Fuel Characteristics of Briquettes Manufactured by Natural Stacking Bamboo/Chinese Fir Mixtures

Zixing Feng, Tao Zhang, Jianfei Yang, Qi Gao, Liangmeng Ni, and Zhijia Liu*

ABSTRACT: Bamboo wastes were naturally stacked for 1 month and were uniformly mixed with Chinese fir. Briquettes were manufactured by a briquette extruder at different process temperatures and mixing ratios. The physical, mechanical, pyrolysis, and combustion characteristics of briquettes were determined. The results showed that the mixing ratios and process temperature had a significant impact on the fuel properties of briquettes. The optimum briquettes were manufactured by 70% bamboo/30% Chinese fir blends at a process temperature of 520 °C. The fuel properties of optimum briquettes met the standard requirement of LY/T 2552-2015 and GB/T 28669-2012. The lower heating rate at the primary pyrolysis stage increased the yield of charcoal during the carbonization process of briquettes. The combustion process of briquettes added a char combustion stage, compared with the pyrolysis process. There were no synergistic interactions of bamboo and Chinese fir during pyrolysis and combustion process. The results of this research are helpful to develop large-scale production of bamboo briquettes or charcoal.

1. INTRODUCTION

Biomass is a type of renewable and sustainable bioresource, which can be converted into value-added energy products through some advanced technologies, such as pyrolysis, combustion, gasification, torrefaction, densification, and so forth. Briquette technology is an effective densification way which improves some shortcomings of raw biomass materials such as low bulk density and calorific value, high moisture content, and reduced transportation and storage costs. Agricultural and forestry wastes are the two main kinds of feedstocks for briquettes, such as rice husk, corn cobs, switchgrass, crop, pine, cardboard/sawdust, and so forth. Briquette properties depend on the physicochemical characteristics of these feedstocks. The cellulose influences the water resistance, the lignin influences the combustion characteristics, and the hemicellulose influences the energy consumption during the manufacturing process of briquettes. Furthermore, the hemicelluloses and lignin of the feedstock are some natural binders which occur due to glass transition, resulting in a durable particle–particle bonding within the biomass briquettes. Boschetti et al. concluded that addition of Kraft lignin improved the apparent density, energy density, and mechanical resistance of wood briquettes. The greater stiffness of the feedstock particles occurs due to the enhanced elastic deformation and elastic recovery, which decreases some natural binding among biomass particles. Process parameters have a significant impact on briquette quality and utilization.

The thermal–mechanical properties of feedstocks change with moisture content. In general, a higher moisture content of feedstocks has a lower glass-transition temperature and storage modulus, which is helpful to improve the mechanical strength of briquettes. However, the high moisture content of raw materials can cause the compaction and blockage of machine during briquette processing. The moisture content of the feedstock between 5 and 15% is suitable to the production of biomass briquettes. Rynkiewicz also confirmed the effect of processing temperature of nonwood and herbaceous ground briquettes on their density, hardness, and fracture incidence. The thermal processing increases the calorific value of raw materials and improves the binder of briquettes. However, the higher processing temperature releases a certain amount of oxygenate structures of feedstock and decreases the mechanical resistance of briquettes. Therefore, it is very important for briquettes to select a suitable type of feedstock and processing process.

Received: July 22, 2020
Accepted: September 15, 2020
Published: September 24, 2020

This is an open access article published under an ACS AuthorChoice License, which permits copying and redistribution of the article or any adaptations for non-commercial purposes.
Bamboo is a type of biomass resource with an area of 6.41 million ha in China, which has a great potential for developing bioenergy. Especially, bamboo has a unique hollow structure, resulting in more than 50% wastes during processing. These wastes are mainly used as raw materials for briquettes, which can further be carbonized to bamboo charcoal for barbecue. The fuel parameters of bamboo briquettes met the quality requirement of industrial development including an ash content of 1.16%, a net calorific value of 16.92 MJ/kg, a mechanical durability of 97.80%, and a bulk density of 986.37 kg/m³. However, authors also found that bamboo had different physicochemical properties compared with other biomass materials. The higher storage modulus of bamboo particles results in the lower mechanical strength of solid fuels and the increase in the difficulty of compression. The waxy layer on the surface of bamboo occurs due to the glass−rubber transition during briquette processing, which inhibits adhesion between bamboo particles. To solve this problem, some factories use natural stacking bamboo to produce briquettes in China. Based on our previous results, natural stacking pretreatment changed the chemical composition, cellulose crystallinity, and pyrolysis characteristics of moso bamboo. Bamboo stacked for 1 month had a higher calorific value and char yield than control or bamboo stacked for 2 months. Mixing bamboo and other biomass materials is also an effective way to improve the mechanical properties of bamboo briquettes. The authors found that the mechanical properties of bamboo pellets were significantly improved when wood wastes were added to bamboo wastes during the manufacturing process. Similar methods to improve the mechanical performances of briquettes were also confirmed, such as rice husk and banana residue mixture, cashew shells and rice husk mixture, rice husk−lignite mixture, corn stover and peanut shell mixture, and so forth. Chinese fir is a type of main plantation in southern China, where there are a lot of factories of bamboo products and charcoal. There are abound wastes of Chinese fir, which have not still been increasingly utilized. Although previous research studies have been conducted on the use of different biomass materials for the preparation of biomass briquettes, the properties of briquettes from Chinese fir and bamboo mixtures are not reported, especially for natural stacking bamboo. Therefore, bamboo wastes that are naturally stacked for 1 month, which had a higher calorific value and char yield according to previous research results, were uniformly mixed with Chinese fir with different mass ratios. The blends were used as raw materials to manufacture briquettes at different process temperatures. The physical−mechanical and thermal characteristics of briquettes were investigated. The results of this research will be helpful to develop large-scale production of bamboo/Chinese fir briquettes or charcoal.

2. RESULTS AND DISCUSSION

2.1. Physical and Mechanical Properties. 2.1.1. Density. The density of briquettes is an important indicator to its physical properties, which affects the storage requirements and cost of transportation. The higher density of briquettes had the closer particle bonding and higher energy density. The density of briquettes with different mixing ratios and process temperatures is shown in Figure 1. It was confirmed that mixing ratios and process temperatures had a significant effect on the density of briquettes. Bamboo briquettes had the highest density of 1.09 g/cm³ at a process temperature of 520 °C and wood briquettes had the highest density of 1.12 g/cm³ at a process temperature of 520 °C. At the same process temperature, the density of all briquettes was different, confirming the effect of mixing ratios on briquette density. It was found that briquettes from 70% bamboo/30% Chinese fir blends had the highest density of 1.12 g/cm³ at a process temperature of 520 °C among all briquettes. Especially at a process temperature of 520 °C, the density of all briquettes from blends was higher than that of bamboo or Chinese fir briquettes. This indicated that bamboo and Chinese fir occurred due to synergistic interactions during briquette processing. The density of all briquettes was higher than 0.95 g/cm³, which met the standard requirement of LY/T 2552-2015 (0.80%).

2.1.2. Durability and Fine Content. Durability and fine content refer to the ability of briquettes to withstand drops and collisions during transportation and storage. Figure 2a shows the durability of briquettes at different mixing ratios and process temperatures. It was found that bamboo and Chinese fir briquettes had the highest durabilities of 90.73 and 96.10% at a process temperature of 520 °C, compared with other process temperatures. Even though the durability of some briquettes met the standard requirement of LY/T 2552-2015 (85%), the briquettes from 70% bamboo/30% Chinese fir blends had the highest durability with a value of 96.71% at a process temperature of 520 °C. Similarly, the fine content of 70% bamboo/30% Chinese fir (4.45%) was the lowest at a process temperature of 520 °C, except for Chinese fir briquettes, as shown in Figure 2b.

2.1.3. Compressive Strength. The ability of briquettes to withstand destructive forces during handling, storage, and transportation can be evaluated by compressive strength. The compressive strength of the briquettes indicates the amount of force required to break the briquette structure. As shown in Figure 3, mixing ratios and process temperatures also significantly affected the compressive strength of briquettes. When the temperature increased, the lignin contained in the sample was softened, which played an important role of a natural binder in the densification of briquettes. All briquettes had the highest compressive strength at a process temperature of 520 °C, except for briquettes from 70% bamboo/30% Chinese fir blends. The compressive strengths of 100% bamboo, 90% bamboo/10% Chinese fir, 80% bamboo/20% Chinese fir, 70% bamboo/30% Chinese fir, 60% bamboo/40% Chinese fir, and 100% Chinese fir were 5.68, 5.94, 6.66, 6.20, 5.45, and 6.83 MPa, respectively, at 520 °C of process temperature. Based on the physical and mechanical properties of briquettes, it was suggested that the briquettes were...
manufactured by 70% bamboo/30% Chinese fir at a process temperature of 520 °C.

2.2. Pyrolysis Characteristics of Optimum Briquettes.

Briquettes can further be pyrolyzed to charcoal for barbecue. Therefore, the investigation of pyrolysis characteristics is very helpful for briquettes to design the carbonization process of charcoal. In this research, briquettes were manufactured by 70% bamboo/30% Chinese fir blends at a process temperature of 520 °C and the pyrolysis characteristics of optimum briquettes were investigated. Figure 4a shows the pyrolysis process of optimum briquettes at different heating rates. The pyrolysis process comprised three stages, including dehydration preheating, primary pyrolysis, and carbonization stage. When the heating rate increased from 10 to 40 °C/min, the pyrolysis curves of briquettes shifted to a high temperature. Figure 4b shows the synergistic interaction of bamboo and Chinese fir during the pyrolysis process at different heating rates. It was found that all the measuring and calculating curves of mass loss (ML) with different heating rates were overlapping, indicating that there were no synergistic interactions during the pyrolysis process. This confirmed that bamboo and Chinese fir had a slight impact on their copyrolysis process and the carbonization process of briquettes was easy to be controlled. Table 1 shows the pyrolysis characteristics of briquettes at different heating rates. The start temperature ($T_i$), end temperature ($T_e$), ML, and char yields of the pyrolysis process varied depending on the heating rates. The $T_i$ values and peak temperature ($T_p$) corresponding to the maximum of ML rate increased with the increase in heating rates. The $T_i$ values were 25.74, 29.19, 29.23, and 29.53 °C at heating rates of 10, 20, 30, and 40 °C/min, respectively. Similarly, the $T_e$ values were 331.42, 342.58, 352.13, and 357.73 °C. However, the $T_i$ values and char yield decreased with the increase in heating rates. The $T_i$ values were 795.64, 791.27, 787.08, and 782.75 °C at heating rates of 10, 20, 30, and 40 °C/min, respectively. It was confirmed that the second step of the pyrolysis process was important to increase the char yield, where hemicelluloses, cellulose, and part lignin occurred due to thermal decomposition. Even though the ML values at a heating rate of 10 °C/min were slightly higher than that at other heating rates at the first and third steps, it was obviously lower at the second step. This indicated that the heating rate of primary pyrolysis should be controlled to increase the char yield when briquettes were carbonized to charcoal.

Table 2 shows the pyrolysis kinetics of briquettes according to the Kissinger–Akahira–Sunose (KAS) method.30 As a nonisothermal model, the KAS model mainly dealt with activation energy required for the different transition stages of the samples during the pyrolysis process.31 During the whole pyrolysis process, the fitting degree ($R^2$) was higher than 0.99, indicating that the KAS model could accurately calculate the pyrolysis kinetics of briquettes. The activation energies of
briquettes were 150.56, 151.33, 153.77, 155.09, 155.65, 155.38, 155.00, and 159.03 kJ/mol at conversion rates of 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, and 0.8, respectively. The energy activation of briquettes slightly increased with the increase in conversion rates, confirming that the pyrolysis reactivity of briquettes gradually decreased.

2.3. Combustion Characteristics of Optimum Briquettes. Figure 5 shows the combustion process of optimum briquettes at different heating rates. The combustion process mainly included drying, volatile emission and oxidation combustion, and char combustion.32 Table 3 shows the proximate analysis, ultimate analysis, and calorific value of briquettes. There were 79.86% of volatiles in the briquettes, whose combustion resulted in more than 60% of ML at the second stage. It was found that briquettes had a lower content of N and S, which is helpful to decrease the emission of pollutant gases. Furthermore, the moisture, ash, and caloric value of briquettes also met the standard requirement of GB/T 28669-2012. Compared with the pyrolysis process of briquettes, there added the char combustion stage, which resulted in a lower content of char yield. This phenomenon was due to the fact that air flux increased the reactivity of briquettes.27 There was about 35% of ML at this stage, less than that of the second stage. With the increase in heating rates, the combustion process of briquettes shifted to higher temperatures. This was due to the fact that the internal and external heating of the samples resulted in thermal hysteresis. Similar to the pyrolysis process, there were no synergistic interactions of bamboo and Chinese fir during the combustion process. This was helpful to control the combustion system of briquettes.

Table 4 shows the combustion characteristics of briquettes at different heating rates. The \( T_i \) values were 35.04, 35.07, 35.12, and 35.14 °C at heating rates of 10, 20, 30, and 40 °C/min, respectively, which were higher than that of pyrolysis process. However, the \( T_p \) values at the second stage were 287.55, 298.58, 307.43, and 310.23 °C, which were lower than that of pyrolysis process. The MLs of this stage were 62.48, 61.82, 63.17, and 61.99% at heating rates of 10, 20, 30, and 40 °C/min, respectively. At the char combustion stage, the \( T_e \) values were 435.95, 454.25, 472.90, and 471.70 °C and the MLs were 33.96, 34.61, 34.73, and 34.56%. The \( T_i \) values were 595.75, 591.29, 586.72, and 582.07 °C, which were obviously lower than that of the pyrolysis process. This phenomenon further confirmed that air flux increased the reactivity of briquettes. Similarly, the yield was also lower than that of the pyrolysis process, whose values were 2.37, 2.39, 0.44, and 1.90% corresponding to the heating rates of 10, 20, 30, and 40 °C/min, respectively.

Table 5 shows the combustion kinetics of briquettes at the oxidation combustion and char combustion stages from the KAS method. The higher fitting degree (R²) confirmed that the KAS model was also suitable to evaluate the combustion process of briquettes. At the oxidation combustion stage, the activation energy of briquettes increased from 147.77 to 205.97 kJ/mol with the increase in conversion rates from 0.1 to 0.8. The values of activation energy were 147.77, 148.25, 155.22, 155.38, and 159.03 kJ/mol at conversion rates of 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, and 0.8, respectively. The energy activation of briquettes slightly increased with the increase in conversion rates, confirming that the pyrolysis reactivity of briquettes gradually decreased.

Table 1. Pyrolysis Characteristics of Briquettes at Different Heating Rates

| Conversion rate (α) | Activation energy (kJ/mol) | Frequency factor (A) | R² (R²) |
|---------------------|-----------------------------|---------------------|---------|
| 0.1                 | 150.56                      | 7.39 × 10⁶          | 0.9934  |
| 0.2                 | 151.33                      | 1.01 × 10⁶          | 0.9949  |
| 0.3                 | 153.77                      | 3.83 × 10⁶          | 0.9961  |
| 0.4                 | 155.09                      | 1.58 × 10⁶          | 0.9938  |
| 0.5                 | 155.65                      | 6.81 × 10⁶          | 0.9950  |
| 0.6                 | 155.38                      | 2.71 × 10⁶          | 0.9962  |
| 0.7                 | 155.00                      | 1.04 × 10⁶          | 0.9972  |
| 0.8                 | 159.03                      | 7.22 × 10⁶          | 0.9990  |

Table 2. Pyrolysis Kinetics of Briquettes

| Conversion rate (α) | Activation energy (kJ/mol) | Frequency factor (A) | R² (R²) |
|---------------------|-----------------------------|---------------------|---------|
| 0.1                 | 150.56                      | 7.39 × 10⁶          | 0.9934  |
| 0.2                 | 151.33                      | 1.01 × 10⁶          | 0.9949  |
| 0.3                 | 153.77                      | 3.83 × 10⁶          | 0.9961  |
| 0.4                 | 155.09                      | 1.58 × 10⁶          | 0.9938  |
| 0.5                 | 155.65                      | 6.81 × 10⁶          | 0.9950  |
| 0.6                 | 155.38                      | 2.71 × 10⁶          | 0.9962  |
| 0.7                 | 155.00                      | 1.04 × 10⁶          | 0.9972  |
| 0.8                 | 159.03                      | 7.22 × 10⁶          | 0.9990  |

Figure 5. Combustion process (a) and synergistic interaction (b) of briquettes.
values of activation energy were 184.65, 170.34, 160.77, 152.78, 143.00, 134.01, 125.33, and 116.72 kJ/mol.

3. CONCLUSIONS

The mixing ratios and process temperatures had a significant impact on the physical and mechanical properties of briquettes. Briquettes from 70% bamboo/30% Chinese fir blends had the highest density of 1.117 g/cm³, a durability of 96.71%, and the highest carbon content of 4.45% at 520 °C of process temperature.

Table 3. Proximate Analyses, Ultimate Analyses, and Calorific Value of Briquettes

| Proximate analysis (%) | Ultimate analysis (%) | Calorific value (MJ/kg) |
|------------------------|-----------------------|-------------------------|
| Moisture ash volatiles fixed carbon | C H N S | |
| 2.58 0.86 79.86 19.28 | 50.17 6.04 0.04 0.04 | 19.81 |

The research has been carried out at the laboratory scale, the outcomes are encouraging for implementation at full scale.

4. MATERIALS AND METHODS

4.1. Materials. The wastes of moso bamboo (Phyllostachys heterocycla) with an initial moisture content of 40% were taken from Zhejiang Province, China. Bamboo wastes were transferred to Ziploc bags and sealed tightly. They were put in the laboratory for natural stacking for 1 month, where the average temperature was 25−35 °C and the relative humidity was 80−95%. The wastes of Chinese fir (Cunninghamia lanceolata) with an initial moisture content of 15% were taken from Anhui Province, China. Both samples were pulverized by a mill (Yunbang YB-2000A), and particles of diameter less than 2 mm were used as feedstocks of briquettes. They were dried in the oven with a temperature of 103 ± 2 °C for 24 h.

Figure 6. Manufacturing process of briquettes.
4.2. Preparation of Moso Bamboo/Chinese Fir Briquettes. The predetermined amounts of distilled water were added to moso bamboo and Chinese fir blends to condition the moisture contents of 2.0, 4.0, 6.0, 8.0, and 10.0%. The briquettes were manufactured using a briquette extruder (JYC-L200) at different temperatures of 510, 515, 520, 525, and 530 °C, as shown in Figure 6. It was found that when the moisture content of blends was 6.0–10.0%, blends easily formed a bridge accumulation in a briquette extruder. The blends with a moisture content of 2.0% caused difficulty in compressing the briquettes. When the moisture content of the blends was 4%, briquettes were produced with better mechanical properties.

4.3. Determination of Briquette Density, Durability, and Fine Content. The briquette density, durability, and fine content were determined according to standard of LY/T 2552-2015.

4.3.1. Density. The initial mass of the briquette (m) was weighted. The surface of the briquette was covered by molten paraffin. Then, its mass (m1) was weighted again. Water was added into the cylinder and the initial height (h1) was recorded. The height (h2) of the cylinder was recorded after the briquette was totally immersed in water. The density of the briquette was calculated based on eq 1

$$\rho = \frac{m}{\pi d^2(h_2 - h_1)/4 - (m_1 - m)/\rho_1}$$

(1)

where ρ is the density of the briquette, m is the initial mass of the briquette, m1 is the mass of the briquette covered with paraffin, ρ1 is the paraffin density, h1 is the initial height of the cylinder, h2 is the initial height of the cylinder after immersing the briquette, and d is the diameter of the cylinder.

4.3.2. Durability. About 500 g of briquettes (m) was put into a soft package and dropped freely from a height of 2 m to the concrete floor. Five replicates of this process were performed. Then, the samples were screened to get the briquettes with a size greater than 15 mm, which were weighed (m15). The durability was calculated based on eq 2

$$\text{durability} = \frac{m_{15}}{m} \times 100\%$$

(2)

where m15 is the mass of the briquettes with a particle size less than 15 mm and m is the initial mass of the briquettes.

4.3.3. Fine Content. A certain amount of the briquettes (m) was put into a soft package. They were dropped freely on iron plates. The briquettes with a size less than 15 mm were weighed (m15). The fine content was calculated based on eq 3

$$\text{fine content} = \frac{m_{15}}{m} \times 100\%$$

(3)

where m15 is the mass of the briquettes with a particle size less than 15 mm and m is the initial mass of the briquettes.

4.4. Determination of Compressive Strength. The compressive strength of the briquette was determined using the universal mechanical testing machine (INSTRON-5582) according to the standard of GB/T 25281-2020. The length (l) and width (b) of the briquette were measured using the caliper. The briquette was put in the testing machine and the compressive load was applied on the sample at a uniform speed of 5 mm/min until the briquette occurred due to crack, as shown in Figure 7. The maximum compression load (force to failure) was recorded and the compressive strength (σ) of the briquette was calculated based on eq 4.

$$\sigma = \frac{P_{\text{max}}}{bl}$$

(4)

where σ is the compressive strength of the briquette, $P_{\text{max}}$ is the maximum compression load, l is the length of the briquette, and b is the width of the briquette.

4.5. Determination of Proximate Analyses, Ultimate Analyses, and Calorific Value. The briquettes were pulverized with a mill (Yunbang YB-2000A) into particles of 250–425 μm. The proximate analyses, ultimate analyses, and calorific value were determined by a proximate analyzer (SDTGA5000a), an ultimate analyzer (ADCHN335), an infrared sulfur determination instrument (SDS212), and a IKA-C2000 calorimeter system. The moisture, volatile matter, inorganic ash, and high heating value were determined according to GB/T 212-2008, D 1102-84, and ASTM E 711. The determination of C, H, and N was carried out according to GB/T 476-2008 and the determination of S was performed according to GB/T 217-2007.

4.6. Determination of Pyrolysis and Combustion Characteristics. The pyrolysis and combustion characteristics of briquettes were studied using a TGAQ500 thermogravimetric analyzer at heating rates of 10, 20, 30, and 40 °C/min. The pyrolysis process was carried out under a nitrogen atmosphere with a flowing rate of 40 mL/min. The combustion process was carried out under the air atmosphere with a flowing rate of 40 mL/min. Pyrolysis and combustion temperature were controlled from room temperature (30 ± 5) to 800 °C. The activation energies of pyrolysis and combustion process were calculated using the KAS model. The synergistic interactions of Chinese fir and moso bamboo were investigated during the pyrolysis and combustion processes.

$$Y_{\text{calculated}} = X_{\text{mopo bamboo}} \times Y_{\text{mopo bamboo}} + X_{\text{Chinese fir}} \times Y_{\text{Chinese fir}}$$

(5)

where $Y_{\text{calculated}}$ is the calculated ML of pyrolysis and combustion process, $X_{\text{mopo bamboo}}$ is the percentage of moso bamboo in the blends, $Y_{\text{mopo bamboo}}$ is the measured ML of moso bamboo, $X_{\text{Chinese fir}}$ is the percentage of Chinese fir in the blends, and $Y_{\text{Chinese fir}}$ is the measured ML of Chinese fir.
AUTHOR INFORMATION

Corresponding Author
Zhijia Liu — International Centre for Bamboo and Rattan, Beijing 100102, China; SFA/Beijing Key Laboratory of Bamboo and Rattan Science and Technology, Beijing 100102, China; Phone: 86-10-84789869; Email: Ljzj@icbr.ac.cn

Authors
Zixing Feng — International Centre for Bamboo and Rattan, Beijing 100102, China; SFA/Beijing Key Laboratory of Bamboo and Rattan Science and Technology, Beijing 100102, China
Tao Zhang — Research Institute of Information and Technology of National Immigration Administration, Beijing 100062, China
Jianfei Yang — International Centre for Bamboo and Rattan, Beijing 100102, China; SFA/Beijing Key Laboratory of Bamboo and Rattan Science and Technology, Beijing 100102, China
Qi Gao — International Centre for Bamboo and Rattan, Beijing 100102, China; SFA/Beijing Key Laboratory of Bamboo and Rattan Science and Technology, Beijing 100102, China
Liangmeng Ni — International Centre for Bamboo and Rattan, Beijing 100102, China; SFA/Beijing Key Laboratory of Bamboo and Rattan Science and Technology, Beijing 100102, China

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.0c03413

Author Contributions
**T.Z., equal contributor as first author.

Notes
The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This research was financially supported by the “Basic Scientific Research Funds of International Centre for Bamboo and Rattan-Manufacturing Technology of Biochar from Mixture of Bamboo and Wood” (grant no. 1632018020) and the “13th Five Years Plan-Study on Manufacturing Technology of Bamboo Wastes and its Mechanism” (grant no. 2016YFD0600906).

REFERENCES

(1) Fahmy, T. Y. A.; Fahmy, Y.; Mobarak, F.; Elsakhawy, M.; Abouzeid, R. Biomass pyrolysis: past, present, and future. Environ. Dev. Sustain. 2020, 22, 17–32.
(2) Demirbas, A. Combustion characteristics of different biomass fuels. Prog. Energy Combust. Sci. 2004, 30, 219–230.
(3) Molino, A.; Larocca, V.; Chinase, S.; Musmarra, D. Biofuels Production by Biomass Gasification: A Review. Energies 2018, 11, 811.
(4) Brachi, P.; Miccio, F.; Miccio, M.; Ruoppolo, G. Torrefaction of Tomato Peel Residues in a Fluidized Bed of Inert Particles and a Fixed-Bed Reactor. Energy Fuels 2016, 30, 4858–4868.
(5) Manasi, V.; Ajinkya, C.; Shubham, T. Biomass briquettes. Int. J. Manage. Technol. Eng. 2018, 8, 1597–1601.
(6) Falemara, B. C.; Joshua, V.; Aina, O.; Nuhu, R. Performance evaluation of the physical and combustion properties of briquettes produced from agro-wastes and wood residues. Recycling 2018, 3, 37–49.
(7) Tembe, E. T.; Adetogun, A. C.; Agbidey, F. S. Density of briquettes produced from bambara groundnut shells and it’s binary and tertiary combinations with rice husk and peanut shells. J. Nat. Sci. Res. 2014, 4, 21–25.
(8) Muazu, R. I.; Stegemann, J. A. Effects of operating variables on durability of fuel briquettes from rice husks and corn cobs. Fuel Process. Technol. 2015, 133, 137–145.
(9) Kaliyan, N.; Morey, R. V. Natural binders and solid bridge type binding mechanisms in briquettes and pellets made from corn stover and switchgrass. Bioresour. Technol. 2010, 101, 1082–1090.
(10) Wang, Q.; Geng, C.; Lu, S.; Chen, W.; Shao, M. Emission factors of gaseous carbonaceous species from residential combustion of coal and crop residue briquettes. Front. Environ. Sci. Eng. 2013, 7, 66–76.
(11) Pandey, J.; Gangwar, P.; Kumar, N.; Grewal, N. Pine briquetting—an endeavour for green fuel. Indian For. 2014, 140, 478–482.
(12) Lela, B.; Barisić, M.; Nižetić, S. Cardboard/sawdust briquettes as biomass fuel: physical-mechanical and thermal characteristics. Waste Manage. 2016, 47, 236–245.
(13) Zhang, X.; Peng, W.; Han, L.; Xiao, W.; Liu, X. Effects of different pretreatments on compression molding of wheat straw and mechanism analysis. Bioresour. Technol. 2018, 251, 210–217.
(14) Boschetti, W. T. N.; Carvalho, A. M. M. L.; Carneiro, A. d. C. O.; Santos, L. C.; Poyares, L. d. B. Q. Potential of Kraft lignin as an additive in briquette production. Nord. Pulp Pap. Res. J. 2019, 34, 147–152.
(15) Liu, Z.; Jiang, Z.; Cai, Z.; Fei, B.; Yu, Y.; Liu, X. Dynamic mechanical thermal analysis of moso bamboo (Phyllostachys heterocylaca) at different moisture content. BioResources 2012, 7, 1548–1557.
(16) Nazari, M. M.; San, C. P.; Atan, N. A. Combustion performance of biomass composite briquette from rice husk and banana residue. Int. J. Adv. Sci. Eng. Inf. Technol. 2019, 9, 455–460.
(17) Rynkiewicz, M.; Travníček, P.; Krčálová, E.; Mareček, J. Influence of annealing temperature of straw briquettes on their density and hardness. Acta Univ. Agric. Silvic. Mendelianae Brun. 2013, 61, 1377–1382.
(18) Tabakaev, R.; Shanenko, I.; Kazakov, A.; Zavorin, A. Thermal processing of biomass into high-calorific solid composite fuel. J. Anal. Appl. Pyrolysis 2017, 124, 94–102.
(19) Blesa, M. J.; Miranda, J. L.; Izquierdo, M. T.; Moliner, R.; Arenillas, A.; Rubiera, F. Curing temperature effect on mechanical strength of smokeless fuel briquettes prepared with humates. Energy Fuels 2003, 17, 419–423.
(20) Zhang, X.; Zhong, Z.; Bian, F.; Yang, C. Effects of composted bamboo residue amendments on soil microbial communities in an intensively managed bamboo (Phyllostachys praecox) plantation. Appl. Soil Ecol. 2019, 136, 178–183.
(21) Feng, Z.; Zhang, T.; Yang, J.; Ni, L.; Gao, Q.; Hu, W.; Liu, Z. Effect of natural stacking pretreatment on pyrolysis characteristics of moso bamboo and Chinese fir blends. J. Therm. Anal. Calorim. 2020, DOI: 10.1007/s10973-020-09686-9.
(22) Brunerová, A.; Roubík, H.; Brožek, M. Bamboo fiber and sugarcane skin as a bio-briquette fuel. Energies 2018, 11, 2216–2205.
(23) Liu, Z.; Liu, X.; Fei, B.; Jiang, Z.; Cai, Z.; Yu, Y. The properties of pellets from mixing bamboo and rice straw. Renewable Energy 2013, 55, 1–5.
(24) Yohana, E.; Arijanto; Kalyana, I. E.; Lazuardi, A. Development of briquette fuel from cashew shells and rice husk mixture. AIP Conf. Proc. 2017, 1788, 030017.
(25) Ozyüğuran, A.; Acma, H. H.; Dahilolu, E. Production of fuel briquettes from rice husk-lignite blends. Environ. Prog. Sustainable Energy 2017, 36, 742–748.
(26) Gong, C.; Lu, D.; Wang, G.; Tabul, L.; Wang, D. Compression characteristics and energy requirement of briquettes made from a mixture of corn stover and peanut shells. BioResources 2015, 10, 5515–5531.
(27) Liu, Z.; Hu, W.; Jiang, Z.; Mi, B.; Fei, B. Investigating combustion behaviors of bamboo, torrefied bamboo, coal and their
respective blends by thermogravimetric analysis. *Renewable Energy* 2016, 87, 346–352.

(28) Navalta, C. J. L. G.; Banaag, K. G. C.; Raboy, V. A. O.; Go, A. W.; Cabatingan, L. K.; Ju, Y.-H. Solid fuel from Co-briquetting of sugarcane bagasse and rice bran. *Renewable Energy* 2020, 147, 1941–1958.

(29) Wang, Z.; Qu, L.; Qian, J.; He, Z.; Yi, S. Effects of the ultrasound-assisted pretreatments using borax and sodium hydroxide on the physicochemical properties of Chinese fir. *Ultrason. Sonochem.* 2019, 50, 200–207.

(30) Ozawa, T. Estimation of activation energy by isoconversion methods. *Thermochim. Acta* 1992, 203, 159–165.

(31) Castellano, J. M.; Gómez, M.; Fernández, M.; Esteban, L. S.; Carrasco, J. E. Study on the effects of raw materials composition and pelletization conditions on the quality and properties of pellets obtained from different woody and non woody biomasses. *Fuel* 2015, 139, 629–636.

(32) Liang, F.; Wang, B.; Jiang, C.; Yang, X.; Zhang, T.; Hu, W.; Mi, B.; Liu, Z. Investigating co-combustion characteristics of bamboo and wood. *Bioresour. Technol.* 2017, 243, 556–565.

(33) Liu, Z.; Mi, B.; Jiang, Z.; Fei, B.; Cai, Z.; Liu, X. Improved bulk density of bamboo pellets as biomass for energy production. *Renewable Energy* 2016, 86, 1–7.