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RESEARCH ARTICLE

Physico-chemical characterisation of corn cob biochar produced through slow pyrolysis in a low-cost metallic kiln

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Abstract

Biochar production represents a sustainable approach to biomass management and soil fertility improvement. This study synthesised biochar from corn cob residue through slow pyrolysis using a low-cost, custom-designed metallic kiln and evaluated its key physico-chemical properties. The produced biochar exhibited an alkaline pH (7.53), moderate electrical conductivity (1.35 dS m^{-1}) and a high total organic carbon content (70.1 %). Nutrient analysis revealed appreciable levels of macro- and micronutrients (N: 1.48 %, P: 0.42 %, K: 2.30 %, S: 0.27 %, Zn: 5.3 ppm and Cu: 5.3 ppm), along with a favorable C:N ratio (47:36). Its high porosity (73 %) and substantial surface area (926 m^2 g^{-1}) suggest strong potential for improving soil structure, nutrient retention and long-term carbon sequestration. The pyrolysis process achieved a biochar recovery of 47 %, indicating efficient carbon retention and minimal biomass loss. The study hypothesised that controlled slow pyrolysis of corn cob residue using an affordable, decentralised kiln could produce biochar with desirable agronomic properties and economic viability. This is particularly important because corn cob waste is abundant and often burned, contributing to pollution, while escalating fertiliser costs demand cost-effective nutrient alternatives. The results confirm that simple, low-cost reactor systems can convert agricultural waste into high-quality biochar with physicochemical properties comparable to those produced using advanced technologies. The findings highlight opportunities for decentralised biochar production, low-cost fertiliser substitution and carbon-credit generation. With the global biochar market valued at USD 0.76–2.2 billion, corn cob-based biochar holds strong commercial potential. Future work should include field-scale evaluation, quality standardisation and techno-economic assessments utilising digital twins and AI-based modeling to optimise its agricultural and environmental applications.

Keywords: biochar; carbon sequestration; corn cob residue; slow pyrolysis; soil amendment

Introduction

Biochar, a carbon-rich solid formed through oxygen-limited pyrolysis, is increasingly integrated into sustainable agriculture for its ability to enhance soil structure, nutrient retention and long-term carbon storage (1). Its performance is governed by feedstock quality and pyrolysis parameters like low-temperature processes (2) generate nutrient-rich char, whereas 450–600 °C produce highly aromatic, porous and chemically stable carbon matrices. However, conventional metrics such as C:N ratio provide limited insight into reactivity because they do not account for biologically accessible carbon and nitrogen, as demonstrated in recent nutrient-management research (3). Corn-cob biochar typically displays alkaline pH (7.5), EC of 1.35 dS m^{-1} and total carbon ranging from 33–70.1 %, attributed to its poly-condensed aromatic structure that resists microbial mineralisation and persists in soil for centuries (4). Despite these advantages, industrial uptake is limited by production cost; cost-breakdown studies emphasise that affordable kilns, optimised heat recovery and efficient feedstock logistics are essential to make biochar economically competitive (5). In response, a low-cost metal kiln was developed at Regional Agricultural Research Station, Agricultural College, Polasa, Jagtial (India) to convert corn-cob residues and characterise the resulting biochar. The central hypothesis is that corn-cob biomass, when processed through an optimised low-cost system, can yield stable, agronomically effective and economically scalable biochar. Establishing this is critical for regions facing soil degradation, rising fertiliser prices and increasing pressures to reduce agricultural emissions (6). In agricultural field applications, biochar has shown potential to enhance soil structure, increase water-holding capacity and improve microbial activity, thereby contributing to improved plant growth (7). Due to its porous structure, it can retain the essential nutrients such as nitrogen, phosphorus and potassium reducing nutrient leaching and improving fertiliser efficiency (8). This hypothesis is urgent for regions facing elevated fertiliser costs and waste disposal pressures, but its confirmation or rejection has global implications for the environmental economic nexus.

Materials and Methods

Design and fabrication of metallic biochar kiln

A field-scale metallic biochar kiln was designed and fabricated, comprising two main components: a metallic drum (reactor body) and a four-legged support stand (Fig. 1). The reactor body, a cylindrical drum (1.12 m diameter × 0.88 m height; 200 L

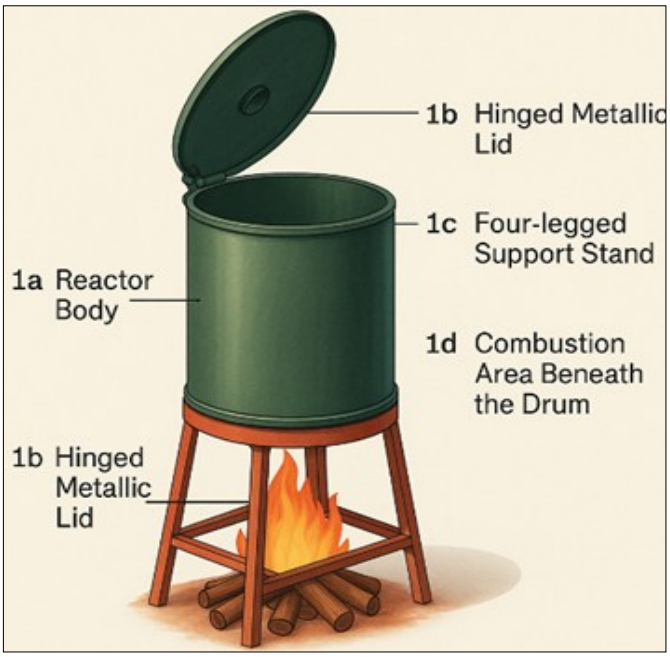


Fig. 1. Schematic diagram of design and fabrication of metallic biochar kiln.

volume) was constructed from mild steel capable of withstanding high-temperature pyrolysis (Fig. 2a). The open-bottom design facilitates direct flame contact, while 9 air inlet holes and a hinged metallic lid (0.54 m diameter) provide controlled oxygen flow, enabling slow pyrolysis. The drum was supported on a welded mild steel stand (0.36 m base diameter × 0.52 m height) to allow sufficient clearance for combustion fuel beneath the drum (Fig. 2b).

Hinged lid and combustion setup

The lid consisted of two semi-circular plates joined by a central hinge with a vent hole (10 cm) for gas release. Handles and reinforced edges ensured safe handling and thermal stability (Fig. 2c). The combustion chamber beneath the drum was manually ignited using dry firewood and crop residues arranged radially to provide uniform heat transfer. The open-bottom design ensured natural airflow, preventing flame suffocation (Fig. 2d). While this setup allows repeatable laboratory-scale pyrolysis, manual fuel addition and open flame heating may introduce batch-to-batch variability. Analytical purity of reactants and small-scale operation limits direct translation to industrial applications. These limitations should be considered when extrapolating the data for commercial use.

Feedstock preparation

Dried corn cob residues were collected and manually cleaned to remove foreign matter. Biomass was cut into 5–10 cm pieces and moisture content was measured using a laboratory oven at 105 °C for 24 hr. For comparative analysis, tender coconut husk was prepared under identical conditions. All feedstock was stored in airtight containers prior to pyrolysis.

Pyrolysis procedure

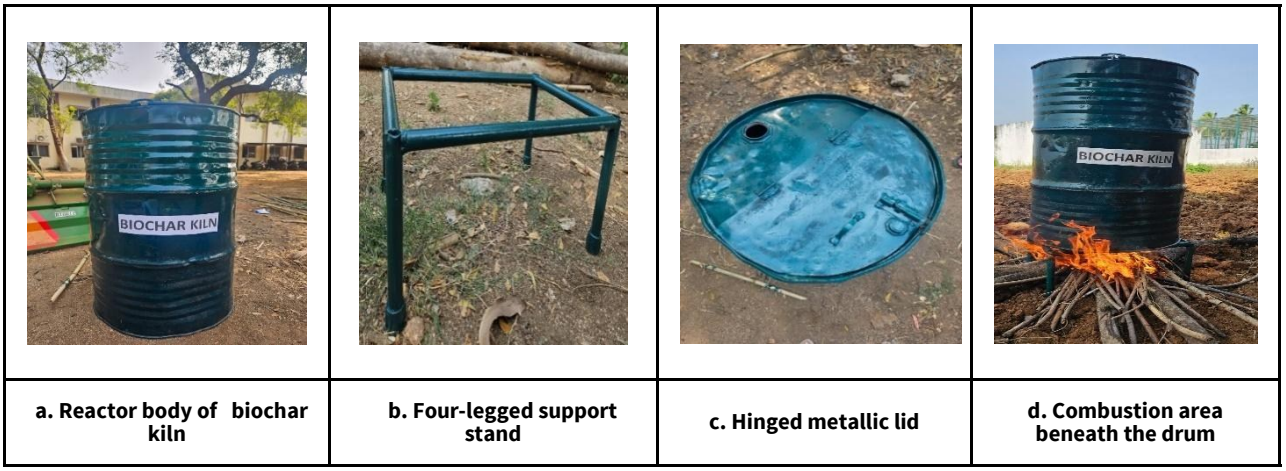
The drum was loaded with 30 kg of prepared corn cob residues. Dry firewood and additional crop residues were arranged radially beneath the drum to supply heat. Combustion was initiated with a kerosene-soaked rag. The hinged lid was closed to maintain limited oxygen while allowing gases to escape. A K-type thermocouple (India, accuracy ± 1 °C) monitored temperature at the centre of the biomass.

The pyrolysis process was conducted until the internal temperature exceeded 350 °C and maintained for 90 min. Flame colour transition from yellow to blue was used as a qualitative indicator of effective pyrolysis. After completion, the kiln was cooled and biochar was collected. The yield was calculated as the mass ratio of biochar to initial biomass (47 %).

Collected biochar was crushed with a ceramic mortar and pestle and sieved through a 2 mm mesh to obtain uniform particle size. Processed biochar was stored in airtight containers for further analysis (Fig. 3).

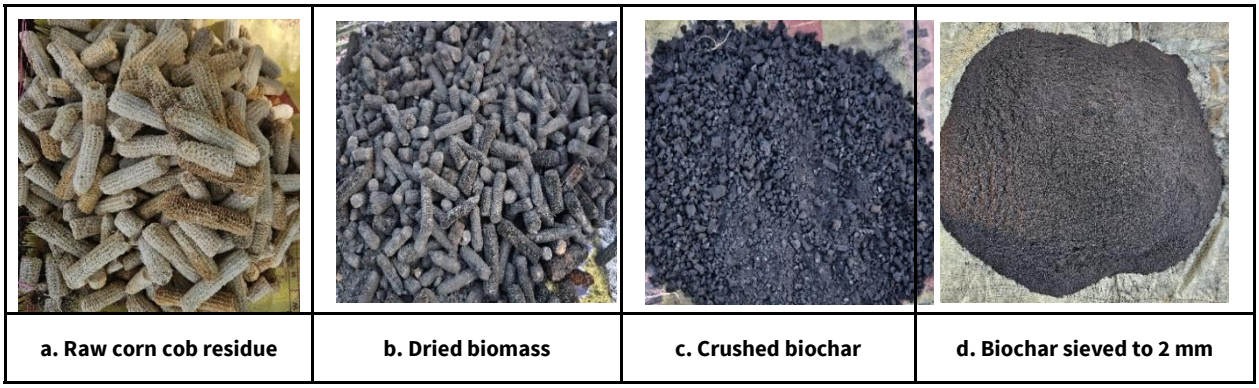
Standard analytical methods used for characterisation of biochar

Three replicated samples of biochar were analysed to determine its physico-chemical properties. The pH was measured by potentiometry using a 1:20 biochar-to-water ratio after 90 min of equilibration in a shaker. Electrical conductivity (EC) was determined by conductometry under the same conditions as pH (9). Total organic carbon (TOC) was analysed using a TOC analyser (10). Nitrogen (N) was estimated through micro Kjeldahl distillation after digestion in H_2SO_4 (11). Phosphorus (P) was analysed by nitric-perchloric acid (9:4) digestion followed by spectrophotometry using the vanado-molybdo yellow colour method (12). Potassium (K) was measured by flame photometry after nitric-perchloric acid digestion (12). Sulphur (S) was determined by turbidimetry after similar acid digestion (12). Zinc (Zn) was analysed using atomic absorption spectrophotometry following nitric-perchloric acid digestion (13).



a. Reactor body of biochar kiln	b. Four-legged support stand	c. Hinged metallic lid	d. Combustion area beneath the drum

Fig. 2. Photographs of the custom-fabricated metallic biochar kiln.



a. Raw corn cob residue	b. Dried biomass	c. Crushed biochar	d. Biochar sieved to 2 mm

Fig. 3. Steps in biochar production.

Material and energy flow considerations

The pyrolysis setup allows calculation of input-output flows, including biomass input, biochar yield and energy consumption from combustion. This facilitates techno-economic assessment and simplified cost breakdown for potential industrial applications.

Results and Discussion

Temperature evolution during pyrolysis

The temperature evolution within the reactor chamber of the micro biochar kiln during the pyrolysis process demonstrated a rapid and consistent rise, indicative of efficient heat transfer and combustion dynamics. The initial chamber temperature was 36 °C at time zero (Table 1). Within the first 5 min, the temperature increased sharply to 119 °C and reached 180 °C by 10 min, indicating the onset of active pyrolytic reactions. By 15 min, the temperature had climbed to 215 °C and continued rising steadily to 225 °C at 20 min. A more pronounced increase was observed thereafter, with the temperature reaching 300 °C at 25 min and exceeding 350 °C by the 30 min mark. This sustained thermal profile aligns with the conditions typically required for slow pyrolysis. Beyond 30 min and up to 90 min, the temperature remained above 350 °C, though specific readings were not recorded during this phase.

The rapid initial heating promotes volatile release, while sustained high temperatures facilitate carbonisation. Variations in feedstock moisture and particle size may influence heat distribution and pyrolysis efficiency, which should be considered in scale-up studies.

Digital twin and AI application

Modern computational approaches, including digital twin simulations and AI-driven predictive modeling, could optimise temperature profiles, fuel consumption and biochar yield, enabling techno-economic evaluation without extensive trial-error experiments. Such approaches have been successfully applied in industrial metaverse frameworks and cyber-physical production systems for complex manufacturing processes.

Table 1. Temperature evolution inside the micro biochar kiln during pyrolysis

Time (min)	Temperature (°C)
0	36
5	119
10	180
15	215
20	225
25	300
30	> 350

A table listing the temperature (°C) inside the reactor at 5 min interval up to 30 min. The data confirms that the low-cost kiln successfully achieved and sustained temperatures (350 °C) required for the controlled slow pyrolysis essential to produce high-quality, stable biochar.

Biochar yield and characterisation

The biochar yield from 30 kg of dried corn cob biomass was 14 kg (47 %), comparable to biochar recovery from tender coconut husk under similar conditions. The synthesised biochar was sieved (2 mm) and stored in airtight containers prior to analysis (Fig. 3).

Electro-chemical properties

The biochar exhibited a moderately alkaline pH of 7.53 and electrical conductivity of 1.35 $dS\,m^{-1}$ at 25 °C (14). The alkalinity is consistent with literature reports for crop residue biochar (e.g., coconut shell biochar) indicating potential for ameliorating acidic soils (15) (Table 2).

Chemical and physical properties

The biochar demonstrated high water-holding capacity (201 ± 2.32 %), surface area (926 ± 3.35 m^2/g), porosity (73 ± 1.24 %) and bulk density (1.6 ± 0.11 g/cm^3) supporting its application as a soil conditioner. Elemental analysis revealed high total organic carbon (70.1±1.82 %) with significant macronutrients (N 1.48 ± 0.85 %, P 0.42 ± 0.10 %, K 2.3 ± 0.05 % and S 0.27±0.03 %) and micronutrients (Zn 0.27±0.02 ppm and Cu 5.3 ±0.06 ppm) (16). Our nutrient levels, EC and water retention are consistent with or superior to those from coconut shell and other biowaste biochars (7, 8).

In another study, biochar combined with nitrogen fertiliser led to higher nitrogen uptake by plants compared to treatments involving biochar or nitrogen alone (18). In contrast, the highest nitrogen and potassium levels were observed in biochar from cow dung and poultry litter. The pyrolysis conditions and feedstock type significantly influence the nutrient content and physicochemical properties of biochar (16). Compared with maize cob biochar pyrolysed at 300–600 °C the nutrient levels and surface area are consistent, though slight deviations may be due to feedstock composition and pyrolysis duration (19). High surface area enhances microbial colonisation and nutrient adsorption, corroborating findings in other studies on biochar-mediated nitrogen retention and phosphorus runoff reduction (20–22).

Nutrient ratios and mechanistic implications

The structural carbon fraction constitutes the major component of biochar and is primarily composed of highly condensed aromatic rings containing 6 carbon atoms, with minimal oxygen and hydrogen substitutions (23). The observed C:N ratio of 47:36 is

Table 2. Electro-chemical characteristics of the biochar synthesised from corn cob residue

Sl. No.	Parameter	Biochar	Coconut shell biochar
1	Water holding capacity (%)	201 ± 2.32	90–160
2	Surface area (m^2/g)	926 ± 3.35	550–820
3	Bulk density (g/cm^3)	1.6 ± 0.11	0.6–0.9
4	Porosity (%)	73 ± 1.24	65–75
5	pH (1:20)	7.53 ± 0.13	7.5–9.0
6	EC (1:20) ($dS\ m^{-1}$ at 25 °C)	1.35 ± 0.02	1.0–1.8
7	TOC (Total organic carbon (%)	70.10 ± 1.82	65–75
8	N (%)	1.48 ± 0.85	0.5–1.2
9	P (%)	0.42 ± 0.10	0.05–0.2
10	K (%)	2.3 ± 0.05	0.8–1.2
11	S (%)	0.27 ± 0.03	0.1–0.2
12	Zn (ppm)	0.27 ± 0.02	15–30
13	Cu (ppm)	5.3 ± 0.06	7–12

A table comparing the measured properties of corn cob biochar with typical ranges for coconut shell biochar. Relevance to the hypothesis: The data directly supports the hypothesis by showing that the biochar possesses desirable agronomic properties (e.g., high surface area, alkaline pH and high K content) essential for a high-value soil amendment.

consistent with values reported for other biowaste-derived biochars, suggesting the potential for long-term organic matter stabilisation and enhanced microbial activity within the rhizosphere. These nutrient ratios highlight the capacity of biochar to act as an effective medium for nutrient stabilisation and slow-release fertilisation. Although the present study provides detailed physico-chemical characterisation at a laboratory scale, industrial-scale variability, feedstock heterogeneity and associated energy demands were not assessed. Future investigations should therefore integrate energy and material flow analyses along with simplified cost assessments to evaluate large-scale feasibility.

The scatter plots depicting the relationships between total organic carbon (TOC) and the nutrient elements nitrogen (N), phosphorus (P) and sulfur (S) demonstrate clear differences in nutrient distribution within corn-cob biochar (Fig. 4). A strong positive correlation was observed between TOC and N, with nitrogen levels increasing steadily from 1.43 % to 1.54 % as TOC rose from 69.9 % to 70.3 %, indicating effective stabilisation of N during pyrolysis. In contrast, phosphorus displayed moderate variability, with only a slight upward trend (0.38–0.45 %), suggesting that P retention is weakly influenced by carbon content and is likely governed by mineral associations. Sulfur exhibited the weakest relationship with TOC, with narrow fluctuations between 0.25 % and 0.28 % and no discernible trend. This pattern reflects the limited stability of S and its partial volatilisation or redistribution during thermal decomposition of biomass.

Emerging trends and applications

While the small-scale experiments provide detailed physico-chemical characterisation, several limitations must be considered when extrapolating the data for commercial use. Variability introduced by manual fuel addition and open flame heating, the use of small sample volumes and the lack of analytical-grade controls limit the precision and direct transferability to industrial applications (21, 24). However, modern computational approaches, including digital twin simulations and AI-driven predictive modeling, could optimise temperature profiles, fuel consumption and biochar yield, enabling techno economic evaluation without extensive trial and error experiments. Such approaches have been successfully applied in industrial metaverse frameworks and cyber physical production systems. Recent advances in artificial intelligence (AI) also allow researchers to estimate the impacts of new concepts and innovations in the conditions of specific economies. Future studies should incorporate energy/material flow analysis and simplified cost evaluation to fully assess commercial feasibility. Furthermore, integration with studies focusing on nutrient recovery from waste streams can enhance sustainability and economic viability (25).

Conclusion

The core revelation of this study is that a decentralised, low-cost pyrolysis system utilising an abundant agricultural residue corn cob

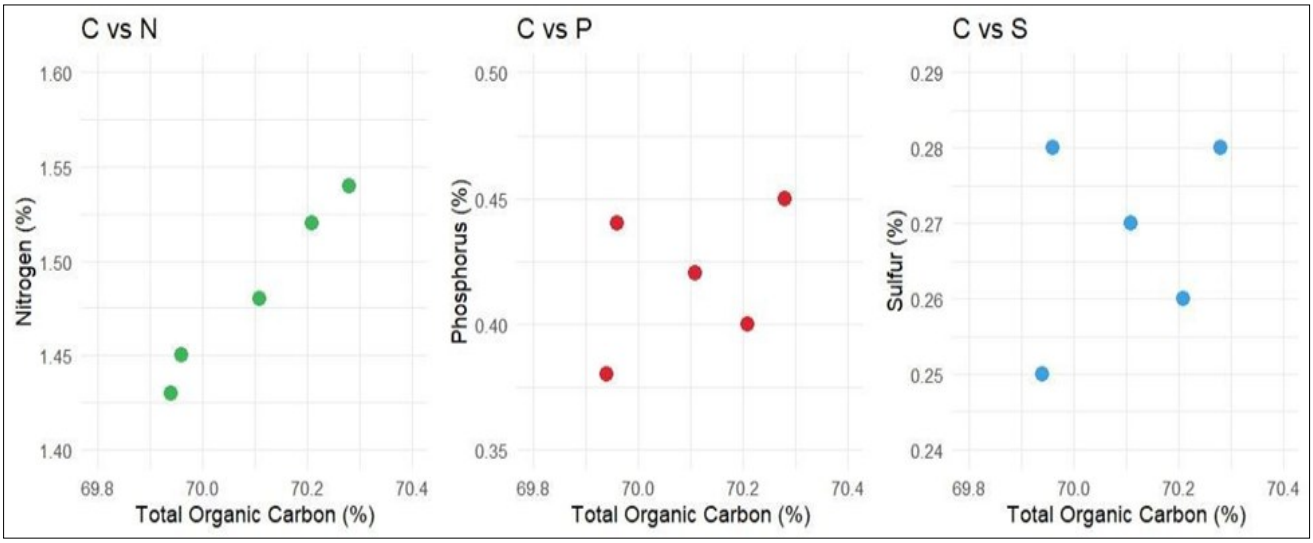


Fig. 4. Nutrient ratios of biochar are presented in terms of C:N, C:P and C:S.

can produce a biochar with physico-chemical properties superior or comparable to those achieved with more advanced, expensive technologies. The corn cob biochar exhibits high carbon stability, an alkaline pH (7.53) for acidic soil amelioration and high porosity (73 %) and surface area (926 m^2 g^{-1}) which are key driving mechanisms for enhanced soil structure and nutrient retention. This supports the potential for the concept to contribute significantly to circular bioeconomy strategies by converting waste into a high-value material. The results tend to confirm the research hypothesis and suggest that the concept is industrially promising, environmentally beneficial and potentially economically viable for smallholder and commercial farming systems. However, full confirmation of sustained environmental and economic performance requires additional multi-scale testing and advanced simulation-based assessments. Future validation using larger volumes, harmonised quality standards and digital twin or AI-based techno-economic modeling will be essential to determine whether the concept can achieve sustained performance in real industrial settings.

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Authors' contributions

HS carried out data analysis and written the original draft. SN made the conceptualisation, supervised the work and supported the review of work. ER carried out data retention and interpretation. GV aided in improvising the content. SB involved in data annotation and curation. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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