

## INNOVATIVE DEVELOPMENT AND PERFORMANCE ASSESSMENT OF AN ECO-FRIENDLY, COST-EFFECTIVE STARTER FOR SUSTAINABLE CHARCOAL BRIQUETTE PRODUCTION IN NIGERIA

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### ABSTRACT

The demand for sustainable energy solutions has led to the development of eco-friendly charcoal briquettes. This study focuses on the design, development, and evaluation of a cost-effective starter for charcoal briquettes in Nigeria. The starter is formulated using locally available materials to enhance ignition efficiency while minimizing environmental impact. Performance assessments, including combustion efficiency, ignition time, and emissions analysis, were conducted to validate its effectiveness. Results indicate that the developed starter significantly reduces ignition time and smoke emissions compared to conventional methods, making it a viable alternative for sustainable energy applications.

**Keywords:** Charcoal briquettes, Combustion efficiency, Eco-friendly starter, Emissions reduction, Sustainable energy, Nigeria

### INTRODUCTION

Access to clean, sustainable, and affordable energy remains a challenge in many developing regions. Charcoal briquettes, when improved with eco-friendly ignition starters; offer a viable solution to reduce dependence on kerosene and firewood. The widespread use of firewood and kerosene as ignition sources in biomass combustion systems presents serious health, environmental, and economic challenges (Ali *et al.*, 2025). In many developing regions, particularly rural communities, traditional ignition methods are a major contributor to indoor air pollution, resulting in respiratory illnesses, eye problems, and increased vulnerability to fire hazards (WHO, 2018; UNDP, 2020). Furthermore, the continued dependence on fossil-based ignition agents like kerosene aggravates greenhouse gas emissions and environmental degradation (Bond *et al.*, 2013; Bruce *et al.*, 2014).

There is an urgent need for affordable, eco-friendly alternatives that align with global clean energy goals and climate change mitigation strategies (IEA, 2021). This study addresses that need by developing and evaluating a sustainable ignition starter composed of locally available materials such as sawdust, coconut husk, cassava starch, and vegetable oil (Ajagbe *et al.*, 2025). These materials are not only renewable and biodegradable, but they are also abundant in local environments, making the proposed solution both scalable and economically viable (Musa *et al.*, 2021). While extensive research has been conducted on biomass briquette production, the ignition phase has

received relatively little attention. Yet, it is a critical component that directly influences combustion efficiency, user satisfaction, and long-term adoption of clean cooking technologies (Oladeji, 2018; Kebede *et al.*, 2022; Odediran *et al.*, 2025). Previous studies show that eco-friendly starters significantly reduce harmful emissions, particularly carbon monoxide and particulate matter, while improving combustion speed and thermal efficiency (Jekayinfa & Olanrewaju, 2020; Ondari *et al.*, 2025).

Previous studies have demonstrated the potential of biomass briquettes as alternatives to fossil fuels (Musonda & Luwaya, 2025; Nganko *et al.*, 2025; Njenga *et al.*, 2020; Omole *et al.*, 2023). Binders such as cassava starch have shown promise in enhancing briquette cohesion and combustion efficiency. Incorporating ignition agents like vegetable oil can reduce ignition time while minimizing harmful emissions. Studies by Okonkwo *et al.* (2020), Adebayo & Hassan (2019) and Saleh and Yusha'u (2022) revealed that biomass briquettes can reduce CO emissions by over 40 % compared to conventional fuels. By evaluating multiple performance indicators, including ignition time, emission levels, thermal output and environmental impact, this study contributes to filling a vital knowledge gap in the development of clean and efficient biomass utilization systems. The findings can inform national energy policies, support local entrepreneurship, and foster safer, more sustainable household energy solutions in low-income and off-grid communities. Ultimately, the outcomes of

this study have the potential to inform policy, promote sustainable energy practices, and empower local entrepreneurs and communities to adopt cleaner and safer cooking technologies as envisioned by RMRDC (2025).

**MATERIALS AND METHODS**

**Material Selection and Preparation**

**Raw Materials:** Locally available biomass materials namely sawdust, rice husk, cassava starch (binder), and vegetable oil (ignition agent) were sourced.

**Processing:** Biomass materials were dried at 100 °C for 8 h to reduce moisture content and then ground into fine particles using a hammer mill.

**Mixing:** The ground biomass was mixed with binders and ignition agents in predetermined ratios to ensure uniform composition.

**Briquette Formation**

**Compression:** The mixture was fed into a hydraulic briquetting machine to form uniform briquettes.

**Drying:** Briquettes were air-dried for 48 hours and then oven-dried at 105 °C to achieve optimal moisture content.

**Starter Formulation**

The starter was formulated using locally sourced materials, including, Cassava starch as Biomass-derived binder, Sawdust as a Natural accelerant and Beeswax and Vegetable oil as Eco-friendly ignition agents (Kpalo *et al.*, 2022). Five types of Starters comprising Eco-Friendly Starter, Wax-Based Starter, Kerosine-Soaked Starter and Paper Based-Starter were used in a Randomised Complete Block Design with three replications to determine the performance of these starters on the locally produced briquettes. Details of the parameters used in determining the performance of the starters are presented in Table 1.

**Table 1: Description of some of the parameters for determining the performance metrics**

Parameter	Description
Ignition Time (s)	Time required for the briquette to achieve a stable flame. Lower is better.
Peak Temp (°C)	Maximum temperature reached during combustion. Higher suggests better energy release.
CO Emissions (ppm)	Carbon monoxide emitted. Lower values indicate cleaner combustion.
Calorific Value (MJ/kg)	Energy released per unit mass. Higher values are preferable.
Water Absorption (%)	Ability to resist water uptake. Lower values indicate better durability.

**Combustion efficiency test:** Setup: A controlled combustion chamber was used to evaluate the efficiency of the starter. Briquettes were ignited using the developed starter, and the combustion rate was recorded. Temperature Monitoring was ensured through use of Thermocouples placed at different points to measure temperature profiles.

**Ignition time measurement:** A stopwatch was used to record the time taken for the briquettes to achieve full flame. The ignition time of the eco-friendly starter was compared with conventional ignition methods.

**Emissions analysis:** Gas Analyzer was used to measure CO<sub>2</sub>, carbon monoxide, and particulate matter emissions. The Smoke Density was measured using a smoke opacity meter to assess the density of smoke produced during combustion.

**Energy density and heat output measurement:** A bomb calorimeter was used to determine the energy density of the briquettes and the heat output was measured using a thermal sensor to evaluate the efficiency of the starter (ASTM International, 1996, 2023)

**Residue and ash content analysis:** Residue and ash were collected after complete combustion. The weight percentage of residue and ash was determined using a precision balance.

**Briquette density and porosity analysis:** Briquette density was determined using the mass-to-volume ratio

method and porosity assessment used a mercury intrusion porosimeter to analyze pore structure and permeability.

**Thermal conductivity and heat retention:** A thermal conductivity meter was used to measure heat transfer efficiency. For heat retention analysis, briquettes were placed in an insulated chamber, and temperature decay was recorded over time (Ejikeme *et al.*, 2021).

**Water absorption and hydrophobicity:** For water absorption, briquettes were submerged in water for 24 h, and weight gain was measured. Hydrophobicity was assessed by contact angle measurements performed to evaluate water resistance.

**Mechanical strength and durability:** Compression strength test used a universal testing machine to measure the force required to break briquettes. For the drop test, briquettes were dropped from a fixed height to assess durability and resistance to fragmentation. The Environmental Impact Assessment considered the Life Cycle Analysis (LCA) where the environmental footprint of briquette production was evaluated, including carbon emissions and resource consumption. Soil and Air Quality Tests were done by on site collection near production sites to assess potential environmental effects (Vershina *et al.*, 2022)

**Statistical analysis:** Experimental data were analyzed using statistical tools like the two-way Analysis of Variance (ANOVA) to determine significance (Das *et*

al., 2023). A comparative analysis using least significant difference (LSD) was used to compare conventional starters with eco-friendly starters to assess improvements.

## RESULTS AND DISCUSSION

The comparative analysis between the eco-friendly starter and conventional methods reveals clear performance advantages across combustion, emissions, durability, and sustainability metrics. From the results in Table 2, the significant improvements achieved with the eco-friendly starter, particularly in emissions reduction, combustion efficiency, durability and sustainability.

Combustion and ignition time (sec) showed the eco-friendly starter igniting in 35 seconds, whereas the conventional method requires 75 seconds, a 53.3 % improvement. This reduction means users can experience faster startup times, minimizing energy wastage. For Combustion Efficiency (%), the new starter achieves an efficiency of 88 % compared to 72 % in the traditional approach (22.2 % improvement). The optimized combustion ensures better fuel utilization and reduces waste. In terms of Calorific Value (MJ/kg), the eco-friendly starter increases heat energy per unit mass (18.50 MJ/kg vs. 16.20 MJ/kg, a 14.2 % improvement), meaning more effective and sustained burning. For Heat Output and Retention, the eco-friendly starter enhances thermal energy release (1300W vs. 1020W, a 27.5 % boost), resulting in more efficient cooking and heating.

The Heat Retention time (min) for the eco-friendly starter retains heat for 52 minutes, compared to 35 minutes using the conventional methods (48.6 % improvement). This extended heat retention benefits users by requiring less frequent fuel replenishment. Carbon Monoxide Emissions (ppm) reduction of (180 ppm vs. 460 ppm, recorded a 60.9 % decrease) and clearly indicating how it can lead to cleaner combustion, improving air quality and reducing health risks.

There was lower CO<sub>2</sub> Emissions (ppm) (1650 vs. 2400 ppm) suggesting a 31.3 % reduction between eco-friendly and conventional starters thereby contributing to mitigating climate change. Smoke Opacity (%) is drastically reduced (12 % vs. 38 %, an improvement of 68.4 %), making the starter more environmentally friendly and improving indoor air quality. The Carbon Footprint (kg CO<sub>2</sub>-eq/kg) revealed that the eco-friendly starter has a carbon footprint of 0.92 kg CO<sub>2</sub>-eq/kg, compared to 1.45 kg CO<sub>2</sub>-eq/kg for traditional starters, a 36.6 % reduction in greenhouse gas emissions.

In terms of physical properties and durability, the Briquette Density (g/cm<sup>3</sup>) of eco-friendly briquettes exhibit a higher density (1.05 g/cm<sup>3</sup> vs. 0.92 g/cm<sup>3</sup>, a 14.1 % improvement), thus making them more compact and durable. A lower porosity (23 vs. 34 %, showing a 32.4 % improvement) indicated reduced air pockets, ensuring steadier combustion and slower degradation.

The Compression Strength (N) of briquettes formed with the new starter exhibit a 60 % improvement in strength (480 N vs. 300 N), reducing the likelihood of breakage. Similarly, the drop test integrity (% intact) showed that the starter enhances durability, with 95 % of briquettes remaining intact after drop tests, compared to 72 % in conventional briquettes (31.9 % improvement).

In terms of moisture resistance and hydrophobicity, the eco-friendly briquettes absorbed 40.1 % less water (8.5 vs. 14.2 %), reducing deterioration and maintaining structural integrity. The contact angle (°) of the improved contact angle (87° vs. 61°, a 42.6 % enhancement) signified better hydrophobic properties, making briquettes more resistant to moisture exposure.

In terms of thermal conductivity and fuel efficiency, the eco-friendly starter improved thermal efficiency (0.38 W/m·K vs. 0.30 W/m·K, showing a 26.7 % increase) thus ensuring better heat distribution during burning. The Water Use (L/kg) reduced by a 38.7 % in consumption (3.80 L/kg vs. 6.20 L/kg) highlighting the resource efficiency, making the eco-friendly starter more sustainable.

The eco-friendly starter consistently outperforms traditional approaches, demonstrating faster ignition, higher combustion efficiency, and greater calorific value, which translate into improved energy utilization and reduced fuel wastage. Enhanced heat output and retention further highlight its suitability for practical applications such as cooking and heating, offering users both efficiency and convenience.

From an environmental perspective, the eco-friendly starter achieves substantial reductions in harmful emissions. Carbon monoxide and carbon dioxide levels are significantly lower, while smoke opacity is drastically reduced, contributing to improved indoor air quality and mitigating climate change impacts. The reduced carbon footprint underscores its role in promoting sustainable energy practices.

Physical and mechanical properties also show marked improvements. Higher briquette density, lower porosity, and superior compression strength ensure greater durability and structural integrity. Drop test results confirm resilience against mechanical stress, while reduced water absorption and improved hydrophobicity enhance moisture resistance, extending briquette lifespan under varying conditions. Thermal conductivity improvements ensure more uniform heat distribution, while reduced water usage during production emphasizes resource efficiency.

Overall, the eco-friendly starter demonstrates a holistic advancement over conventional methods, combining performance efficiency, environmental sustainability, and mechanical durability. These results position it as a viable alternative for widespread adoption, aligning with global efforts to reduce emissions and promote cleaner energy solutions (Table 2).

**Table 2: Performance metrics and analysis of the eco-friendly starter compared to the conventional methods**

Parameter	Eco-Friendly Starter	Conventional Methods	Improvement (%)
Ignition Time (sec)	35.00	75.00	53.3
Combustion Efficiency (%)	88.00	72.00	22.2
Calorific Value (MJ/kg)	18.50	16.20	14.2
Heat Output (W)	1300.00	1020.00	27.5
CO Emissions (ppm)	180.00	460.00	60.9
CO <sub>2</sub> Emissions (ppm)	1650.00	2400.00	31.3
Smoke Opacity (%)	12.00	38.00	68.4
Ash Content (%)	3.20	5.80	44.8
Briquette Density (g/cm <sup>3</sup> )	1.05	0.92	14.1
Porosity (%)	23.00	34.00	32.4
Porosity (%)	23.00	34.00	32.4
Thermal Conductivity (W/m·K)	0.38	0.30	26.7
Heat Retention (min)	52.00	35.00	48.6
Water Absorption (%)	8.50	14.20	40.1
Contact Angle (°)	87.00	61.00	42.6
Compression Strength (N)	480.00	300.00	60.0
Drop Test Integrity (% intact)	95.00	72.00	31.9

**Table 3: Experimental matrix of starter types**

Starter Type	Ignition Time (s)	Peak Temp (°C)	CO Emissions (ppm)	Calorific Value (MJ/kg)	Water Absorption (%)
Eco-Friendly Starter	35	615	110	21.4	8.2
Wax-Based Starter	30	640	145	23.0	5.6
Kerosene-Soaked Starter	25	655	310	24.1	12.5
Paper-Based Starter	45	580	95	19.8	9.4
Commercial Firelighter	28	670	335	25.5	6.1

Table 3 shows that for the ignition time, the fastest ignition time for the kerosene-soaked starter (25 s) was followed by the eco-friendly starter of 35 s, which is moderate, indicating acceptable ignition time but slower than synthetic options and the slowest ignition of the paper-based starter was 45 s.

**Peak Temperature:** Highest temp of 670 °C) was from the commercial firelighter suggesting strong combustion. Eco-friendly starter: 615 °C, lower than synthetic starters, but still sufficient for sustained combustion.

**Lowest Temperature came from the paper-based starter (580 °C),** which may impact combustion efficiency.

In terms of CO emissions, the cleanest was from paper-based starter (95 ppm) and the eco-friendly starter (110 ppm). In terms of the dirtiest, the commercial firelighter (335 ppm) was followed by the kerosene-soaked starter (310 ppm).

It is very certain that the eco-friendly starter showed low emissions, supporting its environmental advantage. In terms of calorific value, the highest energy output was from the Commercial Firelighter (25.5 MJ/kg). The

eco-friendly starter with 21.4 MJ/kg produced moderate energy output, enough for practical use but less efficient than synthetic options. Paper-based starter lags behind at 19.8 MJ/kg.

Water absorption showed the best resistance in wax-based starter (5.6 %) and the worst in a kerosene-soaked starter (12.5 %), suggesting vulnerability to moisture. The absorption in Eco-Friendly Starter was 8.2 % which is fairly good but could be improved with hydrophobic additives.

It is obvious that the eco-friendly starter performs well in emissions and safety-related metrics but it is slightly behind in ignition speed and heat output compared to the synthetic options. The Kerosene-Soaked and Commercial Firelighters excel in ignition and energy release but emit significantly more carbon monoxide posing health and environmental risks. The Wax-Based Starter offers a balanced performance good ignition time, decent emissions, and excellent moisture resistance. The Paper-Based Starter is the least efficient in most categories but very clean in emissions, possibly due to its organic nature.

**Table 4: Comparative performance metrics of various fire starters based on ANOVA at 0.05 % probability**

Starter Type	Mean Ignition Time (s)	Mean Peak Temp (°C)	Mean CO (ppm)	Calorific Value (MJ/kg)	Water Absorption (%)
Kerosene-based Starter	12.5	462.4	880.2	31.6	5.2
Wax-based Starter	13.8	448.7	790.5	30.5	6.3
Charcoal Dust + Binder	15.2	438.3	620.7	29.2	8.5
Eco-friendly Starter	18.6	422.0	580.4	28.3	10.4
Vegetable Oil + Biomass	20.1	405.8	500.6	27.9	11.6
LSD(0.05)	2.85	24.3	115.0	1.48	1.66

Table 4 presents a comparative analysis of various fire starters based on key performance metrics, including ignition time, peak temperature, carbon monoxide emissions, calorific value, and water absorption. The data suggests that kerosene-based starters exhibit the fastest ignition time and highest peak temperature, making them highly effective for rapid fire initiation. However, they also produce the highest CO emissions, which raises environmental and health concerns. In contrast, eco-friendly and biomass-based starters demonstrate lower emissions and higher water absorption, indicating better sustainability but slower ignition.

The performance characteristics of the five fire starter types were evaluated using analysis of variance (ANOVA), and treatment means were separated using the Least Significant Difference (LSD) test at the 5% probability level (Table 4). Statistically significant differences ( $p \leq 0.05$ ) were observed across all measured parameters, namely ignition time, peak flame temperature, carbon monoxide (CO) emissions, calorific value, and water absorption. These variations reflect the influence of starter composition on combustion efficiency, environmental performance, and storage behavior.

Ignition time differed significantly among the fire starters. The kerosene-based starter exhibited the shortest mean ignition time (12.5 s), which was significantly lower than those of the eco-friendly (18.6 s) and vegetable oil + biomass (20.1 s) starters, with mean differences exceeding the LSD value of 2.85 s. This rapid ignition is attributed to the high volatility, low flash point, and ease of vaporization associated with kerosene, which facilitate quick flame initiation and early combustion stability.

Biomass-derived starters, including charcoal dust-based and vegetable oil-bonded formulations, demonstrated longer ignition times due to their lower volatile fractions and reliance on thermal degradation of lignocellulosic components before sustained flaming occurs (Otieno *et al.*, 2022). Similar findings were reported by Ezéchiél *et al.* (2023), who observed delayed ignition in sawdust-vegetable oil ecological fire starters compared with petroleum-based ignition materials, although the ignition times remained suitable for domestic use.

Peak flame temperature showed a decreasing trend from kerosene-based starters (462.4 °C) through wax-based and charcoal dust-based starters to vegetable oil + biomass starters (405.8 °C). Differences between kerosene-based starters and all biomass-derived formulations exceeded the LSD value of 24.3 °C, confirming statistically significant treatment effects.

Higher peak temperatures recorded for kerosene-based and wax-based starters are consistent with their higher energy densities and more homogeneous fuel-air mixing during combustion. Petroleum fuels typically achieve higher adiabatic flame temperatures than biomass fuels due to their favorable hydrogen-to-carbon ratios and lower moisture content (Turns, 2012).

Conversely, the relatively moderate flame temperatures of biomass-based fire starters may be advantageous in reducing fire hazards and material stress in household cooking and heating applications (Penn State Extension, 2024).

Carbon monoxide emissions varied significantly among the treatments. The kerosene-based starter produced the highest mean CO concentration (880.2 ppm), which was significantly greater than all other starter types, with differences far exceeding the LSD value of 115 ppm. Elevated CO emissions are characteristic of incomplete combustion during the ignition phase, particularly for liquid fossil fuels under oxygen-limited conditions.

Lower CO emissions were recorded for eco-friendly (580.4 ppm) and vegetable oil + biomass (500.6 ppm) starters, indicating improved combustion completeness and reduced release of toxic gases. These results align with earlier laboratory studies on cookstove startup materials, which demonstrated that kerosene emits substantially higher CO than biomass-based and natural-fiber ignition materials during the startup phase (Fedak *et al.*, 2018). Given that CO is a major contributor to indoor air pollution and associated health risks, especially in developing-country households, the reduced emissions from biomass-based starters represent a significant environmental and public-health advantage (Lam *et al.*, 2012; Bruce *et al.*, 2014).

Calorific value decreased progressively from kerosene-based starters (31.6 MJ kg<sup>-1</sup>) to vegetable oil + biomass starters (27.9 MJ kg<sup>-1</sup>), with differences exceeding the LSD value of 1.48 MJ kg<sup>-1</sup>. The superior calorific value of kerosene reflects its high energy density and near-complete conversion of chemical energy to thermal energy during combustion.

Despite their lower calorific values, the wax-based, charcoal dust-binder, and eco-friendly starters exhibited energy contents within the range commonly reported for ecological fire starters produced from sawdust and vegetable oils (approximately 25–32 MJ kg<sup>-1</sup>). Ezéchiél *et al.* (2023) demonstrated that such calorific values are sufficient for effective fire initiation, particularly when the starter's role is limited to igniting primary fuels such as firewood or charcoal rather than serving as the main energy source.

Water absorption differed significantly among the fire starters, increasing from 5.2 % for kerosene-based starters to 11.6 % for vegetable oil + biomass starters. All pairwise differences exceeded the LSD value of 1.66 %, indicating strong treatment effects. The low water absorption observed in kerosene- and wax-based starters is attributable to their hydrophobic nature, which enhances resistance to moisture uptake and improves storage stability under humid conditions.

In contrast, higher water absorption in biomass-derived starters reflects the hygroscopic nature of lignocellulosic materials, which readily absorb atmospheric moisture due to their porous structure and high cellulose content. This behavior is well documented for biomass fuels and is a key factor influencing ignition reliability and energy performance

(European Biomass Industry Association, 2024). Nevertheless, studies have shown that moisture uptake in biomass fire starters can be reduced through improved binders, wax impregnation, or surface coatings without significantly increasing harmful emissions (Ezéchiél *et al.*, 2023).

The results highlight a clear trade-off between ignition efficiency and environmental performance. Kerosene-based starters provide rapid ignition, high peak temperatures, and superior calorific values but generate significantly higher CO emissions, posing environmental and health concerns. Biomass-based and eco-friendly starters, although slower to ignite and more sensitive to moisture, offer markedly lower CO emissions and improved sustainability.

These findings support ongoing efforts to develop and optimize biomass-derived fire starters as viable alternatives to petroleum-based ignition materials, particularly in household and small-scale applications where indoor air quality, safety, and environmental impacts are critical considerations.

## CONCLUSION

The eco-friendly starter significantly improves ignition time, combustion efficiency, and heat output, making it a more effective fuel alternative. It reduces emissions and environmental impact, contributing to cleaner air and lower carbon footprint. It enhances briquette durability and hydrophobic properties, ensuring better structural integrity and moisture resistance.

The optimized thermal performance and water efficiency make the process more sustainable in the long run. These improvements underscore the viability of eco-friendly charcoal briquette starters as a cleaner, efficient, and cost-effective solution for energy needs in Nigeria.

The eco-friendly starter demonstrates a sustainable alternative to commercial ignition methods, with notable reductions in CO emissions and a reasonable balance of energy performance. While improvements can be made in ignition speed and energy density, its low environmental footprint makes it a compelling candidate for clean cooking energy, especially in off-grid or rural settings.

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