.27	61.23
Bentonite clay	0.00	0.00	0.00	0.00	32.30	67.70
Biochar	0.00	0.00	0.00	7.21	28.63	64.16
Starch	0.00	0.00	0.00	0.00	0.00	100.00

Table 3. Pellet production with different blends of materials.

Treatment and mixing materials	Composition, %	Pellet production capacity, kg/h
T_1: Wheat straw	100	32
T_2: Wheat straw: Sawdust: Bentonite clay	80: 10: 10	131
T_3: Wheat straw :Sawdust: Corn starch	80:10:10	107
T_4: Wheat straw: Sawdust: Bentonite clay: Glycerol	70: 10: 10: 10	149
T_5: Wheat straw: Sawdust: Bentonite clay: Biochar	70: 10: 10: 10	196
T_6: Wheat straw :Sawdust: Corn starch: Biochar	70: 10: 10: 10	163
T_7: Wheat straw :Sawdust: Corn starch: Bentonite clay: Biochar	60: 10: 10: 10: 10	185

Note; % = fraction of total mass basis.
T_2 and T_3: wheat straw with binding additives.
T_4 and T_5: wheat straw with energy materials.
T_6: wheat straw with both binding and energy additive.
T_7: all combinations with wheat straw.

in the open air under ambient conditions. The pellets were then stored in the laboratory for drying (<10% moisture content). Their moisture content reached approximately 12% after one day, and pellets stabilized 14 days after extrusion (Figure 3).

Standard for biomass and pellets physiochemical characterization

The Association of Official Analytical Chemists (AOAC) and the American Society for Testing and Materials (ASTM E 873–82: bulk density of densified particulates biomass fuel) standard methods were used to determine biomass and pellet's physicochemical characteristics.

Measurement of elemental composition

The Feed Central Laboratory, Toowoomba, Queensland, Australia, performed the chemical analysis of wheat straw, sawdust, biochar, bentonite clay, and produced pellets. Triplicate measurements were carried out for each sample to ensure accurate and reliable results.

Component analysis

The primary components of biomass are lignin, cellulose, and hemicellulose. These were determined from acid detergent fiber (ADF), acid detergent lignin (ADL), and neutral detergent fiber (NDF). ADL and ADF were determined with the Association of Official Analytical Chemists (AOAC) standard technique 973.18 - Fiber (Acid detergent) (AOAC 1990c). NDF was determined using AOAC standard method 992.16 (AOAC 1990b). Cellulose and Hemicellulose content was determined from ADF and lignin as: % Hemicellulose = % NDF - % ADF and % Cellulose = % ADF - % ADL (Mani, Tabil, and Sokhansanj 2006).

Proximate analysis

The Hach method determined moisture content and the volatile compound (AOAC 2002). Also, the AOAC

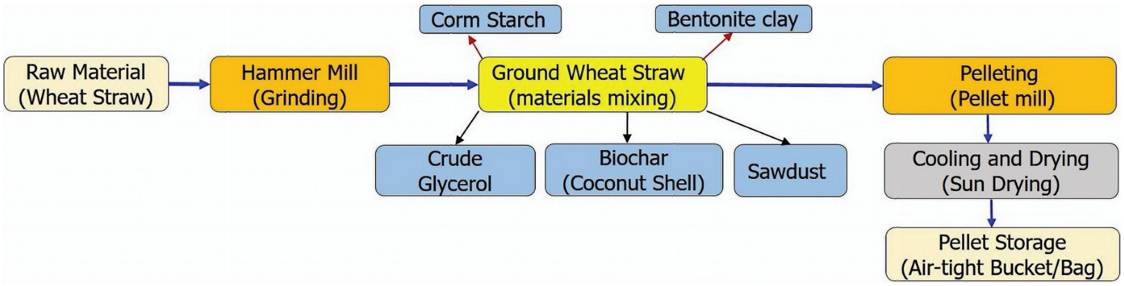

Figure 2. Schematic block diagram of a pellet-making system.

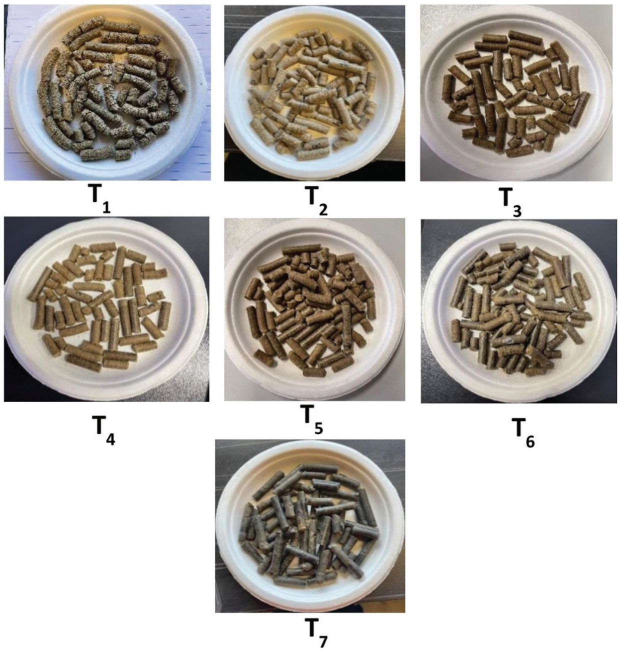

Figure 3. Pellets produced with different additives blends containing wheat straw.

standard method 942.05 was used to determine the total ash, where a 2 ~ 3 gm sample was burned in a furnace above 700°C in an oxygen environment (AOAC 1990a). Next, it took the remaining material (after VM loss). Finally, the fixed carbon (FC) content was considered with Equation 1 (dry basis) (ASTM 2013).

$$FC = 1 - M - Ash - VM \tag{1}$$

Whereas: FC = Fixed carbon, %; M = Mass, %; VM = Volatiles matter, %.

Thermal analysis

Solid material's gross energy (gross heating value) is expressed as calories per gram. Following the ASTM D5865–03 standard (ASTM 2003). The IKA C2000 basic oxygen bomb calorimeter quantified the heating value for thermal analysis. This procedure fixed the instrument to IKA's dynamic mode through an outer vessel temperature of 25°C. In addition, 1.0 gm of Parr standard benzoic acid was used to calibrate the calorimeter. For gross energy determination, around 0.50 gm of the sample was deposited in the combustion capsule and kept in the sample holder head of the bomb calorimeter.

An essential criterion for a material's combustibility is its gross calorific value. Gross calorific value (GCV) is the quantity of energy released per unit of fuel burned. Based on analytical techniques, three types of energy were determined from biomass. In this case, a higher heating value (at constant volume – dry basis), a lower heating value (constant pressure – dry basis), and a gross calorific value (constant pressure – wet basis or as received) are all applicable (Telmo and Lousada 2011). This investigation considered the gross calorific value for all pellets because it is the most practical measurement.

Minor elemental analysis

CN628 Carbon/Nitrogen was used to quantify total organic carbon (TOC) and nitrogen. In addition, AOAC 990.03 - the determinator follows protein (Crude) in Animal Feed (AOAC 2006). In addition, the sulfur was determined by the CEM Application Notes for Acid Digestion method (ASTM 2008). Finally, the difference in elements decided the oxygen.

Measurement of physical properties

Pellet quality assessment checks and compares with the standard and commercially prescribed levels (ISO 17,-225–8). The density, strength, water absorption index, and fines are commonly used to evaluate pellet quality (Zafari and Kianmehr 2014). First, all samples were handled and chosen to ensure a certain homogeneity of the samplings. Then, the laboratory tests, measuring elements such as weight, diameter, length, bulk density, water absorption, and dust content, were undertaken to evaluate the samples (Jiang et al. 2016; Mani, Tabil, and Sokhansanj 2006; Pampuro, Busato, and Cavallo 2018).

Pellet dimension

Typically, pellets are cylindrical. This study used 33 pellets for each treatment to measure physical properties such as diameter, length, weight, and density (individual and bulk). The pellet weights were measured with a digital balance, while a vernier caliper recorded the length and diameter.

Unit density

The pellet's unit density (ρ_u) was calculated using the following equation, which considers each pellet's weight and volume (depending on length and diameter).

$$\text{Unit density}\left(\rho_u\right) = \frac{\pi m_u}{4D^2L} \tag{2}$$

Where: D = diameter of an individual pellet, mm; L= length of an individual pellet, mm; ρ_u = density of an individual pellet, kg/m^{3,} and m_u = mass of an individual pellet, g.

Bulk density

The norm ASTM E 873–82 was used to calculate the bulk density of densified particulate biomass fuels (ASTM 2013). The material’s mass-to-volume ratio was used to calculate the bulk density (ρ_b). First, a digital balance was used to weigh the pellets after leveling the ‘s (model: UTC-0603E and 150 × 250 × 200 mm) top surface. Then, the volume was estimated by measuring the container’s length and diameter (Equation 3).

$$\text{Bulk density}\left(\rho_b\right) = m_b/V_b \tag{3}$$

Where: ρ_b = bulk density, kg/m^3; V_b = volume of a - container, m^3, and m_b = total mass of pellets, kg.

Mechanical durability

The mechanical durability test in this work followed ASTM D3038 with minor modifications. First, a digital scale was used to weigh the pellet, released on a steel pan from a 1.85 m height. Subsequently, the considerable fragment weight was recorded as a pellet’s final mass and repeated three times. Then, Equation 4 was used to calculate the impact resistance/mechanical durability (Gilvari, DE Jong, and Schott 2020).

$$\text{Pellet durability}\,(\%) = \frac{\textit{weight of biggest broken pellet piece}}{\textit{weight of the original pellet}} \times 100 \tag{4}$$

Tensile strength

The pellet diametric compression test is often represented by tensile strength (Horabik et al. 2023). Therefore, in this study, pellets were initially diametrically sliced into a 2 mm thick tablet using a diamond cutter wheel bit in an automatic precision cutting machine (Struers Minitom, Pederstrupvej 84, Denmark) (Shaw, Karunakaran, and Tabil 2009). Then, the Instron plunger inserted the pellet tablet lengthwise in the base plate center and pressed at a 1 mm/min speed. First, the force-displacement information and fracture load data were noted at the pellet tablet’s failure point, such as when the tablet was divided into two semi-circular segments. Next, the pellet tensile strength was determined with the following Equation 5 (Farsi et al. 2020). The test was repeated ten times for every treatment.

$$\text{Tensile strength}\ (\sigma) = \frac{2F}{\Pi dl} \tag{5}$$

Where: σ = Tensile (horizontal) stress, Pa F = load at fracture, Nd = Compact diameter/Pellet diameter, m l = Compact thickness, m

Abrasive test for fines content

The amount of fine materials was measured according to the ASABE 269.4 standard procedure for solid biofuels, using the tumbling method known as the abrasive test (ASABE 2010). In this process, 100 g of pellet samples were weighed and tumbled for 10 minutes at 50 rpm in a dust-tight enclosure. A sieve with a 5.70 mm mesh was used to collect the particles generated during the tumbling operation. Additionally, the particles were graded by 5.6, 3.15, and 1.0 mm sieve sizes. The test was conducted in triplicate, and the small particles were calculated using Equation 6:

$$\%\ \text{of small particles} = \frac{\left(W_i - W_f\right)}{W_f} \times 100 \tag{6}$$

Where: W_i = pellet initial weight before tumbling, g and W_f = pellet final weight after tumbling, g Three types of sieves were considered for analyzing the particle size distribution of small particles (Table 4).

All samples were weighed first and then manually sieved. The dust, particles, and lumps were measured, recorded, and balanced. Finally, the fines were calculated for each particle group using the following method (Equation 7).

$$\%\ \text{of particle type} = \frac{m_i}{m_t} \times 100 \tag{7}$$

Where: m_t = Total mass of pellet/sample before tumbling, g m_i = Final mass of particles after sieve, g.

Wettability index

During transportation and storage, short-term experiences with rain and moisture conditions could harm pellet quality (Kaliyan and Vance Morey 2009). Therefore, the moisture or water resistance of the pellet is an essential parameter evaluated using the wettability index (Papandrea et al. 2021). For the moisture resistance assessment test, 50 g pellets for each treatment were immersed in water for 30 seconds in ambient conditions (26°C and RH 51%) (Kaliyan and Vance Morey 2009; Papandrea et al. 2021; Yoshida et al. 2021). After removing the water, the pellet was placed in ambient conditions for one hour and weighed again. The wettability index was expressed as the percentage of weight variation between the pellet before

Table 4. Sieve for particle size distribution.

Sieve with screen sizes	Particle category
Pan	dust (<1 mm)
1 mm (square holes)	fines (1 mm < fines < 3.15 mm)
3.15 mm (round holes)	lumps (3.15 mm < lumps < 5.6 mm)
5.6 mm (square holes)	whole pellets >5.6 mm

and after water immersion (Papandrea et al. 2021) and repeated the test five times for each sample (Equation 8).

$$\text{Wettability index (WI)} = \frac{\left(W_f - W_i\right)}{W_f} \times 100 \qquad (8)$$

Where: W_i = pellet initial weight before submerging in water, g W_f = pellet final weight after (30 s) submerging in water, g.

Statistical analyses

The one-way analysis of variance (ANOVA) was used to determine the effect of different additive mixing levels on size, density, durability, and strength. In addition, Duncan's multiple range tests were used to examine significant variations in means at a 5% significance level. IBM SPSS software version 27 was used for statistical analysis (IBM corporate, Armonk, New York).

Results and discussions

Pellet composition

Cellulose, hemicellulose, and lignin are the essential components of biomass (Lu et al. 2014). Hemicelluloses and lignin are amorphous polymers that act as binders. It is activated (softening) with temperature and moisture to create strong particle-to-particle bonding. The glass transition temperature of lignin is usually 60 ~ 200°C (Olsson and Salmén 1997). Stelte et al. (2011) However, it was noted that the wheat straw's lignin-softening glass transition was about 53°C. This study found that the pellet development temperature reached around 80°C because of particle friction in the pelletizing machine.

The proximate analysis examined the significant elements, whereas minor features were found in the ultimate analysis. Major and minor chemical components comprise the biomass element characteristics (Table 5). Many research studies have noted that increasing lignin is essential for densification and pellet quality improvement. Wheat straw contains low lignin content and may not bind the particles well (Thomas, VAN Vliet, and VAN Der Poel 1998). In this research, the lignin content of sawdust (26.66%) was significantly higher than that of wheat straw (7.30%) (Table 5).

Table 6 shows that the hemicellulose content for different treatments was moderately varied. The physical process (temperature change) could not change the amount of hemicellulose. Instead, the cellulose content decreased through additive mixing. Hence, the pelletizing temperature might break down the structure and change the cellulose content. Therefore, different additives were mixed with wheat straw to increase the lignin content and help it bond with particles. Among the treatments, the lignin and cellulose content have an inverse relationship. Overall, cellulose decreased by 41% to 28%, and 7–13% increase in lignin (Table 6).

Chemical characteristics of pellets

The chemical analysis of the elemental composition of biomass and pellets is functional for thermochemical conversion modeling, predicting the solid and gas phase and reactant ratio. (Table 7) shows the proximate analysis to identify pellets' moisture content based on dry basis, volatile components, fixed carbon, ash, and gross calorific energy.

Moisture content

The moisture content of pellets directly impacts the combustion efficiency (Gil et al. 2010). Initially, the raw material moisture content was maintained at around 20% for pellet production. However, the generated pellet's moisture content was significantly lower when compared to pelletizing moisture because water evaporated due to the temperature produced by the die and roller frictions (Lisowski et al. 2019). Moreover, the variation in the moisture content of the pellets produced was statistically significant at 95% (p 0.05) among the different treatments (Table 7). Huangfu et al. (2014) found that lowering the biomass moisture content from 20% (initial) to 5% (final) boosted

Table 5. Physiochemical analysis of raw materials used for pellet production.

	Proximate analysis,					Ultimate analysis					Density	Composition		
Sample	MC*, %	VM*, %	FC*, %	Ash*, %	GCV, MJ/kg	C, %	H, %	N, %	S, %	O^a, %	BD, kg/m^3	HC, %	C, %	L, %
Wheat straw	9.62	72.78	10.30	7.30	17.6	46.06	5.00	0.53	0.11	48.3	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	–	–	–

MC: Moisture content; VM: volatile matter, FC: Fixed carbon; GCV: Gross calorific value; C: carbon.
H: Hydrogen; N: Nitrogen; S: Sulfur; O: Oxygen; BD: Bulk density, HC: Hemicellulose; C: cellulose.
L: Lignin; *: Dry basis; ar: As received.
[a] Determined by a difference.

Table 6. The elemental composition of pellets.

	Dry wt, %		
Treatment	Hemicellulose	Cellulose	Lignin
T_1	22.40^a	41.30^a	7.0^a
T_2	27.30^b	30.70^b	8.10^b
T_3	29.00^c	28.80^c	10.50^c
T_4	24.80^d	30.20^b	9.60^d
T_5	23.30^e	30.0^b	10.60^c
T_6	20.0^f	31.10^b	13.10^e
T_7	20.6^g	28.20^d	12.10^f

N = 3 replications.

Superscript letters of alphabets indicate that means followed by the same letter do not significantly differ at $p = 0.05$.

T1: Wheat straw; T2 and T3: wheat straw with binding additives; T4 and T5: wheat straw with energy materialsT6:wheat straw with binding and energy additive, and T7: all combinations with wheat straw.

combustion efficiency by 50%. This study also found that additives improve pellet quality by minimizing moisture content.

Volatile materials and fixed carbon

The volatile content of the produced pellets ranged from 53% to 76%, with the highest volatile content observed in T1 pellets at 75.61%. In contrast, T3 and T4 pellets exhibited comparable volatile content levels, with 61.88% and 60.3% values, respectively. Interestingly, T4 and T6 pellets contained 53% volatile matter, while T3 pellets had the second-highest volatile content at 61.88%. In addition, fixed carbon, a crucial biomass component, was highest in T6 pellets at 32.60% and lowest in T1 pellets. As shown in Table 7, both volatile matter (VM) and fixed carbon (FC) significant effects on combustion differ: VM decreases due to compaction, while FC increases substantially.

Inorganic ash content

The contents of wheat straw and sawdust ash were 7.30% and 0.33%, but the bentonite clay ash was extremely high (89.63%) (Table 5). It was observed that the pellet's inorganic ash presence was significantly influenced by additives composition, fuel source, and elements (Dick et al. 2007). In Table 7, pellet ash content varied from 7.09 to 16.20%. Among the treatments, the ash percentage was highest in T_2 pellets (16.20%), possibly due to the addition of bentonite clay. Also, biochar positively impacted ash reduction, which could be the synergetic effect (T_6). In addition, treatment T_7 had the second lowest ash content (8.80%). Overall, all produced pellets' ash content did not meet the ISO pellet fuels standard (ISO/TS 2016). Consequently, further research is needed to minimize the ash content in pellets by adding alternative additives and applying suitable technologies.

Gross calorific value

The pellet base materials (wheat straw) have a gross calorific value of 17.6 MJ/kg, while the biochar heating value was the highest (30.75 MJ/kg) among the raw materials and pellets (Table 5). Telmo and Lousada (2011) found that the composition of materials significantly impacts the pellet's gross calorific value. From this study, it was evident that pellets with additives (T_2 ~T_7) had a higher gross calorific value than pellets without additives (T_1) (Table 7). Due to additive blending, the gross calorific value (GCV) varied from 17.02 to 20.36 MJ/kg. The analysis data showed that the combination of additives positively impacted the GCV, which was the highest in T_7 (20.36 MJ/kg). Moreover, all pellets had a GCV of more than 17.0 MJ/kg, which satisfies the ISO standard's minimum value for commercial/domestic pellet production (ISO/TS 2016). Mixing additives with wheat straw is worthwhile for the vital combustion parameters (GCV).

Minor chemical elements of pellets

Table 8 shows the minor components of the pellets, while Table 5 denotes the raw materials components, according to the ultimate analysis. The treatments

Table 7. Proximate analysis of wheat straw pellets.

Treatments	MC, % db	VM, % bd	FC, % db	Ash, % bd	GCV, MJ/kg
T_1	6.20^a	75.61^a	11.10^a	7.09^a	17.02^a
T_2	4.20^b	58.9^b	20.70^b	16.20^b	18.67^b
T_3	3.45^c	61.88^c	21.80^c	12.87^c	18.89^c
T_4	7.20^d	60.30^d	18.60^d	13.90^d	18.49^d
T_5	3.50^c	53.03^e	31.60^e	11.87^e	19.06^e
T_6	5.70^e	53.50^f	32.60^f	8.20^f	19.12^f
T_7	3.70^f	56.60^g	30.90^g	8.80^g	20.36^g

MC: Moisture content; VM: Volatile materials; FC: Fixed carbon; HV: Heating value; GCV = Gross calorific value; db: dry basis.

N = 3 replications.

Superscript letters of alphabets indicate that means followed by the same letter do not significantly differ at $p = 0.05$.

T1: Wheat straw; T2 and T3: wheat straw with binding additives; T4 and T5: wheat straw with energy materialsT6: wheat straw with both binding and energy additive, and T7: all combinations with wheat straw.

showed slight differences in carbon, hydrogen, nitrogen, and oxygen. These chemical characteristics help promote clean combustion (Vamvuka and Sfakiotakis 2011). A higher oxygen level in biomass will be more thermally reactive but reduce the heating value (HAYKIRI-ACMA and Yaman 2008). As observed in Table 8, the oxygen content variation levels were not remarkable (43 ~ 50%).

In contrast, higher carbon content is essential for good combustion (Munir et al. 2009). Table 8 shows that the concentration levels of carbon in the pellets were similar to those of oxygen. The variation in hydrogen and nitrogen amounts ranged from 4.40 to 6.30% and 0.56 to 0.81%, respectively. In addition, the pellets had varying sulfur content (~0.21%), which has little influence in combustion.

Measurement of pellet quality attributes

Pellet quality is an essential consideration in handling, transportation, and storage. In this work, pellet quality was indicated by the following six criteria: dimension, bulk density, durability, tensile strength, fines content, and wettability index.

Pellet dimension

The pellet's dimensions (diameter and length) are essential for combustion. It is well known that, especially in small furnaces, the thinner pellet enables a more uniform burning rate than the thicker one (Liu et al. 2013). The pellet length also exaggerated the fuel-feeding qualities. It is easier to facilitate a continuous flow with shorter particles (Lehtikangas 2001).

Table 9 shows the pellet's length, diameter, and weight from 33 pellets. The wheat straw pellet's lowest length was 22.66 mm (T_1). The highest length was 39.77 mm for the T7 treatment (combining all three additives with wheat straw). Therefore, the additive mixing significantly increased the pellet length.

The pellet diameter varied slightly between 8.0 and 8.20 mm, likely due to the piston hole diameter being approximately 8.0 mm, which allowed the material to be compressed and formed into pellets under high pressure (Table 9). The variation may be because water movement among the particles disrupts the pellet formation bond (Mahapatra et al. 2010). It seemed that additives had no considerable impact on pellet diameter.

Pellets' apparent/unit density is a significant reactor design and modeling factor. The unit density depends upon individual weight, length, and diameter influence. The unit weight varied from 1.33 to 2.34 gm but was inconsistent with additive adding (Table 9). In this work, T_4 had the highest unit weight (2.36 gm) as well as the greatest apparent density at 1266.51 kg/m^3. The second highest apparent density was 1181.37 kg/m^3 for T_1, and the lowest was for T_5 (713.38 kg/m^3). The T_5 pellet's apparent density was lowest due to the individual weight of the pellet being higher. A similar trend was found for the apparent density, indicating that additive addition had no impact.

Pellet bulk and unit density

Particle density affects densified fuels such as pellets and briquettes (Filbakk et al. 2011). The pellet's bulk density impacts transportation and storage space necessities. Higher bulk density means better transportation efficiency and less storage space (Liu et al. 2016). The pellets' average density (bulk and unit) from 33 repetitions/treatments is shown in Table 10. The pellets from the pure wheat straw (T_1) had a low bulk density (244.79 kg/m^3), probably because of being more difficult to compact. In comparison, the bulk densities of T_3~T_7 pellets were higher, possibly because of a strong bond among the particles. The significantly highest bulk density in T_7 (665.21 kg/m^3) could be due to additive combinations. Statistical analysis showed that the density varied significantly with additive admixing (Table 10). In addition, the maximum unit density reached 99.66% for T_6, whereas the minimum was 85.22% for T_1.

Table 8. Ultimate analysis of pellets.

Treatments	Carbon, %	Hydrogen, %	Nitrogen, %	Sulphur, %	Oxygen, %
T_1	43.20^{a}	4.90^{a}	0.56^{a}	0.11^{a}	50.11^{a}
T_2	44.60^{bh}	5.20^{b}	0.81^{b}	0.21^{bg}	48.30^{b}
T_3	47.27^{c}	5.00^{a}	0.66^{c}	0.17^{c}	47.60^{cg}
T_4	43.87^{di}	6.20^{cg}	0.68^{d}	0.13^{dh}	47.68^{dg}
T_5	44.51^{eh}	6.30^{dg}	0.72^{e}	0.21^{eg}	46.90^{e}
T_6	43.83^{fi}	4.40^{e}	0.59^{f}	0.12^{ah}	50.00^{a}
T_7	50.37^{g}	5.60^{f}	0.77^{g}	0.19^{f}	43.00^{f}

[a] Determined by a difference.

N = 3 replications.

Superscript letters of alphabets indicate that means followed by the same letter do not significantly differ at $p = 0.05$.

T1: Wheat straw; T2 and T3: wheat straw with binding additives; T4 and T5: wheat straw with energy materialsT6: wheat straw with both binding and energy additive, and T7: all combinations with wheat straw.

Table 9. Physical characteristics of pellet.

Treatment	Length, mm	Diameter, mm	Unit mass, gm	Apparent density, kg/m^3
T_1	22.66 ± 7.34^{a}	8.20 ± .16^{a}	1.33 ± .22^{a}	1181.37 ± 229.26^{a}
T_2	35.26 ± 3.46^{b}	8.15 ± .15^{ab}	1.64 ± .24^{ad}	893.86 ± 103.99^{b}
T_3	29.26 ± 7.64^{c}	8.12 ± .13^{b}	1.40 ± .52^{b}	911.37 ± 213.72^{cb}
T_4	34.97 ± 7.05^{b}	8.25 ± .10^{a}	2.36 ± .54^{aeg}	1266.51 ± 176.06^{d}
T_5	37.44 ± 3.67^{bd}	8.10 ± .10^{ac}	1.36 ± .18^{c}	713.38 ± 104.31^{e}
T_6	34.01 ± 5.58^{bd}	8.02 ± .13^{d}	1.85 ± .38^{af}	1072.17 ± 123.79^{f}
T_7	39.77 ± 2.25^{be}	8.14 ± .06^{ae}	2.34 ± .25^{aeg}	1131.27 ± 98.35^{ag}

The values are expressed as means ± standard deviation.
N = 33 replications.
Superscript letters of alphabets indicate that means followed by the same letter do not significantly differ at $p = 0.05$.
T1: Wheat straw; T2 and T3: wheat straw with binding additives; T4 and T5: wheat straw with energy materialsT6: wheat straw with binding and energy additive, and T7: all combinations with wheat straw.

Pellet durability

Several factors can affect the durability of pellets, such as pressure, pelleting temperature, volume reduction, and material composition (Tilay et al. 2015). This research produced the pellet through the rollers' constant spinning and friction between the plate die and the rollers, which fixed the production pressure. During pellet production, the barrel's temperature was measured using a thermocouple. As previously mentioned, the excellent-quality pellet resulted from the barrel's operating temperature of 60 ~ 80°C.

Table 10 shows the drop test results for each treatment. Pellet durability increased when the binder was increased, and the maximum (99.66%) was observed in T_6. However, according to the statistical analysis, there was no significant variation in durability, excluding the pellets from wheat straw (T_1). In this study, the pellet's durability ranged from 97% to 99% for T_3 to T_7 (pellets with additives), meeting the ISO standard. Iroba et al. (2014) explored the manufacture of ground barley straw pellets via pre-treatment radio-frequency and temperature change during compaction compared to other non-woody biomass pellets. They found the durability was 99.17% (Iroba et al. 2014), similar to this research. This demonstrated that the pellet's durability could be improved through additives mixed with wheat straw. Inversely, wheat straw pellet (T_1) production is more challenging without additives, and quality may fall short of expectations.

Pellet strength

Tensile strength reflects pellet quality when it comes to pellet strength and hardness. High tensile strength resists breaking and dust generation through transportation and handling. The pellet's tensile strength in this work ranged from 0.36 to 2.09 MPa (Table 10). The highest strength was $T_{7,}$ while the lowest was T_1 (pure wheat straw pellet without additives). Moreover, the T_2 to T_6 pellet's strength was similar but significantly different from T_7. The T_7 pellet strength was highest (2.09 MPa), probably a better combination of corn starch and biochar, and made a strong particle bond. Kashaninejad and Tabil (2011) noted that wheat straw pellets had a tensile strength of 0.81 MPa. Additives also help to improve pellet tensile strength.

Pellet wettability

Moisture absorption characteristics of pellets influence the physical deformation encountered throughout storage, transit, and transportation. Yılmaz et al. (2021). It has been reported that increased moisture, followed by a decline in bulk density, causes the formation of loose pellets.

Table 10 shows the pellet wettability index. It can be seen that the binders have a significant effect on the water absorption rates. Among the different pellets, T_1 (without additive) and T_2 (bentonite clay) pellets absorbed the highest amount of water, i.e. 78.63 and

Table 10. Physical properties of wheat straw pellets.

Treatment	BD, kg/m^3	DU, %	GCV, MJ/kg	TS, MPa	FC, %	WI, %
T_1	244.79^{a}	85.22^{a}	17.02^{a}	0.36^{a}	8.58^{a}	78.63^{a}
T_2	204.69^{b}	92.20^{bg}	18.67^{b}	1.07^{b}	5.13^{b}	54.84^{b}
T_3	567.04^{c}	97.17^{b}	18.89^{c}	1.08^{b}	1.92^{c}	22.32^{c}
T_4	513.97^{d}	97.27^{cf}	18.49^{d}	1.15^{b}	1.97^{c}	21.61^{c}
T_5	607.40^{e}	97.06b^{efg}	19.06^{e}	1.09^{b}	1.93^{c}	28.17^{c}
T_6	610.12^{f}	99.66b^{g}	19.12^{f}	1.25^{b}	1.91^{c}	15.57^{c}
T_7	665.21^{g}	97.20^{d}	20.36^{g}	2.09^{c}	1.82^{c}	24.29^{c}

Note; BD = Bulk density; Du = Durability; GCV = Gross calorific value; TS = Tensile strength.
FC: Fines content and Wi = Wettability index.
Superscript letters of alphabets indicate that means followed by the same letter do not significantly differ at $p = 0.05$.
T1: Wheat straw; T2 and T3: wheat straw with binding additives; T4 and T5: wheat straw with energy materials.
T6: wheat straw with binding and energy additive, and T7: all combinations with wheat straw.

54.84%, respectively. The causes might be wheat straw and bentonite clay, which may have enhanced the water-holding ability of pellets. In contrast, T_3 to T_7 pellets had a superior water-proof capacity, leading to advantages for storage in small-scale usage. Kubojima and Yoshida (2015) and Ghiasi et al. (2014) have also examined the various pellet's water absorption capacities. They have shown that the pellet with blending materials (post-torrefied pellet) protects moisture absorption, supporting a similar result in this research. Pellets produced from binders generally showed less water intake than those without binders. Therefore, the results demonstrated that avoiding water uptake needs additives like biochar or a combination.

Pellet fines content

Small particles created directly from the pellet are one kind of quality indicator. Due to the fragile nature of pellets, fines/small particles are generated during transportation, handling, and storage by attrition and breakage (Boac, Casada, and Maghirang 2008; Oveisi et al. 2013). This has implications, including increased dust explosions, equipment fouling, inhaling problems, and the loss of a large amount of the material (Ilic et al. 2018; Ramírez-Gómez 2016).

As part of the sieving analysis, the sieved particle size distribution is presented in Table 11. The fines produced from the abrasive test were in the subsequent order $T_1 > T_2 > T_6 > T_4 > T_5 > T_3 > T_7 >$ (Table 10). The T_1 and T_2 pellets produce more fines than others because of less tensile strength and probably loose particle bonding. The fines content in pellets from T3 to T7 was approximately 2%, likely due to improved structural formation. T7 produced the best pellet, possibly due to the optimal combination of additives. However, T6 contained over 2% fines, likely attributed to the absence of bentonite clay, which helps bind particles and reduce fines. The additives have reduced the fines generation.

Table 11. Produced particle classification.

	Small particles		
Treatment	3.15 mm <Lump ≤ 5.6mm, %	1 mm < Fines ≤3.15 mm, %	Dust ≤1 mm, %
T1	30.88	8.58	4.86
T2	4.43	5.13	2.75
T3	6.68	1.92	0.95
T4	7.89	1.97	0.60
T5	4.52	1.93	1.07
T6	4.03	2.01	2.17
T7	5.13	1.82	2.74

T_1: Wheat straw; T2 and T_3: wheat straw with binding additives; T_4 and T_5: wheat straw with energy materials.

T1: Wheat straw; T2 and T3: wheat straw with binding additives; T4 and T5: wheat straw with energy materials T6: wheat straw with binding and energy additive, and T7: all combinations with wheat straw.

Pellet quality comparison with ISO 17,225–8: 2016

Table 12 compares various pellets with the ISO standards for non-woody/herbaceous biomass/straw biomass, explicitly focusing on factors such as ash content, heating value, durability, moisture content, length, diameter, and bulk density. The ISO standards differentiate between A (household) and B (commercial settings) quality types (ISO/TS 2016). The ash content should be no more than 6% for A-class pellets, while for B-class pellets, it should be no more than 10%. The heating value requirements are ≥18 MJ/kg for A-class and ≥17 MJ/kg for B-class. The durability standards are ≥ 97.5% for A-class and ≥ 96.5% for B-class, while the moisture content should be 10% for both.

It was observed that the pellets produced met ISO standards for durability and moisture content. The pellet dimensions (length and diameter) also fell within the ISO-specified range. The heating values increased with adding additives, and all pellets met the ISO standard. The ISO standard also specifies a minimum bulk density of 600 kg/m3. Treatments T_1 to T_4 did not meet this requirement, but pellets were produced with biochar ($T_5 \sim T_7$). Furthermore, T_2, T_3, T_4, and T_5 pellets failed to meet the ISO ash content standards for both A and B categories. On the other hand, T_1, T_6, and T_7 pellets (with ash content percentages of 7.09%, 8.20%, and 8.80%, respectively) complied with the B-class standards. It shows that T_1 and T_2 also fell short of meeting the fines content standard, according to Table 12.

Study observations and limitations

Examining and identifying the factors affecting the quality of pellets is challenging because they are affected by many factors, such as moisture content, additive addition, and pelleting conditions (Sultana and Kumar 2012).

Figure 4 provides a comprehensive overview of how additives impact various pellet parameters. It highlights the significance of enhanced binding in boosting pellet quality, but the abundance of additives does not necessarily contribute to durable pellet production (Kaliyan and Vance Morey 2009). While additives positively affect specific parameters, their influence on others remains marginal.

Researchers generally agreed that additives improve pellet tensile strength, durability, heating value, and length (Carone, Pantaleo and Pellerano 2011). The value of fines and water absorption capability also decreased, indicating that additives strengthen these characteristics. However, the moisture content and diameter have shown minimal alterations with increasing

Table 12. Comparison of the produced pellets by the *ISO 17,225–8:2016* classification (cereal straw).

	Standard value								
Parameter	A	B	T$_1$	T$_2$	T$_3$	T$_4$	T$_5$	T$_6$	T$_7$
Length, mm	3.15~40		AB	AB	AB	AB	AB	AB	AB
Diameter, mm	6~25		AB	AB	AB	AB	AB	AB	AB
Moisture content, %	≤10		AB	AB	AB	AB	AB	AB	AB
Bulk density, kg/m^3	≥600		X	X	X	X	AB	AB	AB
Ash content, %	≤6	≤10	X	X	X	X	X	X	X
Heating value, MJ/kg	≥18	≥17	AB	AB	AB	AB	AB	AB	AB
Durability, %	≥97.5	≤96.5	X	AB	AB	AB	AB	AB	AB
[a]Fines, %	≤2.0		X	X	AB	AB	AB	AB	AB

Out of standard: X; A = Household use; B = Commercial use, [a]Fines content (<3.15 mm).
T1: Wheat straw; T2 and T3: wheat straw with binding additives; T4 and T5: wheat straw with energy materialsT6: wheat straw with binding and energy additive, and T7: all combinations with wheat straw.

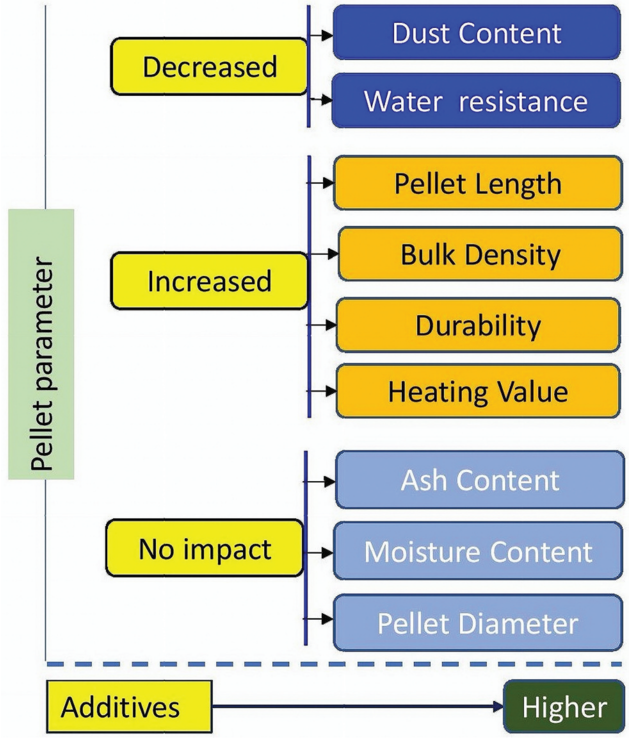

Figure 4. Summary of pellet parameters influenced by additives.

additive content. In summary, it is possible to produce durable wheat straw pellets incorporating additives like sawdust, biochar, and bentonite clay (Whittaker and Shield 2017).

Ash content in biomass plays a pivotal role in the performance of various systems, such as gasifiers and boilers. Cereal crop residues tend to have relatively higher nitrogen, sulfur, chlorine, and potassium levels in their ash composition, potentially leading to complications like slagging and corrosion in boilers (Pastre 2002). The study faces a notable challenge in substantially reducing ash content, which is the main limitation. Consequently, further research is essential to manage the ash content in wheat straw pellets effectively.

Conclusion and recommendations

Various agricultural residues and straws are produced annually from crop production chains. Many countries are looking for alternative options for managing and disposing of field crop residues. The study used wheat straw with additives to improve pellet quality for environmentally friendly waste management and renewable energy production. This research has found that the pellets from wheat straw and a mixture of additives could effectively meet the pellet ISO standard specification requirements, except for inorganic ash content and fines content in some treatments. The following conclusions can be made:

- Wheat straw pellets without additives did not meet most of the ISO solid fuel standards.
- Adding additives to wheat straw for pellet production was an effective way to improve the solid biomass fuel properties and is a viable option.
- The pellet’s physical properties (diameter, length, density, durability, and tensile strength) were significantly improved by adding additives to wheat straw.
- Additives also improve the pellets’ composition and chemical characteristics, particularly for lignin, cellulose content, fixed carbon, etc.
- The combustion parameters, such as decreased moisture content and increased heating value, were obtained from additive mixing.
- The fines content and water absorption decreased in pellet making with additives, promoting safe and secure storage and transportation. However, wheat straw (only) and wheat straw with bentonite clay and sawdust-made pellets failed to comply with ISO solid fuel standards for acceptable content.
- The pellet made from wheat straw, sawdust, corn, biochar, and bentonite clay complies with ISO solid fuel standards, which have met all the requirements for commercial use.

- Research should be conducted to minimize the ash content by considering alternative additives or methods.

Acknowledgment

The authors thank the University of Southern Queensland (UniSQ), Toowoomba, QLD 3450, Australia, for its research facility and for supporting this work.

Disclosure statement

No potential conflict of interest was reported by the author(s).

About the authors

Bidhan Nath, Ph.D., is a senior scientist at the Bangladesh Rice Research Institute and a research assistant at the University of Southern Queensland, Australia. His research focuses on agricultural residue management, farm technology, resource conservation, agronomic practices, soil health management, and ecological pest control strategies.

Guangnan Chen, Ph.D., is an Associate Professor of Agricultural Engineering at the University of Southern Queensland, Australia. He specializes in teaching and researching agricultural machinery, agricultural materials and post-harvest technologies, soil mechanics, and sustainable agriculture.

Les Bowtell, Ph.D., is an Associate Professor of Electronic Engineering at the University of Southern Queensland, Australia. His expertise includes renewable energy, ultrasound power electronics, and the carbon economy. His research fields encompass electrical energy generation (including renewables but excluding photovoltaics), global and planetary environmental engineering, and energy generation, conversion, and storage (excluding chemical and electrical methods).

Thong Nguyen-Huy, Ph.D., is a Senior Research Fellow at the Centre for Applied Climate Sciences, University of Southern Queensland, Toowoomba, QLD, Australia, and the Faculty of Information Technology, Thanh Do University, Hanoi, Vietnam. His research interests include agricultural climate risk modeling, environmental finance, geospatial intelligence, digital farming, renewable energy forecasting, decarbonization, and disaster risk management.

Data availability statement

The data presented in this study are available on request from the corresponding author.

References

Adapa, P.K., G.J. Schoenau, L.G. Tabil, E.A. Arinze, A. K. Singh, and A.K. Dalai. 2007. Customized and value-added high quality alfalfa products: A new concept. *Agric. Eng. Int.* IX:1–28.

Adapa, P., L. Tabil, and G. Schoenau. 2009. Compaction characteristics of barley, canola, oat and wheat straw. *Biosyst. Eng.* 104 (3):335–44. doi: 10.1016/j.biosystemseng.2009.06.022.

AOAC. 1990a. *AOAC method 942.05 – ash in animal feeds. In official method of analysis of the association of official analytical chemists*, 15th ed. 1990, Vol. 70. Gaithersburg, MD: Association of Official Analytic Chemists.

AOAC. 1990b. AOAC method 992.16 – total dietary fiber - enzymatic gravimetric method. In Official methods of analysis of association of official analytical chemists, ed. Gaithersberg, 18th ed. ed. MD, USA: Association of Official Analytic Chemists.

AOAC. 1990c. AOAC method 973.18—fiber (acid detergent) and lignin in animal feeds. In *Official method of analysis of the association of official analytical chemists*, ed. K. Helrick, 15th ed. vol. 82. Arlington, VA: Association of Official Analytical Chemists.

AOAC. 2002. *Official methods of analysis of AOAC international, seventeen, AOAC international, Gaithersburg, 2002.* Loveland, CO, USA: Hach, Water Analysis Handbook, Hach Company.

AOAC. 2006. *Official method 990.03, protein (crude) in animal feed, combustion method, in official methods of analysis of AOAC international, 18th edition revision 1, 2006*, Chapter 4, pp. 30-31. Gaithersburg, MD: AOAC International.

ASABE. 2010. ASAE standard 269.4 DEC1991 (R2007) - cubes, pellets, and crumbles - definitions and methods for determining density, durability, and moisture. In *ASABE standards 2010*, 525–527. St. Joseph, MI: American Society of Agricultural and Biological Engineers, American Society of Agricultural and Biological Engineers.

Ashokkumar, V., R. Venkatkarthick, S. Jayashree, S. Chuetor, S. Dharmaraj, G. Kumar, W.-H. Chen, and C. Ngamcharussrivichai. 2022. Recent advances in lignocellulosic biomass for biofuels and value-added bioproducts-A critical review. *Bioresour. Technol.* 344:126195. doi: 10.1016/j.biortech.2021.126195.

ASTM. 2003. D5865-03-standard test method for gross calorific value of coal and coke. In *Annual book of ASTM standards*, ed F. J. Passman, 517. West Conshohocken, PA, USA: American Society for Testing and Materials.

ASTM. 2008. *Standard D5373, standard test methods for instrumental determination of carbon, hydrogen, and nitrogen in laboratory samples of coal.* West Conshohocken: ASTM International.

ASTM. 2013. *ASTM E873-82: Standard test method for bulk density of densified particulate biomass fuels.* West Conshohocken, PA: ASTM International.

Azocar, L., N. Hermosilla, A. Gay, S. Rocha, J. Díaz, and P. Jara. 2019. Brown pellet production using wheat straw from southern cities in Chile. *Fuel* 237:823–32. doi: 10.1016/j.fuel.2018.09.039.

Bilal, M., M. Asgher, H.M. Iqbal, H. Hu, and X. Zhang. 2017. Biotransformation of lignocellulosic materials into value-added products—a review. *Int. J. Biol. Macromol.* 98:447–58. doi: 10.1016/j.ijbiomac.2017.01.133.

Boac, J.M., M.E. Casada, and R.G. Maghirang. 2008. Feed pellet and corn durability and breakage during repeated elevator handling. *Appl. Eng. Agri.* 24 (5):637–43. doi: 10.13031/2013.25262.

Brand, M.A., R.T. Mariano, S.J. Peretti DA, and J. DE Oliveira. 2021. Recovery of agricultural and wood wastes: The effect of biomass blends on the quality of pellets. *Fuel* 284:284. doi: 10.1016/j.fuel.2020.118881.

Carone, M.T., A. Pantaleo, and A. Pellerano. 2011. Influence of process parameters and biomass characteristics on the durability of pellets from the pruning residues of Olea europaea L. *Biomass and Bioenergy* 35 (1):402–10.

Dick, E., G. Ryabov, A. Tugov, and A. Soboleva. 2007. Comparing properties of coal ash and alternative-fuel ash. *Therm. Eng.* 54 (3):231–35. doi: 10.1134/S004060150703010X.

El-Sayed, S.A., and M.K. Elsaid Mohamed, 2018. Mechanical properties and characteristics of wheat straw and pellets. *Energyamp; Environ.* 29:1224–46. doi:10.1177/0958305X18772414.

Farsi, A., J. Xiang, J. Latham, M. Carlsson, E. Stitt, and M. Marigo. 2020. Strength and fragmentation behaviour of complex-shaped catalyst pellets: A numerical and experimental study. *Chem. Eng. Sci.* 213:115409. doi: 10.1016/j.ces.2019.115409.

Filbakk, T., R. Jirjis, J. Nurmi, and O. Høibø. 2011. The effect of bark content on quality parameters of scots pine (pinus sylvestris L.) pellets. *Biomass Bioenergy* 35 (8):3342–49. doi: 10.1016/j.biombioe.2010.09.011.

Gao, W., L.G. Tabil, T. Dumonceaux, S.E. Ríos, and R. Zhao. 2017. Optimization of biological pretreatment to enhance the quality of wheat straw pellets. *Biomass Bioenergy* 97:77–89. doi: 10.1016/j.biombioe.2016.12.012.

García, R., M. Gil, F. Rubiera, and C. Pevida. 2019. Pelletization of wood and alternative residual biomass blends for producing industrial quality pellets. *Fuel* 251:739–53. doi: 10.1016/j.fuel.2019.03.141.

Ghiasi, B., L. Kumar, T. Furubayashi, C.J. Lim, X. Bi, C.S. Kim, and S. Sokhansanj. 2014. Densified biocoal from woodchips: Is it better to do torrefaction before or after densification? *Appl. Energy* 134:133–42. doi: 10.1016/j.apenergy.2014.07.076.

Gil, M.V., P. Oulego, M.D. Casal, C. Pevida, J.J. Pis, and F. Rubiera. 2010. Mechanical durability and combustion characteristics of pellets from biomass blends. *Bioresour Technol.* 101 (22):8859–67. doi: 10.1016/j.biortech.2010.06.062.

Gilvari, H., W. DE Jong, and D.L. Schott. 2020. The effect of biomass pellet length, test conditions and torrefaction on mechanical durability characteristics according to ISO standard 17831-1. *Energies* 13 (11):3000. doi: 10.3390/en13113000.

Guo, F., J. Chen, Y. He, J. Gardy, Y. Sun, J. Jiang, and X. Jiang. 2022. Upgrading agro-pellets by torrefaction and co-pelletization process using food waste as a pellet binder. *Renewable Energy* 191:213–24. doi: 10.1016/j.renene.2022.04.012.

Harmsen, P.F., W. Huijgen, L. Bermudez, and R. Bakker. 2010. *Literature review of physical and chemical pretreatment processes for lignocellulosic biomass*. Wageningen: Wageningen UR-Food & Biobased Research.

Haykiri-Acma, H., and S. Yaman. 2008. Effect of co-combustion on the burnout of lignite/biomass blends: A Turkish case study. *Waste Manag.* 28 (11):2077–84. doi: 10.1016/j.wasman.2007.08.028.

Horabik, J., M. Bańda, V. Vozárová, Ľ. Kubík, and M. Stasiak. 2023. DEM modelling of wood sawdust compaction and the breakage strength of pellets as determined by a diametral compression test. *Int. Agrophys.* 37 (1):51–58. doi: 10.31545/intagr/156086.

Huangfu, Y., H. Li, X. Chen, C. Xue, C. Chen, and G. Liu. 2014. Effects of moisture content in fuel on thermal performance and emission of biomass semi-gasified cookstove. *Energy Sustain. Devel.* 21:60–65. doi: 10.1016/j.esd.2014.05.007.

Ilic, D., K. Williams, R. Farnish, E. Webb, and G. Liu. 2018. On the challenges facing the handling of solid biomass feedstocks. *Biofuels, Bioprod. Biorefining* 12 (2):187–202. doi: 10.1002/bbb.1851.

Iroba, K.L., L.G. Tabil, S. Sokhansanj, and M. Venkatesh. 2014. Producing durable pellets from barley straw subjected to radio frequency-alkaline and steam explosion pretreatments. *Int. J. Agric. Biol. Eng.* 7:68–82.

ISO/TS. 2016. *ISO/TS 17225-8: 2016 solid biofuels - fuel specifications and classes - part 8: Graded thermally treated and densified biomass fuels*, Online. Iso/Cd 17225-8. https://www.iso.org/standard/71915.html. Accessed 7 January 2022.

Jian, J., Z. Lu, S. Yao, X. Li, and W. Song. 2019. Comparative study on pyrolysis of wet and dry torrefied beech wood and wheat straw. *Energyamp; Fuels* 33 (4):3267–74. doi: 10.1021/acs.energyfuels.8b04501.

Jiang, L.-B., X.-Z. Yuan, H. Li, X.-H. Chen, Z.-H. Xiao, J. Liang, L.-J. Leng, Z. Guo, and G.-M. Zeng. 2016. Co-pelletization of sewage sludge and biomass: Thermogravimetric analysis and ash deposits. *Fuel Process. Technol.* 145:109–15. doi: 10.1016/j.fuproc.2016.01.027.

Jiang, L., X. Yuan, Z. Xiao, J. Liang, H. Li, L. Cao, H. Wang, X. Chen, and G. Zeng. 2016. A comparative study of biomass pellet and biomass-sludge mixed pellet: Energy input and pellet properties. *Energy Convers. Manag.* 126:509–15. doi: 10.1016/j.enconman.2016.08.035.

Kaliyan, N., and R. Vance Morey. 2009. Factors affecting strength and durability of densified biomass products. *Biomass Bioenergy* 33 (3):337–59. doi: 10.1016/j.biombioe.2008.08.005.

Kamruzzaman, M., M. Shahriyar, A.A. Bhuiyan, D. K. Bhattacharjya, M.K. Islam, and E. Alam. 2024. Energy potential of biomass from rice husks in Bangladesh: An experimental study for thermochemical and physical characterization. *Energy Rep.* 11:3450–60. doi: 10.1016/j.egyr.2024.03.019.

Kashaninejad, M., and L.G. Tabil. 2011. Effect of microwave–chemical pre-treatment on compression characteristics of biomass grinds. *Biosyst. Eng.* 108 (1):36–45. doi: 10.1016/j.biosystemseng.2010.10.008.

Kubojima, Y., and T. Yoshida. 2015. Testing method for determining water resistance of wood pellets. *Eur. J. Wood Products* 73 (2):193–98. doi: 10.1007/s00107-014-0868-7.

Kumar, A., D. Jones, and M. Hanna. 2009. Thermochemical biomass gasification: A review of the current status of the technology. *Energies* 2 (3):556–81. doi: 10.3390/en20300556.

Lehtikangas, P. 2001. Quality properties of pelletised sawdust, logging residues and bark. *Biomass Bioenergy* 20 (5):351–60. doi: 10.1016/S0961-9534(00)00092-1.

Li, H., L.-B. Jiang, C.-Z. Li, J. Liang, X.-Z. Yuan, Z.-H. Xiao, Z.-H. Xiao, and H. Wang. 2015. Co-pelletization of sewage sludge and biomass: The energy input and properties of pellets. *Fuel Process. Technol.* 132:55–61. doi: 10.1016/j.fuproc.2014.12.020.

Lisowski, A., M. Pajor, A. Świętochowski, M. Dąbrowska, J. Klonowski, L. Mieszkalski, A. Ekielski, M. Stasiak, and M. Piątek. 2019. Effects of moisture content, temperature, and die thickness on the compaction process, and the density and strength of walnut shell pellets. *Renewable Energy* 141:770–81. doi: 10.1016/j.renene.2019.04.050.

Liu, Z., X.E. Liu, B. Fei, Z. Jiang, Z. Cai, and Y. Yu. 2013. The properties of pellets from mixing bamboo and rice straw. *Renewable Energy* 55:1–5. doi: 10.1016/j.renene.2012.12.014.

Liu, Z., B. Mi, Z. Jiang, B. Fei, Z. Cai, and X.E. Liu. 2016. Improved bulk density of bamboo pellets as biomass for energy production. *Renewable Energy* 86:1–7. doi: 10.1016/j.renene.2015.08.011.

Lu, D., L.G. Tabil, D. Wang, G. Wang, and S. Emami. 2014. Experimental trials to make wheat straw pellets with wood residue and binders. *Biomass Bioenergy* 69:287–96. doi: 10.1016/j.biombioe.2014.07.029.

Lu, D., L. Tabil, D. Wang, G. Wang, and S. Emami. 2014. Experimental trials to make wheat straw pellets with wood residue and binders. *Biomass Bioenergy* 69:287–96. doi: 10.1016/j.biombioe.2014.07.029.

Lu, D., L. Tabil, D. Wang, G. Wang, and Z. Wang. 2014. Optimization of binder addition and compression load for pelletization of wheat straw using response surface methodology. *Int J. Agric Biol. Eng.* 7:67–78.

Mahapatra, A.K., D.L. Harris, D.L. Durham, S. Lucas, T. H. Terrill, B. Kouakou, and G. Kannan. 2010. Effects of moisture change on the physical and thermal properties of sericea lespedeza pellets. *International Agricultural Engineering Journal* 19 (3): 23–29.

Mani, S., L.G. Tabil, and S. Sokhansanj. 2006. Effects of compressive force, particle size and moisture content on mechanical properties of biomass pellets from grasses. *Biomass Bioenergy* 30 (7):648–54. doi: 10.1016/j.biombioe.2005.01.004.

Mansuy, N., E. Thiffault, S. Lemieux, F. Manka, D. PARÉ, and L. Lebel. 2015. Sustainable biomass supply chains from salvage logging of fire-killed stands: A case study for wood pellet production in eastern Canada. *Appl. Energy* 154:62–73. doi: 10.1016/j.apenergy.2015.04.048.

Mehdi, R., N. Raza, S.R. Naqvi, A.H. Khoja, M.T. Mehran, M. Farooq, and K.-Q. Tran. 2021. A comparative assessment of solid fuel pellets production from torrefied agro-residues and their blends. *J. Analytical Appl. Pyrolysis* 156:105125. doi: 10.1016/j.jaap.2021.105125.

MIŠLJENOVIĆ, N., R. ČOLOVIĆ, Đ. VUKMIROVIĆ, T. Brlek, and C.S. Bringas. 2016. The effects of sugar beet molasses on wheat straw pelleting and pellet quality. A comparative study of pelleting by using a single pellet press and a pilot-scale pellet press. *Fuel Process. Technol.* 144:220–29. doi: 10.1016/j.fuproc.2016.01.001.

Munir, S., S. Daood, W. Nimmo, A. Cunliffe, and B. Gibbs. 2009. Thermal analysis and devolatilization kinetics of cotton stalk, sugar cane bagasse and shea meal under nitrogen and air atmospheres. *Bioresource Technol.* 100 (3):1413–18. doi: 10.1016/j.biortech.2008.07.065.

Nanda, S., S.N. Reddy, D.-V.N. Vo, B.N. Sahoo, and J. A. Kozinski. 2018. Catalytic gasification of wheat straw in hot compressed (subcritical and supercritical) water for hydrogen production. *Energy Sci.Amp; Eng.* 6:448–59. doi:10.1002/ese3.219.

Nath, B., L. Bowtell, G. Chen, E. Graham, and T. Nguyen-Huy. 2024. Pyrolytic pathway of wheat straw pellet by the Thermogravimetric analyzer. *Energies* 17 (15):3693. doi: 10.3390/en17153693.

Nath, B.C. 2023. *Thermochemical conversion and upgrading of wheat straw biomass into solid fuel.* Toowoomba: University of Southern Queensland.

Nath, B., G. Chen, L. Bowtell, and E. Graham. 2023. Kinetic mechanism of wheat straw pellets combustion process with a thermogravimetric analyser. *Heliyon* 9 (10):e20602. doi: 10.1016/j.heliyon.2023.e20602.

Nath, B., G. Chen, L. Bowtell, and E. Graham. 2024a. An investigation of thermal decomposition behavior and combustion parameter of pellets from wheat straw and additive blends by thermogravimetric analysis. *Int. J. Thermofluids* 22:100660. doi: 10.1016/j.ijft.2024.100660.

Nath, B., G. Chen, L. Bowtell, and E. Graham. 2024b. Thermal decomposition of wheat straw pellets in a nitrogen environment: Characterization using thermogravimetric analyzer. *Case Stud. Therm. Eng.* 64:105457. doi: 10.1016/j.csite.2024.105457.

Nath, B., G. Chen, L. Bowtell, and R.A. Mahmood. 2023. Assessment of densified fuel quality parameters: A case study for wheat straw pellet. *J. Bioresour. Bioprod.* 8 (1):45–58. doi: 10.1016/j.jobab.2022.10.001.

Nath, B., G. Chen, L. Bowtell, and R.A. Mahmood. 2024. CFDs modeling and simulation of wheat straw pellet combustion in a 10 kW fixed-bed downdraft reactor. *Processes* 12 (5):863. doi: 10.3390/pr12050863.

Nath, B., G. Chen, L. Bowtell, and T. Nguyen-Huy. 2024. Pyrolysis of wheat straw pellets in a pilot-scale reactor: Effect of temperature and residence time. *Energy Science & Engineering* 12 (8):3524–3539.

Nazemi, M., A. Safavi, P. Camille, E. Bonthonneau, C. Richter, and R. Unnþórsson. 2022. Producing high-strength pellets from seaweed, sawdust, and hay for gasification. In *ASME international mechanical engineering congress and exposition*, V006T08A027. New York, NY: American Society of Mechanical Engineers.

OECD. 2016. *Economic, environmental and social statistics.* [Online]. Available. 10.1787/factbook-2015-39-en.Accessed 5 February 2022.

Olsson, A.-M., and L. Salmén. 1997. The effect of lignin composition on the viscoelastic properties of wood. *Nord. Pulp Paper Res. J.* 12 (3):140–44. doi: 10.3183/npprj-1997-12-03-p140-144.

Oveisi, E., A. Lau, S. Sokhansanj, C.J. Lim, X. Bi, S.H. Larsson, and S. Melin. 2013. Breakage behavior of wood pellets due to free fall. *Powder. Technol.* 235:493–99. doi: 10.1016/j.powtec.2012.10.022.

Pampuro, N., P. Busato, and E. Cavallo. 2018. Effect of densification conditions on specific energy requirements and physical properties of compacts made from Hop Cone. *Energies* 11 (9):11. doi: 10.3390/en11092389.

Papandrea, S.F., M.F. Cataldo, A. Palma, F. Gallucci, G. Zimbalatti, and A.R. Proto. 2021. Pelletization of compost from different mixtures with the addition of exhausted extinguishing powders. *Agronomy* 11 (7):11. doi: 10.3390/agronomy11071357.

Park, S., S.J. Kim, K.C. Oh, L. Cho, M.J. Kim, I.S. Jeong, C. G. Lee, and Kim D. 2020. Investigation of agro-byproduct pellet properties and improvement in pellet quality through mixing. *Energy* 190:116380. doi: 10.1016/j.energy.2019.116380.

Pastré, P. 2002. L'analyse du travail en didactique professionnelle. *Revue française de pédagogie* 9–17.

Pradhan, P., S.M. Mahajani, and A. Arora. 2018. Production and utilization of fuel pellets from biomass: A review. *Fuel Process. Technol.* 181:215–32. doi: 10.1016/j.fuproc.2018.09.021.

Quan, C., X. Jia, and N. Gao. 2020. Nitrogen-doping activated biomass carbon from tea seed shell for CO 2 capture and supercapacitor. *Int. J. Energy Res.* 44 (2):1218–32. doi: 10.1002/er.5017.

Rajmohan, K., C. Ramya, and S. Varjani. 2021. Trends and advances in bioenergy production and sustainable solid waste management. *Energy Environ.* 32:1059–85. doi:10.1177/0958305X19882415.

Ramírez-Gómez, Á. 2016. Research needs on biomass characterization to prevent handling problems and hazards in industry. *Particulate Sci. Technol.* 34 (4):432–41. doi: 10.1080/02726351.2016.1138262.

Ribeiro, G.F., and A.B. Junior. 2023. The global energy matrix and use of agricultural residues for bioenergy production: A review with inspiring insights that aim to contribute to deliver solutions for society and industrial sectors through suggestions for future research. *Waste Manag. Res.* 41 (8):1283–304. doi: 10.1177/0734242X231154149.

Ríos-Badrán, I.M., I. Luzardo-Ocampo, J.F. García-Trejo, J. Santos-Cruz, and C. Gutiérrez-Antonio. 2020. Production and characterization of fuel pellets from rice husk and wheat straw. *Renewable Energy* 145:500–07. doi: 10.1016/j.renene.2019.06.048.

Sarkar, N., S.K. Ghosh, S. Bannerjee, and K. Aikat. 2012. Bioethanol production from agricultural wastes: An overview. *Renewable Energy* 37 (1):19–27. doi: 10.1016/j.renene.2011.06.045.

Sarwer, A., S.M. Hamed, A.I. Osman, F. Jamil, A.A.H. Al-Muhtaseb, N.S. Alhajeri, and D.W. Rooney. 2022. Algal biomass valorization for biofuel production and carbon sequestration: a review. *Environ. Chem. Lett.* 20 (5):2797–851. doi: 10.1007/s10311-022-01458-1.

Shahram Emami, L.G.T., A.D.A.P.A. Phani, G.E.O.R.G. E. Elizabeth, T.I.L.A.Y. Ashwini, D.A.L.A.I. Ajay, D.R.I.S. D.E.L.L.E. Mark, and K.E.T.A.B.I. Lily. 2014. Effect of fuel additives on agricultural straw pellet quality. *Int. J. Agric. Biol. Eng.* 7:92–100.

Shaw, M.D. 2008. Feedstock and process variables influencing biomass densification. Doctoral diss., University of Saskatchewan.

Shaw, M., C. Karunakaran, and L. Tabil. 2009. Physicochemical characteristics of densified untreated and steam exploded poplar wood and wheat straw grinds. *Biosyst. Eng.* 103 (2):198–207. doi: 10.1016/j.biosystemseng.2009.02.012.

Singh, G., M.K. Gupta, S. Chaurasiya, V.S. Sharma, and D. Y. Pimenov. 2021. Rice straw burning: A review on its global prevalence and the sustainable alternatives for its effective mitigation. *Environ. Sci. Pollut. Res.* 28 (25):32125–55. doi: 10.1007/s11356-021-14163-3.

Siyal, A.A., Y. Liu, X. Mao, Z.A. Siyal, C. Ran, W. Ao, J. Fu, C. Zhou, L. Wang, and X. Li. 2021. Co-pelletization of sewage sludge, furfural residue and corn stalk: Characteristics and quality analysis of pellets. *Biomass Bioenergy* 150:106121. doi: 10.1016/j.biombioe.2021.106121.

Ståhl, M., and J. Berghel. 2011. Energy efficient pilot-scale production of wood fuel pellets made from a raw material mix including sawdust and rapeseed cake. *Biomass. Bioenergy* 35 (12):4849–54. doi: 10.1016/j.biombioe.2011.10.003.

Stasiak, M., M. Molenda, M. Bańda, J. Wiącek, P. Parafiniuk, and E. Gondek. 2017. Mechanical and combustion properties of sawdust—straw pellets blended in different proportions. *Fuel Process. Technol.* 156:366–75. doi: 10.1016/j.fuproc.2016.09.021.

Stelte, W., C. Clemons, J.K. Holm, J. Ahrenfeldt, U. B. Henriksen, and A.R. Sanadi. 2011. Fuel pellets from wheat straw: The effect of lignin glass transition and surface waxes on pelletizing properties. *Bioenergy Res.* 5 (2):450–58. doi: 10.1007/s12155-011-9169-8.

Stelte, W., J.K. Holm, A.R. Sanadi, S. Barsberg, J. Ahrenfeldt, and U.B. Henriksen. 2011. Fuel pellets from biomass: The importance of the pelletizing pressure and its dependency on the processing conditions. *Fuel* 90 (11):3285–90. doi: 10.1016/j.fuel.2011.05.011.

Sultana, A., and A. Kumar. 2012. Ranking of biomass pellets by integration of economic, environmental and technical factors. *Biomass and Bioenergy* 39:344–55.

Tabil, L.G. 1996. *Binding and pelleting characteristics of alfalfa.* PhD, University of Saskatchewan.

Telmo, C., and J. Lousada. 2011. Heating values of wood pellets from different species. *Biomass. Bioenergy* 35 (7):2634–39. doi: 10.1016/j.biombioe.2011.02.043.

Thomas, M., T. Va Vliet, and A. Va Der Poel. 1998. Physical quality of pelleted animal feed 3. Contribution of feedstuff components. *Anim. Feed Sci. Technol.* 70 (1–2):59–78. doi: 10.1016/S0377-8401(97)00072-2.

Tilay, A., R. Azargohar, M. Drisdelle, A. Dalai, and J. Kozinski. 2015. Canola meal moisture-resistant fuel pellets: Study on the effects of process variables and additives on the pellet quality and compression characteristics. *Ind. Crops Products* 63:337–48. doi: 10.1016/j.indcrop.2014.10.008.

Vamvuka, D., and S. Sfakiotakis. 2011. Effects of heating rate and water leaching of perennial energy crops on pyrolysis characteristics and kinetics. *Renewable. Energy* 36 (9):2433–39. doi: 10.1016/j.renene.2011.02.013.

Whittaker, C., and I. Shield. 2017. Factors affecting wood, energy grass and straw pellet durability–A review. *Renewable and Sustain. Energy Rev.* 71:1–11.

Yang, F., M.A. Hanna, and R. Sun. 2012. Value-added uses for crude glycerol–a byproduct of biodiesel production. *Biotechnol. Biofuels* 5 (1):1–10. doi: 10.1186/1754-6834-5-13.

Yılmaz, H., M. Çanakcı, M. Topakcı, and D. Karayel. 2021. The effect of raw material moisture and particle size on agri-pellet production parameters and physical properties: A case study for greenhouse melon residues. *Biomass. Bioenergy* 150:150. doi: 10.1016/j.biombioe.2021.106125.

Yoshida, T., K. Kuroda, D. Kamikawa, Y. Kubojima, T. Nomura, H. Watada, T. Sano, and S. Ohara. 2021.

Water resistance of torrefied wood pellets prepared by different methods. *Energies* 14 (6):1618. doi: 10.3390/en14061618.

Yu, S., J. Park, M. Kim, H. Kim, C. Ryu, Y. Lee, W. Yang, and Y.-G. Jeong. 2019. Improving energy density and grindability of wood pellets by dry torrefaction. *Energy Fuels* 33 (9):8632–39. doi: 10.1021/acs.energyfuels.9b01086.

Yub Harun, N., A.M. Parvez, and M.T. Afzal. 2018. Process and energy analysis of pelleting agricultural and woody biomass blends. *Sustainability* 10 (6):1770. doi: 10.3390/su10061770.

Zafari, A., and M.H. Kianmehr. 2014. Factors affecting mechanical properties of biomass pellet from compost. *Environ. Technol* 35 (4):478–86. doi: 10.1080/09593330.2013.833639.