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Effects of Elevated CO_2-Grown Napier Grass and Cassava Starch Binder Ratios on Biomass Briquette Properties

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ABSTRACT

Napier grass (*Pennisetum purpureum* cv. Taiwan) has considerable potential as a renewable biomass resource for solid biofuel production; however, the quality of charcoal briquettes depends heavily on binder composition and processing conditions. This study aimed (i) to determine the optimal mixing ratio between burnt Napier grass and cassava starch and (ii) to evaluate the physical properties, combustion-related characteristics, and nutrient profile of Napier grass–based charcoal briquettes. The briquettes were produced through a systematic modelling process involving carbonisation, crushing, drying, briquetting, final drying, and storage. Six treatments (T1–T6) were formulated using different ratios of burnt Napier grass and cassava starch. The briquettes were assessed for compression strength, hydrophobicity, moisture content, particle density, bulk density, porosity, moisture sorption, and nutrient profile. The results indicated that increasing cassava starch content improved briquette density and compression strength but reduced porosity and moisture sorption capacity. Among all treatments, T4 (90% burnt Napier grass + 10% cassava starch) exhibited the most balanced properties, with moderate compression, favourable hydrophobicity, stable moisture content, moderate particle and bulk densities, balanced porosity, and the highest nutrient profile. Treatments with lower binder content showed weaker structural integrity, whereas higher binder proportions resulted in reduced porosity and nutrient performance. In conclusion, T4 was identified as the most suitable formulation for charcoal briquette modelling, offering an optimal balance between physical stability, combustion-related properties, and nutrient retention, and demonstrating strong potential for sustainable biofuel production from Napier grass.

Keywords: Briquette formulation, carbonisation, cassava starch binder, charcoal, green energy, renewable resources

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INTRODUCTION

Malaysia is actively accelerating its energy transition through the implementation of the National Energy Transition Roadmap (NETR) and the Malaysia Renewable Energy Roadmap (MyRER), which aim to increase the share of renewable energy in the national electricity generation mix to 31% by 2025 and 70% by 2050 (Sustainable Energy Development Authority Malaysia [SEDA], 2021). These policies emphasise diversifying renewable energy sources, including solar, hydropower, biogas, biomass, and waste-to-energy, to reduce greenhouse gas emissions while strengthening national energy security. Among these renewable resources, biomass derived from agricultural crops and residues represents a sustainable feedstock for solid biofuel production due to its abundance, renewability, and potential to substitute fossil fuels (Sawasdee & Pisutpaisal, 2021). Consequently, converting high-yield energy crops such as Napier grass into biomass briquettes offers a promising approach to support Malaysia's renewable energy objectives while promoting the sustainable utilisation of biomass resources (Ministry of Economy, 2023).

Among Malaysia's renewable energy resources, biomass has gained considerable attention owing to its abundant availability from agricultural crops and residues, including oil palm, rice husk, sugarcane bagasse, and Napier grass (Jha et al., 2022). Unlike intermittent renewable resources such as solar and wind, biomass provides a dispatchable energy source that can be converted into solid biofuels, including charcoal and biomass briquettes, with improved energy density, storage stability, and transportation efficiency (Economic Planning Unit, 2022). As Malaysia continues to promote biomass utilisation under the Malaysia Renewable Energy Roadmap (MyRER), improving the quality and performance of biomass briquettes has become increasingly important. In this study, Taiwan Napier grass (*Pennisetum purpureum* cv. Taiwan) was selected as the primary feedstock for charcoal briquettes due to its high biomass productivity, rapid growth, and favourable fuel characteristics (Sawasdee & Pisutpaisal, 2021). These policies were introduced not only to reduce carbon emissions but also to increase the usage of renewable resources in Malaysia (SEDA, 2021). In this context, the present study evaluates the properties of biomass briquettes1) to determine the best ratio of combination between burnt Napier grass (*Pennisetum purpureum* cv. Taiwan) and different ratios of cassava starch, and 2) to investigate the physical analysis, combustion properties and nutrient profile of charcoal briquettes from the Napier grass (*Pennisetum purpureum* cv. Taiwan). Interest in alternative energy has increased demand for renewable resources while reducing reliance on non-renewable energy (Dinesha et al., 2019).

MATERIALS AND METHODS

Napier Grass Grown Environment

Napier grass (Pennisetum purpureum) used in this study was obtained from two contrasting growing environments: ambient CO_2 (BNG−eCO_2) and greenhouse (BNG+eCO_2). The BNG−eCO_2 plants were cultivated under natural atmospheric conditions in an open field at Farm 15, Faculty of Agriculture, Universiti Putra Malaysia (UPM), Serdang, Malaysia, whereas the BNG+eCO_2 plants were grown in a controlled greenhouse facility at Tenaga Nasional Berhad Research (TNBR), Jalan Ayer Hitam, Kajang, Selangor, Malaysia. The greenhouse maintained an eCO_2 concentration of 800 μmol mol^{-1}, while the open-field plants were exposed to ambient atmospheric CO_2 concentrations. The $+eCO_2$ treatment was applied for 1 month prior to harvest. All plants were harvested after 1 year of growth, with four biological replicates for each treatment. The harvested biomass was subsequently oven-dried, carbonised, and processed into briquettes.

The nutrient composition of the Napier grass biomass was also characterised prior to carbonisation because mineral elements influence the physicochemical properties of biomass fuels (Botero-Londoño et al., 2021). Elements such as potassium, calcium, magnesium, phosphorus, and silicon contribute to ash composition and may affect combustion behaviour, ash yield, and the potential for slagging or fouling during fuel utilisation (Jungers et al., 2015). Furthermore, biomass grown under $eCO_{2\ exhibits}$ changes in nutrient accumulation due to altered plant physiology and carbon allocation. Therefore, the pre-carbonisation nutrient profile (Table 1) was included to characterise the feedstock and to provide a basis for interpreting differences in briquette properties between ambient- and eCO_2- grown biomass.

Table 1
Growth conditions and pre-carbonisation characteristics of Napier grass biomass used for briquette production (Mohd Nasirudin et al., 2024)

Parameter		BNG−eCO_2 (Open Field)	BNG+eCO_2 (Greenhouse)
Biomass yield (t ha^{-1})		82.90	84.12
Calorific value (MJ kg^{-1})		18.88	15.84
Lignin content (%)		14.26	10.74
Proximate analysis	Moisture content (%)	6.24	5.90
	Volatile matter (%)	87.11	87.21
	Ash content (%)	2.31	3.56
	Fixed carbon (%)	4.34	6.37
Ultimate analysis	Total carbon (%)	35.15	43.96
	Total hydrogen (%)	5.58	5.81
	Total nitrogen (%)	1.14	1.19
	Total sulphur (%)	0.05	0.08

Treatment and Experimental Design

The experiment was arranged in a Completely Randomised Design (CRD) with six treatments to evaluate the effect of different blending ratios of burnt Napier grass (BNG) and cassava starch (CS). Cassava starch was chosen as the binder agent because of its excellent adhesive properties, biodegradability, non-toxicity, and widespread availability. Upon gelatinisation, starch forms a viscous matrix that effectively fills void spaces and promotes strong interparticle bonding, resulting in briquettes with improved particle density, bulk density, and mechanical strength. In addition, cassava starch contributes little ash and does not significantly impair the briquettes' combustion characteristics (Livingston & Babcock, 2006). Burnt Napier grass was derived from crops that were grown in open area conditions (BNG-eCO_2) and under greenhouse conditions (BNG+eCO_2). Each BNG source was combined with cassava starch at three ratios (w/w): 9:1, 8:2, and 7:3. The treatments were as follows: 90% BNG-eCO_2 + 10% CS (T1), 80% BNG-eCO_2 + 20% CS (T2), 70% BNG-eCO_2 + 30% CS (T3), 90% BNG+eCO_2 + 10% CS (T4), 80% BNG+eCO_2 + 20% CS (T5), and 70% BNG+eCO_2 + 30% CS (T6). All treatments were randomly assigned to experimental units to ensure uniformity and reduce experimental bias.

Combustion Process in Modelling for Charcoal Briquettes Production

Carbonisation

Carbonisation is the incomplete, or primary, combustion of plant-based material, such as Napier grass, resulting in charcoal briquettes. The biochar product was fully oxidised through a thermochemical process under limited-oxygen conditions, converting organic material into carbon-rich charcoal (Mohammed et al., 2015). The plant-based material, such as Napier grass, was prepared into smaller cuttings between 50 and 100 cm to optimise the carbonisation process. The sample was burnt under temperatures between 400 °C and 500 °C in a kiln (Figure 1) under low-oxygen conditions (Md Said et al., 2019). The optimal temperature was important for maximising charcoal production while controlling thermal decomposition. Wood vinegar and tar were byproducts of the carbonisation process, while the stable carbon structure was retained during char formation (Murakami & Sato, 2024). The carbonisation process completely burns the organic material within 1 week. Next, the heated sample was left to cool for 3 days in an oxygen-limited environment to prevent spontaneous combustion. After 3 days, the sample was ready for crushing from a large particle size to a finer size, which is more suitable for briquette formation. Proper management in the carbonisation process is important to ensure the quality and burning characteristics are retained at good conditions as it progresses over time (Elehinafe et al., 2021).



Figure 1. Carbonisation process of Napier grass in a kiln for charcoal production

Crushing

The crushing method is important in the combustion process to ensure that all particles are uniformly sized during biochar formation. Particle size plays a crucial role in achieving maximum combustion efficiency (Pang et al., 2019). The sample must be cooled, then only fed into the crushing machine, the roller crusher (Figure 2). The roller crusher breaks hard particles into a fine powder (< 3mm). The fine powder was filtered through a mesh sieve (2–3 mm), and particles larger than 3 mm were removed to ensure uniform particle distribution. Particle size affects the strength of charcoal during the briquetting process: the finer the particles, the better they bind together, whereas uneven particle size can weaken the briquettes' structure (Sunardi et al., 2019). The high number of holes in the briquette structure can lead to poor and inefficient combustion (Rodriguez Correa et al., 2017). Thus, a proper crushing method

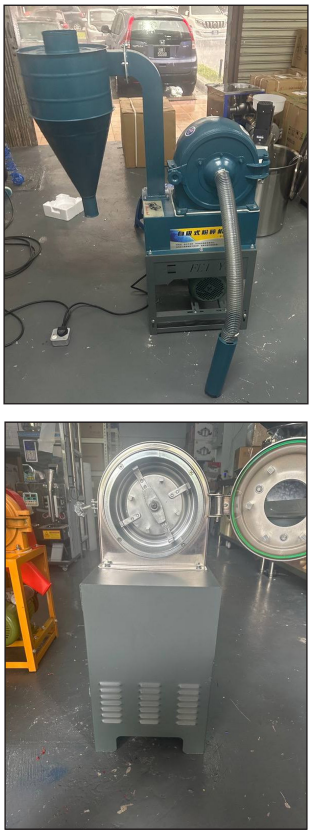


Figure 2. Crushing machines are used to grind carbonised Napier grass into fine charcoal powder for briquette production

can contribute to high density and durability of the charcoal product and improve overall performance, as well as the product's ability to hold solid formation together with binding agents (Chirchir et al., 2013). Finally, the powder was kept at ambient temperature and stored in sealed containers to prevent moisture absorption, maintain burning performance, and minimise ash production (Monti et al., 2008).

Drying

Next, the crushed sample was left to dry until its moisture content was no more than 10%. However, if the sample still contains more than 10% moisture, it must be further dried to reach the required level. The traditional drying method was implemented in this experiment due to its low cost and ease of handling. The crushed sample was exposed to direct sunlight under thin trays for several hours to several days. Drying is important in the briquette process not only to reduce smoke emissions but also to enhance energy output and improve compaction efficiency (Obi et al., 2022). The dried sample was stored in a moisture-free environment to prevent reabsorption before proceeding to the briquette formation stage.

Briquetting

Briquetting is the process of compressing the sample by using a compression machine, which turns plant-based material into a uniform shape with the presence of binding agents. The machine processes loose material into compact charcoal with high mechanical strength, which improves combustion efficiency. Firstly, the dried sample was mixed with a binding agent (cassava starch). In this experiment, cassava stems with different concentrations (10, 20 and 30%) were mixed with plant-based material (Napier grass). The dried sample powder was combined with the binder and a small amount of water to create a uniform paste-like mixture. Next, the mixture was fed into a briquetting machine (Figure 3), which converted it into a solid under reasonable pressure. The charcoal needs to undergo a second drying once the briquettes are formed. The second drying was purposely to remove excess moisture before the final drying process took place. Proper briquetting ensures the briquettes burn efficiently (Olugbade et al., 2019).



Figure 3. Briquetting machines are used to compress biochar powder, along with binding agents, into solid charcoal briquettes

Final Drying and Storage of Charcoal Briquettes

The final drying in the briquetting process deliberately hardened the charcoal mixture between the plant-based material and the binder, thereby optimising its moisture content, especially for long-term storage. Normally, after the briquetting process, the charcoal still retains a slightly high moisture content of 15-20%. However, after final drying, the new moisture content is less than 8%, thereby reducing smog production and enhancing combustion efficiency (Rocha et al., 2017). Both initial and final drying were exposed to direct sunlight under racks or trays in an eCO_2 area for 2 to 5 days until the briquettes reached a constant weight. After drying, the briquettes were stored in sealed polyethene bags at room temperature (25 to 30 °C) in a dry, well-ventilated environment, protected from direct sunlight and moisture to minimise moisture uptake and preserve their physical and combustion properties prior to analyses, including physical and combustion tests (Song et al., 2010). The final step guarantees that the charcoal briquettes provide high heat output, long burn duration, and eco-friendly fuel properties.

Data Collection

Physical Analysis

Compression strength (CS) and hydrophobicity (HP) are important indicators for assessing briquette quality, measured with a digital hardness tester (YHKC-2A, particle strength tester, from Xinghuan, Jiangsu, China), which records the maximum force applied to the briquette charcoal. The hydrophobicity of a sample can be expressed as equilibrium moisture content (ECM), the amount of moisture retained by the material after reaching moisture equilibrium with the surrounding environment at specified temperature and relative humidity. Hydrophobicity (Equation 1) was defined as the tendency of a material to resist water absorption or repel moisture when exposed to humid environments or direct contact with water. Good hydrophobicity was indicated with a lower ECM reading of the briquettes. The ECM reading was calculated by exposing the briquettes to a relative humidity of 82-84% at 24-25 °C for 18 hours (controlled environment). The ECM was calculated using the following formula (ASAE, 2006):

$$\mathrm{ECM} = \frac{\mathrm{M} - \mathrm{Mi}}{\mathrm{M} \times 100\%} \quad [1]$$

Combustion Properties

The moisture content (MC, % db) of the samples was calculated after grinding 10 g of each charcoal sample at 130 °C for 1 hour in an air convection oven (Song et al., 2023). The particle density (PD) and porosity (Po) were measured by using a digital calliper

(Model CD-6CSX, Mitutoya Corp., Kawasaki, Japan), which recorded the diameter (d) and length (L) of each charcoal sample. The total charcoal sample was 5 individual briquettes from each treatment. The total weight of 5 briquettes was measured with a digital balance (KERN 572, Germany) with an accuracy of 0.01 g, while volume (Equation 2) and particle density (Equation 3) were calculated using the following formula.

$$vP = \frac{\pi}{4} d^2 L \quad [2]$$

$$PD \times \frac{mP}{vP} \quad [3]$$

Where,
vP = Volume of pellet (m^3)
PD = Particle density of pellet (kg/m^3)
d = Diameter of pellet (m)
L = Length of pellet (m)
mP = Mass of pellet (kg)

The bulk density (BD) was calculated in accordance with the ASAE standard. A cylindrical container with a size of 300 mm (height) and 310 mm (diameter) was used to measure the mass of briquettes (Bhagwanrao & Singaravelu, 2014). The ratio of the collective mass of charcoal in the container to its total volume (1,137 mm^3) was recorded. Using the following formula, the intergranular porosity (Equation 4) of the pellets will be determined by calculating the bulk density (BD) and particle density (PD).

$$\epsilon = 1 - \frac{BD}{PD} \quad [4]$$

Where,
ϵ = Porosity
PD = Particle density of pellet (kg/m^3)
BD = bulk density of pellets (kg/m^3)

Moisture sorption is the process by which a material absorbs and/or adsorbs water vapour from the surrounding atmosphere until it reaches equilibrium with the ambient temperature and relative humidity. Moisture sorption (MS, % w.b) was measured under fixed air humidity (70% and 80%) and temperature (400 °C) in a conditioned air chamber (1.8 × 0.9 × 0.9 m). Measure 300 g of the charcoal sample and place it in the sample

container. The sample was left in the chamber for 24 h in a conditioned-air environment. The charcoal sample was observed to see whether the briquettes further absorbed the moisture or disintegrated. The mass of the charcoal (g) was measured every 30 min. The recorded data will be analysed by expert software that fits an exponential model to the moisture sorption data (Equation 5). The formula is as follows.

$$MS = (Mi - Me) \times e - k + Me \quad [5]$$

Where,
T = Time
Me = Moisture content at time (%, w.b.)
Mi = Initial moisture content (%, w.b.)
K = Coefficient of sorption

Nutritional Profile

Measure and record the weight of 1.0 g of crushed charcoal before placing the sample into a digestion tube. Add 10 mL of concentrated nitric acid, then gently shake the digestion tube to mix the sample thoroughly. Left the sample overnight. Prepared a control digestion tube consisting of concentrated nitric acid with no sample. The digestion tube was boiled for 2 hours at 115 °C in the holes of the heating block. Next, 5 mL of concentrated hydrochloric acid was added, and the procedure was continued for 2 hours at 115 °C until a clear solution was observed. The charcoal sample was left to cool at room temperature for 2 hours. Then, transfer to a test tube and top up to 100 mL with deionised water. The sample was gently shaken and then filtered through filter paper (Whatman 42, 113, or equivalent) into a plastic container. The digested test material solution is ready for analysis by ICP-OES. Calculation:

1. Analysis of P, K, Ca, Mg and S by using ICPOES (Eq. 6):

$$\%\ \text{element} = \frac{\text{Reading from ICPOES} \times \text{dilution} \times \text{volume (mL)}}{\text{Weight of test material in gm} \times 10000} \times 100 \quad [6]$$

2. Analysis of reported in µg/g (ppm) (Eq. 7):

$$\mu\frac{g}{g}\text{element} = \frac{\text{reading from ICPOES} \times \text{dilution} \times \text{volume (mL)}}{\text{weight of test material in gm} \times 10000} \times 100 \quad [7]$$

Statistical Analysis

All data collected in this experiment were analysed by using two-way analysis of variance (ANOVA) by Statistical Analysis System (SAS 9.4) for a Completely Random Design (CRD) with two factors and consisted of four replications to ensure consistent results of significant differences between treatment means by using least significant difference (LSD) at $P < 0.05$ level.

RESULT AND DISCUSSIONS

Physical Analysis

Compression Strength

In this study, modelling and simulation of charcoal briquettes from Napier Grass (Pennisetum purpureum cv. Taiwan) are crucial, as they determine the briquettes' durability, handling efficiency, and structural integrity. Figure 4 showed that T6 (70% of BNG + eCO2 + 30% of CS) exhibited the highest peak force (~5.5 kN), indicating the strongest briquette structure due to its high starch content, which acted as a superior binder. T5 and T2 (20% cassava starch) also demonstrated good strength but slightly lower than T6, indicating a balanced effect of binding and compaction. On the other hand, T3 (70% of BNG-eCO2 + 30% of CS) showed the lowest peak force (~2.5 kN), implying weaker briquette formation under -eCO_2. Notably, T4 (90% BNG + eCO2 + 10% CS) had an ideal compression strength (~3.5 kN), supporting the view that eCO2 improves hydrophobicity but yields moderate mechanical strength due to its lower starch content. These results were particularly beneficial, facilitating easier lignification, allowing the briquettes to retain their shape and resist premature degradation while remaining workable for combustion applications.

The variation in force (kN) directly affects displacement (mm), influencing the way briquettes deform and break under pressure (Mitchual et al., 2013). Treatments with higher starch content (T6 and T3) generally exhibited greater displacement before breakage, were more ductile, and absorbed more energy before failure, thereby affecting burning efficiency. In contrast, briquettes with lower starch content (T1, T4) exhibited lower displacement, indicating that they were more brittle and easier to ignite. This suggests that increasing starch concentration improves structural flexibility but reduces the energy performance (Knoll et al., 2013). However, T4 emerged as the ideal treatment, as it achieved a balance between high hydrophobicity and moderate compressive strength, making it more resistant to moisture while still maintaining structural integrity (Mitchual et al., 2013). The relationship between force and displacement further indicates that starch enhances both strength and flexibility, reducing brittleness and improving coal durability (Safana & Usman, 2019). Therefore, optimising binder composition while considering hydrophobicity is essential for producing high-quality Napier grass charcoal briquettes (T4).

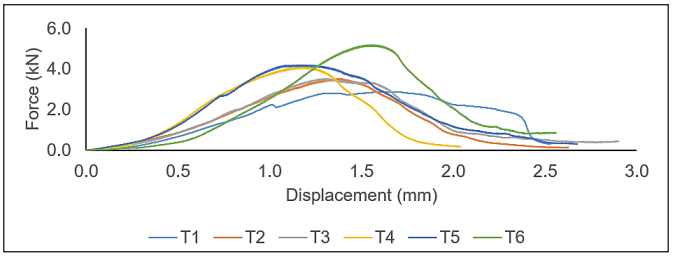


Figure 4. Effect of different material ratios between burnt Napier grass (BNG) and cassava starch (CS) on compression strength (Cs) of charcoal briquettes from Napier grass (Pennisetum purpureum cv. Taiwan)
Note. [T1] 90% of burnt Napier grass (BNG-eCO_2) + 10% of cassava starch (CS); [T2] 80% of BNG-eCO_2 + 20% of CS; [T3] 70% of BNG-eCO_2 + 30% of CS; [T4] 90% of BNG+eCO_2 + 10% of CS; [T5] 80% of BNG+eCO_2 + 20% of CS; and [T6] 70% of BNG+eCO_2 + 30% of CS

Hydrophobicity

Figure 5 shows that the combination ratio of Napier grass and cassava starch significantly affects hydrophobicity performance. In this study, T4 (90% BNG + eCO2 + 10% CS) showed the highest hydrophobicity reading among the treatments. Meanwhile, T5 (80% of BNG+eCO2 + 20% of CS) was recorded as the second-most hydrophobic, followed by T6 (70% of BNG+eCO2 + 30% of CS), which showed reductions of 28.04% and 32.75%, respectively, compared to T4. The results showed that a decreasing amount of burnt Napier grass reduced hydrophobicity from T4 to T6. T6 exhibits higher moisture absorption than T4, resulting in reduced charcoal stability, durability, and combustion performance. All treatments with -eCO_2 remained lower than the eCO2 treatment, with T1 (80% BNG-eCO2 + 20% CS) showing the highest reading among the groups. However, T2 and T3 show a negative impact on hydrophobicity, with reductions of 1.78% and 6.22%, respectively, compared to T1. This result shows that an increasing percentage of cassava starch negatively impacts hydrophobicity.

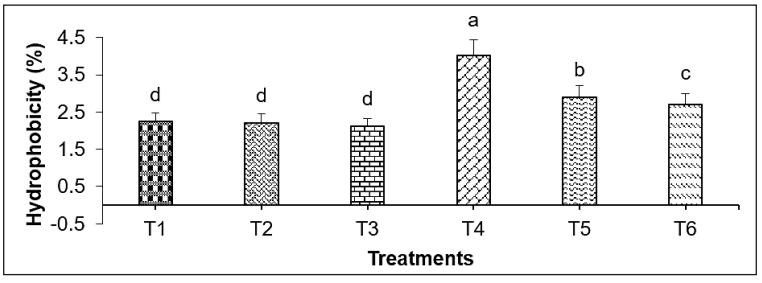


Figure 5. Effect of different material ratios between burnt Napier grass (BNG) and cassava starch (CS) on hydrophobicity (Hb) of charcoal briquettes from Napier grass (Pennisetum purpureum cv. Taiwan). Mean values with the same letter are not significantly different at P>0.05 by the least significant difference (LSD)
Note. n = 24, [T1] 90% of burnt Napier grass (BNG-eCO_2) + 10% of cassava starch (CS); [T2] 80% of BNG-eCO_2 + 20% of CS; [T3] 70% of BNG-eCO_2 + 30% of CS; [T4] 90% of BNG+eCO_2 + 10% of CS; [T5] 80% of BNG+eCO_2 + 20% of CS; and [T6] 70% of BNG+eCO_2 + 30% of CS

The lowest hydrophobicity was observed in T3 (2.11%), making it 47.6% less hydrophobic than T4, further proving that higher cassava starch proportions negatively impact moisture resistance due to the physical characteristics of starch as a hydrophilic material, absorbing moisture and reducing the water-repellent nature of the briquettes (Kupryianchyk et al., 2016). T1 and T4 exhibited greater hydrophobicity among their groups, especially T4, which has a more carbonised structure because of short eCO2, which can repel moisture.

In conclusion, a higher Napier grass content under T4 significantly improved hydrophobicity, thereby increasing ignition time and energy output from charcoal briquettes (Silviana et al., 2023). Additionally, T4 has become the most prominent treatment for biochar production, as it absorbs less moisture, achieves complete combustion, and exhibits high flame stability, resulting in reduced smoke production (Nyambati et al., 2010). Ultimately, the integration of hydrophobicity-enhanced briquettes in bio-coal applications can lead to more sustainable and high-performance biomass fuels, contributing to the advancement of renewable energy technologies, which are preferable for industrial and domestic use, as they maintain their quality over longer storage periods and provide a more consistent energy output (Ibeto et al., 2011).

Moisture Content

Figure 6 showed a significant effect of the combination ratio of burnt Napier grass and cassava starch on moisture content. The results show that T1 (90% of BNG-eCO2 + 10% of CS) recorded the highest moisture content, but no significant difference compared with treatment T2 (80% of BNG-eCO2 + 20% of CS) at 5.57% and T3 (70% of BNG-eCO2 + 30% of CS) at 5.74%. Besides that, treatment that exposed to $+eCO_2$ was showed significantly lower moisture content, with T6 (70% of BNG+eCO2 + 30% of CS) was recorded the lowest reading at 3.25%, T5 (80% of BNG+eCO2 + 20% of CS) at 2.94%, and T4 (90% of BNG+eCO2 + 10% of CS) at the lowest moisture content of 2.55%. The results show that eCO2 has enhanced the carbonisation of Napier grass, making it more repellent to moisture absorption compared to treatments T1–T3. The positive response improved the briquette's combustion quality and storage stability, attributable to the benefits of a good drying process (Fatmayati et al., 2025). Specifically, T4 emerges as the best candidate for industrial applications, with the lowest moisture content at 2.55% and the highest hydrophobicity, which are beneficial for shorter drying times, higher energy output, and decreased susceptibility to microbial degradation. Even T6 contributes positively to improved binding, reducing brittleness and improving handling characteristics, but excessive starch content can increase water absorption. In contrast, treatments T1–T3, which contain higher moisture levels, require more time to dry out all water content before they can be processed into briquette form (Hu et al., 2015).

In conclusion, T4 met all the physical and combustion properties required for industrial use due to its high hydrophobicity, high compressive strength, ease of ignition, and high combustion efficiency. Additionally, the balance between structural integrity and faster ignition makes T4 an ideal choice for industrial applications (Liao et al., 2025). Low moisture content is beneficial not only for combustion but also for survival during transportation, which is prone to breakage. The study highlights the importance of optimising raw material ratios and drying conditions to enhance the quality of plant-based charcoal briquettes, thereby supporting sustainable and efficient biofuel production (Vieira et al., 2020).

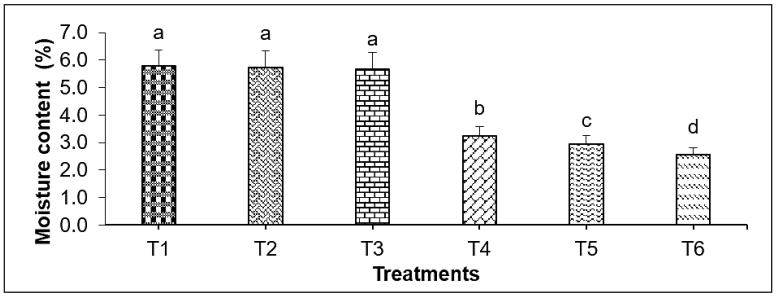


Figure 6. Effect of different material ratios between burnt Napier grass (BNG) and cassava starch (CS) on moisture content (MC) of charcoal briquettes from Napier grass (Pennisetum purpureum cv. Taiwan). Mean values with the same letter are not significantly different at P>0.05 by the least significant difference (LSD)
Note. n = 24, [T1] 90% of burnt Napier grass (BNG-eCO_2) + 10% of cassava starch (CS); [T2] 80% of BNG-eCO_2 + 20% of CS; [T3] 70% of BNG-eCO_2 + 30% of CS; [T4] 90% of BNG+eCO_2 + 10% of CS; [T5] 80% of BNG+eCO_2 + 20% of CS; and [T6] 70% of BNG+eCO_2 + 30% of CS

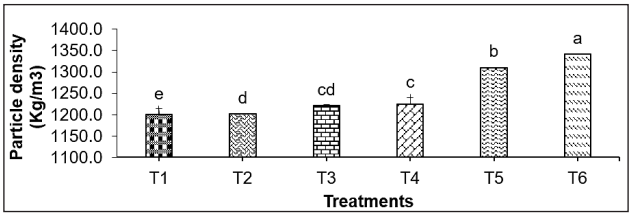
Particle Density (PD), Bulk Density (BD) and Porosity (Po)

In Figure 7, T6 exhibits the highest particle density (1341.826 kg/m³), which is approximately 20.1% higher than T1 (1119.461 kg/m³), indicating the strong compaction effect of increased cassava starch. Similarly, T5 and T4 have moderately high particle densities (1310.534 kg/m³ and 1224.216 kg/m³, respectively), reflecting a balance between binding efficiency and air permeability. In terms of bulk density, T6 records the highest value (355.992 kg/m³), about 9.5% higher than T1 (325.250 kg/m³), while T4 maintains a moderate bulk density (339.065 kg/m³), ensuring stability without excessive compaction. Regarding porosity, T1 has the highest value (0.741), approximately 21.5% higher than T6 (0.612), indicating that excessive cassava starch leads to a denser, less porous structure. T4, with a porosity of 0.726, offers a moderate balance between density and airflow, making it suitable for efficient combustion.

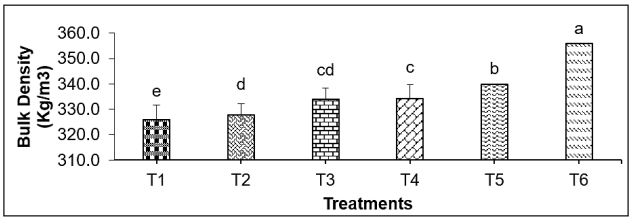
Among the six treatments, T4 (90% BNG + eCO2 + 10% CS) emerges as the best candidate for industrial application. This treatment provides a moderate particle density, an optimal bulk density, and balanced porosity, thereby improving combustion efficiency,

durability, and moisture resistance (Bhagwanrao & Singaravelu, 2014). Additionally, eCO_2 exposure enhances biomass quality by modifying lignin-cellulose composition, further strengthening the briquette structure. Even though T6 has the highest particle and bulk densities, with lower porosity, it reduces ignition efficiency, making it less desirable for industrial-scale production. Conversely, T1 and T2 exhibit lower density and higher porosity, leading to weaker structural integrity and increased moisture absorption, making them less suitable for commercial use (Wu & Kong, 2005).

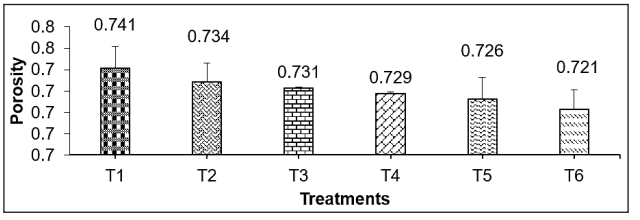
In conclusion, T4 stands out as the best choice for industrial use, as it ensures efficient combustion, mechanical durability, and resistance to environmental moisture. By carefully controlling the ratio of burnt Napier grass to cassava starch while exposing the mixture to +eCO2, this study provides a strong foundation for optimising charcoal briquette production from Napier grass as a sustainable energy source (Atumo et al., 2022).



(a)



(b)



(c)

Figure 7. Effect of different material ratios between burnt Napier grass (BNG) and cassava starch (CS) on (a) particle density (PD); (b) bulk density (BD) and (c) porosity (Po) of charcoal briquettes from Napier grass (Pennisetum purpureum cv. Taiwan). Mean values with the same letter are not significantly different at P>0.05 by the least significant difference (LSD)

Note. n = 24, [T1] 90% of burnt Napier grass (BNG-eCO_2) + 10% of cassava starch (CS); [T2] 80% of BNG-eCO_2 + 20% of CS; [T3] 70% of BNG-eCO_2 + 30% of CS; [T4] 90% of BNG+eCO_2 + 10% of CS; [T5] 80% of BNG+eCO_2 + 20% of CS; and [T6] 70% of BNG+eCO_2 + 30% of CS

Moisture Sorption (Ms). Moisture sorption reflects the performance of charcoal, showing a significant reduction in energy efficiency and briquette stability as drying costs increase. While low moisture content influences the briquettes' sturdiness, which leads to the occurrence of breakage (Engineer et al., 2016). In Figure 8, treatment with -eCO2 consistently showed higher readings than treatment with +eCO2, which recorded 90% BNG-eCO2 + 10% CS (T1). The value sharply increased after 10 hours of exposure and reached an accumulated value of ~27% over 50 hours. The results showed the briquettes had high porosity and hygroscopicity due to high BNG content. As the starch content increased from 80% BNG-eCO2 to 20% CS, the briquettes improved the binding proportion by reducing water uptake, slightly lowering moisture sorption (~21% at 50 hours) compared with T1. Meanwhile, T3 (80% of BNG-eCO_2 + 20% of CS) showed a lower moisture sorption value of ~18% at 50 hours, indicating the greatest hydrophobicity compared to T1 and T2. All treatments under +eCO_2 recorded much lower values than -eCO2, with T4 experiencing the highest (~13% at 50 hours) among the +eCO_2 treatments (T5 and T6). Besides, T4 is considered the best option for briquette charcoal, as it recorded a moderate reading across all treatments (+eCO2 and -eCO2), which likely reduced porosity better than the others. Followed by 80% of BNG+eCO_2 + 20% of CS (T5), which significantly reduced to ~11% after 50 hours of exposure, and most likely affected by both factors. A further decrease in the BNG ratio influenced the moisture sorption reading, which recorded the lowest moisture sorption (~9% at 50 hours), indicating a highly significant effect of hydrophobicity (Kymäläinen et al., 2015).

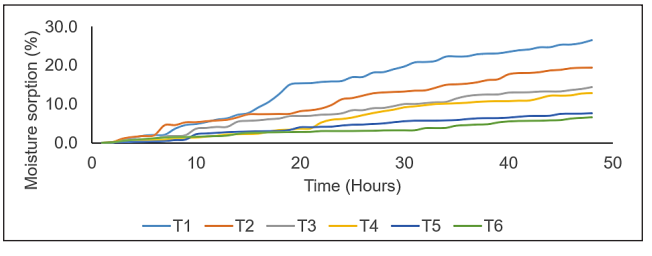


Figure 8. Effect of different material ratios between burnt Napier grass (BNG) and cassava starch (CS) on moisture sorption (Ms) of charcoal briquettes from Napier grass (Pennisetum purpureum cv. Taiwan)
Note. [T1] 90% of burnt Napier grass (BNG-eCO_2) + 10% of cassava starch (CS); [T2] 80% of BNG-eCO_2 + 20% of CS; [T3] 70% of BNG-eCO_2 + 30% of CS; [T4] 90% of BNG+eCO_2 + 10% of CS; [T5] 80% of BNG+eCO_2 + 20% of CS; and [T6] 70% of BNG+eCO_2 + 30% of CS

Treatment that exposed to +CO_2 were demonstrated lower moisture sorption (T4, T5 & T6) as compare -CO_2 (T1, T2 & T3), which resulting increasing in hydrophobicity under CO_2 exposure. However, T6 showed much lower moisture sorption as the starch content increased, which correlated with lower moisture absorption. The results indicated that briquettes improved the binding performance while reducing the porosity (Rodriguez

Correa et al., 2017). T4 (90% of BNG-eCO_2 + 0% of CS) represents the best option for coal production as it results from moderate moisture sorption and strongly correlates with particle density (PD), bulk density (BD), and porosity (Po) of charcoal briquettes (Mujeebu et al., 2009).

To achieve maximum charcoal performance, briquette formation must exhibit moderate moisture sorption, moderate compression strength, and high hydrophobicity, as shown in T4 (90% BNG + eCO_2 + 10% CS). Thus, a strong correlation between moisture sorption and particle density and porosity was important to maximise the potential of material composition to ensure higher energy yield, durability, and cost-efficiency in industrial applications.

Nutrient Profile

Table 2 showed a significant interaction between CO2 elevation and different ratios of burnt Napier grass + cassava starch for nitrogen, phosphorus, potassium, carbon, and sulphur content. Nitrogen content was remarkably higher when exposed to +eCO2, recorded at 54.5% compared to -eCO_2. Meanwhile, 90BNG + 10CS recorded the highest N concentration compared to other ratios, which lowered by 10.07% at 80BNG + 20CS and 17.3% at 70BNG + 30CS, respectively, with increased starch proportion. A similar trend was observed for phosphorus content, where the treatment exposed to +eCO2 had a higher P content by 63.16% compared to the treatment with -eCO_2. Meanwhile, 90BNG + 10CS is also remarkable as the highest P concentration, followed by 80BNG + 20CS, which reduced 16.67% and 36.4% at 70BNG + 30CS, respectively. Potassium content also presented the same pattern as other parameters, with eCO_2 causing a 5.0% increase overall, while the optimal ratio (90BNG + 10CS) maintained significantly higher K (4.22%) compared to 80BNG + 20CS (2.60%) and 70BNG + 30CS (4.27%). The results demonstrated that +eCO2 successfully enhanced nutrient uptake efficiency, with the highest BNG ratio and the lowest CN, likely supplying greater mineral ash content, collectively driving the significant interactions observed for N, P, and K.

In contrast, calcium and magnesium did not show a significant interaction between these two factors but were significantly affected by a single factor: +CO_2 showed much higher values than -CO_2, and the highest 90BNG + 10CS ratio among the ratios. However, carbon and sulphur showed a significant response, but not calcium and magnesium, which indicates differential nutrient sensitivity to CO_2 enrichment and amendment composition. In Table 2, carbon content was recorded as modestly increased when exposed to +CO_2 compared with -CO_2, with a difference of 7.11%. Carbon content also showed the highest value consistently recorded at 90BNG + 10CS, which is 2.34% higher than 80BNG + 20CS and 5.67% higher than 70BNG + 30CS. Sulphur content was exhibited more

pronounced in the interaction effect between eCO_2 and different ratios of BNG + CS, corresponding to 164.7% increase as compare to -eCO_2. While 90BNG + 10CS also recorded as the highest S concentration compared to 80BNG + 20CS (11.11%) and 70BNG + 30CS (25.00%), highlighting the strong dependency of sulphur availability on both carbon fertilisation and ash-rich BNG input. The results reflected the sulphur assimilation pathways; the effectiveness of mineral input from BNG was likely due to enhanced protein synthesis and the availability of sulphur-containing amino acids.

Combining both factors, eCO_2 and different BNG + CS ratios significantly affected the N, P, K, C and S contents, which increased the soil amendment or biochar value, and potentially contributed to improved nutrient-enriched charcoal. Potassium and phosphorus play important roles in enhancing nutrient retention and soil fertility, while nitrogen and sulphur concentrations activate microbial activity post-application. Even calcium and magnesium content were found not to have a significant interaction, but they contribute to pH buffering capacity without excessive variability. In conclusion, eCO2 enhanced the effectiveness of high BNG content in producing nutritionally superior modelling charcoal.

Table 2
The effect of different ratios of burnt Napier grass and cassava starch on nitrogen content, phosphorus content, potassium content, calcium content, magnesium content, carbon content and sulphur content of Napier grass (Pennisetum purpureum cv. Taiwan)

Treatments	Nitrogen (%)	Phosphorus (%)	Potassium (%)	Calcium (%)	Magnesium (%)	Carbon (%)	Sulphur (%)
Elevated CO_2 (eCO_2)							
-eCO_2	0.99b	0.19b	4.02b	0.31b	0.27b	40.08b	0.17b
+eCO_2	1.53a	0.31a	4.22a	0.35a	0.31a	42.93a	0.45a
LSD $_{(P<0.05)}$	0.08	0.03	0.09	0.03	0.02	1.12	0.04
Ratio (Burnt Napier grass + cassava starch)							
90BNG + 10CS	1.39a	0.30a	4.22a	0.35a	0.30a	42.65a	0.36a
80BNG + 20CS	1.25b	0.25b	4.11b	0.33b	0.29b	41.65b	0.32b
70BNG + 30CS	1.15c	0.22c	4.04c	0.32b	0.28b	40.23c	0.27c
LSD $P<0.05$	0.07	0.02	0.08	0.02	0.02	1.05	0.03
ECO_2 × Ratio	*	*	*	NS	NS	*	*

Note. Means followed by the same letter within a column are not significantly different at $P>0.05$ by the least significant difference (LSD) test with n = 32; NS = Not significant

CONCLUSION

This study demonstrated that the ratio of burnt Napier grass and cassava starch significantly influenced the physical, mechanical, combustion-related, and nutrient properties of the charcoal briquettes. Increasing the cassava starch binder improved compression strength and density but reduced porosity and moisture sorption. Among the formulations tested, T4 (90% burnt Napier grass + 10% cassava starch) exhibited the most balanced overall properties, including favourable mechanical strength, density, porosity, moisture sorption behaviour, and nutrient profile.

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LIST OF ABBREVIATIONS

°C	-	degree Celsius
%	-	percentage
BD	-	bulk density
BNG	-	burnt Napier grass
CO_2	-	Carbon Dioxide
cm	-	centimeter
CRD	-	Completely Randomised Design
CS	-	cassava starch
cv.	-	Cultivar
d	-	diameter
ECM	-	equilibrium moisture content
eCO_2	-	elevated carbon dioxide
g	-	gram
HP	-	hydrophobicity
L	-	length
mm	-	millimeter
MC	-	moisture content
NEP	-	National Energy Policy

PD - particle density
Po - porosity
U.S. - United States
vP - volume particle

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