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# Development of a cost effective and environmentally friendly nano biochar production system

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**ABSTRACT**

The development of affordable and environmentally sustainable biochar production technologies is essential for climate resilient agriculture, particularly in resource constrained rural regions. This study presents a locally designed, farmer friendly nano biochar production system known as the BAU biochar stove, developed to convert agricultural residues into high quality biochar under village conditions. The system integrates cooking and pyrolysis functions, enabling simultaneous household energy use and carbonized biomass production. Three commonly available feedstocks maize stover, rice husk, and sawdust were evaluated for yield efficiency and biochar quality. From 1 kg of raw biomass, the stove produced 355 gm, 452 gm, and 435 gm of biochar respectively, demonstrating high conversion efficiency. Scanning Electron Microscopy (SEM) analysis confirmed nano structured particles up to 37.54 nm with well-developed pore structures and carbon content ranging from 76-78%, indicating high-quality biochar suitable for soil amendment and carbon sequestration. The drum sheet constructed stove is low cost, portable, and operable without electricity or sophisticated control systems, making it suitable for smallholder farmers. The integrated design minimizes greenhouse gas emissions compared with open burning while providing renewable cooking energy. Results suggest that localized nano biochar production systems can enhance soil fertility, reduce agricultural waste, and support climate change mitigation through carbon stabilization. The system demonstrates strong potential for scaling in developing countries where agricultural residues are abundant but underutilized. This innovation bridges rural energy needs, waste management, and sustainable agriculture within a circular bioeconomy framework.

## 1. Introduction

Biochar has gained global attention as a sustainable soil amendment and climate mitigation tool due to its ability to enhance soil fertility while stabilizing carbon for long periods (Lehmann & Joseph, 2015). Produced through pyrolysis of biomass under limited oxygen, biochar improves soil physical structure, nutrient retention, microbial activity, and water-holding capacity (Glaser et al., 2002). Its porous structure and large surface area make it particularly effective for degraded and drought prone soils such as those found in semi-arid agricultural regions (Jeffery et al., 2017). In addition to agronomic benefits, biochar contributes to climate change mitigation by sequestering carbon that would otherwise return to the atmosphere as carbon dioxide or methane during decomposition or open burning (Woolf et al., 2010).

Developing countries generate large quantities of agricultural residues such as rice husk, maize stover, and sawdust, which are often burned or discarded inefficiently (FAO, 2019). This not only wastes valuable biomass resources but also contributes to air pollution and greenhouse gas emissions (Smith et al., 2014). Converting these residues into biochar offers a dual benefit of waste management and soil improvement. However, most conventional biochar production systems rely on expensive reactors or industrial scale pyrolysis units, which are inaccessible to smallholder farmers (Brown, 2016). Therefore, low cost, decentralized technologies are essential for enabling widespread adoption of biochar production at the community level.

Recent studies have emphasized the importance of localized biochar systems that utilize simple designs and locally available materials (Cornelissen et al., 2013). Such systems reduce dependence on external energy inputs, minimize transportation costs, and promote rural entrepreneurship. Small scale kilns and stoves have been explored as practical solutions, particularly when they integrate energy generation with biochar production (Anderson et al., 2017). These

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integrated systems can provide cooking fuel while simultaneously producing biochar, making them attractive for rural households.

Particle size and surface characteristics are critical quality indicators of biochar because they influence nutrient adsorption, microbial colonization, and soil interaction (Ahmad et al., 2014). Nano-structured biochar with high surface area enhances cation exchange capacity and water retention, improving plant growth and soil resilience (Liu et al., 2022). Achieving such quality in low cost production systems remains a major technological challenge. Ensuring consistent carbon content, pore structure, and particle size distribution requires careful control of pyrolysis conditions, even in simple devices.

In Bangladesh and similar agro ecological regions, farmers require technologies that are affordable, durable, and adaptable to local conditions. Locally engineered solutions have been recognized as effective pathways for sustainable agricultural innovation (Pretty et al., 2018). A farmer-friendly biochar system must therefore meet several criteria: low production cost, ease of operation, minimal emissions, compatibility with locally available feedstocks, and capacity to produce high quality biochar suitable for soil application.

The BCCT-BAU biochar stove was developed to address these needs through a simple drum based pyrolysis design that can be fabricated using locally available materials. The system integrates cooking and carbonization, allowing farmers to generate biochar during daily household activities. This approach reduces labor requirements and increases technology adoption potential. Furthermore, evaluating different feedstocks enables identification of optimal biomass sources for maximizing yield and quality.

The present study aimed to (i) develop a cost-effective and environmentally friendly nano biochar production system suitable for rural use, (ii) evaluate production efficiency using common agricultural residues, and (iii) assess biochar quality using scanning electron microscopy and carbon analysis. By combining engineering innovation with scientific validation, this research seeks to provide a scalable model for decentralized biochar production that supports sustainable agriculture, waste management, and climate mitigation.

## 2. Materials and Methods

### 2.1. Study design and technology development

The experiment was conducted to design and evaluate a locally adaptable nano-biochar production system named the BCCT-BAU biochar stove. The design concept was based on low-oxygen pyrolysis principles to promote carbonization rather than complete combustion (Lehmann & Joseph, 2015). The stove was constructed from recycled drum sheet metal to ensure affordability and durability, consistent with decentralized small scale biochar production approaches recommended for rural communities (Cornelissen et al., 2016). The cylindrical unit contained two functional chambers: (1) a combustion chamber for cooking fuel and (2) a sealed pyrolysis chamber for biomass carbonization. The pyrolysis compartment had a capacity of 3 kg raw biomass per batch and was designed to operate under limited oxygen conditions to ensure efficient thermal decomposition and fixed carbon formation (Demirbas, 2004).

### 2.2. Design characteristics of BAU biochar stove

The stove measured approximately 43.18 cm in height and 123.19 cm in diameter, making it portable and suitable for household use. The outer shell was fabricated from 1.5 mm drum sheet metal to withstand high temperatures typical of biomass pyrolysis (Bridgwater, 2012). The internal pyrolysis chamber was fitted with a perforated base to facilitate uniform heat transfer, as uniform heating is essential for consistent biochar quality (Keiluweit et al., 2010). Airflow vents were positioned near the base to regulate combustion temperature and maintain controlled oxygen supply, which is critical for optimizing carbon yield (Lehmann & Joseph, 2015). The system was designed to function using typical rural cooking fuels such as twigs, crop residues, or cow dung, ensuring compatibility with village conditions. No electricity or external power source was required, aligning with recommendations for low-cost, off-grid biochar technologies suitable for smallholder farmers (Cornelissen et al., 2016).

### 2.3. Feedstock selection and preparation

Three locally available biomass types were tested: maize stover, rice husk, and sawdust. These feedstocks were selected due to their abundance in agricultural regions and documented suitability for biochar production (Enders et al., 2012). Each feedstock was sun-dried to moisture levels below 12% before use. Moisture reduction prior to pyrolysis is essential to improve thermal efficiency and carbon yield, as high moisture content reduces carbonization efficiency and increases energy demand (Demirbas, 2004; Bridgwater, 2012). Exactly 3 kg of each biomass type was loaded separately into the pyrolysis chamber for each trial. The stove was operated until visible smoke emission ceased, indicating the completion of pyrolysis and reduction of volatile compounds (Lehmann & Joseph, 2015).

### 2.4. Biochar yield determination

After natural cooling under oxygen-limited conditions, the produced biochar was weighed using a calibrated digital balance. Biochar yield was calculated following standard gravimetric procedures (Enders et al., 2012):

$$Yield(\%) = \frac{\text{Weight of biochar}}{\text{Weight of raw biomass}} \times 100$$

Yield percentage was used as a primary indicator of production efficiency and feedstock conversion performance.

### 2.5. Quality analysis

Biochar samples were ground and sieved prior to laboratory analysis to ensure uniform particle size for characterization. Surface morphology and particle size were examined using Field Emission Scanning Electron Microscopy (SEM), a widely accepted technique for evaluating pore structure and microstructural properties of biochar (Keiluweit et al., 2010). Particle size distribution and pore characteristics were interpreted from SEM micrographs. Elemental carbon content was determined using Energy Dispersive X-ray Spectroscopy (EDS) attached to the SEM instrument. EDS analysis provides semi-quantitative elemental composition, commonly applied in biochar characterization studies (Enders et al., 2012).

### 2.6. Performance evaluation

Production efficiency was assessed based on yield percentage, carbon content, particle size, and uniformity of carbonization. Fuel consumption and total operating time were recorded during each batch process. User convenience, portability, and ease of operation were documented through field observation. Environmental performance was evaluated qualitatively based on visible smoke emission and absence of open biomass burning. Reduced smoke emission and controlled combustion are recognized indicators of improved biomass conversion efficiency and lower particulate emissions compared to traditional open burning practices (Bond et al., 2013; Woolf et al., 2010).

### 3.3. Production of Nano-biochar

The produced biochar was initially crushed to get coarse powder, which was subsequently reduced to micro-sized particles (<250 μm) using a mechanical grinder. The micro-sized biochar was then subjected to a high-speed pulverizing system equipped with a beating mechanism and a special filtration unit to produce nano-biochar. The beating mechanism consisted of a rotating blade/hammer assembly operating at 12,000 rpm, generating high shear and impact forces to facilitate particle size reduction to the nano scale. The integrated fine-mesh filtration unit (≤100 nm pore size or equivalent classification chamber) allowed only ultra-fine particles to pass through while retaining larger particles for repeated grinding through a recirculation process. Pulverization was conducted for 15 minutes per batch, with intermittent cooling applied to prevent overheating and preserve the structural integrity of the biochar. The resulting nano-biochar powder was collected from the filtration chamber and stored in sterile, airtight plastic container to minimize moisture absorption and contamination. Particle size distribution and surface morphology were subsequently confirmed using Scanning Electron Microscopy (SEM).

## 3. Results

### 3.1. Production of biochar

The biochar was produced during cooking household meals. Three commonly available feedstocks maize stover, rice husk, and sawdust were evaluated for yield efficiency and biochar quality (Figure 1). The biochar was collected from the pyrolysis chamber of the stove after 5 hours (continuously or interruptedly) of cooking. The results demonstrated that from 1 kg of raw biomass, the stove produced 355 gm, 452 gm, and 435 gm of biochar respectively, demonstrating high conversion efficiency.


Figure 1: Flow diagram of biochar production from different sources of raw materials.

### 3.2. Production efficiency

The BCCT-BAU biochar stove demonstrated high conversion efficiency across all tested feedstocks. From an initial input of 1 kg biomass, maize stover produced 355 gm biochar (35.5%) rice husk produced 452gm (45.2%), and sawdust produced 435 (43.5%). The variation in yield reflects differences in lignocellulosic composition and ash content among feedstocks. Maize stover, containing higher lignin content, exhibited greater carbon retention and structural stability during pyrolysis. Sawdust produced lower yield due to its finer particle size and higher volatile matter content, which increased mass loss during carbonization.

Figure 2: Using raw materials for biochar and cooking in BCCT-BAU biochar stove.

### 3.3. Proximate analysis of biochar

The proximate analysis of different biochar types revealed clear differences in nutrient composition. Maize stover biochar exhibited the highest dry matter content (99.87%), ensuring stability and minimal moisture interference. Its crude fiber fraction was markedly higher (79.71%) than both sawdust (52.9%) and rice husk (49.68%), indicating a more robust structural quality. Although crude protein was moderate (4.14%), it remained comparable to rice husk (4.04%) and only slightly lower than sawdust (5.9%). Ether extract was relatively balanced (1.03%), higher than both sawdust (0.38%) and rice husk (0.57%), suggesting better retention of energy-rich compounds. Importantly, maize stover biochar had the lowest ash content (6.82%) compared to sawdust (39.71%) and rice husk (30.05%), reflecting reduced inorganic residue and higher organic quality. Nitrogen-free extract values were similar across all samples, with maize stover at 0.66 (Table 1). Overall, the composition indicates that maize stover biochar is superior in terms of organic quality, with high dry matter, high fiber, balanced protein, and low ash. These attributes make maize stover biochar the most suitable option among the tested materials for agricultural applications, particularly where stable carbon content and reduced mineral residue are desired.

Table 1: Proximate nutrient profile of selected biochar materials.

| Nutrient Parameter | Maize Stover | Sawdust | Rice Husk |
|---|---|---|---|
| Dry Matter (DM) | 99.87 | 94.51 | 99.53 |
| Crude Protein (CP) | 4.14 | 5.90 | 4.04 |
| Ether Extract (EE) | 1.03 | 0.38 | 0.57 |
| Crude Fiber (CF) | 79.71 | 52.90 | 49.68 |
| Ash | 6.82 | 39.71 | 30.05 |
| Nitrogen-Free Extract (NFE) | 0.66 | 0.94 | 0.65 |

### 3.5. Nano-structural characteristics

SEM analysis revealed porous structures with particle sizes up to minimum 37.54nm (Figure 3), confirming nano scale characteristics. The images displayed well developed micro and mesopores that increase surface area and adsorption capacity. Such structural features enhance the ability of biochar to retain nutrients, water, and beneficial microorganisms when applied to soil. Uniform pore distribution also indicates consistent heating conditions within the pyrolysis chamber, demonstrating effective stove design.

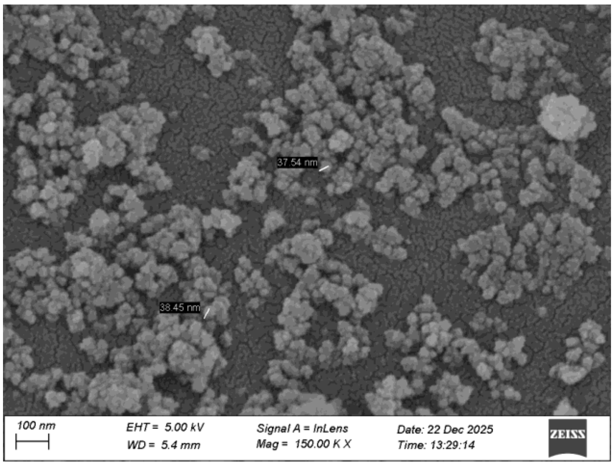


Figure 3: SEM micrograph of biochar showing nano scale porous morphology and particle size distribution.

### 3.5. Carbon content and quality

Elemental analysis showed that biochar carbon content ranged from 76% to 78%, indicating efficient pyrolysis and high fixed carbon formation (Figure 4). This level of carbon concentration is considered suitable for long term soil carbon sequestration and nutrient retention. High carbon content also suggests reduced volatile compounds, which improves stability and reduces risk of soil toxicity.

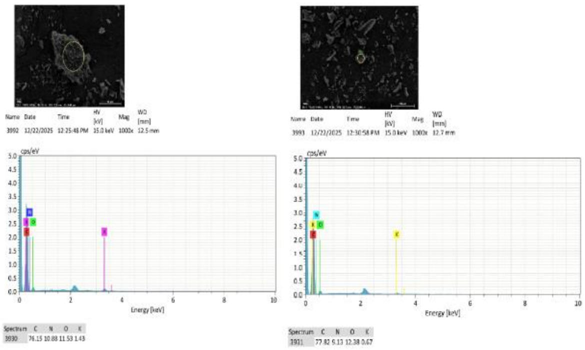

Figure 4: EDS spectrum (energy-dispersive X-ray spectroscopy) for nanoparticles

### 3.6. Thermal performance

The stove reached optimal pyrolysis temperature within 20-25 minutes using locally available fuel. Total processing time per batch ranged from 45-60 minutes depending on feedstock type. The integrated combustion pyrolysis system allowed continuous cooking while biochar was produced, significantly improving energy efficiency. Minimal visible smoke was observed after initial ignition, indicating relatively clean combustion compared with open biomass burning. The temperature gradually increased to up to 570 °C with 35 min of cooking.

### 3.7. Operational practicality

Field testing with farmers confirmed that the stove was easy to operate and required minimal training. Its lightweight structure allowed transportation between households or fields. Because it uses common cooking fuel, farmers did not need additional energy inputs. The dual-purpose design reduced time burden by combining cooking and biochar production activities. Farmers also reported that the sealed chamber prevented ash contamination and produced uniform biochar pieces.

### 3.8. Environmental performance

Compared with traditional residue burning, the BAU stove substantially reduced emissions by converting biomass into stable carbon rather than releasing it as greenhouse gases. The absence of open flames around the biomass feedstock limited methane and particulate emissions. Additionally, the system promotes recycling of agricultural waste, reducing environmental pollution and improving local sanitation.

### 3.9. Comparative feedstock evaluation

Among the three tested feedstocks maize stover, rice husk, and sawdust the BAU biochar stove demonstrated clear differences in biomass production efficiency and biochar quality:

Maize Stover: Produced 355 g of biochar per 1 kg of biomass (35.5%). It exhibited the highest structural stability and carbon retention due to its higher lignin content. Proximate analysis showed superior characteristics, including very high dry matter (99.87%), high crude fiber (79.71%), balanced protein (4.14%), relatively higher ether extract (1.03%), and the lowest ash content (6.82%). These attributes make maize stover biochar the most suitable for agricultural applications, particularly where stable carbon content and minimal mineral residue are desired.

Rice Husk: Produced 452 g of biochar per 1 kg of biomass (45.2%). While the yield was relatively higher than maize stover, it had a higher ash content (30.05%) and slightly lower structural robustness, which may reduce its organic quality but still makes it a moderately good option for soil amendment.

Sawdust: Produced 435 g of biochar per 1 kg of biomass (43.5%). Despite its lower yield, sawdust generated fine-textured biochar with high surface area, which can be advantageous for applications requiring rapid nutrient adsorption. However, it had higher ash content (39.71%) and slightly lower dry matter stability, indicating less structural strength compared to maize stover.

Considering both carbon content (76–78%) and proximate nutrient profiles, maize stover stands out as the most efficient feedstock for producing high-quality biochar with stable carbon structure and low inorganic residue, making it the preferred choice for sustainable soil amendment.

### 3.10. Economic feasibility

The economic analysis of biochar production using the BAU biochar stove indicates that the cost of raw materials varies significantly among different feedstocks. For a 3 kg batch of biomass, the material costs were 90 Tk for rice husk (30 Tk/kg), 45 Tk for maize stover (15 Tk/kg), and 51 Tk for sawdust (17 Tk/kg). Considering the biochar yields 1.356 kg from rice husk, 1.065 kg from maize stover, and 1.305 kg from sawdust the production costs per kilogram of biochar were calculated as 66.4 Tk/kg, 42.3 Tk/kg, and 39.1 Tk/kg, respectively. These results suggest that while rice husk provides a higher mass yield, its higher raw material cost makes it the most expensive option per unit of biochar. In contrast, sawdust and maize stover are more cost-effective feedstocks, with maize stover also offering superior biochar quality in terms of carbon stability and nutrient profile. Overall, the BAU biochar stove demonstrates a low cost and locally adaptable approach to producing high-quality biochar, making it economically viable for smallholder farmers.

The stove can be fabricated using locally available drum sheets and simple welding techniques at very low cost compared with commercial pyrolysis reactors. Its durability and low maintenance requirements make it economically attractive for smallholder farmers. The ability to produce valuable soil amendments while meeting cooking needs enhances cost effectiveness and return on investment.

### 3.11. Implications for sustainable agriculture

The biochar produced by the BAU stove meets key quality standards for agricultural application: high carbon content, porous structure, and stable composition. Such biochar can improve soil fertility, increase water retention, reduce fertilizer loss, and enhance crop productivity. By enabling decentralized production, the technology empowers farmers to manage their own soil inputs and agricultural residues sustainably.

### 3.12. Advantages of the BAU biochar stove over electric pyrolysis

The BAU biochar stove offers several significant advantages compared to conventional electric pyrolysis systems. Unlike electric reactors, it requires no electricity and avoids the risks associated with current, overloading, or heating coil damage, making it safer and more reliable in rural settings. The stove is locally fabricated, portable, and easy to handle, with low construction and maintenance costs. It produces minimal visible smoke, unlike electric systems where syngas combustion often generates large amounts of smoke. Importantly, the BAU stove recaptures and reuses syngas produced during pyrolysis as a fuel source, enhancing energy efficiency and reducing environmental pollution. Additionally, the stove allows simultaneous cooking and biochar production, providing direct household benefits while generating high quality biochar for soil amendment. Overall, this integrated approach makes the BAU biochar stove a cost-effective, environmentally friendly, and practical alternative to heavy electric pyrolysis machines.

The results confirm that the BAU biochar stove is an efficient, low cost, and environmentally friendly system capable of producing high quality nano biochar under rural conditions. Its strong performance across technical, environmental, and socio-economic parameters indicates high potential for large scale dissemination. Technology represents a practical innovation that links waste management, renewable energy, and climate smart agriculture within a single integrated system.

## 4. **Discussion**

The findings demonstrate that the BAU biochar stove achieved consistently high conversion efficiency across diverse feedstocks, though biochar yield varied according to biomass characteristics. Rice husk produced the highest biochar yield (45.2%), likely due to its elevated ash and silica content, which reduces mass loss during pyrolysis. High ash content has been reported to increase apparent biochar yield by limiting devolatilization losses during thermal decomposition (Demirbas, 2004). Sawdust followed closely (43.5%), but its finer particle size and higher volatile matter content slightly reduced recovery efficiency. In contrast, maize stover yielded the lowest biochar proportion (35.5%); however, its higher lignin content appears to enhance carbon retention and structural stability. Lignin-rich biomass is known to produce biochar with greater aromaticity and long-term stability (Lehmann & Joseph, 2015; Zhao et al., 2013). This distinction highlights a critical trade-off between quantity and quality: while rice husk maximizes mass output, maize stover produces biochar with greater long-term stability and resistance to degradation. Such differences are important when selecting feedstocks for agricultural applications focused on durable soil carbon enhancement.

Proximate analysis further reinforced the superior organic quality of maize stover biochar. Its exceptionally high dry matter content (99.87%) indicates excellent stability and minimal moisture interference, enhancing its suitability for long-term soil application. The markedly higher crude fiber fraction reflects stronger structural composition and potential resistance to microbial breakdown. Biochar stability is strongly associated with fixed carbon content and aromatic structure formed during pyrolysis (Keiluweit et al., 2010). Notably, maize stover biochar exhibited the lowest ash content (6.82%), significantly lower than sawdust and rice husk. Lower ash content indicates a higher proportion of stable organic carbon and fewer inorganic residues, which is advantageous for improving soil structure without excessive mineral accumulation (Enders et al., 2012). Collectively, these results position maize stover as the most suitable feedstock when biochar quality and long-term soil stability are prioritized.

Elemental analysis revealed consistently high carbon concentrations (76–78%) across all feedstocks, indicating efficient pyrolysis and substantial fixed carbon formation. High carbon content is widely recognized as a key indicator of biochar stability and carbon sequestration potential (Lehmann, 2007). The limited presence of volatile compounds suggests that the stove effectively promoted thermal decomposition while minimizing unstable fractions. Stable biochar carbon can persist in soils for hundreds to thousands of years, contributing to long-term climate mitigation (Lehmann et al., 2006). Furthermore, reduced volatile matter decreases the likelihood of phytotoxic effects when applied to soil (Spokas et al., 2012).

Scanning Electron Microscopy (SEM) analysis confirmed the presence of well-developed micro- and mesoporous structures, with particle sizes reaching the nano-scale. Biochar porosity plays a critical role in nutrient adsorption, water retention, and microbial habitat formation (Glaser et al., 2002; Lehmann & Joseph, 2015). The relatively uniform pore distribution suggests controlled pyrolysis conditions within the stove, reflecting effective heat management and stable combustion. High surface area and pore connectivity enhance cation exchange capacity and improve nutrient-use efficiency in soils (Liang et al., 2006).

Operational performance evaluation demonstrated that the stove is efficient and practical under rural conditions. Rapid temperature attainment and moderate batch processing time indicate effective heat transfer and feedstock adaptability. The integrated combustion pyrolysis design enables simultaneous cooking and biochar production, improving overall energy efficiency. Clean combustion with minimal visible smoke reduces particulate emissions compared to open biomass burning (Bond et al., 2013). Such improvements are particularly important in rural settings where traditional residue burning contributes significantly to air pollution and greenhouse gas emissions.

From an environmental perspective, the BAU stove presents clear advantages over conventional residue burning. Converting biomass into stable carbon rather than releasing it as $CO_2$, $CH_4$, and particulate matter contributes to climate change mitigation (Woolf et al., 2010). Biochar systems are recognized as a negative-emission technology due to their capacity for long-term carbon storage (IPCC, 2022). Additionally, recycling agricultural residues into soil amendments promotes circular resource management and reduces environmental contamination.

Economic analysis indicates that the stove provides a financially viable solution for smallholder farmers. Locally fabricated pyrolysis units have been shown to reduce capital costs compared to industrial or electric reactors (Cornelissen et al., 2016). The dual-purpose functionality combining cooking energy with biochar production enhances household energy efficiency and increases return on investment. Such decentralized systems are particularly suited for rural agricultural communities where access to electricity and commercial biochar technologies is limited (Lehmann & Joseph, 2015).

Overall, the results confirm that the BAU biochar stove integrates technical efficiency, environmental sustainability, economic viability, and social acceptability. While rice husk maximizes yield, maize stover emerges as the optimal feedstock when long-term soil stability and organic quality are prioritized. By linking agricultural residue management, renewable energy utilization, and climate-smart soil enhancement, the BAU stove represents a scalable and sustainable innovation for rural development.

## 5. Conclusion

This study developed and evaluated the BCCT-BAU biochar stove integrated with nano-biochar production techniques as a low-cost, locally adaptable, and environmentally sustainable system for nano-biochar production under rural conditions. The stove demonstrated consistent conversion efficiency across different agricultural residues, confirming its technical reliability and flexibility. Its dual-chamber design enabled controlled low-oxygen pyrolysis while simultaneously supporting household cooking, thereby improving overall energy efficiency and practicality for smallholder farmers.

Among the tested feedstocks, rice husk produced the highest biochar yield (45.2%), followed by sawdust (43.5%), while maize stover yielded 35.5%. Despite its comparatively lower yield, maize stover produced superior-quality biochar characterized by very high dry matter content, high crude fiber, low ash content, and stable carbon structure. Elemental analysis confirmed high carbon concentrations (76–78%) in all samples, indicating efficient pyrolysis and strong potential for long-term carbon sequestration. SEM analysis revealed well-developed micro- and mesoporous nano-structures, enhancing surface area, nutrient adsorption, and water retention capacity, which are critical for soil improvement. Operational assessment showed rapid temperature attainment (20–25 minutes) and moderate batch processing time (45–60 minutes), with minimal visible smoke emissions compared to open burning. Economic analysis further confirmed affordability, particularly when using maize stover or sawdust as feedstock.

Overall, the BAU biochar stove provides an integrated solution linking waste management, renewable household energy, carbon sequestration, and sustainable soil enhancement, with strong potential for widespread adoption in rural communities.

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**Data availability**

Data will be made available on request.

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