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*Research Article*

# Performance and economic evaluation of a locally fabricated biochar kiln for sustainable production from agricultural residues in Ghana

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**Abstract**
Biochar has gained attention due to its potential to improve soil carbon storage and mitigate climate change. However, to encourage widespread adoption, biochar production must be cost-efficient and easily accessible, particularly from farm residues. The present study evaluates the performance of a self-energy-recirculating, locally fabricated biochar kiln using five feedstocks: maize cob, rice husk, coconut shell, and flamboyant pods. The specialised kiln can char all organic-based feedstocks, regardless of the particle size. The focus was on energy use efficiency, biochar yield, and the quality of the produced biochar. The study used a slow pyrolysis ranging from 300 ˚C to 600 ˚C. Results showed that biochar quality varied across feedstocks, with coconut shells and rice husks requiring more energy but yielding higher amounts of biochar than flamboyant pods, maize cob, and maize stover. Economic analysis indicated that coconut shells and maize cob were the most profitable feedstocks, with profit margins of 57.05% and 76.96% and internal rates of return of 3.75 and 1.84, respectively. This suggests that while some feedstocks are more energy-intensive, they offer higher financial returns. Further studies on the environmental benefits of these biochars, both short-term and long-term, are necessary. The findings of this study provide a basis for the development of kilns suited to local conditions, promoting the economical production of biochar from agricultural residues.

**Keywords**: Locally fabricated biochar kiln, Biochar production efficiency, Farm residue, Climate change mitigation

## INTRODUCTION

With the global population rising, ensuring food security for the expanding populace has become imperative (Kolog *et al*., 2023; Wambogo *et al*., 2018). This challenge involves addressing critical issues such as land degradation caused by poor agricultural practices and environmental damage. Over the past four decades, 30% of the world's fertile land has become barren due to erosion (Li *et al*., 2025; Ma *et al*., 2024). If this trend is not reversed, meeting the dietary needs of the growing population will become increasingly difficult. A crucial aspect of reversing soil degradation is enriching soil with carbon, creating an environment where substantial amounts of atmospheric carbon can be stored (Huang *et al*., 2024; Wang *et al*., 2025). Prioritizing the preservation and restoration of soil carbon must become humanity's guiding principle for sustainably nourishing ourselves, mitigating climate change, and safeguarding our planet's future (Lal, 2020). Inadequate carbon management within biomass feedstocks can result in its release as gases, contributing to global warming (Mustika *et al*., 2025). This issue is exacerbated by environmental factors, such as biomass decomposition, which releases large amounts of greenhouse gases, and inadequate waste management practices, including open-burning of agricultural residues (Ullah *et al*., 2024; Geronimo *et al*., 2022).

Effectively harnessing the carbon and nutrients in agricultural and forest residues is essential for advancing a circular economy. These residues can enhance soil quality after decomposition, either by direct incorporation into the soil or through composting or anaerobic digestion. Alternatively, agricultural residues with high fibre content can serve as valuable livestock feed, aiding digestion and supplying essential nutrients (Urdaneta *et al*., 2024). However, certain residues, such as rice husks and straw, decompose slowly and are less digestible due to their high silicon content and carbon-to-nitrogen ratio (Aung *et al*., 2024). As a result, these residues are often inefficiently burned for energy, leading to significant nutrient depletion and the release of particulate matter, ammonium ($NH_3$), and carbon monoxide (CO) emissions (Othman *et al*., 2024; Brauch *et al*. 2019 ). The indiscriminate burning of rice husk, maize cob, and maize stover in open environments releases hazardous substances that can cause respiratory diseases and death (Phuong *et al*., 2021; Kumar *et al*., 2019). Therefore, kilns that are less expensive and better suited to the local environment are needed to produce biochar, which can improve carbon storage and soil nutrition. Limited information regarding locally developed biochar kilns is available due to a lack of characterization. This characterization process will provide engineers with valuable insights into optimizing kiln performance for maximum efficiency.

The conversion of agricultural waste into biochar addresses waste disposal challenges while combating climate change, as the carbon inherent in biochar, can be sequestered in soil for extended periods (Sarode *et al*., 2023). Significant potential exists for localized benefits and broader global advantages from scaled-up carbon-financed Improved Cook Stove (ICS) programs, underscoring the importance of sustainable engineering designs in effectively harnessing these benefits (Alawa *et al*., 2025). Efforts over recent decades to develop improved kilns have resulted in various types that reduce fuel consumption by 40% and associated emissions by an equivalent amount, with over 100,000 units produced annually (Joseph *et al*., 2015). The utilization of improved biochar kilns for biochar production shows promise, and the ability to characterize these devices is invaluable, particularly when it can be achieved without compromising biochar yield, expanding the existing knowledge base (Unsomsri *et al*., 2025; Patel and Panwar, 2024;).

Evaluating this kiln will give engineers insights into its simplicity of fabrication, portability, lack of proprietary constraints, and economic feasibility. The potential for significant biochar yields upon scaling up its design is a compelling factor driving this endeavour. Technologies that balance user-friendliness, energy efficiency, adaptability, and emission reduction can be seamlessly integrated into local communities for sustainable and environmentally friendly biochar production, addressing both technical and socio-economic aspects (Chaudhary *et al*., 2024; Mittal *et al*., 2023). Nonproprietary high-quality technologies can be tailored to recover the heat generated during production and produce biochar for soil enhancement, thereby improving agricultural attributes. While biochar can be produced using traditional charcoal kilns, these methods are highly inefficient and significantly contribute to environmental pollution (Mukherjee *et al*., 2014). Developing more environmentally friendly biochar kilns would mitigate this issue (Tan *et al*., 2023; Zhang *et al*., 2024).

Using agricultural waste for biochar production can benefit the agricultural sector if these residues are efficiently converted into biochar and applied to the soil. Incorporating biochar into the soil as an amendment enhances crop yields and productivity, lowers soil acidity, and reduces the need for certain chemical fertilizers (Yue *et al*., 2017; Hossain *et al*., 2021; Mia *et al*., 2015)). Furthermore, biochar offers a potential long-term carbon sink due to its resistance to chemical and biological degradation, allowing it to persist in soil for extended periods (Singh *et al*., 2025). Biochar also promises to enhance low-fertility soils by improving their cation exchange capacity, raising soil pH levels, and enhancing water retention capacity, thereby increasing crop yields (Chen *et al*., 2023; Rhymes *et al*., 2024; Wang *et al*., 2023). Cost-benefit analysis is crucial in evaluating the economic viability of various applications, including biochar production and utilization. Numerous studies emphasize the importance of comprehensive cost-benefit analyses to assess the financial implications of biochar projects (Campion *et al*., 2023; Ha *et al*., 2025). These analyses consider factors such as revenue generation, total costs, profits, Return on Investment (ROI), Cost-Benefit Ratio, Net Present Value (NPV), and Internal Rate of Return (IRR) to provide insights into the financial performance of biochar initiatives ((Ng *et al*., 2017; Danso *et al*., 2023). Studies comparing biochar technologies with traditional methods demonstrate the economic benefits of biochar in terms of greenhouse gas mitigation, energy balance, and overall economic gains ((You & Wang, 2019; Danso *et al*., 2023). However, challenges like production costs and pricing remain significant hurdles in biochar cost-benefit analyses. The financial feasibility of biochar projects depends on factors such as subsidies for carbon sequestration, as evidenced in studies focusing on soybean production in Poland (Ha, 2025;). While some analyses show positive net benefits associated with soil organic amendments, others indicate that the economic viability of biochar applications can vary (Martins *et al*., 2025; Merida *et al*., 2024; Dhingra & Kumar, 2025).

The general objective of the present study was to compare the performance of the locally developed biochar kiln on maize cob, rice husk, coconut shell, and flamboyant pods and determine its economic viability, specifically: 1) determine the energy efficiency, specific fuel consumption (SFC), biochar yield, and energy expended for maize cob, rice husk, coconut shell, maize stover, and flamboyant pods; 2) determine the quality of the biochar produced, charring rate, and time for maize cob, rice husk, coconut shell, maize stover, and flamboyant pods; 3) determine the economic feasibility of the locally developed biochar kiln. These insights are crucial for guiding the local fabrication of kilns to promote biochar production from farm residues, thereby enhancing farm productivity for smallholder farmers in Ghana.

## MATERIALS AND METHODS

### Study area

The experiment was conducted at the CSIR—Crops Research Institute, Fumesua, in the Ashanti Region of Ghana (Table 1). The location lies between 6° 41' N and 1° 28' W (Fig. 1).

### Description and operation of the biochar kiln

The locally developed biochar kiln, shown in Fig. 2, operates on a two-chamber principle similar to other kilns. The first chamber is the pyrolysis chamber, while the second is the charring chamber. Before ignition, the pyrolysis chamber is filled with combustible materials such as firewood or organic residues. The charring chamber is filled with the materials to be carbonized. The kiln features a double-walled construction with bricks and cotton wool insulation to minimize heat loss through conduction (Fig. 2). It has a conical top equipped with a chimney for vapour escape. The charring chamber is supported by a metal frame structure, with the pyrolysis heat chamber positioned beneath it. An inlet is located on the conical top of the charring chamber, and a discharge unit is positioned at the front for feedstock loading and removal.

The biochar kiln utilizes direct heating with a circulating system. The heat produced in the pyrolysis chamber is directed to the charring chamber to initiate the carbonization process. This heat transfer occurs through a grate, a conducting metal sheet separating the two chambers. The grate conducts and radiates heat to materials in close contact with the charring chamber. Accurate monitoring of smoke through the chimney enhances the efficiency and quality of biochar by preventing both under- and over-carbonization. Brick insulation enhances thermal balance, while chimneys ensure complete and homogeneous combustion by improving flue gas flow and reducing emissions. Some syngas produced during pyrolysis is recirculated to the pyrolysis chamber, creating an inert atmosphere conducive to efficient carbonization. As the temperature rises, the feedstock in the charring chamber undergoes degradation, converting to biochar. Heat transfer within the kiln includes both conduction and convection. Conduction occurs from the inner brick surface to the outer core surface and from the outer core surface to the pyrolysis chamber. Convection transfers heat from the outer kiln wall to the surroundings. Table 2 provides detailed technical specifications of the locally developed biochar kiln.

### Materials used

Materials used in the study, along with their details of use, are listed in Table 3 below.

### Sample collection and data collection

Rice husks, coconut shells, maize stover, maize cobs and flamboyant pods were collected for biochar production within and around the study area. The collection process involved gathering and loading feedstocks, which were then transported to the biochar pro-


**Fig. 1**. *Map of Ghana showing the location of the study site*

**Table 1**. Agro-ecological characteristics of the study site

| Characteristics | location (6° 41' N, 1° 28' W) |
|---|---|
| Agro-ecological zone | Humid forest |
| Soil type | Ferric Acrisol; Asuasi series upper topsoil consisted of 5cm greyish brown sandy loam topsoil of dark brown gritty clay loam. |
| Temperature (Min – Max.) | 21 °C – 31 °C |
| Major season | March – mid-August |
| Minor Season | September – November: Peak in October |
| Total annual rainfall (mm) | Averaging 1184mm/yr. |

Adapted from Owusu-Danquah et al. (2017).

**Table 2.** Technical specification of the biochar kiln used for the study

| Parameter | Specification |
|---|---|
| The cross-sectional area of the pyrolysis chamber | 2.531 $m^2$ |
| The cross-sectional area of the charring chamber | 7.912 $m^2$ |
| The cross-sectional area of a cone | 3.108 $m^2$ |
| The cross-sectional area of the returning tube | 0.016 $m^2$ |
| The thickness of the charring chamber | 0.198 m |
| The area of the grate | 0.669 $m^2$ |
| The space in the grate | 0.008 m |
| The scooper handle | 1.735 m |
| The area of the scooper foot | 0.657 $m^2$ |
| The dimension of the frame stand (L x B x H) | 1.2 x 1.14 x 0.62 m |
| The area of the discharging unit | 0.448 $m^2$ |
| The area of the inlet | 0.167 $m^2$ |
| The area of the pyrolysis chamber inlet | 0.167 $m^2$ |
| The loading capacity of the kiln | 180 – 400 kg |

duction site. The feedstock was dried to reduce its moisture content. The weight of the feedstocks was measured using a weighing scale, while the charring temperature was monitored with an infrared thermometer (Raytek model). The duration of the gradual charring process was noted at one-hour intervals using a stopwatch. Once the biochar was generated, it was promptly cooled and air-dried, and its final weight, actual fuel consumption, and total processing time were meticulously documented for precise analysis.

**Experimental setup**

Five types of biomass (Maize cob, Rice husk, Flamboyant pods, Coconut shell, and Maize Stover) were used as treatments, each subjected to the kiln in a randomized complete block design with three replications per block. Thus, biochar was produced from each of the selected biomass and used for the study. For each replication, the kiln was filled to the fullest at a volume of 1.65 $m^3$. The kiln was operated under slow pyrolysis conditions at a Temperature of 300°C-600°C. Dry wood was used as the fuel material for the biochar kiln. The kiln was preconditioned with firewood, which was measured using a weighing scale, placed into the kiln's pyrolysis heat chamber, and ignited with a match. This pretreatment process typically took a minimum of 30 minutes, during which the discharging unit and kiln outlets were closed. With the assistance of a staircase, the feedstocks were transported into the kiln through its feedstock inlet. Once the charring process was completed, the biochar was removed from the kiln using a scooper and transported onto the cemented floor in front of the kiln through the discharging unit.

**Determination of biochar quality**

The lab experiment was conducted at the Soil Science Lab at KNUST. Three samples from each biochar produced were collected and combined into a single composite sample for analysis at the laboratories. A completely randomized design was used for the analysis.

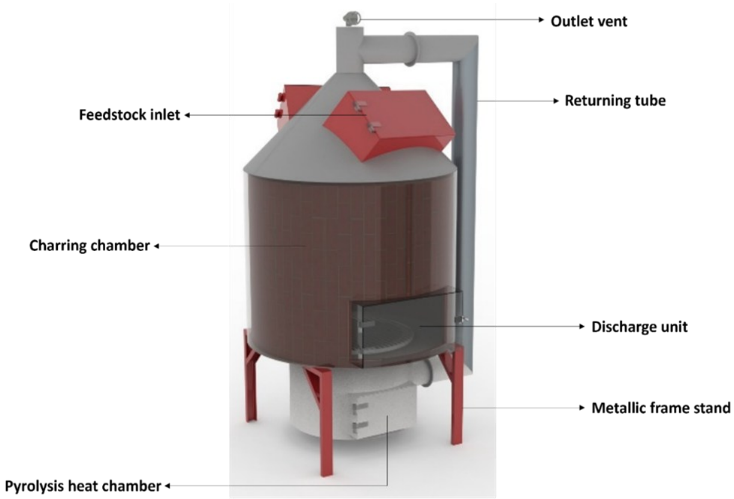


**Fig. 2**. *Schematic drawing of the biochar kiln*

**Table 3.** Materials used for the experiment and their functions

| Name of Material | Function |
|---|---|
| Matches or lighter | To start the fire. |
| Scooper and shovel | To transfer the firewood to the kiln and to remove the biochar after production. |
| Wheelbarrow | To transport the feedstock and biochar. |
| Cutlass | To chop the fuel wood into pieces. |
| Infrared thermometer gun (RAYMX2TD CFU) | For temperature measurements. |
| Stopwatch | To measure the total time for the charring process. |
| Weighing scale | To measure the weight of the feedstock. |
| Staircase or ladder | To access the feedstock inlet. |
| Plastic bucket | To help in the measuring procedure. |
| Personal protective equipment (PPEs) | Protective cloth, boots, leather gloves, dust masks, and eye protection to ensure safety during the charring process. |

The biochar quality was assessed by conducting proximate and Ultimate analysis pH measurements and EC measurements on each biochar produced. The proximate analysis was conducted to determine the Moisture Content (%), Ash Content (%), Volatile Matter (%) and Fixed Carbon (%). An ultimate analysis was performed to determine the elemental composition of the biochar. It quantifies the proportions of carbon (C), hydrogen (H), nitrogen (N), oxygen (O), and sulfur (S), providing insights into each biochar's stability, nutrient content, and environmental impact,

The pH and the electrical conductivity (EC) of various biochars were measured following a standard procedure by Singh *et al*. (2017). The materials used included a pH meter, an EC meter, a beaker, distilled water, and a weighing scale. For sample preparation, 20 grams of corn cob, rice husk, and coconut shell biochar were ground into powder and weighed in a beaker. To each sample, 100 millilitres of distilled water was added, and the mixture was thoroughly stirred to ensure proper contact between the biochar and water. The samples were then left to equilibrate for 24 hours. A well-calibrated pH meter was used to determine the pH of the biochar samples after the equilibration period, with the electrode rinsed with distilled water between measurements. Similarly, EC measurement was conducted using a well-calibrated EC meter after 24 hours, ensuring the electrode was rinsed with distilled water between readings.

**Economic assessment**

This study employed the Cost-Benefit Analysis model to evaluate the economic viability of the locally manufactured biochar kiln and outline in equations 1,2,3,4 and 5 (Dambaulova *et al*., 2023; Hidayah *et al*., 2024; Robb *et al*., 2020; Wu *et al*., 2017).

$$\text{Profit Margin }\% = \frac{\text{Profit}}{\text{Total Revenue}} \times 100 \quad (1)$$

$$\text{Return on Investment (ROI)} = \frac{\text{Profit}}{\text{Total Cost}} \times 100 \quad (2)$$

$$\text{Benefit-Cost Ratio} = \frac{\text{Total Revenue}}{\text{Total Cost}} \quad (3)$$

Where,

Total Revenue= Weight of Biochar (kg) X price per kg, Profit = Total Revenue-Total cost, Total cost = Machine cost+ Feedstock cost + Firewood cost + Labour cost

$$\text{Net Present Value} = \sum \frac{C_t}{(1+r)t\text{-}I} \quad (4)$$

$$\text{Internal Rate of Returns (IRR)} = \sum \frac{C_t}{(1+r)t\text{-}I} = 0 \quad (5)$$

Where, Ct = Cash flow in period (t), r = Discount rate (10%), t = Time period (10 years), I= Initial investment (20,000 cedis).

**Performance metrics**

The performance of the biochar kiln was evaluated using five feedstocks based on relevant performance metrics. Data were collected on specific fuel consumption (SFC), Biochar yield, energy efficiency of the biochar kiln, energy expended during charring, charring rate, and charring time.

The specific fuel consumption (SFC) was determined using Equation 1 as adopted by (Shittu *et al*., 2012):

$$SFC = \frac{\text{Total mass of fuel consumed (kg)}}{\text{Total mass of biochar produced(kg)}} \times 100 \quad (6)$$

Biochar yield from the various feedstock was calculated using the relationship in equation 2 (Luwaya *et al.*, 2015);

$$\text{Biochar Yield (\%)} = \frac{\text{Weight of Biochar}}{\text{Weight of fuel}} \times 100 \quad (7)$$

The energy efficiency of the biochar kiln was calculated using the expression in Equation 3, adopted from Amponsah *et al.* (2022).

$$\text{Energy efficiency} = \frac{T_{cc}\text{-}T_{out}}{T_{cc}\text{-}T_{amb}} \times 100 \quad (8)$$

Where, $T_{amb}$ = Mean temperature outside the kiln;, $T_{cc}$ = Mean Pyrolysis chamber temperature, $T_{out}$ = Outlet Temperature (chimney)

The energy expended in charring with a wood heat source was calculated using Equation 4 (Babatunde Oluwatobi *et al*., 2021)

$$E_c = E_w \times M_w \quad (9)$$

Where, $E_c$ : Energy expended in charring (MJ), $E_w$ : Energy present in fuel material (Wood) (MJ/Kg), $M_w$ : Mass of wood

The charring time or Resident Time was determined using equation 5 as adopted by (Wondmagegan *et al*., 2023)

$$\text{Resident Time (h/kg)} = \frac{\text{Total time spent in charring (h)}}{\text{Weight of feedstock (kg)}} \quad (10)$$

The charring rate or heating rate was determined using the relationship in Equation 6, as adopted by Amponsah *et al.* (2022).

$$\text{Charring rate (kg/h),} = \frac{\text{Mass of feedstock(kg)-Mass of Biochar (kg)}}{\text{Total time spent in charring (h)}} \quad (11)$$

**Data analysis**

The data collected were subjected to a one-way Analysis of variance (ANOVA) test, Type III error. The significant differences were determined where possible after meeting normality and homoscedasticity tests by the Shapiro-Wilk and Levene Tests, respectively. A post hoc test was then conducted to separate the means using Tukey's significant difference test. All statistical analyses were performed using JASP statistical software version 0.19.0 (JASP Team, 2024). Significant differences ($p < 0.05$) among treatment means were estimated.

## RESULTS

**Biochar quality test**

The quality test of the biochar from the five feedstocks is shown in Table 4 and 5.

The elemental and proximate analyses of the five feedstocks are presented in Tables 4 and 5. The proximate analysis results for biocharwere expressed as percentages of moisture content, volatile matter, ash content, and fixed carbon. The elemental analysis included carbon, nitrogen, hydrogen, sulfur, and oxygen percentages. According to the proximate analysis results in Table 5, the ash content of the feedstocks decreased from 20.0% to 7.64%. The highest moisture content was recorded for coconut shell biochar at 5.67%, while the soybean residue had the lowest moisture content at 2.33%. The volatile matter in the biochar also decreased from 9.89% to 4.02%. The elemental analysis revealed that the carbon percentage in biochar increased as the ash content decreased. The fixed carbon content, as determined by proximate analysis, was higher for all feedstocks than that measured by elemental analysis. There were notable differences in the fixed carbon content among the feedstocks. Rice husk biochar had the lowest fixed carbon content at 71.34 %, while coconut shell biochar had the highest at 88.34%. Furthermore, fixed carbon is a key factor in determining biochar quality, and a high fixed carbon content is characteristic of good biochar. The electrical conductivity (EC) values were measured in deciSiemens per meter (dS/m). According to Table 4, all feedstock exhibited non-saline values and high electrical conductivity potential. Coconut shell and maize stover had the lowest EC levels, indicating low salinity. High EC values (EC > 4 dS/m) can indicate salinity issues, hindering microbial growth, reducing water absorption, and affecting microbial activity. The electrical conductivity (EC) observed in this study ranged from 1.0 dS/m to 3.0 dS/m, which falls within the accepted EC range for crop cultivation (Singh *et al*., 2017).EC does not measure specific ions or compounds but correlates with the concentrations of potassium, sodium, chloride, sulfate, ammonia, and nitrate in the soil. EC itself does not directly affect plant growth but serves as an indirect indicator of nutrient availability and salinity.

Results showed that the pH of biochar generally increased with increasing pyrolysis temperature and varied depending on the feedstock, as shown in Table 4. Coconut shell and maize stover recorded the highest pH values of 10.12 and 9.17, respectively, corresponding to the high pyrolysis temperatures shown in Fig. 3 (d). Variations in feedstock could also explain the differences in recorded pH values.

**Temperature measurements**

The reaction conditions during the pyrolysis process are mainly responsible for producing biochar. Slow pyrolysis is a commonly used method for biochar production, which is generally carried out at temperatures between 300°C and 600°C . The temperature at which the biochar was produced influences its physicochemical properties and structure, such as elemental components, pore structure, surface area, and functional groups. Results from the experiment at various temperatures are presented as follows.

Fig. 3(a) shows the results for ambient temperature. The mean ambient temperature was measured in degrees Celsius, and the minimum and maximum temperatures were recorded at 34.49 and 41.11, respectively. However, the ambient temperature for the five feedstocks used was found to be not significantly different from each other at a confidence level of 95 percent.

The biochar kiln recorded a minimum temperature of 285.86 °C and a maximum of 564.70 °C for the pyrolysis chamber. However, as shown in Fig. 3(d), the analysis did not reveal significant differences in the feedstock. However, the charring chamber temperature recorded minimum and maximum temperatures of 109.457°C and 456.89°C, respectively. Results from the analysis in Fig. 3 show that the charring chamber temperature of the kiln is not statistically significant considering the feedstocks maize cob, flamboyant pods, maize stover, rice husk and coconut shell. In Fig.

**Table 4.** Results on elemental analysis, electrical conductivity (EC) and pH of biochar

| Biochar | pH | EC (dS/m) | Elemental Analysis (%) | | | | |
|---|---|---|---|---|---|---|---|
| | | | C | N | H | S | O |
| Maize Cob | 10.1 | 1.6 | $72.2^{ab}$ | $6.8^{a}$ | $1.67^{a}$ | $0.26^{a}$ | $18.5^{a}$ |
| Soyabean Crop residue | 9.1 | 1.6 | $67.3^{b}$ | $7.8^{c}$ | $1.68^{c}$ | $0.66^{c}$ | $28.6^{c}$ |
| Maize Stover | 10.2 | 1 | $77.4^{a}$ | $5.6^{a}$ | $2.02^{a}$ | $0.35^{a}$ | $14.6^{a}$ |
| Rice husk | 8.8 | 1.3 | $69.2^{b}$ | $4.6^{b}$ | $2.4^{b}$ | $0.66^{b}$ | $21.4^{b}$ |
| Coconut Shell | 9.0 | 2.6 | $76.4^{a}$ | $5.6^{a}$ | $2.6^{a}$ | $0.34^{a}$ | $15.1^{a}$ |

a, b, c different superscript letters are significantly different ($p<0.05$)

**Table 5**. Proximate analysis results of biochar

| Biochar | Ash Content of Feedstock (%) | Proximate analysis (%) | | | |
|---|---|---|---|---|---|
| | | Moisture content | Volatile matter | Ash Content | Fixed Carbon |
| Maize Cob | 5.29 | $5.34^{a}$ | $7.30^{b}$ | $9.25^{b}$ | $83.45^{a}$ |
| Soyabean Crop residue | 4.65 | $2.33^{c}$ | $9.89^{a}$ | $18.0^{a}$ | $72.11^{b}$ |
| Maize Stover | 3.28 | $5.67^{a}$ | $5.23^{bc}$ | $13.55^{b}$ | $81.22^{a}$ |
| Rice husk | 2.21 | $4.64^{b}$ | $8.66^{a}$ | $20.0^{a}$ | $71.34^{b}$ |
| Coconut Shell | 1.60 | $5.67^{a}$ | $4.02^{c}$ | $7.64^{c}$ | $88.34^{a}$ |

a, b, c different superscript letters are significantly different ($p<0.05$)

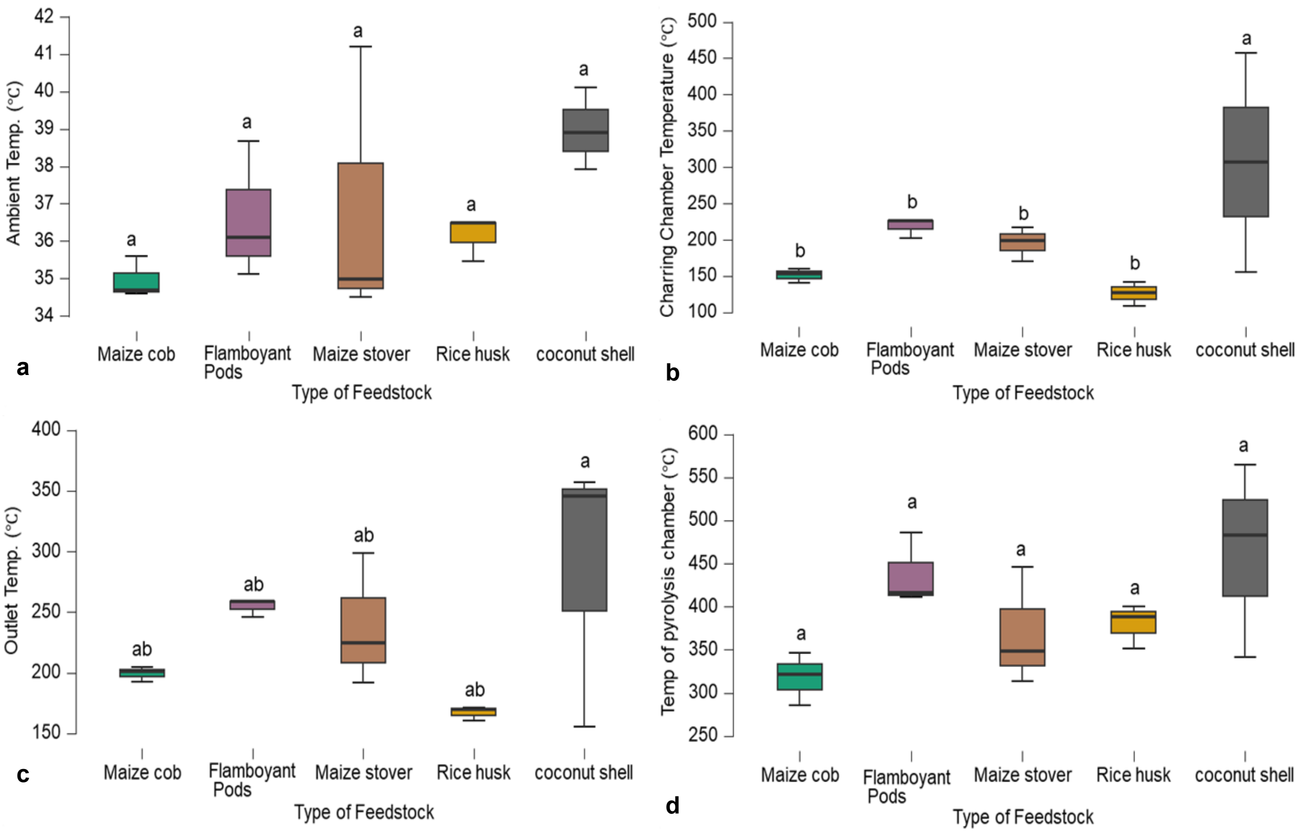


**Fig. 3.** *Showing (a) Mean ambient temperature, (b) Mean charring chamber temperature, (c) Mean outlet temperature and (d) Mean pyrolysis chamber temperature for the five feedstocks used*

3(c), the temperature at the kiln outlet was found not to be significantly different, considering the diverse feedstocks, with the maximum and minimum values recorded at 155.68°C and 356.9°C , respectively.

**Effect of feedstock variation on energy**

Fig. 4(a) shows that the energy efficiency of the biochar kiln was statistically insignificant between the feedstocks. The locally fabricated biochar kiln can pyrolyze maize cobs, flamboyant pods, maize stover, rice husk, and coconut shell at minimum and maximum energy efficiencies of 31.98% and 64.75%, respectively. The energy expended by the biochar kiln in charring the various feedstocks was statistically significant at $p$ = 0.001. As shown in Fig. 4(b), the mean energy expended by the kiln for maize cob, flamboyant pods, maize stover, rice husk and coconut shell was recorded at 389.92MJ, 639.667MJ, 412.427MJ, 625.176MJ and 766.967MJ, respectively. Compared to maize cobs and stovers, the energy expended during the charring process was highly significant for coconut shells, rice husks, and flamboyant pods. In Fig. 4(c), the results show that the specific fuel consumption (SFC) for the locally fabricated biochar kiln using slow pyrolysis is statistically significant ($P$ < 0.001). The minimum and maximum fuel requirements to convert maize cobs, flamboyant pods, maize stover, rice husk, and coconut shell feedstock to biochar were 0.25, 0.80, 0.45, 0.30, and 0.31, respectively.

**Resident time, heating rate and total time spent in charring on the feedstocks**

The heating rate or charring rate in Fig. 4a was statistically significant for the different feedstocks (p=0.001). In this study, the average speed at which the selected feedstock undergoes thermal decomposition to produce biochar was found to be between 1.747 kg/h and 4.845 kg/h for maize cob, 6.075 kg/h and 7.784 kg/h for flamboyant pods, 11.499 kg/h and 14.182 kg/h for maize stover, 2.01 kg/h and 2.689 kg/h for rice husk, and 7.938 kg/h and 12.825 kg/h for coconut shell. The results in Fig. 4c show that the total time spent in charring for the biochar kiln was statistically significant at (p= 0.001) for the different feedstocks. It takes an average time of 24.33h, 26.50h, 9.76h, 31.10h and 28.2h for maize cob, flamboyant pods, maize stover, rice husk and coconut shell, respectively, to complete the conversion of this biomass to biochar. The resident time was found to be significant for the feedstock used. Consequently, Fig. 4b shows that the overall duration of heat circulation through the feedstock ranged from a minimum of 0.21 kg/h to a maximum of 0.56 kg/h.

**Biochar yield, weight of feedstock and fuel wood used for thermal degradation**

The study recorded the minimum and maximum weights of wood material used to supply heat to the kiln: 14.56 kg and 44.9 kg, respectively. Notably, the weight of the fuel wood was statistically significant for each feedstock. Here are the average weights of fuelwood used for the different feedstocks: maize cob (20.5 kg), flamboyant pods (33.66 kg), maize stover (21.79 kg), rice husk (32.9 kg), and coconut shell (40.36 kg). Additionally, the weight of the various feedstocks used to produce biochar exhibited statistical differences (p = 0.001). Furthermore, when considering the kiln volume of 1.65 m³, the minimum and maximum weights of feedstock that filled the kiln were 141.95 kg and 434.56 kg, respectively.

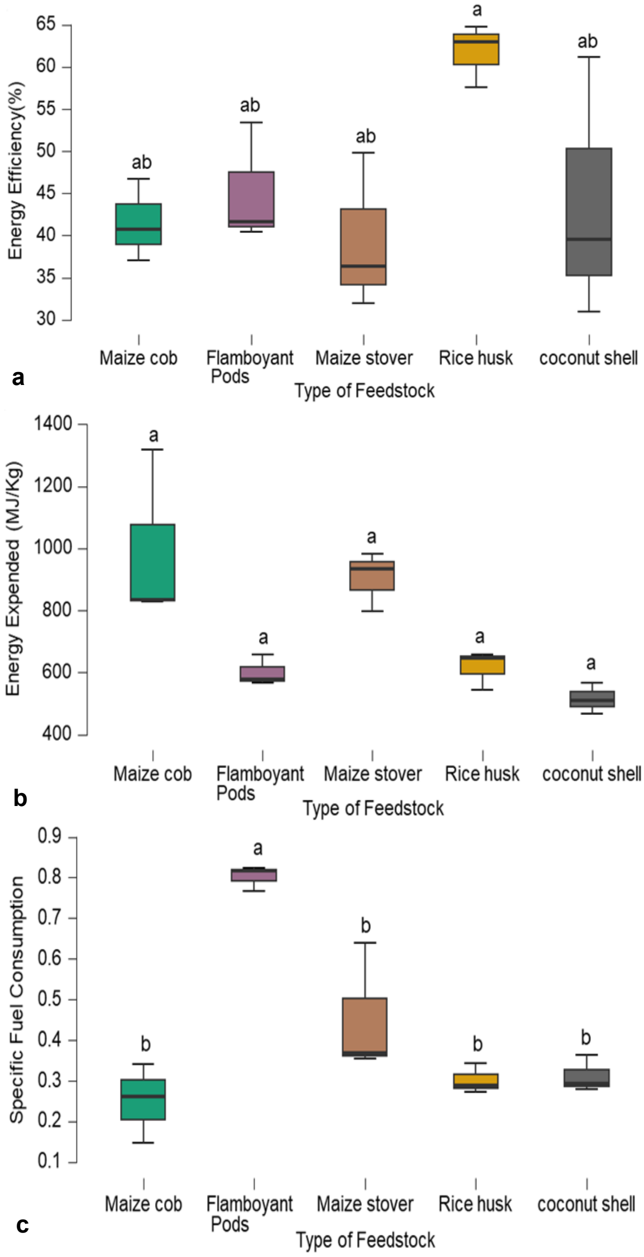


**Fig. 4.** *Showing (a) Energy Efficiency, (b) Energy Expended and (c) Specific Fuel Consumption for Maize cob, flamboyant pods, maize stover, rice husk and coconut shell*

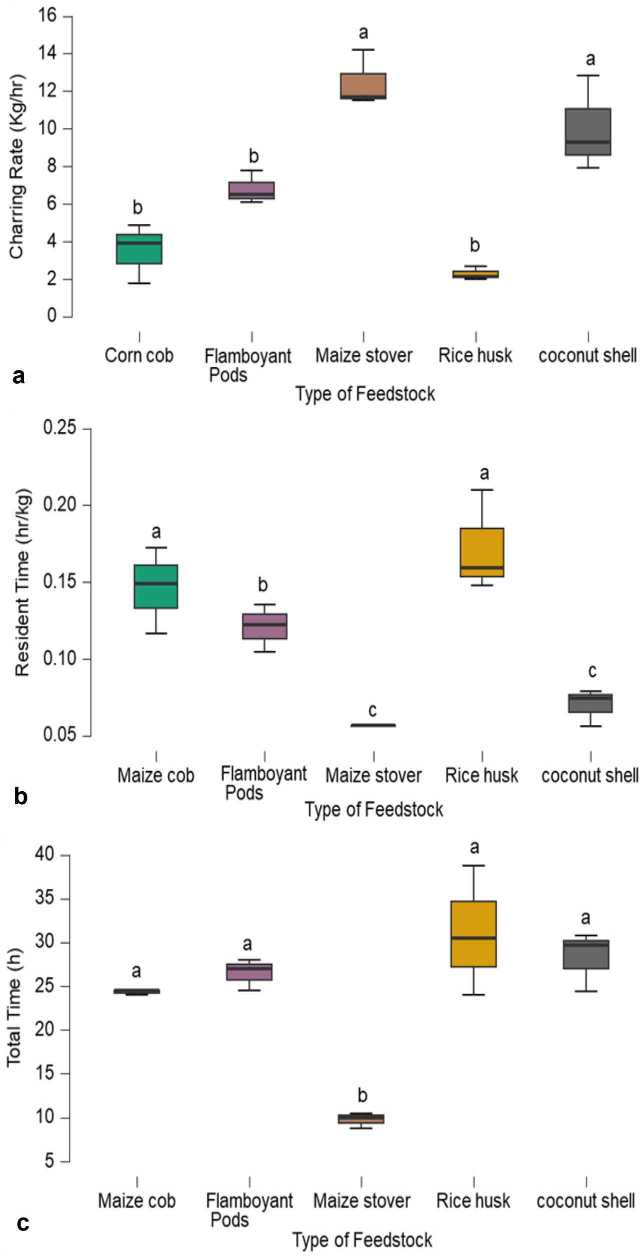


**Fig. 5**. *Showing (a) Charring Rate (b) Resident Time (c) Total Time for the five types of feedstocks used.*

After the analysis, the weight of the biochar was found to be statistically significant at *p=0.001.* The weight of the solid biochar was recorded as ash-free content. The minimum and maximum biochar weights were recorded at 30.9 kg and 144.50 kg. The highest average biochar weight was recorded for Coconut shell feedstock at 129.97 kg, and the lowest for flamboyant pods at 42.03 kg, as shown in Fig. 6C. The amount of biochar produced after the pyrolysis process was statistically significant at (p=*0.001*) considering maize cob, flamboyant pods, maize stover, rice husk and coconut shell. The feedstock with the highest percentage yield was rice husk at 68.55%, and flamboyant pods recorded the lowest percentage yield at 17.74%.

The analysis of the processing parameters and the performance metrics on the Biochar kiln reveal a range of correlations, with some parameters showing significant relationships with each other and others showing no significant associations despite the feedstock. (Fig. 7). As shown in Fig. 7, biochar yield had significant associations with various parameters regardless of the feedstock. It had a negative correlation with the charring rate (r = -0.721**), specific fuel consumption (r = -0.77*), and outlet temperature (r = -0.55). Biochar yield showed a strong positive correlation with the total time and the weight of biochar produced. The weight of the fuelwood used was positively correlated with the pyrolysis chamber temperature (r = 0.724**), charring chamber temperature (r = 0.586*), total time (r = 0.611**), and the weight of feedstock (r = 0.738**). It had a strong negative correlation with energy expended (r = -1***). The weight of feedstock had a positive association with the weight of biochar (r = 0.571*), energy expended (r = 0.738**), and charring chamber temperature (r = 0.646*). Outlet temperature strongly correlated negatively with biochar yield and energy efficiency (r = -0.697**).

The pyrolysis chamber temperature had strong positive associations with outlet temperature (r = 0.793***), charring chamber temperature (r = 0.793**), ambient temperature (r = 0.668**), energy expended (r = 0.724**), and the weight of fuel used (r = 0.724**). During the carbonization process, these temperatures depend on the pyrolysis chamber temperature. Charring chamber temperature was strongly positively correlated with pyrolysis chamber temperature (r = 0.778**), outlet temperature (r = 0.838***), energy expended (r = 0.586*), weight of fuelwood (r = 0.586*), and weight of feedstock (r = 0.646*). Specific fuel consumption had a strong negative relationship with biochar's weight and yield. Energy expended showed various correlations, with positive correlations recorded at r = 0.724** for pyrolysis chamber temperature, r = 0.586* for charring chamber temperature, r = 0.611* for total time, and r = 0.738** for weight of feedstock, and a negative correlation at r = -1*** for weight of fuel wood. Total time had a negative significant correlation with the charring rate (r = -0.654*) but a strong positive correlation with resident time (r = 0.633**), energy expended (r = 0.611*), and weight of fuelwood (r = 0.611*). The charring rate had a significant negative correlation with total time (r = -0.654*), resident time (r = -0.938***), and biochar yield (r = -0.721**). Resident time had a strong positive association with total time (r = 0.663**) and biochar yield (r = 0.637).

### Economic viability of the locally manufactured biochar kiln

Total revenue from biochar production was determined by the weight of biochar produced and the price per

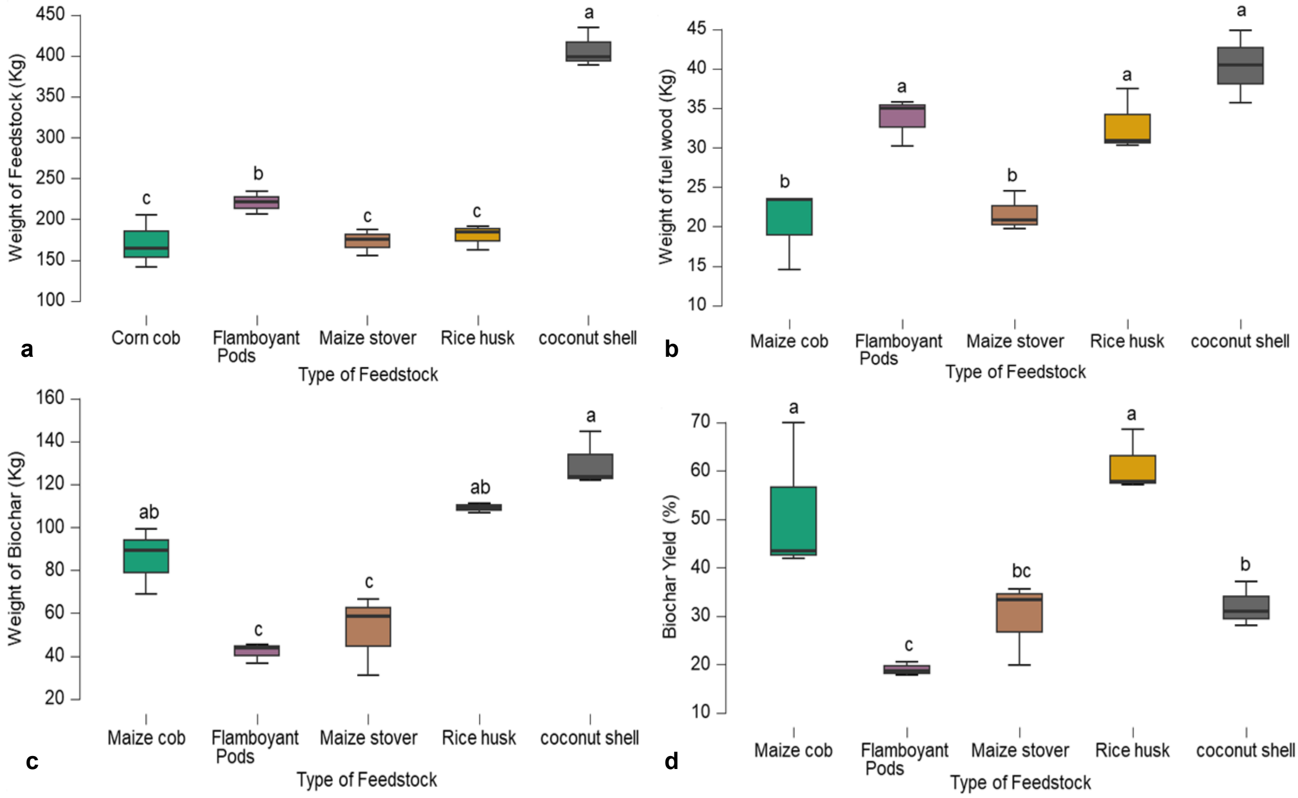


**Fig. 6.** *Showing (a) the Weight of feedstock, (b) the Weight of fuel wood, (c) the Weight of Biochar, and (d) the Biochar yield for the different feedstock*

kilogram. Coconut shell yields the highest revenue at ₵ 649.90, followed by rice husk at ₵545.50 and maize cob at ₵428.95. In contrast, maize stover generates the most negligible revenue at ₵260.50. The labour cost incurred in processing varies across the feedstocks. The costs are quite similar, but maize stover has the lowest labour cost at only ₵0.24, showcasing the efficiency of labour practices. This is further evidenced by the fact that the labour cost represents a small fraction of the total expenses for most feedstocks. When looking at the total costs, we see a substantial variation. Maize Stover has the lowest total cost at ₵76.51, making it a favourable starting point. On the other hand, a coconut shell has the highest total cost at ₵ 149.76. This cost includes machinery, feedstock, fuel, and labour, all critical to financial performance. Profit Fig.s reflect the financial angle of each feedstock's production efficiency. Maize cob generates a profit of ₵ 244.71, translating to a profit margin of approximately 57.05%, making it quite favourable. While generating the highest revenue, Coconut Shell provides a profit of ₵500.14 with a profit percentage of 76.96%, which indicates effective cost management despite its high total cost.

The Return on Investment (ROI) is a critical indicator of financial success. Coconut shell leads with an ROI of 3.75, suggesting that the return is approximately ₵ 3.75 for every cedi invested. In contrast, maize stover has the lowest ROI at 1.38, indicating a lesser return than investment. The Cost-Benefit Ratio further exemplifies the efficiency of the investments. Here, maize cob shows a very high ratio of 2.33, indicating strong profitability, while maize stover maintains a lower ratio of 1.11, signifying that benefits are not significantly surpassing costs. The Net Present Value (NPV) offers insight into the potential profitability of investments over time, with coconut shells again topping the list at 440,971.57 cedis, with flamboyant pods displaying the lowest NPV at ₵116003.85. In terms of IRR, coconut shell also stands out with 3.75, indicating a strong return on investment relative to its cost, while maize stover presents the least attractive IRR at 1.38. The production of biochar from different feedstocks showcases varied financial outcomes. While coconut shell appears to be the most lucrative, considering revenue and proportional returns, maize cob performs well, especially when analyzing profit margins and ROI. On the other hand, despite lower costs, maize stover does not yield satisfactory returns, which could impact its attractiveness for potential investment.

## DISCUSSION

The volatile matter content in all biochar types was low, which can be attributed to the fact that volatile substances are released during pyrolysis. Additionally, the ash content in the biochar was higher than in the origi-

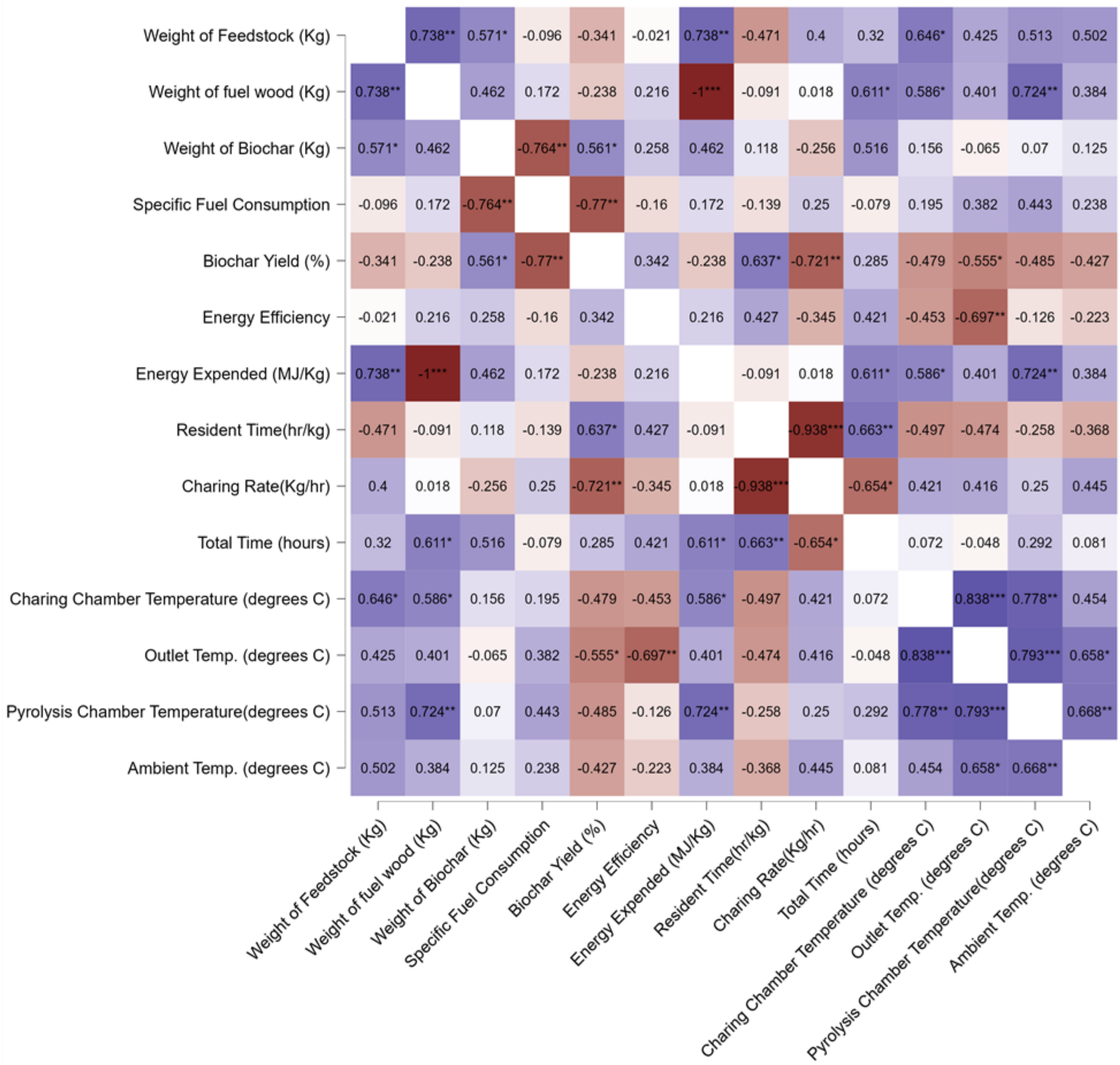


**Fig. 7.** *Correlation matrix for processing parameters and Performance metrics of the locally fabricated Biochar Kiln on maize cob, flamboyant pods, maize stover, rice husk and coconut shell. The Vertical and horizontal axes indicate the parameters studied. Values of correlations and significance are indicated with stars. *: significant ($p < 0.05$), **: moderately significant ($p < 0.01$), ***: highly significant ($p < 0.001$)*

nal feedstocks, likely due to the mineral matter that forms ash and remains after the slow pyrolysis process. The elemental analysis of the biochar reveals a higher percentage of fixed carbon compared to other elements. This is because most volatile compounds, such as water and gases, are removed during pyrolysis, leaving behind a more concentrated, stable carbon structure that is less prone to decomposition; thus, the fixed carbon content increases relative to the original biomass feedstock. The pH of biochar generally increased with higher pyrolysis temperatures and varied according to the feedstock. This may be because higher temperatures remove a large fraction of the acidic functional group, leaving the biochar with higher alkalinity. A study by Gezahegn *et al*. (2019) found that biochar from 19 Canadian temperate wood feedstocks had alkaline pH values ranging from 8.8 to 10 at pyrolysis temperatures between 300 and 700 °C. Biochar prepared at higher temperatures exhibited higher pH values, likely due to the loss of organic functional groups such as –COOH and –OH, on the biochar surface (Dai *et al.,* 2021).

In the present study, the ambient temperature recordings for the five feedstocks in the kiln indicated no statistical variation among the different feedstocks, as shown in Fig. 3. This consistency suggests that the kiln effectively retains heat and maintains good circulation regardless of the feedstock. However, notable differences were observed in the energy expended by the kiln during pyrolysis, likely due to differences in their calorific values and inherent nature (Ramuand Hariharan, 2024). Despite similar operating conditions,

**Table 6**. Cost-benefit analysis of locally manufactured kiln for Biochar production

| Feedstock | Biochar (weight) kg | Price per kg (¢) | Total Revenue (¢) | Machine Cost (¢) | Feed Stock Cost (¢) | Fuel Cost (¢) | Labour Cost (¢) | Total Cost (¢) | Profit (¢) | Profit (%) | ROI (¢) | Benefit/Cost Ratio (¢) | NPV (¢) | IRR |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Corn cob | 85.79 | 5.00 | 428.95 | 80.69 | 68.63 | 34.31 | 0.61 | 184.24 | 244.71 | 57.05 | 132.82 | 2.33 | 205,545.55 | 1.84 |
| Rice husk | 109.10 | 5.00 | 545.50 | 121.14 | 87.28 | 43.64 | 0.72 | 252.78 | 292.72 | 53.66 | 115.80 | 2.16 | 249,795.65 | 2.20 |
| Maize stover | 52.10 | 5.00 | 260.50 | 18.96 | 36.47 | 20.84 | 0.24 | 76.51 | 183.99 | 70.63 | 240.48 | 3.40 | 149,580.84 | 1.38 |
| coconut shell | 129.98 | 5.00 | 649.90 | 58.49 | 38.99 | 51.99 | 0.29 | 149.76 | 500.14 | 76.96 | 333.96 | 4.34 | 440,971.57 | 3.75 |
| Flamboyant Pods | 42.03 | 5.00 | 210.15 | 32.67 | 12.61 | 16.81 | 0.50 | 62.59 | 147.56 | 70.22 | 235.76 | 3.36 | 116,003.85 | 1.11 |

higher amounts of fuel wood are required to pyrolyze coconut shells, rice husks, and flamboyant pods, likely due to variations in their densities and particulate nature (Tripathi *et al*., 2016).

The weights of the feedstocks varied significantly due to the differing volumes required to fill the kiln. Consequently, the weight of the biochar produced without ash varied, influenced by the diverse weights used. Notably, flamboyant pods and maize stover produced more ash than maize cobs, coconut shells, and rice husks (Fig. 4). The heating or charring rate is crucial in biomass pyrolysis, as it affects the final product's composition and biochar yield. A strong negative correlation was observed between the charring rate and biochar yield; as the charring rate increases, thermal cracking increases, converting more biomass into ash rather than biochar. This was particularly high for maize stover, coconut shells, and flamboyant pods (Fig. 5). Research by Keske *et al*. (2020) and Lin *et al*. (2018) suggests that a low heating rate prevents the thermal cracking of biomass, leading to higher biochar yield, while a high heating rate enhances the depolymerization of biomass into volatile components, reducing the char yield.

Consequently, rice husk and maize cob, which experienced the lowest heating rates, yielded the highest biochar. The residence times or charring times recorded in this study were high for rice husks, maize cobs, and coconut shells. According to Ortega *et al*. (2023), a low temperature associated with long residence time is required for higher biochar production, aligning favourably with this study's findings. Biswas *et al*. (2017) found that at high temperatures, an increase in residence time increases the biochar yield, whereas at low temperatures, an increase in residence time reduces the biochar yield. The effect of residence time is often overshadowed by temperature, heating rate, and other parameters, making it challenging to provide a straightforward understanding of its role in biochar production (Zhao *et al*., 2018). Research by Owsianiak *et al*. (2021) investigated the impact of various pyrolysis process parameters on biochar yield, including temperature, charring rate, residence time, and feedstock type. The study found that these factors can have both positive and negative influences on biochar yield. The recorded biochar yield ranged from a minimum of 17.75% to a maximum of 69.85%, with variations strongly associated with these process parameters (Fig. 6 & 7). The study reported average energy efficiencies for various feedstocks, with maize cob (41.52%), flamboyant pods (45.16%), maize stover (39.4%), rice husk (61.74%), and coconut shell (43.89%). Although statistical significance was not observed across the different feedstocks, the consistent average energy efficiency suggests the locally designed kiln safety measures and performance.

Specific fuel consumption refers to the amount of energy (in the form of fuel) required to produce a specific quantity of biochar. Fig. 4d shows that rice husk, coconut shell, and maize cob had the lowest average specific fuel consumption, suggesting that these biomasses required relatively less energy to be converted into biochar. These results are consistent with findings from studies by Wu *et al*. (2017) and Hidayah *et al*. (2024), demonstrating that feedstock type and heating rate are primary factors influencing this behaviour. The viability of biochar production is well-documented, underscoring its significance in enhancing farming practices, promoting environmental sustainability, and improving the livelihoods of smallholder farmers. Several references align with the findings on the financial outcomes of biochar production from different feedstocks (Aguirre *et al*., 2023; Fan *et al*., 2023; Keske *et al*., 2020). Guvava *et al*. (2022), focusing on sewage sludge valorization, opined that insight into alternative feedstocks for biochar production could contribute to discussions on revenue generation and cost-effectiveness in biochar ventures. Biochar production from various feedstocks presents a complex interplay between revenue, costs, and profitability (Blenis *et al*., 2023; Ippolito *et al*., 2020). A comparative analysis of different feedstocks for biochar production revealed that total revenue is influenced by the weight of biochar produced and the price per kilogram, with varying yet positive economic implications, as reported by Aguirre *et al.* (2023). Unlike other kilns, such as earth mound kilns, drum retort kilns, and funnel kilns, this kiln can char all organic-based feedstocks. It also features a high loading capacity and self-energy-recirculating mechanism, enhancing its efficiency and operation.

### Conclusion

The quality of biochar varies depending on the feedstock used. While coconut shells and rice husks produce less ash than flamboyant pods, maize cob, and maize stover, they require more energy for biochar production. In the present study, the self-energy-recirculating kiln maintained similar ambient temperatures for all five feedstocks, indicating its suitability for biochar production. Economic analysis showed that coconut shells and maize cob were particularly profitable for producing biochar. However, evaluating the short- to long-term environmental benefits of using this biochar in a changing climate is crucial. This evaluation will enhance our understanding of biochar's role in mitigating agroecosystem impacts. To make informed decisions on the best feedstock for producing high-quality biochar, assessing the medium- to long-term impact of each feedstock's biochar on soil and crop productivity is necessary. Therefore, the fabrication of kilns tailored to local conditions is economically viable for promoting biochar production and should be pursued with guidance from comprehensive research.

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### Conflict of interest

The authors declare that they have no conflict of interest.

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