

Research Article

Physical and Combustion Properties of Charcoal Briquettes Produced from Mangrove Wood and Coconut Shell Waste

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ABSTRACT

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This research examines the physical and combustion properties of charcoal briquettes produced from mangrove wood and coconut shell agricultural residues, which were fabricated using a cylindrical compression mould. The seven formulations were prepared with mangrove wood and coconut shell ratios of 100 : 0, 90 : 10, 80 : 20, 70 : 30, 60 : 40, 50 : 50, and 0 : 100. The entire mixture consists of 0.5 kg of tapioca starch (binding agent) and 3 L of tap water. The charcoal briquettes have an outer diameter of 40 mm, an inner diameter of 14 mm, and a height of 80 mm. The properties analysed included physical properties: particle size, true density, moisture content and combustion properties: total heat value, and fuel usage characteristics. The particle size analysis revealed that mangrove charcoal powder had a finer average particle size of $48.2 \pm 1.75 \mu\text{m}$ compared to coconut shell charcoal powder of $285.4 \pm 20.36 \mu\text{m}$. The true densities of mangrove wood and coconut shell charcoals were $1.3690 \pm 0.0019 \text{ g/cm}^3$ and $1.4095 \pm 0.0016 \text{ g/cm}^3$, respectively, indicating similar intrinsic density. Every formulation satisfied the Community Product Standard for Charcoal Briquettes (M.P.Ch. 238/2547) and had a gross calorific value ranging from $5,897 \pm 510 \text{ kcal/kg}$ to $6,886 \pm 420 \text{ kcal/kg}$ and a moisture content ranging from $4.211 \pm 0.127\%$ to $4.887 \pm 0.164\%$. A higher coconut-shell fraction generally increased calorific value. During combustion, formulation M60C40 ignited fastest (7 min) and had the longest burn-to ash-time, 223 min, making it well-suited for long-duration applications. No formulation produced sparks during usability tests. In summary, the M70C30 formula releases little smoke and provides a consistent medium flame, indicating excellent performance for this research.

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1. Introduction

Renewable energy continues to grow in importance amid global anxiety over climate change (Lomunyak *et al.*, 2024). The Earth's surface temperature tends to rise continuously. The scientific consensus suggests that the increase in temperature should be limited to 2 °C or less (Malte *et al.*, 2009). The rise in global temperatures is mainly due to the continued expansion of fossil fuel use and various human activities that increase the

concentration of greenhouse gases in the atmosphere. To address the significant impacts of climate change, international cooperation and agreements are initiated to control and reduce greenhouse gas emissions. Thailand has embraced international approaches to mitigate and adapt to such changes through its active participation in the 26th Conference of the Parties (COP 26) within the United Nations Framework Convention on Climate Change. The 13th National Economic and Social Development Plan (2023-2027) integrates

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the concept of bio-circular economy-green economy (BCG Model) with a special emphasis on the green economy dimension, with a focus on the sustainable use of natural resources and environmental management, in line with Strategic Goal 10 to promote a circular economy and a low-carbon society (Jomsurang and Anamai, 2024). This approach is also in line with Sustainable Development Goal 13, which focuses on urgent action to address climate change and its impacts (Winfried and Claudia, 2018). The conceptual framework and operational approach serve as an important mechanism to support the development of a variety of renewable energy sources, such as solar energy, hydroelectric and hydro power, wind energy, waste-to-energy, geothermal energy, and biomass energy (Department of Renewable Energy Development and Conservation, 2024). This study focuses mainly on biomass energy as a potential alternative energy source. It focuses on utilizing agricultural waste generated after harvest (Saleem, 2022). According to 2023 data, Thailand has about 101.82 million km² of rainforest area, while the total agricultural area is 153,184,527 km², or 47.77% of the country's total area. The agrarian terrain that covers this large area generates substantial biomass waste, which can be efficiently processed into solid fuel (Pattaraanong *et al.*, 2021).

Previous studies have examined the potential of various biomass sources for producing charcoal briquettes. The feasibility of using pineapple peel as a raw material for briquettes was assessed by reviewing different weight-based mixing ratios 80 : 20, 70 : 30, 60 : 40, and 50 : 50. The resulting cylindrical briquettes with an outer diameter of 4 cm, an inner diameter of 1 cm and a length of 10 cm have calorific values ranging from 5,051.51 cal/g to 5,240.95 cal/g (Titiporn and Chotika, 2018). Briquettes made from agricultural waste include coconut shells (tall varieties), dried lamut leaves, and durian sawdust, reported heating values of 4,910.82 cal/g, 3,195.757 cal/g, and 5,067.55 cal/g, respectively (Roseleena *et al.*, 2019). The influence of composite materials on the mechanical and thermal properties of coconut shell briquettes resulted in an average moisture content of 5.6% and a maximum average calorific value of 5,515.33 cal/g (Amnouy *et al.*, 2019). The briquettes developed from longan wood charcoal powder, water, and tapioca starch in a ratio of 0.47:0.47:0.06 have a moisture content of 6.65 ± 0.03% and a calorific value of 5,509.85 ± 0.65 cal/g (Kritsada and Nirubol, 2020). The use of waste materials from durian and mangosteen plantations, by combining large branches, small branches, leaves, and fruits in a ratio of 1:1:1:1, with tapioca starch and molasses as binders at weight ratios of 8:2 and 7:3, resulted in briquettes having calorific values ranging from 5,100 to 5,840 cal/g and 5,205-5,640 cal/g, respectively (Amon, 2021). The grapefruit peel cubes have an average calorific value of 5,344 cal/g and a moisture content ranging from 8.35% to 11.14% (Sirichai and Changwat, 2022). Only four bamboo charcoal briquette formulations complied with

the community product standards for charcoal briquettes (M.P.Ch. 238/2004) (Jutapol *et al.*, 2022). The fuel briquettes are produced from biowaste materials, including municipal wastewater sludge, agricultural waste, and tapioca starch sludge as binders at mixing ratios of 0.35:0.40:0.25 and 0.65:0.15:0.20 (kg:kg:kg), with a calorific value of 5,158.09 cal/g (Ratchatorn and Jaruwat, 2022). Overall, most previous studies have indicated that briquettes obtained from various biomass sources and mixing ratios can achieve acceptable calorific values. Moisture content and related properties that comply with the requirements of the Community Product Standard M.P.Ch. 238/2547. However, other high-potential local biomass sources, such as mangrove charcoal and coconut shells, have not been comprehensively studied or evaluated, so further investigation is needed (Kabir *et al.*, 2022). This study investigated charcoal derived from coconut shells as a biomass fuel, with particular emphasis on its calorific value, which reached 19.4 MJ/kg, and its moisture content of 5.6%, both of which exceeded previously reported values. Additionally, charcoal briquettes are biomass fuels produced from agricultural residues, such as sawdust, rice husks, and coconut shells. They provide consistent heat, long burning duration, and low smoke and ash emissions, while reducing waste, lowering costs, and promoting sustainable, renewable energy use.

Therefore, this research aims to investigate the physical and combustion properties of composite charcoal briquettes made from waste mangrove wood charcoal and coconut shell charcoal using a cylindrical compression mold. This sustainable energy alternative can indirectly help reduce greenhouse gas concentrations by replacing fossil fuels in everyday activities like cooking, thereby alleviating environmental concerns.

2. Materials and Methods

2.1 Raw materials

This research utilized agricultural waste materials consisting of various sizes of mangrove wood scraps from the species *Rhizophora mucronata* (Nuryawan *et al.*, 2025) and coconut shell fragments from native coconut varieties are dense, durable, and resistant to breakage and abrasion due to their composition of lignin, cellulose, and hemicellulose, which were obtained from a community forest in the mangrove area of Songkhla Province, Thailand.

2.2 Sample preparation

The charcoal samples were prepared by carbonizing the raw agricultural waste residues, specifically the mixed-sized mangrove wood and coconut shell waste, to serve as the primary materials for composite briquette production. Each type of waste was separately carbonized using a 200 L charcoal kiln. This charcoal kiln consists of (1) the furnace body, (2) a smoke pipe for observing combustion, (3) three smoke pipes for releasing smoke from the furnace, (4) a chimney pipe, (5)

a wood vinegar collection chamber, (6) a fuel feeding inlet, and (7) a front furnace cover, as shown in the Figure 1.

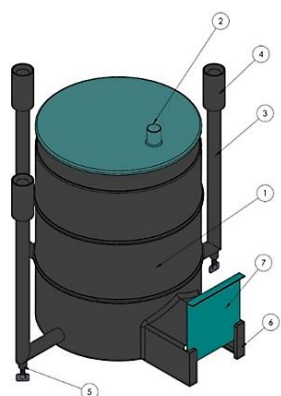


Figure 1 The illustration of a 200-litre charcoal kiln.

For efficient carbonization, the waste materials were uniformly distributed within the kiln to ensure even heat distribution and complete charring. After loading, the kiln lid was sealed. The combustion process was initiated through the fuel feeding port. Smoke emissions were monitored for 15 min. to ensure complete discharge of the initial, toxin-rich plume. After 3 h, when the smoke had turned white, the kiln lid and fuel-feeding port were sealed tightly with clay-soaked cloths. After an additional 2 h, three clay-wrapped "poultices" were used to seal the ends of the left, right, and rear smoke pipes, leaving only the accelerating air vent open. When the smoke emanating from this vent became diluted, the vent was sealed, allowing the charring process to complete within the kiln. The kiln carbonizes biomass by pyrolysis heating in limited oxygen at roughly 300–800 °C. This process effectively drives out moisture from the wood, transforming the material into charcoal. The resulting charcoal was black in appearance and was retrieved from the kiln on the following day, as shown in Figure 2.

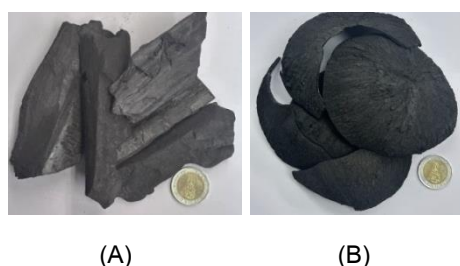


Figure 2 Charcoal types (A) Mangrove charcoal and (B) Coconut shell charcoal.

2.3 Preparation of charcoal powder and mixture design

Following the carbonization process, both mangrove wood charcoal and coconut shell charcoal were separately ground into fine powder using a grinding machine equipped with a 5 hp motor operating at 2,890 revolutions per minute (rpm) was used, and the mixing process was conducted for 20 min.

Subsequently, mixtures were prepared for the fabrication of cylindrical charcoal briquettes. A total of seven experimental ratios were designed based on the weight percentages of

mangrove wood charcoal (M) and coconut shell charcoal (C) as follows: 100:0, 90:10, 80:20, 70:30, 60:40, 50:50, and 0:100. These ratios were designated as M100C0, M90C10, M80C20, M70C30, M60C40, M50C50, and M0C100, respectively. For all mixtures, cassava starch (Siwakorn *et al.*, 2026) was consistently used as a binder at a fixed volume of 0.5 kg, and tap water was added at a constant volume of 3 L. All measurements were performed precisely using a digital weighing scale (Model SF 400) with a resolution of ± 1 g. The detailed experimental design is presented in Table 1.

Table 1 Experimental design showing the mixing ratios of mangrove charcoal and coconut shell charcoal.

Recipe name	Mixing ratio	Raw Materials			
		Mangrove (kg)	Coconut shell (kg)	Tapioca starch (kg)	Water (L)
M100C0	100 : 0	100	0	0.5	3
M90C10	90 : 10	90	10	0.5	3
M80C20	80 : 20	80	20	0.5	3
M70C30	70 : 30	70	30	0.5	3
M60C40	60 : 40	60	40	0.5	3
M50C50	50 : 50	50	50	0.5	3
M0C100	0 : 100	0	100	0.5	3

Once the desired weights of the ingredients were obtained, the finely ground charcoal powder, cassava starch, and tap water were thoroughly mixed to achieve a homogenous consistency. The prepared mixture was then fed into a cylindrical compression mould at a predetermined quantity. A TMC hydraulic press, with a maximum compaction force of 160 N was used to compress the mixture into briquettes. Immediately after compression, while still moist, the cylindrical briquette samples were carefully demoulded.

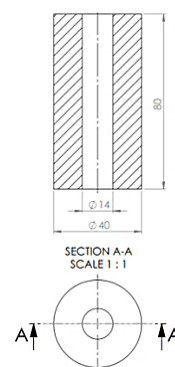


Figure 3 The illustration of a green charcoal.

The resulting "green charcoal" briquettes had an outer diameter of 40 mm, an inner hole diameter of 14 mm, and a height of 80 mm, as illustrated in the Figure 3 and representative green charcoal briquette specimens for different mixing ratios in Figure 4.

2.4 Physical properties testing

Figure 5 illustrates the charcoal powder utilized for the particle size analysis of the initial raw materials, specifically the

mixed-sized mangrove wood charcoal powder and coconut shell charcoal powder. Random samples of the fine-ground powder were sieved and then analyzed using a Laser Particle Size Analyzer (LPSA2), ANALYSETTE 22 Nano Tec, FRITSCH, and Germany.

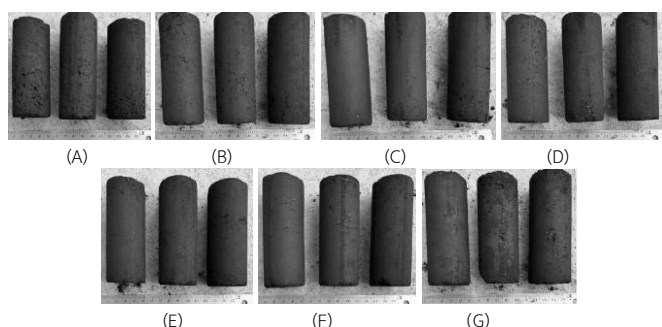


Figure 4 Representative green charcoal briquette specimens for different mixing ratios: (A) M100C0, (B) M90C10, (C) M80C20, (D) M70C30, (E) M60C40, (F) M50C50, and (G) M0C100.

This instrument can analyze particle size in both liquid and air dispersed media, covering a range from 0.01 μm to 2,000 μm in liquid and 0.1 μm to 2,000 μm in air. Furthermore, the true density of the mixed-sized mangrove wood charcoal powder and coconut shell charcoal powder was determined. Random samples of the fine-ground powder were analyzed using a True Density Analyzer, AccuPyc II 1340, U.S.A., Mettler Toledo Density Meter D4. All measurements were performed in triplicate ($n = 3$). This instrument operates by inducing vibrations through electromagnetic waves within a U-shaped glass tube. A sensor then measures the oscillation period, which is correlated to the true density.

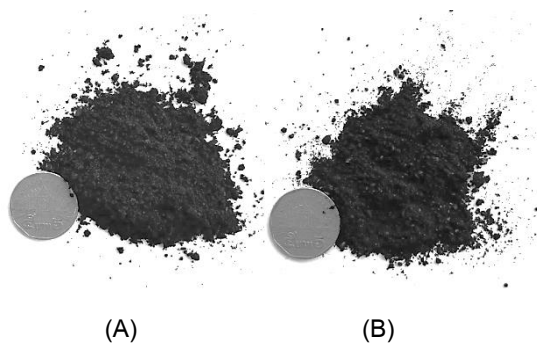


Figure 5 Types of charcoal powder: (A) Mangrove and (B) Coconut shell.

2.5 Gross calorific value analysis

The gross calorific value of the moulded cylindrical briquette samples was analyzed. After shaping, the briquettes were sun-dried until completely dry. Random samples were then collected from various locations for each of the seven mixing ratios, all measurements were performed in triplicate ($n = 3$), as shown in Figure 4. According to the Community Product Standard for Charcoal Briquettes (M.P.Ch. 238/2547), the testing method adheres to ASTM D 5865 (ASTM International, 2019)

A Bomb Calorimeter (C5000, IKA, Germany) was used to determine the calorific value. The principle of this method involves the combustion of the material in an oxygen-rich environment, releasing heat. This heat is absorbed by a surrounding water tank, and the resulting temperature increase of the water is measured to calculate the calorific value.

2.6 Moisture content analysis

The moisture content (expressed as a percentage of analysis sample) of the composite charcoal briquette samples was determined. After being mixed and moulded into cylindrical shapes, the briquettes were sun-dried to a ready-to-use condition. Random samples were then collected from various locations for all seven mixing ratios, as depicted in Figure 4. The testing procedure adhered to ASTM D3173 (Canales *et al.*, 2022), as specified by the Community Product Standard for Charcoal Briquettes (M.P.Ch. 238/2547). Samples were heated in a hot air oven (Mettler) at a controlled temperature of $110 \pm 1^\circ\text{C}$. The oven maintained a heating rate of 2 to 4 times per minute, with an internal air atmosphere humidity of 1.9 mg L⁻¹ or less. All measurements were performed in triplicate ($n = 3$). The percentage moisture content of the charcoal briquette samples was calculated using Equation 1.

$$\text{Moisture in analysis sample, \%} = ((W_1 - W_2)/W_1) \times 100\% \quad (1)$$

where: W_1 is the mass of the sample before drying (g)

W_2 is the mass of the sample after drying (g)

2.7 Thermal and combustion properties

In these tests, a constant briquette weight of 0.5 kg and a fixed water volume of 1 L were used for all formulations. Each experiment lasted for a total of 60 min and was replicated four times. The heat generated resulted in varying boiled water temperatures across different time intervals. For all formulations, the highest water temperature was consistently recorded at the 20-minute mark. Beyond this point, as the burning time increased, the water temperature began to decrease, which is attributed to the continuous consumption of the charcoal briquettes as fuel, leading to a reduction in their effective burning volume.

2.8 Fuel properties and usability testing

This section details the evaluation of the fuel properties and usability of the briquettes by determining the combustion duration per unit of mass. For this test, a charcoal briquette sample weighing 0.5 kg was used as fuel to boil 1 kg of water. The experiment recorded time intervals at 0, 20, 40, and 60 min to assess ignition time, time to boiling water, and boiling water temperature. The overall usability of each of the seven briquette formulations, as shown in Figure 4, was evaluated from the initial ignition until complete ash formation.

3. Results and Discussion

The results and discussion on the physical, calorific, and combustion properties of composite charcoal briquettes made from waste mangrove wood charcoal and coconut shell charcoal, fabricated using a cylindrical compression mould, yielded the following key findings:

3.1 Particle size analysis

The particle size distribution analysis of the mixed charcoal powder derived from mangrove wood and coconut shells was conducted to evaluate the relationship between particle size (in micrometres) and cumulative particle volume (in percentage), as presented in Figure 6.

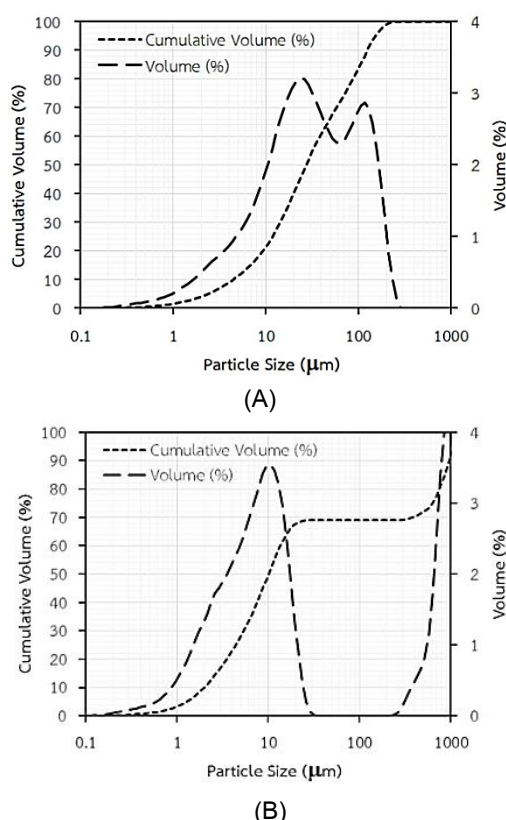


Figure 6 Particle size distribution graphs for (A) Mangrove wood charcoal and (B) Coconut shell charcoal.

As presented in the Figure 6(A), the particle size distribution for mangrove wood charcoal powder exhibited a bimodal distribution, with two distinct peaks observed in the volume percentage graph, indicating two primary particle size populations. The d_{10} , d_{50} , and d_{90} values were 4.3 μm , 27.0 μm , and 128.4 μm , respectively, with an average particle size of $48.2 \pm 1.75 \mu\text{m}$. This broad distribution, spanning from very fine particles ($d_{10} = 4.3 \mu\text{m}$) to relatively coarse particles ($d_{90} = 128.4 \mu\text{m}$), suggests that the grinding process produced a wide range of particle sizes (Zamora *et al.*, 2015).

In contrast, for coconut shell charcoal powder, depicted in Figure 6(B), the volume percentage graph primarily showed a prominent peak in the range of 8-12 μm , indicating a significant fraction of fine particles. However, the cumulative volume

percentage curve rose sharply beyond 100 μm , culminating in d_{10} , d_{50} , and d_{90} values of 2.0 μm , 10.4 μm , and 972.6 μm , respectively, with a much larger average particle size of $285.4 \pm 20.36 \mu\text{m}$. The exceptionally high d_{90} value for coconut shell charcoal powder (972.6 μm) highlights the presence of a considerable proportion of very large particles, despite the fine primary peak. This suggests a highly heterogeneous particle size distribution for coconut shell charcoal (Yuliah *et al.*, 2017).

In summary, a direct comparison reveals that while both charcoal types contain fine particles (indicated by low d_{10} values), the overall average particle size of mangrove wood charcoal powder ($48.2 \pm 1.75 \mu\text{m}$) was considerably finer and more uniformly distributed than that of the coconut shell charcoal powder ($285.4 \pm 20.36 \mu\text{m}$), which exhibited a broader and more heterogeneous distribution with very large particles. These distinct particle size characteristics are expected to influence the compaction behavior and final physical properties of the briquettes, particularly affecting density and structural integrity. The finer and more diverse particle sizes of mangrove wood charcoal may facilitate better particle packing and inter-particle bonding during compression. Consistent with the findings of Anan *et al.* (2022), fine grinding and mixing of the ingredients enabled the compression molding process to produce charcoal with higher true density and calorific value.

3.2 True density analysis

The true density of the powdered charcoal particles, derived from carbonized mixed-sized mangrove wood and coconut shell waste, was analysed. Random samples of each charcoal powder type were collected from their respective piles and tested at room temperature, specifically within a range of 25.37 $^{\circ}\text{C}$ to 25.93 $^{\circ}\text{C}$. The results showed that mangrove wood charcoal powder had a true density of $1.3690 \pm 0.0019 \text{ g/cm}^3$, while coconut shell charcoal powder had a true density of $1.4095 \pm 0.0016 \text{ g/cm}^3$. These results indicate that the true densities of both charcoal powders are very similar, with a minimal difference of only 0.0405 g/cm^3 . This similarity in true density, despite differences in particle size distribution, suggests that the intrinsic material properties of the charcoals are comparable. This is similar to studies on mata buaya (*Bruguiera sexangula*), which has a density of 0.9 g/cm^3 (Hardiansyah *et al.*, 2023).

3.3 Gross calorific value analysis

Table 2 presents the results of the gross calorific value analysis of charcoal briquettes and illustrates the relationship between the briquette formulations and their respective calorific values. Briquettes made solely from coconut-shell charcoal powder (MOC100) exhibited a calorific value of $6,886 \pm 420 \text{ kcal/kg}$. In comparison, briquettes composed entirely of mangrove wood charcoal powder (M100C0) yielded a lower calorific value of $5,897 \pm 510 \text{ kcal/kg}$ (Rahman *et al.*, 2019; Kabir *et al.*, 2022). When examining the calorific values across the composite formulations, a clear trend emerged. Starting from

the M100C0 formulation, which had the lowest calorific value, and progressing towards the M0C100 formulation, which had the highest at $6,886 \pm 420$ kcal/kg, the calorific value generally increased with an increasing proportion of coconut shell charcoal powder (from C10, C20, C30, C40, to C50 ratios). The calorific values for the mixed formulations were $6,021 \pm 145$, $5,917 \pm 108$, $6,141 \pm 570$, $6,389 \pm 214$, and $6,292 \pm 500$ kcal/kg, respectively. This indicates that coconut shell charcoal contributes significantly to the overall heat content of the briquettes, as its high density and carbon content yield a rigid, dense cellulose structure during combustion. Additionally, the moisture content for all tested formulations ranged between $4.211 \pm 0.127\%$ and $4.887 \pm 0.164\%$.

Every briquette formulation successfully met the Community Product Standard for Charcoal Briquettes (M.P.Ch. 238/2547). This standard stipulates a minimum gross calorific value of not less than $5,000 \text{ cal g}^{-1}$ (equivalent to $5,000$ kcal/kg) and a maximum moisture content of not exceeding 8% by weight. All formulations developed in this study, with calorific values ranging from $5,897 \pm 510$ kcal/kg to $6,886 \pm 420$ kcal/kg and moisture contents between $4.211 \pm 0.127\%$ and $4.887 \pm 0.164\%$, were found to satisfy these criteria.

Table 2 Gross calorific values of charcoal briquette formulations.

Recipe Name	Mangrove (kg)	Coconu t Shell (kg)	Gross Calorific Value (kcal/kg)	Moisture in analysis (%)
M100C0	100	0	$5,897 \pm 510$	4.887 ± 0.164
M90C10	90	10	$6,021 \pm 145$	4.211 ± 0.127
M80C20	80	20	$5,917 \pm 108$	4.446 ± 0.136
M70C30	70	30	$6,141 \pm 570$	4.676 ± 0.152
M60C40	60	40	$6,389 \pm 214$	4.427 ± 0.130
M50C50	50	50	$6,292 \pm 500$	4.842 ± 0.158
M0C100	0	100	$6,886 \pm 420$	4.489 ± 0.142

3.4 Thermal and combustion properties

Table 3 presents the results of the thermal properties testing for each formulation of mangrove wood and coconut shell charcoal briquettes, showing the boiling water temperature at various time intervals. In these tests, a constant briquette weight of 0.5 kg and a fixed water volume of 1 L were used for all formulations. Each experiment lasted for a total of 60 min and was replicated four times. The heat generated resulted in varying boiled water temperatures across different time intervals. For all formulations, the highest water temperature was consistently recorded at the 20 min mark. Beyond this point, as the burning time increased, the water temperature began to decrease, which is attributed to the continuous consumption of the charcoal briquettes as fuel, leading to a reduction in their effective burning volume.

Upon analysing the data in Table 3 in conjunction with the calorific values presented in Table 2, a clear correlation emerges. The M0C100 formulation, which exhibited the highest

gross calorific value ($6,886 \pm 420$ kcal/kg), also demonstrated the highest water temperature at 20 min (93.5°C), as this duration was sufficient for the charcoal to fully ignite, resulting in efficient heat transfer and greater energy release that enabled the water to reach its boiling point. On the other hand, the M100C0 formulation, with the lowest calorific value ($5,897 \pm 510$ kcal/kg), yielded a comparatively lower maximum temperature at 20 min (95.8°C). However, M100C0 unexpectedly reached a slightly higher water temperature (95.8°C) than M0C100 (93.5°C), possibly reflecting experimental variability or ignition efficiency. The overall trend suggests that higher calorific values generally lead to better thermal performance. Formulations with a higher proportion of coconut shell charcoal, such as M0C100, tended to achieve higher water temperatures, aligning with their higher energy content. Furthermore, the highest value was observed for the M90C10 formulation at 20 minutes. This result can be attributed to the higher proportion of coconut shell charcoal relative to mangrove wood charcoal in the mixture. This correlation highlights the direct impact of the briquette's energy density on its practical thermal performance for heating applications (Wasu *et al.*, 2021).

Table 3 Results of the water boiling test.

Recipe Name	0 minute	20	40	60
	$^\circ\text{C}$	minutes $^\circ\text{C}$	minutes $^\circ\text{C}$	minutes $^\circ\text{C}$
M100C0	32.2	95.8	86.3	73.6
M90C10	32.6	98.1	85.8	80.3
M80C20	32.1	86.2	85.9	77.2
M70C30	32.3	84.7	77.9	71.2
M60C40	32.4	91.1	83.5	72.8
M50C50	32.1	89.9	81.8	74.5
M0C100	32.2	93.5	85.6	78.4

In addition to heat output, Table 4 details other key combustion properties, including ignition time, time to burn to ash, and actual combustion time. These characteristics varied among the different briquette formulations, primarily influenced by the true density of the briquettes and the specific composition of each mixture. The ignition time, defined as the duration from initial lighting until stable flame combustion, ranged from 7 min (M60C40) to 19 min (M80C20). Notably, the M60C40 formulation exhibited the shortest ignition time (7 min), indicating its superior ease of initial lighting. Regarding the overall burning duration, the M60C40 formulation demonstrated the longest time to burn to ash (223 min), followed by M80C20 and M0C100 (210 min each). This indicates that the M60C40 briquettes sustained combustion for the longest period until complete ash formation. The actual combustion time, which excludes the initial ignition phase, also showed M60C40 having the longest duration of 216 min (Onuegbu *et al.*, 2011).

In addition to the quantitative thermal and combustion metrics, Table 5 presents the qualitative usability test results for each charcoal briquette formulation, focusing on smoke

emission, flame characteristics, spark generation, and ease of ignition.

Table 4 Combustion test results.

Recipe Name	Ignition Time (min)	Time to Burn to Ash (min)	Actual Combustion Time (min)
M100C0	17	192	175
M90C10	16	200	184
M80C20	19	210	191
M70C30	9	204	195
M60C40	7	223	216
M50C50	8	211	203
M0C100	10	210	200

Table 5 Fire characteristics.

Recipe Name	Fire characteristics			
	Smoke	Flame	Sparks	Ignition
M100C0	Little	Much	None	Slow
M90C10	Moderate	Moderate	None	Slow
M80C20	Moderate	Little	None	Slow
M70C30	Little	Moderate	None	Moderate
M60C40	Moderate	Moderate	None	Fast
M50C50	Much	Moderate	None	Fast
M0C100	Little	Little	None	Moderate

One key result was the absence of spark generation across all tested formulations, indicating a safer burning characteristic. When considering minimal smoke emission, the M70C30 formulation proved to be the most suitable for practical use. This formulation also exhibited moderate levels of flame and ignition characteristics, striking a balance between ease of lighting and clean burning (Chaney, 2010).

4. Conclusion

Charcoal briquettes made from agricultural residues, specifically a blend of mangrove wood charcoal and coconut shell charcoal, represent a significant alternative biomass energy source. These briquettes offer a promising solution to replace fossil fuels in essential daily activities such as cooking, grilling and heating, while simultaneously contributing to the reduction of environmental problems. This research investigated the physical, calorific, and combustion properties of these composite briquettes. Key findings from the study are as follows:

The average particle size of ground mangrove wood charcoal was $48.2 \pm 1.75 \mu\text{m}$, while that of coconut shell charcoal was $285.4 \pm 20.36 \mu\text{m}$. This indicates that mangrove charcoal powder is generally finer than coconut shell charcoal powder, a characteristic that influences compaction and briquette integrity.

The true densities of mangrove charcoal powder ($1.3690 \pm 0.0019 \text{ g/cm}^3$) and coconut shell charcoal powder ($1.4095 \pm 0.0016 \text{ g/cm}^3$) were found to be very similar, with only a minor

difference of 0.0405 g/cm^3 . All briquette formulations met the Community Product Standard for Charcoal Briquettes (M.P.Ch.238/2547), requiring a minimum of 5,000 cal/g. The calorific values ranged from $5,897 \pm 510 \text{ kcal/kg}$ (M100C0) to $6,886 \pm 420 \text{ kcal/kg}$ (M0C100). A clear trend showed that increasing the proportion of coconut shell charcoal led to higher calorific values. The moisture content across all formulations was low, ranging between $4.211 \pm 0.127\%$ and $4.887 \pm 0.164\%$, well within the standard's limit of 8% by weight. The moisture content is still high, so it should be dried or sun-dried before being used as fuel. In the water boiling tests, all formulations reached their highest water temperature at the 20-minute mark. The M60C40 formulation demonstrated the shortest ignition time (7 min.) and the longest time to burn to ash (223 min.), making this formulation the most suitable choice for applications requiring prolonged and sustained burning. No spark generation was observed in any formulation. The M70C30 formulation produced minimal smoke while exhibiting moderate flame and ignition characteristics, making it suitable for practical household applications. Notably, its heating value of $6,141 \pm 570 \text{ kcal/kg}$ was substantially higher than that reported for briquettes prepared with a 5% cow dung binder of 4,794.38 kcal/kg. This finding suggests that the M70C30 formulation offers greater energy efficiency and improved fuel quality while maintaining desirable combustion characteristics. In summary, the research results indicate that M70C30 blended charcoal briquettes made from mangrove wood and coconut shells are an efficient and suitable alternative biomass fuel. They possess excellent physical properties, high calorific value, and excellent combustion characteristics, meeting relevant standards and practical application requirements. To facilitate commercial implementation, a detailed break-even analysis should be undertaken to evaluate economic feasibility and identify the conditions that yield the greatest profit per unit.

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6. Declaration of Generative AI Use

During the preparation of this manuscript, the authors used ChatGPT (OpenAI) solely for language editing and improvement of readability. All research design, data collection, analysis, interpretation, and conclusions were performed by the authors.

The authors assume full responsibility for the content of this manuscript.

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