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Characterization of Rice Straw for Energy use in Grain Drying: A Comparative Study

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ABSTRACT

The utilization of rice straw for energy in grain drying has garnered significant attention in rice-producing countries. However, its effectiveness as a fuel in grain drying is uncertain due to a lack of information on its fundamental properties. Rice straw is considered a low-quality feedstock due to its high ash content 10-17%, which is higher than that of wheat straw a ~3%, and its high silica content in the ash 75% for rice straw and 55% for wheat straw. Conversely, rice straw has relatively low total alkali content less than 15% Na_2O and K_2O in total ash, while wheat straw has less than 25% alkali content in ash. Based on its slagging index (Rs 0.04) and fouling index (RF 0.24), it is expected that rice straw will not pose significant operational issues or result in different emissions compared to wheat straw and rice husk under similar conditions. This paper aims to explore these properties and how they can be enhanced through pretreatment technologies. The focus is on two fundamental properties: calorific (heating) value and density, and the pretreatment technologies employed are sizing and compression. Existing literature indicates that both the physical and chemical properties of rice straw can be significantly improved through these pretreatment methods. The compressive strength and heating value of the biomass briquette are influenced by the hot-pressing temperature. Increasing the percentage of rice bran in the briquette enhances its compressive strength and heating value. Interestingly, the energy required for compressing the rice straw briquette can be minimized by adding a certain percentage of binder (such as rice bran, sawdust, or other biomass waste) to the crushed rice straw.

Keywords: Rice straw, Heating Value, Bulk Density, Pretreatment, Grain drying, Sizing, Compression.

1. Introduction

Straw continues to be a primary energy source in many countries, accounting for 14% of global energy consumption. It serves various purposes, such as fuel for cooking, drying agricultural products, bedding for animals, and as a material in industrial processes like paper making. The utilization of rice straw as a renewable energy source has gained traction due to the current energy crisis and the threat of global warming. However, when compared to dominant fossil fuels like coal and oil, straw often exhibits inferior properties. It has low grade characteristics, including high volatility, low calorific value, and low density, making it bulkier and more challenging to handle, transport, and store efficiently. Its fibrous nature and high alkali compound content can potentially lead to issues like slagging, fouling, and grate sintering, further complicating its use as an energy source. The pretreatment of rice straw has been successful in enhancing its physical and chemical properties, thereby reducing costs associated with transport, handling, and storage. These pretreatment methods focus on improving combustion efficiency and reducing pollution emissions. However, to justify the expenses involved in straw collection, transport, handling, and storage, the pretreatment technologies must be highly efficient.

Before utilizing rice straw as biomass energy, it is crucial to determine its physical and chemical properties. With this context in mind, this paper delves into existing literature to gather information

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about these fundamental properties and the pretreatment technologies applied to rice straw. The aim is to establish a foundation for comprehending how these pretreatment methods have enhanced the properties of rice straw for energy use in grain drying. In recent times, several studies have focused on the preparation of biomass briquettes. For instance, Wamukonya and Jenkins explored the feasibility of producing binderless briquettes from sawdust and wheat straw. Yaman et al. manufactured fuel briquettes using olive refuse and paper mill waste. Li and Liu employed the piston-mold process to create densified logs from wood residues. Chin and Siddiqui also utilized the piston-mold process to compress sawdust, rice husks, peanut shells, coconut fibers, and palm fruit fibers into biomass briquettes. Li et al. examined the high-pressure compaction of municipal solid waste to produce densified fuel. Granada et al. developed a die and prepared lignocellulosic briquettes by combining African Mongoy and Canadian Oak. Rhén et al. investigated the impact of raw material moisture content, densification pressure, and temperature on various properties of Norway spruce pellets.

The mechanical properties of biomass pellets derived from grasses (e.g., wheat straw, barley straw) were examined by Marsh et al., focusing on the impact of compressive force, particle size, and moisture content. Kaliyan and Morey conducted a review discussing the factors influencing the strength and durability of densified biomass products. However, the references cited only pertain to biomass briquettes made directly from bio-waste materials. The feasibility of producing biomass briquettes using solid waste like rice straws and rice bran has received limited attention. In Taiwan, an annual average of 1.3 to 1.8 million tons of waste rice straw is generated, most of which is either burned or left abandoned in fields after rice harvesting. Burning rice straws not only causes environmental pollution but also poses a potential hazard near highways. Furthermore, abandoned rice straws in fields can block drainage systems during the rainy season or serve as a breeding ground for bacteria. Therefore, the effective conversion of these abandoned rice straws into a renewable energy resource, such as fuel briquettes, is the motivation behind this study. The study involves the design of a homemade machine to efficiently and rapidly crush rice straw, and the piston-mold process is employed to produce fuel briquettes. The investigation also examines the effects of rice straw size, the ratio of rice straw to rice bran, and hot-pressing temperature on the air-dry density and compressive strength of the fuel briquettes.

2. Experimental Methods or Methodology

2.1. Calorific value

The calorific value of straw serves as an important indicator of its energy content as a fuel. There are two types of calorific values: high heating value (HHV) and low heating value (LHV). For most agricultural residues, the HHV typically ranges from 15 to 17 MJ/kg. Rice straw specifically has a high calorific value of 15.3 MJ/kg, which is relatively lower compared to other biomass sources, as illustrated in Table 1. This lower value can be attributed to the high ash content of rice straw (10-17%) in comparison to wheat straw (around 3%), as well as its high silica content in the ash (SO_2 is 75%). However, rice straw exhibits a relatively low total alkali content, with Na_2O and K_2O comprising less than 15% of the total ash, while wheat straw has alkali content below 25% in ash. Considering its slagging index (Rs 0.04) and fouling index (RF 0.24), rice straw is not expected to pose significant operational issues or result in different emissions when compared to wheat straw and rice husk under similar operating conditions.

Table. 1 Displays the experimental results regarding the high heating values (HHV) of various biomass categories.

Biomass value MJ/Kg	Rice Straw	Rice husk	Ha	Wheat straw	Wood
High heating	15.3	17.5	17.1	17.8	19.0

2.2. Bulk density

The evaluation of packaging and storage techniques is crucial when considering the utilization of raw biomass as an energy feedstock. One of the major challenges associated with using raw biomass is its

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low bulk density. This issue is particularly relevant in the case of rice straw, which needs to be transported to power plant sites. However, due to its low density, long-distance transportation becomes more challenging, especially in areas with inadequate transportation systems. The bulk density of rice straw typically ranges from 75 kg/m^3 for loose straws to 100-180 kg/m^3 in packed and baled forms. The low bulk density of rice straw imposes limitations on the quantity that can be used as an energy source, primarily due to the increased costs associated with handling, transportation, and storage.

Table 2. Different forms of biomass based on experimental measurements.

Form (Kg/m^3) dry basis	Loose	Chooped	Bales	Moduled	Hammer milled	Cubed	Pelleted
Bulk density	20-40	40-80	110-200	96-128	40-100	320-640	560-720

2.3. Pretreatment Technologies

Despite the availability of numerous pretreatment techniques for rice straw, the commercial utilization of rice straw for energy purposes is still limited in many rice-producing countries. This is primarily due to the associated costs involved and the absence of sufficient incentives or benefits for farmers to collect the straw instead of burning it in the fields. The practice of burning rice straw in the fields contributes to greenhouse gas emissions and environmental pollution. The following sections outline the fundamental procedures and principles of potential pretreatment technologies for rice straw, as well as their advantages and challenges encountered in its utilization.

2.4. Sizing

To enhance boiler efficiency, one approach involves the reduction of rice straw size. The process begins by air-drying rice straws for a period of two weeks. These dried straws, with lengths ranging from 70 to 140 cm, are then cut into smaller sizes (less than 50 mm) at the inlet using a rotating knife holder equipped with a blade in a homemade machine such as a grinding or hammer mill. This preparation of rice straw is necessary for co-firing it in a boiler, as it improves energy conversion efficiency and combustion performance. Comparatively, larger particle biomass feedstock like palm shell and wood chips can achieve a boiler efficiency of around 70%, whereas smaller biomass sizes such as rice husk, cut straw, and sawdust can provide a boiler efficiency of approximately 75%.

Matching the size and shape of biomass feedstock to that of coal is generally impractical and unnecessary. However, using large and spherical biomass particles presents challenges in terms of fuel conversion efficiency, as such sizes tend to result in incomplete combustion of biomass. On the other hand, fine-sized straws (5-2 mm) enhance combustion behavior, while larger sizes (10-5 mm) of biomass do not significantly impact combustion performance. Despite these considerations, the technology of achieving uniform biomass sizes is not widely employed or feasible in most rice-producing countries due to the associated costs and the lack of readily available, simple straw cutting or sizing machines.

2.5. Raw material

A custom-built machine was developed to efficiently break down rice straws into smaller pieces, allowing control over their size. The machine, as depicted in Fig. 1, consists of a 2.24 kW motor, a transmission mechanism, a set of cutters, and a sieve. The rice straws are initially cut into smaller pieces at the inlet using the blade located on the rotating knife holder. These cut rice straws are then further pulverized as they pass through the gap between the blade on the inner wall of the chamber and the blade on the rotating knife holder. The resulting smashed rice straw, which has a size smaller than the mesh of the sieve, passes through the sieve. Finally, the smashed straws with the desired size are transported to the outlet via a screw mechanism positioned at the bottom of the machine. The average throughput, measured in kilograms per minute, increases with higher rotation speeds. For instance, when using a sieve with a 10 mm mesh, the average throughput rises from 2.31 to 2.50 kg/min as the rotation speed elevates from 620 to 980 rpm.

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Table 3. Raw Materials Characterization

Raw Material	Particle Size	M.C. (%)	Heating Value (MJ/kg)	Weight rations of elements (%) (dry-ash-free)				
				C	H	N	O	S
Rice Straw	10-5 mm	12.2						
	5-2 mm	12.1	16.1	50.37	7.76	1.13	40.66	0.08
	< 2 mm	12.6						
Rice Bran	250-450 µm	12.5	20.5	55.01	8.11	2.72	33.77	0.39

Both the rice straws and rice bran were subjected to air drying for a duration of two weeks. The dried rice straws, with lengths ranging from 70 to 104 cm, were then crushed into pieces of varying sizes (10-5 mm, 5-2 mm, or less than 2 mm). Subsequently, both the rice bran and the crushed rice straws (as shown in Fig. 2) were further ground into powder with a particle size falling between 40 and 60 meshes. The moisture content, extractives, and ash content of the ground powder derived from rice bran (referred to as GP_{rb}) and the ground powder derived from rice straw (referred to as GP_{rs}) were determined in accordance with CNS standards. The heating values of GP_{rb} and GP_{rs} were measured using an adiabatic calorimeter (Plain Jacket 1314). Additionally, the weight ratios of the elements present in rice bran and rice straw were analyzed using an elemental analyzer (Elementar vario EL III). The respective values for these characteristics can be found in Tables 1 and 2.

Fig. 2. Cut rice straw with different sizes

Fig. 3 Images of compressed rice straws.

2.6. Compression

The objective of this process is to produce uniform fuel with a high energy density, shaping it into square, rectangular, or cubed forms with dimensions of 50×50×50 mm³. A manual hot press, capable of compressing the solid fuel, is utilized for this purpose. Fig. 3 illustrates the various compressed shapes of rice straws. Through this compression technique, the bulk density and calorific value of the straw are increased, resulting in potential benefits such as reduced transportation costs and optimized storage space when compared to other biomass materials. However, it is important to note that the limited capacity of the boiler impact system may impose constraints on the co-firing ratio.

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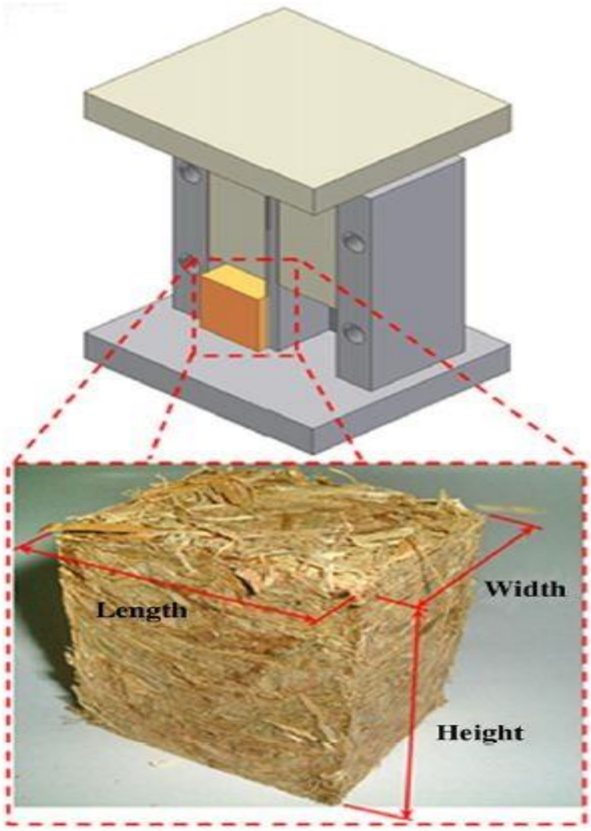

Fig. 4. Schematics of Preparing the Briquette.

The following is a schematic representation of the process for preparing briquettes:

1. Biomass Collection: Gather the desired biomass material such as wood chips, sawdust, agricultural residues, or any other suitable biomass source.
2. Drying: Properly dry the biomass material to reduce its moisture content. This can be done by natural drying, sun drying, or using mechanical drying techniques.
3. Size Reduction: Use a crusher or grinder to reduce the size of the dried biomass material into smaller particles or powders. This increases the surface area and improves the binding properties.
4. Mixing: Thoroughly mix the biomass material with a binder material. Common binders include starch, clay, molasses, or any other suitable adhesive that can help hold the briquette together.
5. Additives (Optional): Incorporate any desired additives such as sawdust, charcoal fines, or carbonized materials to enhance the burning properties or provide specific characteristics to the briquette.
6. Briquetting: Feed the mixture into a briquette press or extruder machine. Apply sufficient pressure to compact the material and form it into the desired briquette shape. The machine may include a die or mold with specific dimensions and designs.
7. Drying and Curing: Place the newly formed briquettes in a well-ventilated area to allow for proper drying and curing. This helps to remove any remaining moisture and strengthen the briquettes.
8. Packaging and Storage: Once the briquettes are completely dry and cured, package them in suitable containers or bags for storage or transportation. Proper packaging ensures that the briquettes retain their shape and quality.

It is crucial to ensure that the moisture content of the raw material does not exceed the range of 12-17% (w.b.) before it enters the compression press. Exceeding these moisture content values can lead to undesirable outcomes. If the material is too dry, the surface may carbonize and the binders may burn prematurely during the process. On the other hand, if the material is too wet, the moisture trapped within the pressing cannot escape, resulting in an enlarged product volume and reduced mechanical strength. The use of this technique presents challenges during the loading and unloading of the pellets, as they are sensitive to mechanical damage and can absorb moisture from the surrounding

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environment. This absorption can cause the pellets to swell, lose their shape and consistency, resulting in handling difficulties.

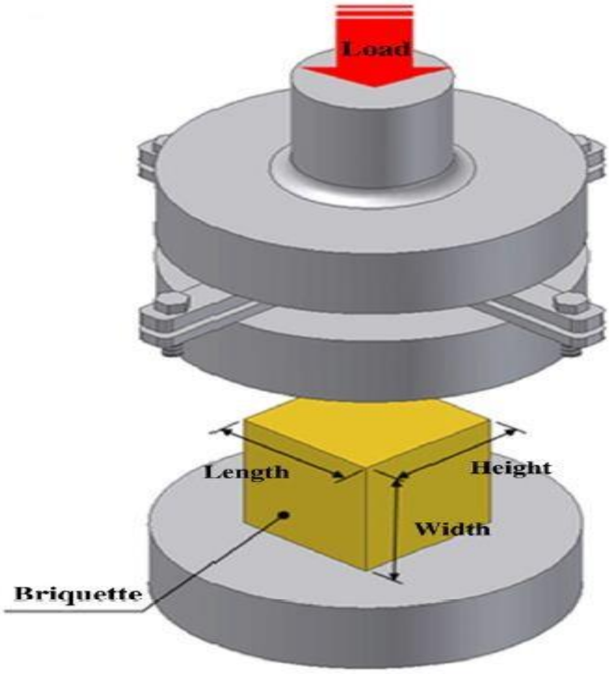

Fig. 5. Measuring compressive strength of the briquette

To measure the compressive strength of a briquette, follow these steps:

1. Preparation: Ensure that the briquettes have been properly dried and cured before conducting the compressive strength test.
2. Test Apparatus: Use a compression testing machine or a universal testing machine (UTM) equipped with a load cell capable of measuring the applied force.
3. Sample Selection: Randomly select briquettes from the batch for testing. It is recommended to test multiple samples to obtain reliable results.
4. Sample Preparation: Measure and record the dimensions of each briquette, including length, width, and height. Make sure the dimensions are consistent for accurate comparison.
5. Test Setup: Place the briquette on the testing machine's lower platen. Align the briquette so that the load is applied evenly on the top surface.
6. Testing Procedure: Start the testing machine and gradually apply a vertical compressive force to the briquette at a constant rate. The rate of loading should typically be within a range specified by testing standards or research requirements.
7. Record the Data: Monitor the load applied to the briquette by the testing machine and record the corresponding deformation or displacement. Continue the test until the briquette fractures or reaches a specified point, such as a predetermined deformation limit.
8. Compressive Strength Calculation: Calculate the compressive strength of the briquette using the formula: Compressive Strength = Load at Failure / Cross-sectional Area of the Briquette. The cross-sectional area can be calculated based on the briquette's dimensions (length × width or diameter).
9. Repeat and Average: Repeat the compressive strength test for multiple briquettes and calculate the average value. This helps to account for any variations in the briquette composition or manufacturing process.

It is recommended to store the pellets in enclosed facilities such as halls, rooms, silos, bunkers, or airtight containers such as plastics or zip bags in dry conditions. It is important to minimize the storage duration to prevent the pellets from absorbing moisture from the atmosphere. For small-scale applications, the pellets can be distributed in bags. However, when it comes to co-firing, where larger quantities of biomass are required, bulk material supply is necessary. The compressed rice straws can be utilized either on their own or mixed with other biomass materials for co-firing. In the co-firing

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process, the biomass is combusted in a chamber where air is injected to ensure complete combustion of the biomass.

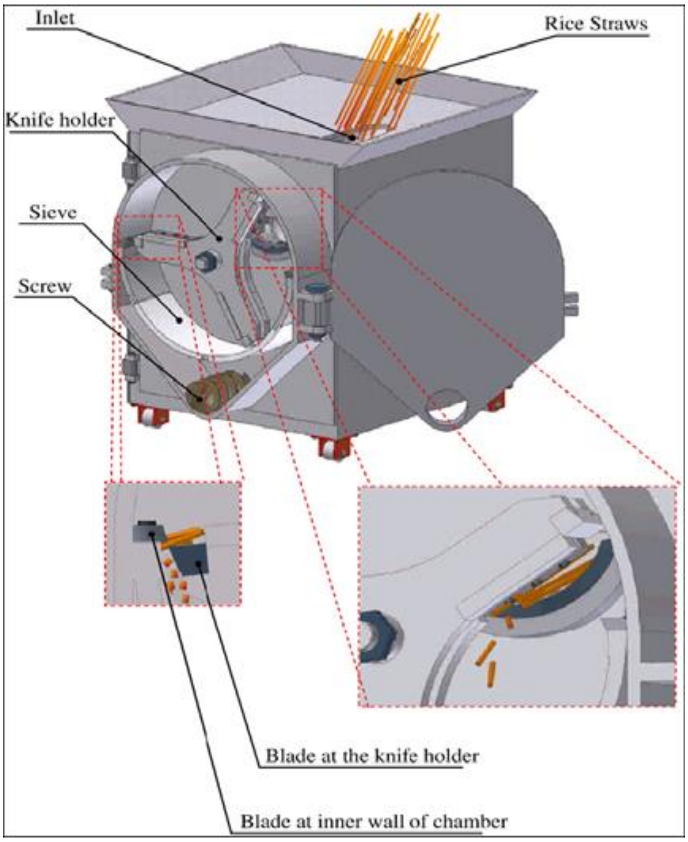

Fig 1 shows the schematic of a homemade machine used to size straw.

2.7. Fuel Briquettes

To fabricate the biomass briquette, a stainless steel mold was employed (as shown in Fig. 3(a)-(b)). The briquette was designed to have dimensions of 40 mm in length, 40 mm in width, and 35 mm in height. For the preparation process, a manual-operation hot press (as depicted in Fig. 3(c)) was utilized. This hot press had a maximum capacity to compress the solid fuel at a gauge pressure of 100 kgf/cm^2, a maximum heating capability of 200 °C, and a pressure increase rate of 8 $kgf/cm^2/min$. The upper and lower plates of the hot press had an area of 30×30 cm^2.

The process for preparing the solid fuel is outlined as follows:

1. The weights of the smashed rice straws and rice bran were measured using an electronic balance.
2. The mixture of the measured smashed rice straws and rice bran was introduced into the lower section of the mold (Fig. 3(b)).
3. The upper and lower parts of the mold were assembled, and the mold was positioned between the upper and lower plates of the hot press (Fig. 3(c)).
4. By moving the lower plate of the hot press upward with the assistance of a hydraulic jack, the contents in the mold were compressed to form a biomass briquette (Fig. 4(a)) until the gauge pressure reached 83.7 kgf/cm2.
5. The upper and lower plates of the hot press were heated to the predetermined temperature (specified in Table 3) using an electric heater, and this temperature was maintained for a duration of 10 minutes.
6. Once the temperature of the mold had cooled to room temperature, the bolts securing the lower part of the mold (Fig. 3(b)) were loosened, and the biomass briquette was removed from the mold. During the initial stage of compaction, it is necessary to continually adjust the applied pressure to account for moisture dissipation and the compaction of the powdered mixture.
7. The biomass briquettes, with an oven-dry density of 1 g/cm3, were subsequently placed in a PE bag until further measurements of their properties were conducted.

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The solid fuel briquettes were photographed using a digital camera (Panasonic DMC-LZ2). Microscopic images of the briquettes were captured using a scanning electron microscope (Hitachi S-3000N). The compressive strength of the briquettes was determined in accordance with the CNS 453 O2004 standard using a universal testing machine (Shimadzu AG-AR4). The pressure applied during the test increased at a rate of 10 kgf/cm^2/min. A schematic of the process for measuring the compressive strength of the briquette is depicted in Fig. 4(b).

3. Results and Discussion

3.1. Appearance of solid fuel briquette

Fig. 5(a) presents the photographs of the solid fuel briquettes tested in B1-B8, which were composed of 100% smashed rice straw. The figure consists of two panels: the top panel displays the briquettes containing (10-5 mm) smashed rice straw, while the bottom panel showcases the briquettes containing (5-2 mm) smashed rice straw. In Fig. 5(b), the images of biomass briquettes tested in B9-B23 are shown. These briquettes had the size of the smashed rice straw smaller than 2 mm. Fig. 5(b) comprises three panels: the top panel exhibits briquettes made entirely of smashed rice straw, the central panel displays briquettes consisting of 80% smashed rice straw and 20% rice bran, and the bottom panel illustrates briquettes composed of 60% smashed rice straw and 40% rice bran. The size of the smashed rice straw significantly impacts the appearance of the briquettes. Notably, the briquettes with (10-5 mm) smashed rice straw exhibit a rougher appearance compared to those with (5-2 mm) smashed rice straw (Fig. 5(a)).

Moreover, the application of hot-pressing temperature plays a significant role in promoting the solidification of the briquette and minimizing its expansion. This effect can be observed in the top panel of Fig. 5(b), where the volume of the briquette in test B9 (room temperature) is considerably larger than that of the briquette in test B10 (90 ^{0}C). Additionally, when the proportion of the binder (i.e., rice bran) increases in the briquette produced at room temperature, the briquette becomes more compact. This comparison can be made between the first image of the central panel (test B14) and that of the bottom panel (test B19) in Fig. 5(b). Overall, the images in Fig. 5(b) demonstrate that the combination of smashed rice straws and rice bran can be effectively molded into a solid biomass briquette under the specified conditions. As the percentage of rice bran increases, the surface of the biomass briquette becomes smoother, and its hardness is enhanced. These outcomes can be attributed to two factors: firstly, the rice bran contains a substantial amount of extractives (Alcohol-Toluene) with a value of up to 23.2% (Table 1), indicating its rich oily components; secondly, the release of oil or grease from the rice bran during the thermal-compression process promotes the densification of the biomass briquette. Zhang et al. have previously discussed the feasibility of utilizing chemically-treated biomass, such as rice straw, as a binding agent in briquette production.

3.2. $\boldsymbol{\eta}_V, \boldsymbol{\eta}_M$, air-dry density, and compressive strength

Fig. 6a, b, c, and d illustrate the changes in the percentage of briquette volume, the percentage of loss of briquette mass, the air-dry density, and the compressive strength, respectively, with respect to the hot-pressing temperature. In Fig. 6a-d, different symbols, including square, triangle, circle, diamond, and cross, represent the briquette compositions, such as 60% rice straw (< 2mm) and 40% rice bran, 80% rice straw (< 2mm) and 20% rice bran, 100% rice straw (< 2 mm), 100% rice straw (5–2mm), and 100% rice straw (10–5mm), respectively. The data presented in Fig. 6 were obtained under room temperature conditions.

3.2.1. Briquette with 100% of the smashed rice straw

As the hot-pressing temperature rises, there is a decrease in the percentage of change in briquette volume $(\boldsymbol{\eta}_V)$ and an increase in the percentage of loss of briquette mass $\boldsymbol{\eta}_M$, regardless of the test conditions such as the size of the smashed rice straw. Additionally, both the air-dry density and the compressive strength of the briquette exhibit an upward trend with increasing hot-pressing temperature. For instance, in the case of the briquette with 100% of the smashed rice straw (10–5 mm), the value of $\boldsymbol{\eta}_V$ decreases from 35.2% to 12.1%, while the value of $\boldsymbol{\eta}_V$ increases from 1.03% to 5.56%. Furthermore, the air-dry density rises from 0.82 to 0.94 g/cm^3, and the compressive strength

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increases from 10.5 to 28.4 kgf/cm^2 as the hot-pressing temperature is elevated from 90 ^{0}C (test B1) to 150 ^{0}C (test B4). The higher hot-pressing temperature leads to increased dehydration of moisture in the smashed rice straw and greater pyrolysis of its constituents, resulting in an elevated $\boldsymbol{\eta}_M$. The smashed rice straw becomes more malleable and pliable at higher hot-pressing temperatures, reducing the expansion of the briquette during densification and enhancing both its air-dry density and compressive strength. Rhén et al. have suggested that high temperature and low moisture content are crucial variables for increasing the compression strength and dry density of pellets made from Norway spruce sawdust. The SEM micrographs (Fig. 7(a) and (b)) provide evidence supporting the influence of hot-pressing temperature on the solidification of the briquette consisting of 100% smashed rice straw (< 2 mm). Examining the SEM micrographs (40×) of the briquettes, it is observed that the structure of the briquette in test B9 (compressed at room temperature) is more porous compared to the briquette in test B13 (compressed at 150 ^{0}C). Additionally, as the hot-pressing temperature rises from room temperature to 150 ^{0}C, the air-dry density of the briquette increases significantly from 0.56 g/cm^3 (test B9) to 0.99 g/cm^3 (test B13), and the compressive strength of the briquette also experiences a notable increase from 2.2 kgf/cm^2 (test B9) to 65.7 kgf/cm^2 (test B13). When the hot-pressing temperature remains constant, it is observed that both the air-dry density and the compressive strength of the briquette increase as the size of the smashed rice straw decreases. For example, at a fixed temperature of 130 ^{0}C, as the size of the smashed rice straw decreases from 5–2 mm (test B7) to (< 2 mm (test B12), the air-dry density of the briquette increases from 0.89 to 0.99 g/cm^3, and the compressive strength of the briquette shows a significant increase from 33.3 to 65.4 kgf/cm^2. This finding aligns with the research by Bergström et al., who reported that the particle size distribution had an impact on the compression strength of fuel pellets made from Scots pine sawdust.

3.2.2. The effect of the rice bran

At a constant percentage of rice bran, it is observed that both the air-dry density and the compressive strength of the briquette made with smashed rice straw (< 2 mm) increase as the hot-pressing temperature rises. This trend is similar to that observed in the briquette with 100% smashed rice straw. For example, when the hot-pressing temperature increases from the room temperature (test B14) to 150 °C (test B18) for a briquette containing 20% rice bran, the air-dry density significantly increases from 0.57 to 1.02 g/cm^3, and the compressive strength increases substantially from 4.1 to 85.0 kgf/cm^2. These results can be attributed to the structural changes in the briquette. Comparing the micrographs in Fig. 7(c) of test B14 and Fig. 7(d) of test B18, it is evident that the briquette structure at 150 °C (test B18) is more compact than that at the room temperature (test B14). However, at a fixed hot-pressing temperature, the impact of the percentage of rice bran on the air-dry density and compressive strength is not significant. For example, at a constant temperature of 130 °C, as the percentage of rice bran increases from 20% (test B17) to 40% (test B22), the air-dry densities in tests B17 (1.01 g/cm^3) and B22 (1.02 g/cm3) are almost the same, with only a slight increase observed in compressive strength from 70.5 to 77.2 kgf/cm^2.

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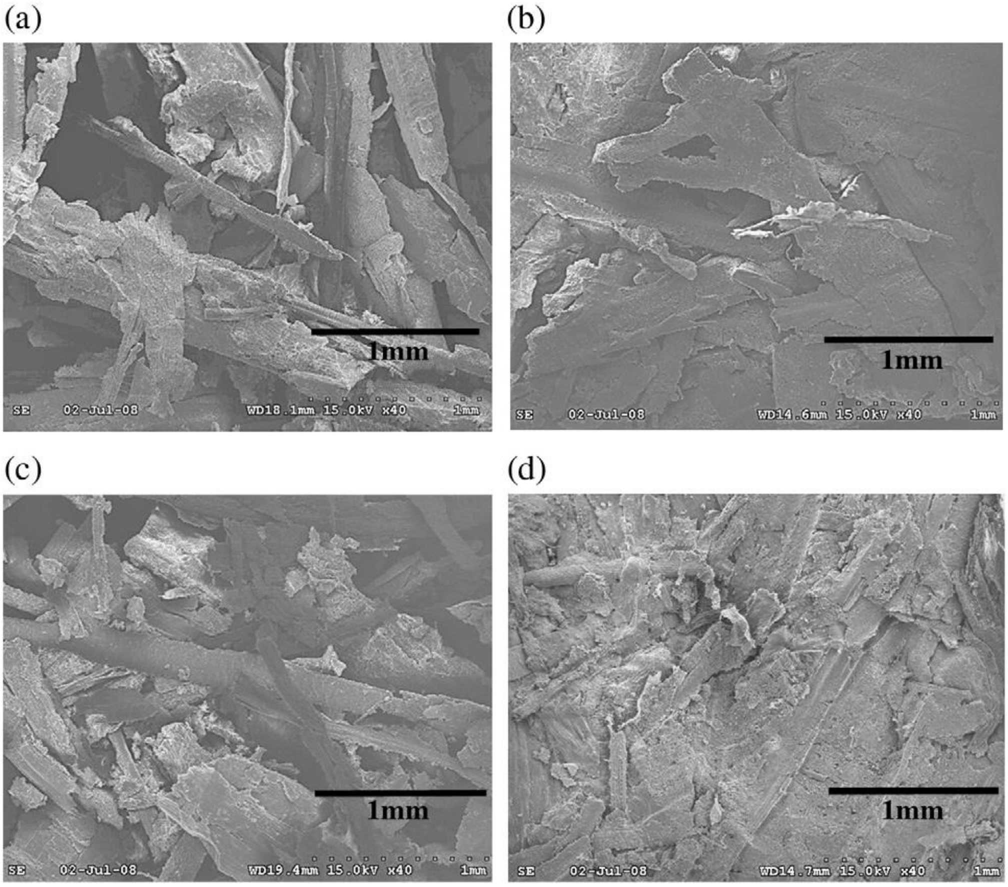

Fig. 7. SEM micrographs for the cross-sections of the fuel briquettes with the smashed rice straw (< 2 mm).

Interestingly, it is observed that the hot-pressing temperature required to achieve a certain compressive strength can be reduced by incorporating a specific percentage of rice bran into the smashed rice straw. For instance, the briquette in test B11 (with a compressive strength of 41.2 kgf/cm^2) exhibits similar strength to the briquette in test B15 (with a compressive strength of 41.4 kgf/cm^2), but the hot-pressing temperature can be lowered from 110 °C (test B11, using 100% smashed rice straw b2 mm) to 90 °C (test B15, using 80% smashed rice straw < 2 mm and 20% rice bran). This implies that the energy required to compress rice straw briquettes can be minimized by incorporating a suitable binder such as rice bran, sawdust, or other biomass waste. The improved compactness achieved by the presence of rice bran particles can be attributed to the formation of "solid bridges" between particles. These solid bridges are formed by the interaction of rice bran particles and the release of natural binding components present in both rice bran and rice straw. The increased number of solid bridges between straw particles, facilitated by the inclusion of rice bran, enhances particle binding and leads to higher compressive strength. The application of pressure and temperature during the compression process allows for the diffusion of molecules between particles, aiding in the formation of solid bridges. Additionally, the flat-shaped particles of rice straw and the particles of rice bran may interlock with each other during compression, creating interlocking bonds that contribute to the briquette's strength.

3.2.3. Heating value of the solid fuel briquette

The variations in the heating value of the briquette, measured at room temperature, with respect to the hot-pressing temperature are depicted in Fig. 8. The briquette with 60% of rice straw (< 2 mm) and 40% of rice bran is represented by squares, the briquette with 80% of rice straw (<2 mm) and 20% of rice bran is represented by triangles, and the briquette with 100% of rice straw (< 2 mm) is represented by circles. Additionally, a dashed line represents the theoretical heating value of the briquette. According to Eq. (3), the theoretical heating values of the briquette with 60% of rice straw (b2 mm) and 40% of rice bran, the briquette with 80% of rice straw (< 2 mm) and 20% of rice bran,

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and the briquette with 100% of rice straw (< 2 mm) are calculated to be 17.9, 17.0, and 16.1 MJ/kg, respectively.

In general, the hot-pressing process has a slight impact on increasing the heating value of the briquettes. For example, at a hot-pressing temperature of 150 ^{0}C, the heating value of the briquette composed of 100% rice straw (< 2 mm) increases from the theoretical value of 16.1 MJ/kg to 17.3 MJ/kg. This can be attributed to the dehydration of moisture during the solidification of the briquette. However, at a hot-pressing temperature of 90 °C, the measured heating values of the briquette with 60% rice straw (b2 mm) and 40% rice bran, as well as the briquette with 80% rice straw (< 2 mm) and 20% rice bran, are slightly lower than their theoretical values. This discrepancy could be due to the sampling inaccuracies when measuring the heating value of the test piece, which is a mixture of rice straw (b2 mm) and rice bran. Furthermore, at a fixed hot-pressing temperature, the heating value of the briquette tends to increase with a higher percentage of rice bran.

For instance, at a constant hot-pressing temperature of 150 °C, the heating value of the briquette increases from 18.2 to 18.6 MJ/kg as the percentage of rice bran increases from 20% (B18) to 40% (B23). This outcome is likely due to the higher heating value of rice bran compared to rice straw. Therefore, the inclusion of a specific percentage of rice bran, such as 20% or 40%, not only enhances the densification of the biomass briquette but also improves its heating value. As a result, the presented technology for producing biomass briquettes from rice straw, with or without a binder like rice bran, holds significant value, especially in areas where rice straw is a prominent biomass waste.

4. CONCLUSION

In many countries that produce rice, there is potential to use rice straw as a substitute for fossil fuels in heat and power generation. This substitution would help reduce sulphur dioxide and greenhouse gas emissions, as well as prevent pollution caused by the open burning of rice straw. However, before utilizing rice straw as biomass energy, it is essential to determine its physical and chemical properties. This information is necessary to address the challenges related to transportation, handling, and storage, which can be costly. Compared to other biomass sources, rice straw has lower calorific value and bulk density. Nevertheless, these properties do not significantly impact the overall performance of the energy production process. Additionally, when compared to wheat straw and rice husk under similar operating conditions, rice straw demonstrates lower emissions of chlorinated organic compounds and nitrogen oxides (NOx). Consequently, reducing the size of rice straw particles may be necessary or beneficial for optimal utilization.

Reducing the length of rice straw leads to higher storage and bale density, improving the quality and heating value of the feedstock. Compressing rice straw into a homogeneous fuel enhances energy conversion efficiency and combustion performance while increasing bulk density, thus reducing transportation, handling, and storage costs. Pretreatment technologies can further enhance the properties of rice straw, making it a desirable fuel for grain drying. Although this paper does not delve into detailed economic considerations and analysis of these technologies, the insights provided can serve as a basis for future research that includes economic analysis. Such studies can encourage the utilization of rice straw, prevent open burning in rice-producing countries, and also be applicable to research on other agricultural residues. This paper focuses on the preparation and characterization of solid biomass fuel derived from bio-waste materials, specifically rice straw and rice bran.

The air-dry density and compressive strength of the briquette are greatly influenced by the hot-pressing temperature. The inclusion of rice bran in the thermal-compression process enhances the densification of the biomass briquette. Moreover, the heating value of the briquette rises as the percentage of rice bran and hot-pressing temperature increase. Significantly, this study showcases the viability of producing solid biomass fuel from rice straw and rice bran, providing a potential solution for utilizing these discarded rice straws as a renewable energy resource.

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