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Research article

A Circular Economy Approach in Sustainable Energy Transitions: Converting Agro-Industrial Waste into Solid Biofuel

Klel Sien A. Cordova, Glen Piere U. Babia, Gisan Mae L. Señorin, Eugene Ray U. Generalao, Val Irvin F. Mabayo* and Jonas Karl C. Liwanag

College of Engineering and Technology, University of Science and Technology of Southern Philippines, Claveria 9004, Philippines

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Abstract

Agricultural biomass waste poses environmental challenges if not managed properly. This study investigated the conversion of agro-industrial residues into hybrid charcoal briquettes as solid biofuel. Using coconut shell charcoal fines and carbonized rice hulls, briquettes were produced via 33 MPa compaction with 12% cassava starch binder. The optimal blend (74.80% coconut shell, 25.20% rice hulls) yielded a heating value of 15.44 MJ kg^{-1}, with favorable properties: 40.94% fixed carbon, 38.6% ash, 7.12% moisture, and 20.46% volatile matter. The briquettes exhibited high durability (99.80% shatter index), ensuring resistance to breakage. These results highlight the potential of hybrid briquettes as a sustainable, eco-friendly fuel alternative, supporting waste valorization and energy efficiency. By repurposing agro-waste, this approach promotes a circular economy while offering a cost-effective substitute for conventional fuels.

Keywords: hybrid charcoal briquettes; agro-industrial waste; solid biofuel; circular economy; waste management

1. Introduction

Agricultural waste is a significant global issue, with an estimated 140 billion metric tons produced annually (Fayomi et al., 2020). This waste includes residues from crops such as rice husks, corn stalks, wheat straw, and coconut shells (Adeleke et al., 2023; Bot et al., 2024). The Philippines is a significant producer of agricultural products, including coconuts and rice. These industries generate substantial amounts of waste, specifically coconut shells and rice hulls. Coconut shells, which constitute about 15.18% of the coconut fruit, are often discarded as waste (Espina et al., 2022; Bidol et al., 2025). In 2020, the Philippines produced 14.7 million tons of coconuts, resulting in approximately 2.2 million tons of coconut shells (Espina et al., 2022). Similarly, the rice industry generates around 2 million tons of rice hull waste annually (Fung & Jenkins, 2003). These agricultural residues, if not appropriately managed, can lead to environmental pollution through open burning or

*Corresponding author: E-mail: valmabayo@gmail.com
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improper disposal (Yuliah et al., 2017). Considering the significance of the annual production of these wastes, several strategies have been employed to manage them. Traditional methods include burning, dumping, and using the residues as animal fodder or compost (Tripathi et al., 2019; Shahar et al., 2024). Circular-economy approaches have been implemented, which involve recycling these waste materials into value-added products, such as bioplastics, biofertilizers, and biochemicals. Advanced technologies have also been explored, which include techniques like pyrolysis, gasification, and anaerobic digestion, converting these wastes to biofuels, biochar, and biogas (Tripathi et al., 2021; Abdo et al., 2024; Meena et al., 2024; Saxena et al., 2025). However, high costs and technical complexities hinder the widespread adoption of advanced waste conversion technologies. Transporting agricultural waste to processing facilities is often impractical and costly. Worse is that there are inconsistent policies and regulations across regions that complicate waste management efforts (Gontard et al., 2018; Siwach & Gupta, 2024).

Agricultural waste can be effectively utilized to produce biomass briquettes, which serve as an eco-friendly alternative to traditional fuels. Several studies have already demonstrated that utilizing agricultural waste for briquette development offers environmental, social, and economic benefits, including the reduction of greenhouse gas emissions and the generation of renewable energy, thereby contributing to a more circular and sustainable economy (Suryaningsih & Nurhilal, 2018; Kannah et al., 2020; Bamisaye et al., 2023). In addition to these advantages of using biomass briquettes, previous research has also found that they have higher calorific values and longer burning times, making them efficient fuel sources (Biswas, 2018; Patil, 2019; Surono, 2019). Furthermore, from an economic perspective, in emerging markets, low-income households spend a significant fraction of their total income on charcoal, indicating a substantial market for alternative products, such as green charcoal briquettes (Kung et al., 2015).

In this study, a hybrid charcoal briquette was developed using coconut shell charcoal fine residues from an industry that manufactures coconut shell-based activated carbon, and rice hull residues from a local rice milling establishment. Cassava starch was used as a binder, considering its robust binding characteristics in making briquettes, as reported in a previous study (Duangkham & Thuadaij, 2023). Unlike many studies that rely on non-industrial sources, this study utilizes actual waste residues from coconut shell-based activated carbon production and rice milling operations, demonstrating real-world applicability. Using the Design Expert 7.0 software, the combination of these agro-industrial wastes was optimized to come up with a hybrid charcoal briquette with the best properties through the Mixture D-Optimal design. Proximate analysis and the measurement of its calorific values were also done to see the viability of this product as an alternative solid biofuel. This work highlights a practical and scalable approach to sustainable energy transitions using real-world waste streams.

2. Materials and Methods

2.1 Raw materials for hybrid charcoal briquette making

The coconut shell charcoal fine was sourced from Jacobi Carbons Philippines, Inc., located in Kirahon, Villanueva, Misamis Oriental, Philippines. Meanwhile, the rice hull residue was gathered from Fabela's Rice Mill at Zone 1, Poblacion, Claveria, Misamis Oriental, Philippines. Cassava starch served as the binder.

The hybrid charcoal briquettes were produced using a blend of coconut shell charcoal fines and carbonized rice hulls as raw materials. Additionally, cassava starch was included as a binding agent in the mixture. The cassava starch binder used in this study was produced from waste cassava peelings collected and processed. The resulting starch had an approximate moisture content of 10.5% and a neutral pH. Its high binding capacity made it suitable for briquette production. Using a waste-derived binder reinforces the circular economy focus of this study. Furthermore, the researchers investigated how combining these two feedstocks could improve the thermal properties of the charcoal briquettes.

2.2 Experimental design

The experimental runs were generated using the Mixture D-Optimal design in Design Expert 7.0. Two components were used in the mixture: carbonized rice hull and coconut shell charcoal fines, each with a range of 0-100%. Table 1 displays the ranges and levels of the variables. Additionally, Table 2 presents the runs generated by Mixture D-Optimal Design within the Design Expert 7.0 software.

Table 1. Ranges and levels of variables used in the Mixture D-Optimal Design

Variable	Low (wt%)	High (wt%)
Coconut shell charcoal fines	0.00	100.00
Carbonized rice hull	0.00	100.00

Note: Binder was held constant at 12% (by weight)

Table 2. Experimental runs generated by the Mixture D-Optimal Design

Run	Coconut Shell Charcoal Fines (%)	Carbonized Rice Hull (%)
1	0.00	100.00
2	12.60	87.40
3	62.21	37.79
4	100.00	0.00
5	87.40	12.60
6	74.80	25.20
7	25.20	74.80
8	50.00	50.00

2.3 Preparation and characterization of raw material

The coconut shell charcoal fines and rice hull residue underwent various pre-treatment processes after accumulating the raw materials from their respective sources. The coconut shell charcoal fines were characterized based on particle size and moisture content. The coconut shell charcoal fines were sieved to determine their particle size, and the moisture content was measured using the drying oven method according to ASTM D2974-87 (ASTM International, 1993) with some modifications. This involved drying the coconut shell charcoal fines in an oven (JK-DO-9030A) for 2 h at 80°C.

On the other hand, the raw rice hull underwent a carbonization process at an average temperature of 413°C using a carbonizer. The carbonized rice hull was then characterized for particle size and moisture content. The carbonized rice hull was sieved to ascertain its particle size and was oven-dried for 2 h at 105°C. The cassava starch was set aside and mixed with the raw materials only during the mixing and binding process.

2.4 Carbonization set-up

The carbonization setup used in the study was a conventional open-type carbonizer (Figure 1), located at the Research Office of the University of Science and Technology of Southern Philippines in Claveria, Misamis Oriental. The burning took place in the combustion chamber, while the rice hull was stacked just outside the chamber. The average temperature during the carbonization process was 413°C, which lasted approximately 4.5 h. Temperature was monitored at 30-min intervals using a thermocouple-based sensor. The rice hulls were arranged to minimize oxygen entry, allowing for controlled pyrolysis and carbonization.

2.5 Mixing and binding process

The coconut charcoal fines and rice hull residues were combined to create biochar. During this process, the components were mixed according to the runs generated by the D-Optimal design. Carbonized rice hull was incorporated into the coconut shell charcoal fines. Additionally, the cassava starch served as a binding agent in the production of the hybrid charcoal briquettes. A consistent 12% cassava starch was included in each mixture ratio. The mixture was combined using a 6-speed Heavy-Duty Electric Mixer (DQU160) in a plastic pail. A photo of this process is shown in Figure 2.

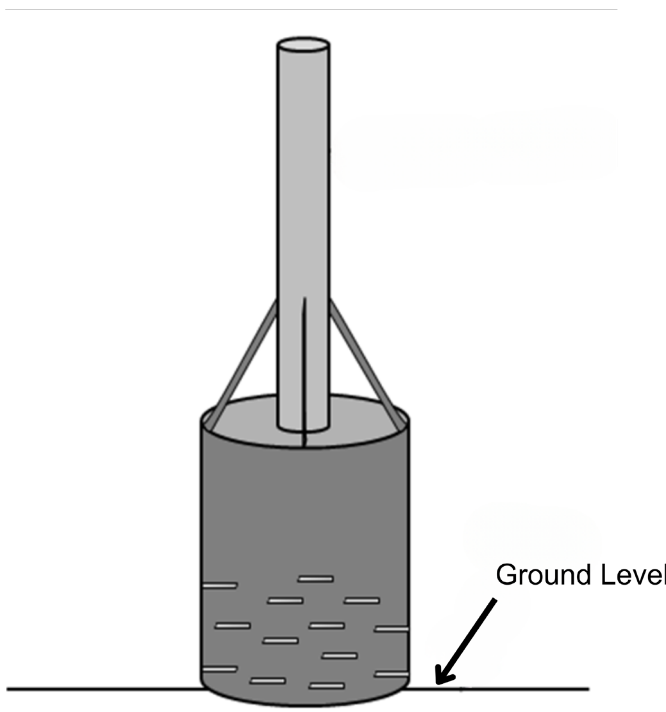

Figure 1. Conventional open-type carbonizer

Figure 2. Mixing and binding process

2.6 Briquetting process by compaction

The briquettes were compacted by a hydraulic briquetting machine (GC 14), as shown in Figure 3a. The pressure applied on each briquette was constant at 33 MPa. The molder of the hydraulic briquetting machine had a diameter of 11.5 cm and a height of 7.5 cm. The design of the briquette was honeycomb style as shown in Figure 3b.

2.7 Sun-drying of the compacted briquettes

The charcoal briquettes were sun-dried for seven days. The temperature was recorded using an infrared thermometer (GM900) that can measure temperatures from -50 to 900°C. The highest temperature recorded was 55°C.

2.8 Determination of the optimum hybrid charcoal briquette

The optimum hybrid charcoal briquette was selected based on the highest heating value obtained during the testing of the hybrid charcoal briquette samples sent to the Philippine Sinter Corporation Laboratory at PHIVIDEC Industrial Estate, Villanueva, Misamis Oriental, Philippines. The calorific value was determined according to ASTM D5865 (ASTM International, 2019). The optimum hybrid charcoal briquette underwent further testing, specifically proximate analysis.

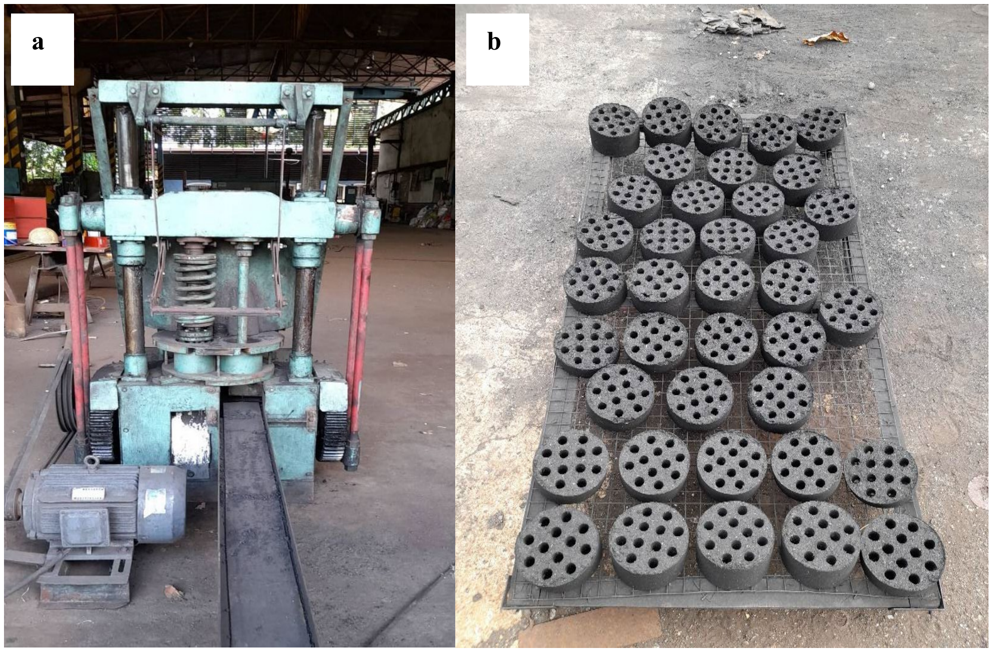

Figure 3. Photo of (a) Hydraulic briquetting machine; (b) produced charcoal briquettes

2.9 Charcoal briquette characterization

The density of the hybrid charcoal briquettes was determined in accordance with ASTM D 2395-17 (ASTM International, 2022). The density was calculated by dividing the mass of the briquette by its volume. The volume was determined by measuring the diameter, height, and central hole diameter at different points through a vernier caliper. Furthermore, the mass of each sample was measured by a digital weighing balance scale (number one). The density was calculated by using equation 1.

$$\rho = \frac{m}{V} \quad (1)$$

where ρ = density, m = mass of biomass briquette, V = volume of the hybrid charcoal briquette.

For the determination of the calorific value**,** an 80 g powdered sample was sent to the Philippine Sinter Corporation Laboratory located at PHIVIDEC Industrial Estate, Villanueva, Misamis Oriental, Philippines. The calorific value was determined in accordance with the ASTM D5865 (ASTM International, 2019).

The kindling time of the charcoal briquette samples was tested through the ignition of each sample using a lighter and 10 mL fire starter. A stopwatch was used to record the kindling time of each hybrid charcoal briquette sample.

The burning time of the charcoal briquettes was recorded using a stopwatch. The recording of the burning time of each sample of the charcoal briquettes started after the ignition of the charcoal briquettes, when the charcoal briquettes started to burn, and ended after the appearance of white-gray ash.

The shatter index was calculated in accordance with the ASTM-D440-86 (ASTM International, 2002) with some modifications. The calculation of the shatter index involved weighing and recording of the initial mass of each briquette sample. All of the charcoal briquette samples were subjected to a drop test from a 1.2 m height. The drop test was repeated two times. The shatter index of each of the charcoal briquette samples was calculated using equation 2.

$$K = \frac{B_z \times 100}{B} \quad (2)$$

where K = shatter index, B_z = weight of the charcoal briquette after shattering, B = weight of charcoal briquette before shattering.

The optimum hybrid charcoal briquette was subjected to proximate analysis for the determination of its volatile matter, fixed carbon, and ash content. An 80 g powdered sample was sent to the Philippine Sinter Corporation Laboratory located at PHIVIDEC Industrial Estate, Villanueva, Misamis Oriental, Philippines. The ash content was determined in accordance with ISO 1171 (ISO, 2024a) and volatile combustible matter in accordance with ISO 562 (ISO, 2024b). Furthermore, the moisture content was tested separately.

3. Results and Discussion

3.1 Properties of coconut shell charcoal fines and carbonized rice hull

The particle sieve size for characterizing the coconut shell charcoal fines and carbonized rice hull was set to 25 mm, as it was the most commonly available sieve. An electric mixer and roller press effectively reduced the 25 mm particle size to 5 mm during the mixing and briquetting processes. The moisture content of the coconut shell charcoal fines was measured at 10.85%, while the carbonized rice hull had a moisture content of 13.18%. With both materials exhibiting moisture levels below 15%, they were deemed suitable for briquetting and compaction. For optimal results, the moisture content of the raw materials should range from 8-15% before the briquetting process to ensure the charcoal briquettes are durable and easy to dry and transport.

3.2 Physical, thermal, and mechanical properties of the hybrid charcoal briquettes

3.2.1 Density

The briquette density was significantly affected by the raw materials. Figure 4 shows that the mixture containing 100% coconut shell charcoal fines had the highest density, at 965 kg m^{-3}. In contrast, the mixture composed of 100% carbonized rice hull had the lowest density, at 673 kg m^{-3}. It is evident that the densities of the raw rice hull, which had a density range of 670-740 kg m^{-3} and coconut shell, which had a density range of 600-800 kg m^{-3}, had a significant effect on the densities of the produced charcoal briquettes.

Furthermore, a higher density of charcoal briquettes translates to a higher energy or volume ratio, resulting in a longer burning time. Studies have found that briquettes made with hydraulic piston presses have unit densities of less than 1000 kg m^{-3} (Eriksson & Prior, 1990; Kpalo et al., 2020). It should be noted that combining rice hull charcoal fines with coconut shell charcoal fines increased the density of the hybrid charcoal briquettes produced, as can be observed in Figure 4.

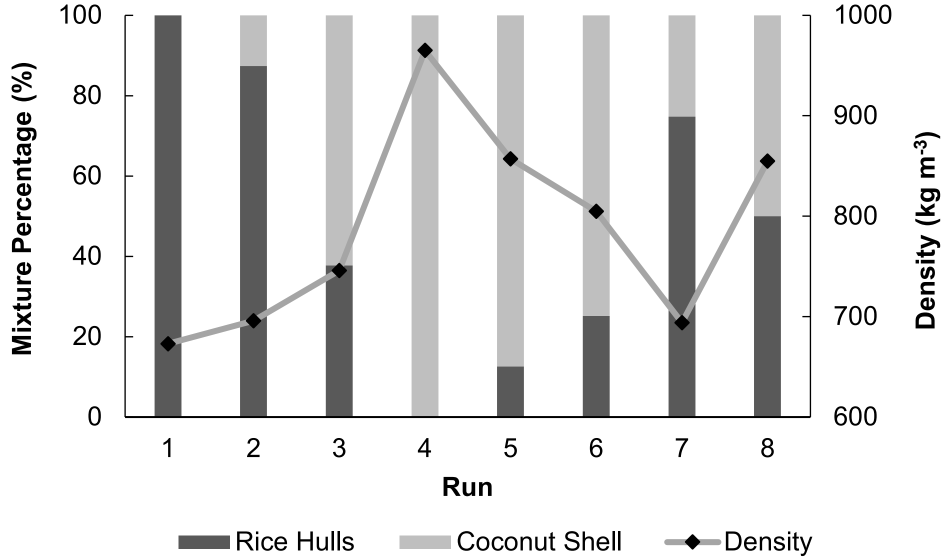

Figure 4. Density of the hybrid charcoal briquettes with different mixtures

3.2.2 Shatter index

Shatter index determines the strength of briquettes for handling, transit, and storage. Figure 5 shows that the shatter index percentages of the hybrid charcoal briquettes varied minimally. Furthermore, the Figure also shows that the mixture composed of 25.20% rice hull and 74.80% coconut shell charcoal fines had the highest shatter index percentage of 99.80%, which was slightly higher than the mixture composed of 12.60% carbonized rice hull and 87.40% coconut shell charcoal fines. In contrast, the mixture composed of 100% coconut shell charcoal fines had the lowest shatter index percentage of 97.57%. However, all of the mixtures had shatter index percentages of more than 90%. According to Borowski et al. (2017), the shatter index percentage should be at least 90%. It was observed that the greater the shatter index number, the better the briquette quality and the higher the resistance to gravitational deterioration. Furthermore, the hybrid charcoal briquettes produced in this study were suitable for transportation, storage, and handling.

3.2.3 Kindling time

Several factors influence the kindling or igniting time of a solid fuel. The volatile combustible matter (VCM) content of the solid fuel is one of the indicators of its igniting qualities; thus, the greater the VCM, the better, and the more easily the fuel will ignite. Moreover, the hybrid charcoal briquette with the longest kindling time was composed of 74.80% coconut shell charcoal fines and 25.20% carbonized rice hull, with a kindling time of 271 s. Meanwhile, the mixture composition with the lowest kindling time was the one composed of 12.60% coconut shell charcoal fines and 87.40% carbonized rice hull, with a kindling time of 139 s. The results are compared in Figure 6. Some studies have shown that the kindling time of coconuts is approximately 125 s, while wood takes 130 s to ignite (Mike, 2024; Escalante & Alcaraz, 2025). This indicates that the lowest kindling time recorded in this study was comparable to those found in other studies.

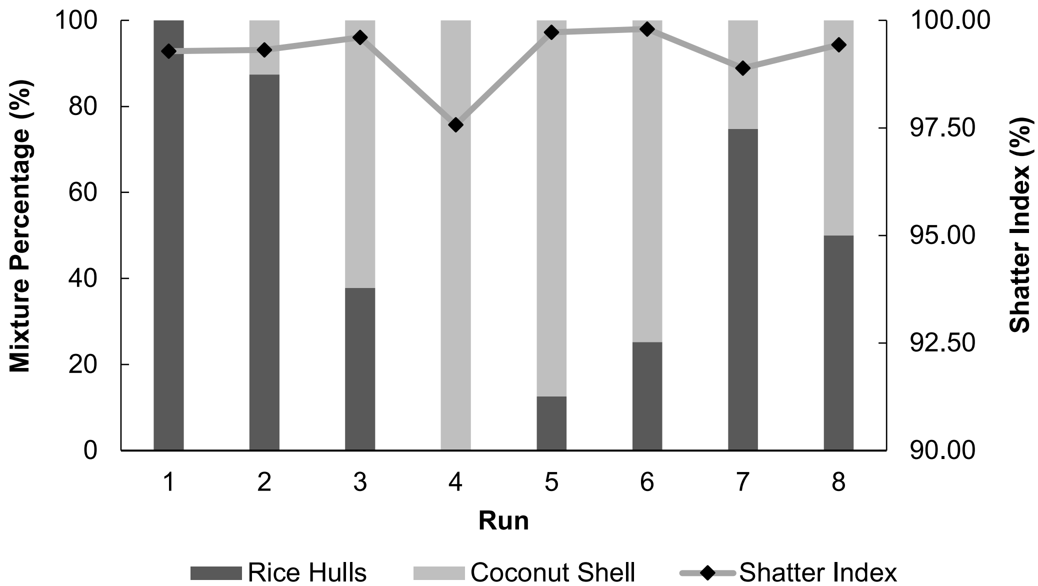

Figure 5. Shatter index of the hybrid charcoal briquettes with different mixtures

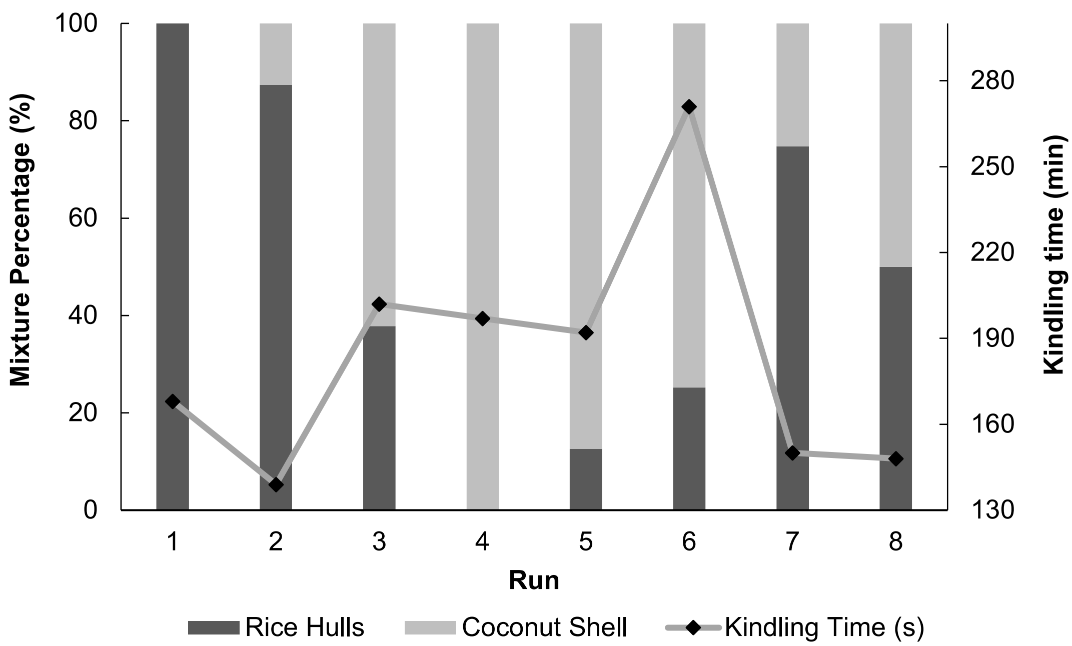

Figure 6. Kindling time of the hybrid charcoal briquettes with different mixtures

The kindling time varied significantly across different formulations, ranging from approximately 140 to 270 s. The longest kindling time was observed in Run 6, which had a high percentage of coconut shell charcoal fines. This suggests that coconut shell may require more heat input to ignite compared to rice hulls, possibly due to its higher fixed carbon and lower volatile matter. Additionally, the moisture-retentive nature of the cassava binder and the uniform compaction process may have contributed to these variations. These results indicate that mixture composition, especially coconut shell content, influences kindling behavior.

3.2.4 Burning time

Figure 7 illustrates that the hybrid charcoal briquette with the longest burning time (237 min) consisted of 74.80% coconut shell charcoal fines and 25.20% carbonized rice hull. In contrast, the mixture consisting of 25.30% coconut shell charcoal fines and 74.80% carbonized rice hull had the shortest burning time of 143 min. Additionally, the data indicate that the hybrid charcoal briquette with a higher ratio of coconut shell charcoal fines exhibited a longer burning time than the mixture with a higher percentage of rice hull. Moreover, the raw material ought to affect the burning time of the briquettes, as in some studies where it was indicated that the more coconut shells in the briquette, the longer the combustion time will be (Syarif et al., 2023; Putri, 2024).

The burning time showed notable variation across the different mixture ratios, ranging from 143 to 237 min. The longest burning time was observed in Run 6, which had a higher percentage of coconut shell charcoal fines, whereas the shortest occurred in Run 7, which had a higher rice hull content. This suggests that coconut shell contributes to longer combustion due to their higher fixed carbon and lower ash content, while rice hulls may burn more rapidly. Uniform briquette shape and compaction pressure may have helped stabilize the burning conditions, but the feedstock composition still played a significant role in determining the combustion duration.

3.2.5 Calorific value

The results of the analysis are shown in Figure 8. The calorific values of the samples ranged from 14.78 MJ kg^{-1} to 15.44 MJ kg^{-1}, respectively. Moreover, the charcoal briquette made from a mixture of 74.80% coconut shell charcoal fines and 25.20% carbonized rice hull achieved the highest calorific value of 15.44 MJ kg^{-1}. In contrast, the charcoal briquette consisting of 12.60% coconut shell charcoal fines and carbonized rice hull yielded the lowest calorific value of 14.78 MJ kg^{-1}. The slightly higher calorific value observed in the hybrid formulation compared to single-material briquettes may be explained by a synergistic effect. The low ash and high fixed carbon content of coconut shell, combined with the porous structure of carbonized rice hull, likely improved combustion efficiency and heat release. Furthermore, understanding the calorific values of each sample is significant since it indicates the quality of a briquette by measuring its energy content.

All the charcoal briquettes produced in this study had a calorific value greater than wood, which has a calorific value of 13.80 MJ kg^{-1}, and the briquettes from rice husks have a calorific value of 12.31 MJ kg^{-1}.

The hybrid charcoal briquette with a mixture composition of 74.80% coconut shell charcoal fines and 25.20% carbonized rice hull had the highest calorific value of 15.44 MJ kg^{-1}, which was a calorific value higher than that of the briquette from rice husk, with a calorific value of 13.09 MJ kg^{-1}.

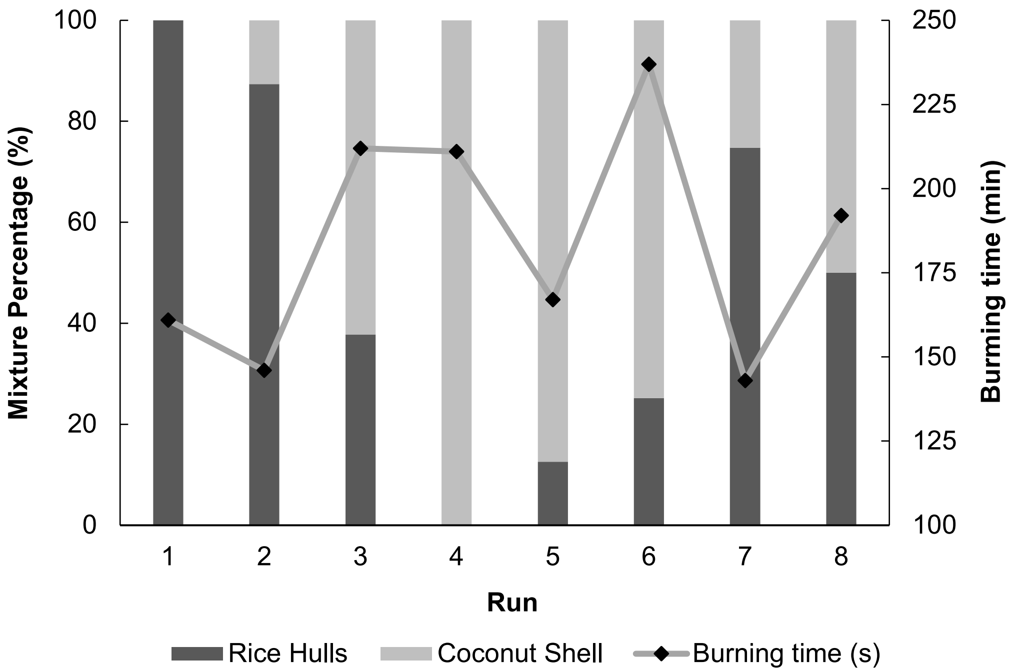

Figure 7. Burning time of the hybrid charcoal briquettes with different mixtures

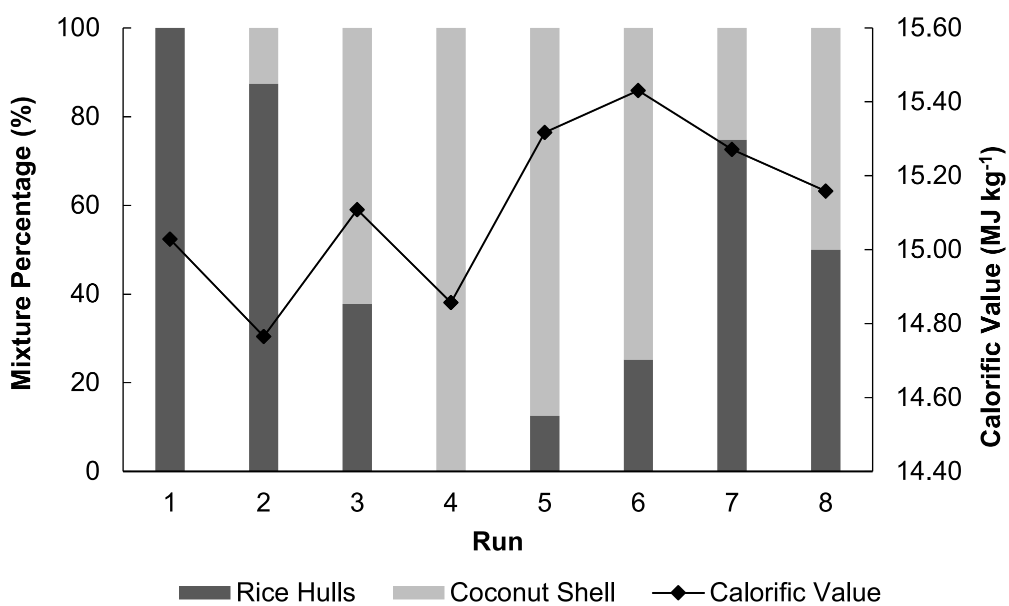

Figure 8. Calorific value of the hybrid charcoal briquettes with different mixtures

Furthermore, the study by Sansolis and Villalva (2017) showed that a hybrid charcoal briquette made from rice hull had a calorific value of 12.31 MJ kg^{-1}, which was slightly lower than the optimum hybrid charcoal briquette value obtained in this study. In addition, the heating value of the optimum hybrid charcoal briquette was higher than that of a charcoal briquette produced from wood and wood charcoal, as reported by Yuliah et al. (2017). However, in the study by Tanko et al. (2020), the calorific value of the charcoal briquette produced from 100% coconut shell is higher than that of the optimum hybrid charcoal briquette produced in this study. However, the coconut shell used in the production of the optimum hybrid charcoal briquette in this study differs from the one used in the study by Tanko et al. (2020), as this study utilized coconut shell charcoal fines from the waste product of activated carbon production. The charcoal briquettes produced in our study can be effectively used as household fuel for cooking and heating.

Table 3 presents a comparison of the calorific values in this study with the results of previously published related studies.

Table 3. Calorific value of the hybrid charcoal briquette compared to related studies

Biomass	Calorific Value (MJ kg^{-1})	Reference
Coconut shell and carbonized rice hull	15.44	This study
Coconut shell	18.60	(Tanko et al., 2020)
Rice hull	12.31	(Sansolis & Villalva, 2017)
Wood charcoal	13.22	(Suryaningsih et al., 2018)
Wood	13.80	(Suryaningsih et al., 2018)

3.3 Optimum hybrid charcoal briquette

Table 4 presents the parameters that determine the physical, mechanical, and thermal properties of the optimum hybrid charcoal briquette, including calorific value, density, shatter index, kindling time, and burning time. The hybrid charcoal briquette was selected based on the calorific value.

Table 4. Characteristics of the optimum hybrid charcoal briquette

Parameters	Values
Calorific value (MJ kg^{-1})	15.44
Moisture content (%)	7.12
Density (kg m^{-3})	805
Shatter index (%)	99.80
Kindling time (s)	271
Burning time (min)	237

Among the different mixture compositions, the mixture composed of 74.80% and 25.20% carbonized rice hull obtained the highest calorific value of 15.44 MJ kg^{-1}. Furthermore, the optimum hybrid charcoal briquette had the longest burning time of 237 min. However, the optimum hybrid charcoal briquette also had the longest kindling time of 271 s. Moreover, its density was 805 kg m^{-3}. Additionally, it achieved the highest shatter index percentage of 99.80%.

The characteristics of the hybrid charcoal briquettes produced in this study can be considered desirable for a charcoal briquette.

The moisture content of the hybrid charcoal briquettes varied significantly depending on the temperature, drying time, and weather conditions. The amount of heat from the sun was sufficient to release the free water, as evidenced by a moisture content of less than 15%. As shown in Table 4, the optimum hybrid charcoal briquette had a moisture content of 7.12%. Furthermore, the lower moisture content of the briquette implied that less heat energy was wasted, resulting in briquettes that produced sufficient heating value. This is because moisture content has a significant influence on the calorific value of briquettes; high moisture reduces combustion efficiency since a portion of the energy is used to evaporate water instead of generating heat (Onukak et al., 2017).

3.4 Proximate analysis

The proximate analysis of the hybrid charcoal briquette was characterized, and the results are shown in Table 5.

Table 5. Proximate analysis of the hybrid charcoal briquette

Parameters	Values %
Volatile matter	20.46
Ash	38.6
Fixed carbon	40.94

The determination of fixed carbon is linked to the calorific value, as it implies that the higher the fixed carbon, the higher the calorific value. As seen in Table 5, the fixed carbon content of the optimum hybrid charcoal briquette was 40.94%.

As can be seen in the Table, the fixed carbon content is slightly lower than the typical charcoal range of 50-95%. It could be due to the unsteady temperature during the carbonization of the rice hull, which is in line with the study of Ycaza & Barre (2018).

The volatile matter content of the optimum hybrid charcoal briquette was 20.46%. Furthermore, the volatile matter content of the optimum hybrid charcoal briquette aligned with the VCM, which was 20 to 35%. Moreover, it is very important that the volatile matter falls within the recommended range as it corresponds to the smoke level of the briquettes, which should have either low or high volatile matter content. The ash content of the optimum hybrid charcoal briquette was 38.60%. Furthermore, the study by Efomah and Gbabo (2015) states that a low ash content is associated with a low calorific value, based on the proximate analysis of the carbonized rice hull.

4. Conclusions

This study demonstrates the potential of utilizing agro-industrial waste to create solid biofuel through a hybrid charcoal briquette. By combining coconut shell charcoal fines and carbonized rice hulls with cassava starch as a binder, the research presents an innovative strategy for waste valorization and sustainable energy production. The use of cassava starch binder from waste cassava further strengthens the study's alignment with circular economy principles. The hybridization process improved the briquettes' physical and thermal properties, confirming their effectiveness as an alternative fuel for households. Moreover, the study highlights the economic and environmental advantages of transforming industrial byproducts into an affordable and efficient biofuel source. Future research should focus on optimizing binders, refining carbonization conditions, and scaling up production to enhance fuel efficiency, durability, and market viability.

5. Acknowledgements

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6. Authors' Contributions

K.S.A.C, G.P.U.B., G.M.L.S., and E.R.U.G..: Conceptualization, methodology, investigation, data curation, writing – original draft; V.I.F.M.: Supervision, investigation, formal analysis, writing – review and editing. J.K.C.L.: Supervision, investigation. All authors read and approved the final manuscript.

ORCID
Klel Sien A. Cordova https://orcid.org/0009-0009-9530-4536
Glen Piere U. Babia https://orcid.org/0009-0003-2202-7220
Gisan Mae L. Señorin https://orcid.org/0009-0001-6650-3837
Eugene Ray U. Generalao https://orcid.org/0009-0009-6934-2926
Val Irvin F. Mabayo https://orcid.org/0000-0003-2231-5604
Jonas Karl C. Liwanag https://orcid.org/0009-0002-8294-252X

7. Conflicts of Interest

The authors declare no competing interests.

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