

Article

Characterization of Community-Scale Smokeless Biochar Production from Corncobs for Potential Soil Amendment and Climate-Smart Agriculture

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Abstract

Open burning of agricultural residues remains a significant source of air pollution and greenhouse gas emissions in Southeast Asia. This study evaluated a community-scale smokeless vertical charcoal kiln for biochar production from corncob residues under practical operating conditions. Carbonization at 415–435 °C for 150–180 min produced biochar yields of 23.3–28.3%, with the 150 min treatment giving the highest yield. The biochar exhibited high carbon content (71–71.5%), low volatile matter (15.7–16.7%), fixed carbon content of 51–54%, and moderately alkaline pH (8.97–9.08). Atomic H/C and O/C ratios (approximately 0.55 and 0.27) indicated moderate aromaticity and stability consistent with IBI Class 1 criteria, while SEM revealed a macropore-dominated porous structure. Theoretical carbon sequestration potential was estimated at 0.69–0.74 tCO₂-eq per tonne of dry feedstock. These findings demonstrate the technical feasibility of community-scale smokeless biochar production and provide physicochemical characterization of the resulting biochar, suggesting potential relevance for carbon storage and soil amendment; however, agronomic performance and emissions require direct evaluation, and results are specific to corncob feedstock. Overall, this work contributes to sustainable agricultural waste management by demonstrating a low-cost, community-accessible pathway that simultaneously supports climate change mitigation, air quality improvement, and socio-economic accessibility for smallholder farming systems in Southeast Asia.

Keywords: biochar; smokeless kiln; soil amendment; carbon sequestration; air pollution; agricultural residues; climate-smart agriculture; sustainability



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1. Introduction

Agricultural systems in Southeast Asia, including Thailand, are increasingly affected by climate variability, rainfall irregularity, and growing water stress [1]. The region is recognized as one of the most climate-vulnerable areas globally, where smallholder farming systems face compounding pressures from shifting monsoon patterns, prolonged dry seasons, and more frequent extreme weather events [1,2]. Climate change is altering hydrological processes, leading to reduced soil moisture availability and increasing pressure

on both rainfed and irrigated systems [1–3]. Projections indicate that continued warming and changing precipitation patterns will further intensify water deficits in tropical agricultural zones, threatening both food security and rural livelihoods [1,2]. Under these conditions, improving soil water retention and strengthening soil resilience have become central strategies in climate-smart agriculture [4–6].

At the same time, agricultural residue management remains a major environmental challenge that is deeply intertwined with both air pollution and climate change. Large volumes of crop residues are generated annually, particularly from rice, maize, and sugarcane, and are often disposed of through open burning due to its low cost and operational simplicity [3]. In Thailand alone, millions of tonnes of agricultural residues are burned in the field each year, releasing substantial quantities of pollutants directly into the lower atmosphere [7,8]. This practice contributes significantly to air pollution and greenhouse gas emissions, including PM_{2.5}, CO₂, CH₄, CO, and nitrogenous compounds, thereby affecting both local air quality and climate systems [7,8]. Epidemiological evidence links elevated PM_{2.5} exposure from agricultural burning to increased respiratory and cardiovascular disease burden, disproportionately affecting rural and peri-urban communities near burning areas [9]. Beyond health impacts, these emissions contribute to radiative forcing and regional climate feedback, reinforcing the urgency of transitioning toward cleaner residue management alternatives [7,8]. This issue is particularly critical in Thailand, where reducing agricultural burning has become a national priority embedded in air quality management and climate mitigation policy frameworks [7,10].

Given the widespread availability of agricultural residues, converting these materials into biochar presents a promising dual-benefit alternative that simultaneously addresses residue management, air pollution, and climate change [11]. Previous studies have reported that biochar production systems may contribute to greenhouse gas mitigation relative to open burning through lower emissions of CH₄ and N₂O and through stabilization of a portion of biomass carbon in biochar [7,11,12]. However, the magnitude of these climate benefits depends on system design, operational conditions, and broader life-cycle considerations. Life cycle assessment studies have reported that well-designed biochar systems can provide net climate benefits through carbon stabilization and long-term carbon storage [13]. However, no life cycle assessment or comprehensive carbon accounting was performed in the present study. Therefore, the current work evaluates carbon sequestration potential based on biochar yield and carbon content rather than overall net carbon balance. Biochar production is increasingly recognized as a feasible and scalable solution in Southeast Asian contexts, where the combination of abundant biomass feedstocks and pressing air quality challenges creates strong incentives for adoption [7,12].

Biochar is a carbon-rich material produced via thermochemical conversion of biomass under oxygen-limited conditions and is widely recognized for its potential to improve soil properties and provide long-term carbon storage [14]. It can enhance soil porosity, aggregation, and water retention, particularly in water-limited soils [15], while also contributing to crop productivity and carbon sequestration [16,17]. In addition, biochar has been reported to reduce the mobility and bioavailability of toxic heavy metals in contaminated soils and to mitigate greenhouse gas emissions from agricultural systems through multiple physicochemical and biological mechanisms [18,19]. The recalcitrant aromatic carbon structure of biochar resists microbial decomposition, enabling carbon residence times that may extend over centuries to millennia under field conditions, making it a meaningful tool for long-term climate mitigation [20,21]. The role of biochar in long-term soil carbon storage has also been evaluated in the context of climate scenarios and soil management practices. Qiu et al. [22] reported that biochar can contribute to sustained soil

carbon retention while supporting climate change mitigation objectives, further reinforcing its relevance to climate-smart agriculture and sustainable land management.

However, biochar performance depends strongly on production conditions, including feedstock type, peak temperature, residence time, and kiln design [14,19]. Traditional kilns (Figure 1) commonly used in rural settings often suffer from poor airflow control and incomplete carbonization, resulting in inconsistent product quality, low carbon retention efficiency, and elevated emissions of particulate matter and incomplete combustion products, which undermine both the environmental and agronomic value of the biochar produced [20,21]. These emission characteristics are particularly problematic from an air quality perspective, as open or poorly controlled kilns can release concentrated plumes of PM_{2.5} and polycyclic aromatic hydrocarbons (PAHs) that pose risks to operators and nearby communities [21]. In contrast, improved smokeless systems are specifically engineered to circulate and combust pyrolysis gases more completely, thereby substantially reducing visible smoke, particulate emissions, and carbon losses while improving thermal efficiency [20].

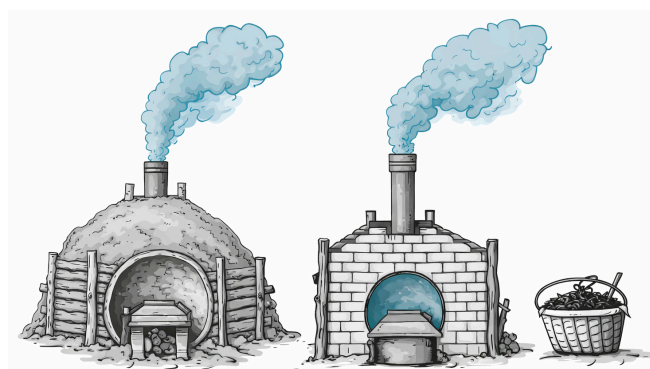


Figure 1. Illustration of traditional charcoal kilns with visible smoke emissions.

For corncob feedstock, carbonization at moderate temperatures (approximately 400–450 °C) typically yields around 25–27%, representing a practical balance between carbon retention and the development of stable aromatic structures that resist decomposition [22,23]. The choice of feedstock and operating temperature jointly determines the elemental composition, surface chemistry, and stability of the resulting biochar—all of which are relevant to both its soil amendment value and its effectiveness as a carbon sequestration medium [17,22]. Such conditions are particularly relevant for climate-smart agriculture, where the combined goals of improving soil water dynamics and delivering durable carbon storage must be met simultaneously [17].

Despite extensive research on biochar under laboratory and controlled experimental conditions, many studies have been conducted at laboratory, pilot, or technology-development scales, with limited evaluation of community-scale smokeless kilns under practical operating environments [24,25]. Operational variability arising from feedstock heterogeneity, manual loading practices, and ambient weather conditions is rarely captured in laboratory-based assessments, yet it critically determines the consistency and reliability of biochar quality at the field level [24,25]. Integrated assessments that simultaneously evaluate kiln performance, biochar physicochemical properties, carbon sequestration potential, and implications for soil–water processes remain limited [26]. This gap is especially significant for rural and smallholder contexts in climate-vulnerable regions, where a technology must simultaneously be technically feasible, economically accessible, environmentally preferable to open burning, and capable of delivering meaningful agronomic and climate co-benefits [27].

Previous studies have reported the use of improved biochar production systems, including retort kilns, flame-curtain kilns, and smokeless carbonization technologies, with emphasis on emission control, thermal efficiency, and biochar quality [20,24]. For example, Adam [20] demonstrated the environmental advantages of low-cost retort kilns, while Jayakumar et al. [28] evaluated biochar quality and operational performance in flame-curtain pyrolysis systems. However, many of these studies focused primarily on kiln design, combustion performance, or laboratory-scale biochar characterization. Relatively few investigations have simultaneously examined operational performance, physicochemical properties, carbon sequestration potential, and implications for agricultural applications under practical community-scale operating conditions. This gap is particularly relevant in Southeast Asian agricultural systems, where residue management technologies must be technically feasible, environmentally acceptable, and suitable for decentralized adoption by smallholder farmers.

Therefore, this study evaluates a community-scale smokeless vertical kiln for producing biochar from corncob residues in the context of Thailand's agricultural system. The objectives are to: (i) analyze carbonization behavior and temperature characteristics under practical operating conditions; (ii) characterize the physicochemical properties of the produced biochar; and (iii) assess the implications of this production system for carbon sequestration potential, potential air-pollution mitigation, and biochar properties associated with soil water retention within a climate-smart agriculture framework. By integrating kiln performance, material characterization, and environmental relevance, this study contributes practical evidence to support the adoption of cleaner biomass management strategies in smallholder agricultural systems facing climate change. In doing so, this research directly addresses core dimensions of sustainability by generating quantitative evidence on environmental performance (greenhouse gas mitigation and air pollution reduction), while also considering the socio-economic accessibility of the technology for resource-limited farming communities, in line with the Sustainable Development Goals on climate action (SDG 13), responsible production and consumption (SDG 12), and sustainable agriculture (SDG 2).

2. Materials and Methods

2.1. Feedstock Preparation

Corncoobs were collected from three maize-processing facilities located in central Thailand (Nakhon Pathom, Suphan Buri, and Kanchanaburi provinces) immediately following kernel removal. The raw corncoobs had an average length of approximately 10–14 cm, consistent with dimensions commonly reported for maize cob biomass in thermochemical conversion studies [22].

Prior to carbonization, the corncoobs were manually cut into two equal sections (approximately 5–7 cm in length) to improve packing uniformity within the kiln and promote more homogeneous heat distribution during carbonization [24,29]. This size reduction step is particularly important in community-scale systems, where feedstock geometry directly influences airflow patterns and the consistency of thermal conversion across the biomass bed.

The prepared corncob sections were subsequently sun-dried under natural outdoor conditions at ambient temperatures of 30–35 °C for 2–3 days. Sun drying is widely applied as a low-energy pre-treatment method for agricultural residues prior to thermochemical conversion [23,24]. After drying, the moisture content was reduced to approximately 9–11% (wet basis), as determined by oven-drying at 105 °C until constant weight, following standard procedures for biomass moisture analysis [30]. Moisture levels below 15% are generally recommended to ensure efficient slow carbonization and minimize latent heat

losses associated with water evaporation during thermal conversion [25]. All biochar yield calculations reported in this study were expressed on a dry-weight basis.

2.2. Smokeless Vertical Charcoal Kiln Design and Biochar Production

Biochar was produced using a smokeless vertical charcoal kiln developed by the Energy and Environmental Engineering Center (EEEC), Faculty of Engineering at Kamphaeng Saen, Kasetsart University. The kiln was specifically designed for community-scale application, integrating controlled airflow management, enhanced heat utilization, and secondary combustion of pyrolysis gases to reduce visible smoke emissions during biomass carbonization [24]. These design principles are consistent with low-emission kiln technologies developed for decentralized biomass conversion systems, where improved combustion conditions are critical for minimizing particulate emissions and improving process efficiency [20,24,30].

2.2.1. Kiln Configuration and Operating Principle

The smokeless vertical charcoal kiln consists of a double-layer cylindrical structure, as illustrated in Figure 2a. The inner chamber houses the biomass feedstock, while the outer layer is constructed from ceramic fiber insulation to minimize conductive loss of heat and enhance thermal retention during operation. Double-layer configurations of this type have been widely applied in small-scale biomass reactors to improve thermal efficiency and stabilize internal temperature profiles [24,27].



Figure 2. Schematic illustration and actual prototype of the smokeless vertical charcoal kiln: (a) schematic diagram showing the double-layer structure and gas circulation pathway for secondary combustion and heat recovery; (b) actual prototype of the kiln used in this study.

Ignition is initiated at the upper section of the inner chamber, where air is supplied through adjustable intake openings on the lid, establishing controlled oxygen-limited conditions appropriate for slow carbonization [20]. As pyrolysis progresses, volatile gases generated from biomass thermal decomposition are partially recirculated within the system and subjected to secondary combustion, thereby promoting complete oxidation and substantially reducing visible smoke emissions [27]. This gas recirculation mechanism directly addresses the emission limitations associated with conventional open kilns, where uncontrolled combustion leads to elevated concentrations of PM_{2.5} and incomplete combustion products, as discussed in Section 1 [21]. Effective airflow management and controlled gas

recirculation are therefore critical operational parameters for maintaining stable thermal conditions, ensuring carbonization consistency, and reducing environmental emissions at the community scale [30]. It should be noted that quantitative emission characterization was not performed in the present study. Therefore, the term “smokeless” refers to the absence of visible smoke observed during kiln operation under the tested conditions rather than to experimentally verified reductions in particulate matter or gaseous emissions. Direct measurements of PM_{2.5}, CO, CH₄, N₂O, volatile organic compounds (VOCs), and other pollutants are required to validate the emission performance of the system.

The double-layer configuration additionally contributes to process stability by buffering against ambient temperature fluctuations, a consideration that is particularly important under practical field conditions, where external variability can otherwise compromise carbonization uniformity and final biochar quality [25].

The prototype used in this study, shown in Figure 2b, integrates a gas circulation unit with a smoke condensation system for wood vinegar recovery. Such integrated designs have been reported to enhance both the environmental performance and overall resource efficiency of community-scale biochar production systems [24,30].

2.2.2. Temperature Monitoring

Temperature monitoring was conducted using K-type thermocouples connected to a digital data logger, a standard approach widely applied in thermochemical biomass conversion studies [23,25,30]. A dual-channel digital thermocouple thermometer (Model GM1312, Benetech, Shenzhen, China) equipped with Type K thermocouples (Chromel–Alumel, NiCr–NiAl) was used throughout all carbonization runs. Type K sensors were selected due to their suitability for moderate- to high-temperature carbonization processes, with a measurement range of -200 to 1350 °C, an instrument display range of -100 to 1300 °C, a resolution of 0.1 °C, and a specified accuracy of ± 1.5 °C or $\pm 0.4\%$ of the reading, whichever was greater (Benetech GM1312 technical specifications). These specifications are consistent with thermocouple systems commonly employed in biomass thermal conversion studies [24].

Temperature was measured at two locations to capture spatial variation within the kiln: (i) internal temperature, using a probe inserted approximately 20 cm below the top of the biomass bed to represent conditions within the active carbonization zone; and (ii) external temperature, recorded at a fixed point near the outer wall of the kiln to reflect surface thermal behavior and heat dissipation during operation. Similar multi-point measurement approaches have been applied to characterize heat distribution and thermal transfer in biomass conversion systems [30,31]. Although the two monitoring locations provided useful information regarding overall thermal behavior, they do not fully capture spatial temperature variation within the biomass bed. Temperature gradients may have existed between the upper, central, and lower regions of the kiln during operation—a pattern common in fixed-bed biomass carbonization systems—potentially contributing to local differences in devolatilization intensity, carbonization degree, and final biochar properties, and may partly explain the observed run-to-run variability in biochar yield and bulk density. Therefore, the recorded temperatures should be interpreted as representative monitoring points rather than a complete characterization of the internal thermal field.

Prior to each measurement session, the thermocouples were verified against reference temperature points (ice water at 0 °C and boiling water at 100 °C) to ensure measurement consistency within the specified accuracy range. Temperature data were subsequently recorded at 10 min intervals throughout the entire carbonization process to capture temporal thermal dynamics and assess process stability under practical community-scale operating conditions [24,27,31].

2.2.3. Carbonization Conditions

Biochar production was conducted at low-to-moderate temperatures (approximately 350–450 °C), corresponding to the primary thermal decomposition range of lignocellulosic biomass, where hemicellulose and cellulose undergo progressive degradation and lignin experiences partial structural transformation [23,29]. Operating within this temperature range has been associated with improved carbon retention and biochar yield while maintaining structural stability and surface functionality relevant to both agronomic and environmental applications [14,25,32].

Carbonization durations of 150 and 180 min were evaluated to assess the influence of residence time on biochar yield and physicochemical properties. Residence time is a key process parameter governing the extent of devolatilization, mass loss, and final carbon content, and its optimization is especially important under practical small-scale operating conditions where thermal gradients and feedstock packing variability can introduce additional process uncertainty [23,24].

Upon completion of each carbonization run, all air inlets were sealed, and the kiln was allowed to cool naturally to ambient temperature under oxygen-limited conditions. This controlled cooling procedure is a standard post-carbonization practice employed to prevent oxidation of the produced biochar and preserve fixed carbon content and structural integrity [14,29]. The produced biochar was subsequently collected and weighed to determine batch yield on a dry-weight basis. Samples were then stored in sealed airtight containers to minimize moisture reabsorption and prevent compositional changes prior to physicochemical characterization [25].

2.3. Biochar Sample Preparation

The produced biochar was manually cleaned to remove loosely adhered ash and uncarbonized biomass residues, minimizing analytical interference from surface impurities prior to characterization [14,28]. The cleaned material was subsequently subjected to gentle mechanical crushing using a mortar and pestle, followed by sieving to obtain a particle size fraction smaller than 2 mm. A sub-2 mm particle size is commonly employed in physicochemical and agronomic characterization of biochar to ensure sample homogeneity, improve analytical reproducibility, and enable representative subsampling across heterogeneous batch-produced materials [14,31].

All prepared samples were oven-dried at 105 °C for 24 h prior to analysis, following standard procedures for moisture determination and dry-weight preparation of biomass-derived materials [33]. Moisture removal at this temperature is essential to eliminate residual water that would otherwise introduce systematic bias into proximate composition, elemental analysis, and mass-based property measurements [25]. Drying continued until a constant weight was achieved to ensure complete moisture removal. The dried and prepared biochar samples were subsequently stored in sealed airtight containers at room temperature to prevent moisture reabsorption and minimize compositional changes between preparation and analysis [14,31].

2.4. Proximate Analysis Procedure

Proximate analysis was performed to determine moisture content, volatile matter, ash content, and fixed carbon content in accordance with ASTM D7582 standard procedures [33]. These parameters are widely used to evaluate the thermal behavior, carbonization efficiency, and overall material quality of biochar produced under varying process conditions [14,23,25].

Moisture content was determined by oven-drying at 105 °C to constant weight, consistent with standard biomass moisture determination procedures [25]. Volatile matter was measured by heating samples under oxygen-limited conditions following the pre-

scribed temperature program specified in ASTM D7582, providing an indicator of the degree of devolatilization achieved during carbonization [23,31]. Ash content was quantified by complete combustion of samples at 750 °C in a muffle furnace until constant weight was achieved, representing the total inorganic mineral fraction remaining after thermal oxidation [14,28]. Fixed carbon content was calculated by difference on a dry basis, subtracting the combined fractions of moisture, volatile matter, and ash from 100%, and serves as a key indicator of carbonization efficiency and the degree of carbon concentration achieved during thermal conversion, with higher values generally reflecting more complete devolatilization and greater carbon stability [18,23,25].

2.5. Biochar Characterization and Adsorptive Property Assessment

Biochar produced from corncob residues using the smokeless vertical charcoal kiln was characterized to evaluate physicochemical properties, surface behavior, and agronomic relevance. Comprehensive characterization is essential for understanding both the environmental performance and the soil amendment potential of biochar produced under practical community-scale conditions [14,28]. The selected characterization methods were designed to reflect realistic performance under non-activated, community-scale production conditions rather than laboratory-optimized systems, as non-activated biochar typically exhibits distinct structural and surface characteristics compared to thermally or chemically activated materials [24,34]. These approaches are consistent with internationally recognized frameworks for biochar quality assessment [19].

The characterized properties are also directly relevant to soil water-retention behavior, as biochar pore structure and surface chemistry jointly influence water holding capacity and plant-available water. Biochar application has been shown to improve these properties, particularly in coarse-textured and water-limited soils, contributing to enhanced drought resilience and water-use efficiency under conditions of increasing climate variability [15,16,35].

2.5.1. Proximate and Ultimate Analysis

Proximate analysis was conducted in accordance with ASTM D7582 to determine moisture content, volatile matter, ash content, and fixed carbon content, parameters that are widely used to characterize thermal decomposition behavior and assess the fundamental material quality of biochar [14,25,31,33]. Ultimate analysis was performed using a CHNS elemental analyzer to quantify carbon (C), hydrogen (H), nitrogen (N), and sulfur (S) content, with oxygen (O) content calculated by difference. Elemental composition provides critical insight into the degree of carbon enrichment and heteroatom distribution achieved during carbonization, both of which influence biochar surface reactivity, stability, and environmental performance [28,32].

Atomic H/C and O/C ratios were subsequently calculated on a molar basis from the ultimate analysis data. These ratios are widely used as diagnostic indicators of the degree of carbonization, aromaticity, and chemical stability of biochar, with lower H/C values generally associated with a more condensed aromatic structure and greater resistance to microbial and chemical degradation [18,34].

2.5.2. Determination of Adsorptive and Surface Properties

Adsorption-related surface properties were evaluated through measurement of bulk density, pH in aqueous suspension (pH_{sol}), point of zero charge (pH_{zpc}), and iodine number. These parameters are commonly applied to characterize surface chemistry, charge behavior, pore-related adsorption potential, and overall surface functionality of biochar materials [31,35,36].

Bulk density was determined using a standard mass-to-volume method and expressed in $\text{g}\cdot\text{cm}^{-3}$, providing an indicator of material compactness, pore development, and structural characteristics relevant to soil physical interactions [14,29].

The solution pH (pH_{sol}) was determined by mixing biochar with deionized water at a ratio of 10% (*w/v*), shaking at 100 rpm for 3 h at 30 °C, and recording the equilibrium pH after stabilization. This method provides an indication of the alkalinity contributed by ash-derived minerals and surface functional groups, which influences nutrient availability and soil buffering capacity when biochar is applied as a soil amendment [28,37]. Surface charge properties are widely recognized as important indicators of biochar physicochemical behavior [38], soil interactions [39], environmental applications [40], and analytical characterization [41].

The point of zero charge (pH_{zpc}) was determined using the pH drift method as described by Rangel-Mendez and Streat [42], enabling evaluation of the net surface charge characteristics of the biochar across a range of pH conditions. The relationship between pH_{sol} and pH_{zpc} provides insight into the dominant surface charge under application conditions, which is directly relevant to electrostatic interactions with ionic species in soil solution [42].

Micropore-related adsorption capacity was assessed using the iodine number method in accordance with ASTM D4607 [43], a widely applied indicator of accessible microporosity and adsorption potential in carbon-based materials [29,41].

2.5.3. SEM Analysis of Surface Morphology and Pore Structure

Surface morphology and pore structure of the produced biochar were examined using scanning electron microscopy (Model SU3800, Hitachi High-Tech Corporation, Tokyo, Japan). Samples were prepared by mounting on aluminum stubs, sputter-coated with gold to enhance surface conductivity, and imaged at magnifications of 150× and 1200× to qualitatively assess pore morphology, pore connectivity, surface heterogeneity, and microstructural features potentially relevant to adsorption-related properties and soil physical functionality [14,28]. The two magnification levels were selected to capture both the macroporous architecture inherited from the lignocellulosic feedstock structure at lower magnification and finer surface features, including pore openings and wall characteristics, at higher magnification.

SEM observations were interpreted in conjunction with bulk physicochemical and adsorption-related property measurements to provide a more integrated understanding of pore architecture, surface accessibility, and overall material functionality under community-scale production conditions [34,36]. It should be noted that SEM provides qualitative information regarding surface morphology only. Quantitative differentiation between micro-, meso-, and macropores would require dedicated pore size distribution analyses such as BET characterization and was beyond the scope of the present study.

2.5.4. Determination of Agronomic Property Indicators

Agronomic-related indicators, including electrical conductivity (EC) and cation exchange capacity (CEC), were determined using standard soil amendment testing methods. These parameters are commonly used to evaluate soil buffering capacity, nutrient retention potential, and the overall suitability of biochar for agricultural applications under field conditions [15,37].

EC was measured in aqueous biochar suspension as an indicator of soluble salt content, which influences osmotic potential and ionic balance in soil systems following biochar amendment [16,37]. CEC was determined using the ammonium acetate (NH₄OAc) saturation method at pH 7.0, in accordance with standard procedures for biochar characterization,

providing a measure of the material's capacity to retain exchangeable cations relevant to plant nutrition [15,37].

Together, these indicators provide a practical assessment of biochar performance in soil systems by linking surface chemical properties to nutrient dynamics and soil functionality, and are particularly relevant for evaluating the agronomic potential of biochar produced under community-scale conditions [16,44].

2.6. Data Analysis

Experimental data from feedstock preparation, biochar yield determination, proximate and ultimate analysis, adsorption-related property assessment, surface morphology characterization, and agronomic indicator measurements were analyzed using a descriptive statistical approach. Results are presented as individual values, means, and standard deviations where replicate measurements were available. Given the limited number of replicates ($n = 2$), these statistics are provided primarily to improve transparency regarding experimental variability rather than to support formal inferential comparisons [24,31]. This approach is intended to reflect the nature of variability encountered under real-world operating conditions, where feedstock heterogeneity, manual loading practices, and ambient environmental fluctuations contribute to process variability that is not fully captured by controlled laboratory assessments.

Formal statistical hypothesis testing was not applied, as the primary objective of this study was to evaluate process feasibility, operational consistency, and material characteristics of biochar produced under representative community-scale conditions, rather than to optimize process parameters under controlled experimental settings [27,30]. Similar descriptive approaches have been adopted in studies evaluating decentralized biomass carbonization systems, where inherent variability in feedstock properties and operating conditions limits the applicability of conventional inferential statistical frameworks [24,30].

Accordingly, the reported values should be interpreted as indicative of system performance and material characteristics rather than statistically representative estimates derived from a fully replicated experimental design. In addition, carbon sequestration potential was estimated based on measured biochar yield and elemental composition, as described in Section 2.7.

2.7. Carbon Sequestration Potential

The carbon sequestration potential of the produced biochar was estimated based on biochar yield and elemental carbon content obtained from ultimate analysis [17]. This approach has been widely adopted to evaluate carbon storage potential in biochar systems and is considered appropriate for simplified assessments under practical production conditions [13]. Life cycle-based assessments have similarly applied yield- and carbon content-based calculations to quantify the carbon sequestration benefits of biochar production systems [13,45].

Biochar yield was expressed on a dry feedstock basis, and carbon content was reported as the mass fraction of carbon in the produced biochar as determined by ultimate analysis. The use of these two parameters as primary inputs is consistent with previous studies linking carbonization conditions to carbon retention efficiency and long-term biochar stability [17,32]. The mass of carbon retained per unit mass of dry feedstock was calculated as:

$$C_{\text{retained}} = \text{Yield} \times C_{\text{content}} \quad (1)$$

where Yield represents the biochar yield expressed as tonnes of biochar per tonne of dry feedstock, and C content is the mass fraction of carbon in the produced biochar as determined by elemental analysis.

The corresponding CO₂-equivalent carbon storage potential was estimated by applying a stoichiometric conversion factor of 44/12, based on the molecular weight ratio of CO₂ to carbon, consistent with greenhouse gas accounting methodologies used in national emission inventories [1,2]:

$$\text{CO}_2\text{-eq} = C_{\text{retained}} \times (44/12) \quad (2)$$

These calculations provide a theoretical upper-bound estimate of carbon sequestration potential under community-scale production conditions. The estimation does not account for potential carbon losses occurring during biochar handling, transport, or post-application field processes, and should therefore be interpreted as an approximation of maximum achievable carbon storage rather than a field-validated sequestration value [46–48].

3. Results

3.1. Biochar Production Performance

Biochar yields ranged from 23.33% to 28.33% across all carbonization runs, indicating effective conversion of corncob biomass under practical community-scale operating conditions (Table 1). The highest yield (28.33%) was obtained at a carbonization duration of 150 min (Run 1), while the lowest yield (23.33%) was recorded at 180 min (Run 1). Yield variation was also observed between replicate runs conducted at the same nominal carbonization duration, reflecting operational variability inherent to community-scale biomass carbonization systems [22,24,30].

Table 1. Biochar yield and carbonization characteristics of corncob-derived biochar.

Batch ID	Feedstock Mass (kg)	Biochar Mass (kg)	Yield (%)	Max. Internal Temperature (°C)	Max. External Temperature (°C)
180 (Run 1)	30	7.0	23.33	425	803
180 (Run 2)	30	8.0	26.67	435	789
150 (Run 1)	30	8.5	28.33	415	789
150 (Run 2)	30	8.0	26.67	420	767

Note: Internal temperature was measured at the top of the kiln with the thermocouple probe inserted ~20 cm into the kiln. External temperature was measured at one point outside the kiln body. Temperatures were recorded every 10 min.

Maximum internal temperatures ranged from 415 to 435 °C across all runs, falling within the temperature regime associated with slow carbonization of lignocellulosic biomass [23,34]. Maximum external surface temperatures were substantially higher, ranging from 767 to 803 °C, reflecting heat transfer through the kiln wall and combustion processes occurring at the outer chamber during operation. The relatively narrow range of internal peak temperatures observed across all runs suggests generally stable thermal behavior at the monitored locations [24,30]. It should be noted that each carbonization duration was evaluated with two replicate runs ($n = 2$); therefore, variability is reported descriptively rather than statistically, consistent with the analytical approach described in Section 2.6.

For descriptive purposes, the mean biochar yield was $27.50 \pm 1.18\%$ for the 150 min treatment and $25.00 \pm 2.36\%$ for the 180 min treatment. The corresponding coefficients of variation (CV) were 4.3% and 9.4%, respectively, indicating moderate operational variability typical of community-scale batch production.

The temporal temperature profiles recorded during carbonization are presented in Figure 3. Internal temperatures increased progressively throughout the process, reaching maximum values of 415–420 °C for the 150 min runs and 425–435 °C for the 180 min runs.

External temperatures increased more rapidly and reached substantially higher values (767–803 °C), reflecting combustion activity in the outer chamber and heat release associated with secondary combustion. The overall temperature evolution was generally consistent between replicate runs, suggesting stable thermal behavior at the monitored locations under practical operating conditions.

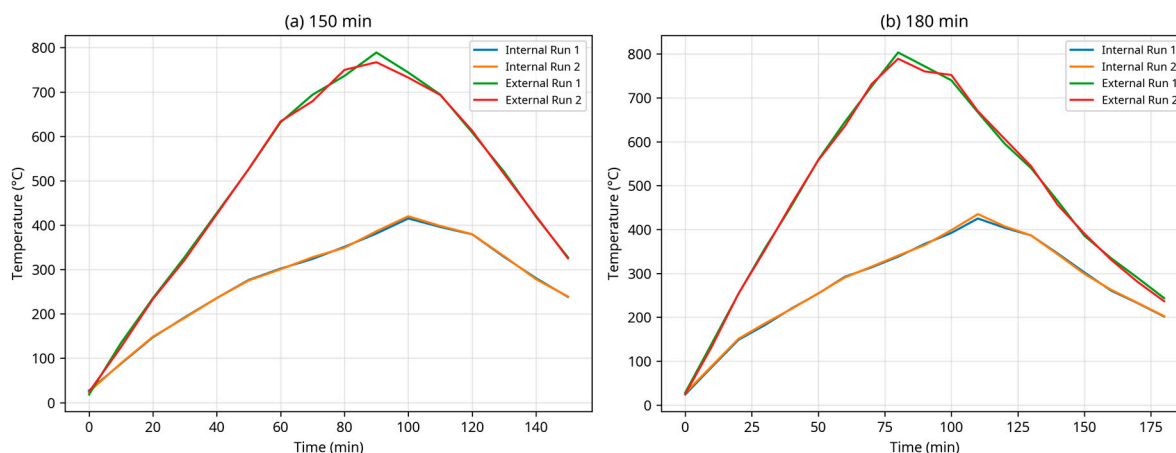


Figure 3. Temperature profiles recorded during corncob carbonization under (a) 150 min and (b) 180 min operating durations. Internal and external temperatures were monitored at 10 min intervals throughout the carbonization process. Replicate runs exhibited similar thermal trajectories, indicating generally stable thermal behavior at the monitored locations during kiln operation.

Based on the results presented in Table 1, biochar produced at a carbonization duration of 150 min was selected for further physicochemical characterization because it provided the highest observed biochar yield together with a shorter processing time among the evaluated conditions. Both replicate runs at 150 min were included in subsequent analyses to represent reproducibility under practical operating conditions.

3.2. Proximate and Ultimate Composition of Biochar

Based on the production performance results presented in Section 3.1, biochar samples produced at a carbonization duration of 150 min were selected for detailed physicochemical characterization. This condition yielded the highest biochar output (26.67–28.33%) within a shorter processing time compared with the 180 min duration. Both replicate runs conducted at 150 min were included in all subsequent analyses to represent reproducibility under practical community-scale operating conditions.

3.2.1. Proximate Analysis

The proximate analysis results of the raw corncob feedstock and biochar produced at 150 min carbonization duration are summarized in Table 2.

The raw corncob feedstock exhibited a moisture content of 9–11% and volatile matter of 80–83%, consistent with the compositional characteristics typically reported for lignocellulosic agricultural residues [23]. Following carbonization at 150 min, moisture content decreased substantially to 0.54–0.56%, and volatile matter was reduced to 15.74–16.68%, indicating effective dehydration and devolatilization during thermal conversion.

Ash content decreased from 15–18% in the raw feedstock to 9–11% in the produced biochar. Although ash enrichment is frequently reported during biomass carbonization, reductions in ash content have also been observed when feedstock heterogeneity, sampling variability, or loss of fine mineral-rich particles occurs during handling and processing. Because mineral composition was not directly analyzed in the present study, the mechanism responsible for the observed ash reduction cannot be conclusively identified [45]. Fixed

carbon content increased markedly from 2.5–2.9% in the raw feedstock to 51–54% in the biochar, confirming successful conversion of corncob biomass into a carbon-enriched solid material. Correspondingly, the higher heating value increased from 16–17 MJ·kg^{−1} for the raw feedstock to 22–24 MJ·kg^{−1} for the biochar, reflecting the improved energy density of the carbonized product [23,34].

Table 2. Proximate and ultimate analysis of corncob-derived biochar.

Parameter	Sun-Dried Feedstock	Biochar
Proximate analysis		
Moisture (%)	9–11	0.54–0.56
Volatile matter (%)	80–83	15.74–16.68
Ash (%)	15–18	9–11
Fixed carbon (%)	2.5–2.9	51–54
Higher heating value (MJ·kg ^{−1})	16–17	22–24
Ultimate analysis		
Carbon (%)	44–45	71–71.5
Oxygen (%)	43–44	24.4–25.4
Nitrogen (%)	0.54	0.59
Hydrogen (%)	5.8–6	3–3.5
Sulfur (%)	0.04	0.04
Atomic ratios		
H/C (–)	–	≈0.55
O/C (–)	–	≈0.27

Note: (1) Biochar values represent the observed ranges from two independent production runs ($n = 2$). Because individual analytical replicate data were not retained, standard deviations could not be calculated for these parameters. (2) IBI Class 1 stability criteria: H/Corg < 0.7 and O/Corg < 0.4.

3.2.2. Ultimate Analysis and Atomic Ratios

Ultimate analysis results illustrating compositional changes induced by carbonization at 150 min are summarized in Table 2. Carbon content increased substantially from 44–45% in the raw corncob feedstock to 71–71.5% in the produced biochar, while oxygen content decreased from 43–44% to 24.4–25.4%, indicating progressive deoxygenation during thermal conversion. Hydrogen content declined from 5.8–6% to 3–3.5%, consistent with dehydration and devolatilization reactions occurring during slow carbonization.

Nitrogen and sulfur content remained low both before and after carbonization. Nitrogen increased slightly from 0.54% to 0.59%, while sulfur remained constant at 0.04% in both the raw feedstock and the produced biochar. The low heteroatom content of the produced biochar indicates minimal impurity levels in both materials.

Together with the proximate and ultimate analysis results, the measured atomic ratios indicate substantial carbon enrichment, reduced volatile matter content, and low heteroatom concentrations in the produced biochar. The H/C ratio (~0.55) and O/C ratio (~0.27) are consistent with a moderately carbonized material exhibiting appreciable aromaticity and structural stability [18,34].

3.3. Adsorptive and Surface Chemical Properties

Based on the results presented in Sections 3.1 and 3.2, biochar produced at a carbonization duration of 150 min was selected for evaluation of adsorptive and surface chemical properties. Two independent production runs were included to represent reproducibility under community-scale operating conditions.

The measured properties, including bulk density, pH in aqueous suspension (pH_{sol}), point of zero charge (pH_{zpc}), and iodine number, are summarized in Table 3.

Table 3. Adsorptive and surface properties.

Sample (150 min)	Bulk Density ($\text{g}\cdot\text{cm}^{-3}$)	pH_{sol}	pH_{zpc}	Iodine Number ($\text{mg}\cdot\text{g}^{-1}$)
Run 1	0.698	8.97	7	32.31
Run 2	0.551	9.08	7.78	33.24
Mean $\pm$ SD	0.625 ± 0.104	9.03 ± 0.08	7.39 ± 0.55	32.78 ± 0.66

Bulk Density: bulk density values of $0.698 \text{ g}\cdot\text{cm}^{-3}$ (Run 1) and $0.551 \text{ g}\cdot\text{cm}^{-3}$ (Run 2) were recorded for the biochar produced at 150 min, with a mean of approximately $0.625 \text{ g}\cdot\text{cm}^{-3}$. The variation between runs is consistent with the operational variability inherent to community-scale batch production, where differences in feedstock packing density and heat distribution can influence the physical structure of the resulting biochar.

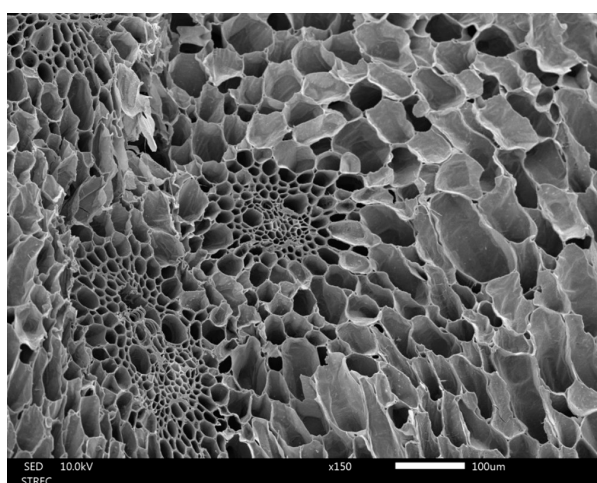
pH in Aqueous Suspension (pH_{sol}): pH_{sol} values measured in deionized water suspension (10% *w/v*) were 8.97 (Run 1) and 9.08 (Run 2), indicating moderately alkaline characteristics in both production runs. The pH_{sol} values were consistent across the two runs, with a difference of 0.11 pH units, suggesting reproducible surface chemistry under the applied carbonization conditions.

Point of Zero Charge (pH_{zpc}): pH_{zpc} values were 7.00 (Run 1) and 7.78 (Run 2), both of which were lower than their corresponding pH_{sol} values. The difference between pH_{sol} and pH_{zpc} was 1.97 pH units for Run 1 and 1.30 pH units for Run 2, indicating that under the measured aqueous conditions, the biochar surface carried a net negative charge in both production runs.

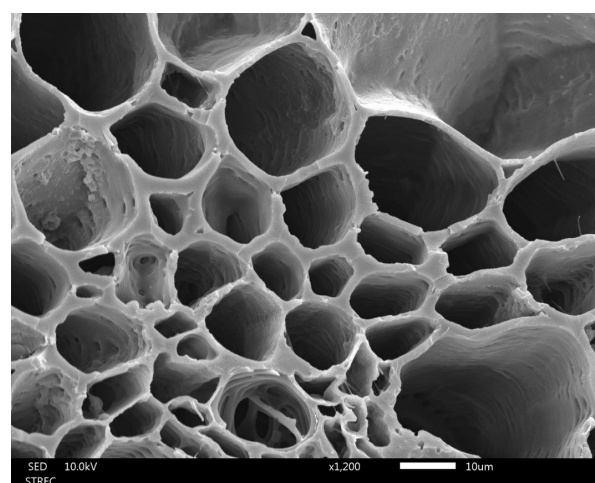
Iodine Number: iodine number values of $32.31 \text{ mg}\cdot\text{g}^{-1}$ (Run 1) and $33.24 \text{ mg}\cdot\text{g}^{-1}$ (Run 2) were recorded, with a mean of approximately $32.78 \text{ mg}\cdot\text{g}^{-1}$ and a difference of $0.93 \text{ mg}\cdot\text{g}^{-1}$ between runs. The close agreement between replicate measurements indicates consistent micropore-related adsorption characteristics across the two production runs.

3.4. Surface Morphology and Pore Structure

Surface morphology and pore structure of corncob-derived biochar produced at a carbonization duration of 150 min were examined using scanning electron microscopy (SEM). Representative micrographs obtained at low magnification ($150\times$) and high magnification ($1200\times$) are presented in Figure 4.



(a) macroporous structure at $150\times$



(b) higher magnification at $1200\times$

Figure 4. SEM micrographs of corncob-derived biochar: (a) macroporous structure at $150\times$ illustrating preserved vascular architecture; (b) higher magnification ($1200\times$) showing surface microfractures and interconnected pore openings associated with devolatilization during carbonization.

At 150 $\times$ magnification, the biochar surface exhibited a highly heterogeneous morphology characterized by abundant macropores distributed throughout the carbon matrix. The macroporous features varied in size and shape across the observed surface area, reflecting the structural complexity of the original corncob biomass [45]. The overall pore architecture at this magnification was dominated by large, open cavities with irregular geometries, interspersed with denser carbon regions. Quantitative pore characterization, including BET surface area measurement or mercury intrusion porosimetry, was not performed in this study; therefore, pore size distribution and total surface area were not determined [49].

At 1200 $\times$ magnification, additional microstructural features were resolved, including thin carbon walls, surface microfractures, and interconnected pore openings distributed across the biochar surface. The carbon walls separating adjacent pore spaces appeared thin and relatively uniform in thickness. Surface microfractures were observed at multiple locations, presenting as linear or irregular discontinuities across the carbon matrix. Interconnected pore openings of varying dimensions were also identified, indicating the presence of a connected internal pore network within the biochar structure [45,47]. However, SEM observations provide only qualitative information regarding surface morphology. Quantitative characterization of surface area and pore size distribution would require techniques such as BET analysis and was beyond the scope of the present study.

The combined observations at both magnification levels indicate a hierarchical pore structure dominated by macropores at the larger scale, with smaller pores, surface irregularities, and microfractures providing additional structural complexity at finer scales. No evidence of well-developed microporosity, such as that typically associated with physically or chemically activated carbons, was observed in the SEM micrographs, which is consistent with the relatively low iodine number values reported in Section 3.3.

3.5. Agronomic Property Indicators

The agronomic-related properties of corncob-derived biochar produced at a carbonization duration of 150 min were evaluated based on bulk density, pH_{sol} , pH_{zpc} , iodine number (reported in Section 3.3), electrical conductivity (EC), and cation exchange capacity (CEC). The EC and CEC measurements are summarized in Table 4.

Table 4. Agronomic chemical properties of corncob-derived biochar (150 min carbonization).

Property	Biochar (150 min)
Electrical Conductivity (dS/m)	1.6
Cation Exchange Capacity (cmol/kg)	30

Note: Values represent single measurements following standard procedures. The reported CEC value should be interpreted as indicative, and further replicated measurements are recommended for confirmation.

Bulk density values ranged from 0.551 to 0.698 $\text{g}\cdot\text{cm}^{-3}$ across the two production runs, as reported in Table 3. The pH_{sol} values ranged from 8.97 to 9.08, indicating moderately alkaline characteristics. The pH_{zpc} values ranged from 7.00 to 7.78, and in both production runs, pH_{sol} exceeded pH_{zpc} , indicating a net negative surface charge under the tested aqueous conditions [38]. Iodine number values ranged from 32.31 to 33.24 $\text{mg}\cdot\text{g}^{-1}$, as detailed in Section 3.3.

The biochar exhibited an EC of 1.6 dS/m, based on a single measurement conducted under standard procedures. The measured CEC was 30 cmol/kg, falling within the range commonly reported for non-activated biochars [14,37]. This value was obtained from a single measurement and should therefore be interpreted as indicative. Both EC and CEC values are presented in Table 4.

3.6. Carbon Sequestration Potential and Physicochemical Indicators Related to Soil Water Retention

Carbon sequestration potential was estimated based on measured biochar yield and elemental carbon content obtained from ultimate analysis, following the calculation approach described in Section 2.7. The mass of carbon retained per unit mass of dry feedstock (Cretained) and the corresponding CO₂-equivalent carbon storage potential (CO₂-eq) are summarized in Table 5.

Table 5. Estimated carbon sequestration potential of corncob-derived biochar produced at 150 min carbonization duration.

Batch	Yield (%)	Carbon Content (%)	Cretained (t C/t Feedstock)	CO ₂ -eq (tCO ₂ -eq/t Feedstock)
Run 1	28.33	71.5	0.203	0.743
Run 2	26.67	71.0	0.189	0.693

Based on biochar yields of 26.67–28.33% and carbon content of 71–71.5%, the estimated Cretained ranged from 0.189 to 0.203 t C per tonne of dry feedstock [13]. The corresponding CO₂-eq ranged from 0.693 to 0.743 tCO₂-eq per tonne of dry feedstock.

Key physicochemical and structural properties potentially related to soil–water processes are summarized in Table 6, based on measurements reported in Sections 3.3–3.5. These indicators should be interpreted as property-based evidence rather than direct measurements of soil water retention.

Table 6. Key physicochemical indicators potentially related to soil water retention mechanisms based on literature interpretation.

Indicator	Measured Value	Potential Relevance to Soil–Water Processes (Based on Literature)
Bulk density	0.551–0.698 g/cm ³	Low-density porous structure
Macroporous structure	Observed via SEM	Open pore architecture with interconnected networks
O/C ratio	≈0.27	Presence of oxygen-containing functional groups
H/C ratio	≈0.55	Moderate carbon stability
Surface charge (pH _{sol} > pH _{zpc})	8.97–9.08 vs. 7.00–7.78	Net negative surface charge under aqueous conditions
Pore structure	Macropores with microfractures	Hierarchical pore architecture

4. Discussion

4.1. Biochar Production Performance and Kiln Efficiency

Biochar yields of 23.33–28.33% obtained in this study are consistent with values reported for corncob and other lignocellulosic agricultural residues carbonized under slow carbonization conditions at moderate temperatures [22,23]. The highest yield (28.33%) was achieved at 150 min, while the lowest (23.33%) was recorded at 180 min, indicating that extending residence time beyond 150 min resulted in additional mass loss attributable to continued devolatilization and progressive decomposition of residual organic matter [23,25]. This inverse relationship between carbonization duration and biochar yield is consistent with established slow pyrolysis mechanisms and suggests that 150 min may represent a preliminary, promising operating condition among those evaluated. However, because each treatment was evaluated using only two replicate runs ($n = 2$), this observation should be regarded as indicative rather than statistically conclusive and does not establish an

optimal carbonization duration [22,23]. However, because each treatment was evaluated using only two replicate runs ($n = 2$), this observation should be interpreted cautiously and does not establish a statistically validated optimum carbonization duration.

The coefficient of variation was 4.3% for the 150 min treatment and 9.4% for the 180 min treatment, further illustrating the level of operational variability encountered under practical community-scale conditions, arising from differences in feedstock packing density, local heat distribution, and gas flow behavior during operation [24,30]. Similar run-to-run variability has been reported in previous evaluations of small-scale decentralized charcoal production systems and is considered an expected characteristic of community-scale thermal conversion [30].

Maximum internal temperatures of 415–435 °C across all runs fall within the regime associated with slow carbonization of lignocellulosic biomass, where hemicellulose and cellulose undergo primary thermal decomposition and lignin experiences partial structural transformation [23,34]. This temperature range favors carbon retention, moderate devolatilization, and preservation of surface functional groups relevant to agronomic and environmental applications [14,34]. The narrow spread of internal peak temperatures (20 °C range across all runs) indicates stable and reproducible thermal behavior of the smokeless vertical charcoal kiln, which is an important performance characteristic for community-scale systems where product consistency directly influences agronomic and environmental outcomes [24,30].

Maximum external surface temperatures of 767–803 °C were substantially higher than internal temperatures, reflecting active combustion in the outer chamber and effective heat transfer through the kiln wall. The large differential of approximately 350–370 °C between internal and external temperatures confirms that the double-layer kiln configuration effectively maintains oxygen-limited conditions within the inner biomass chamber while supporting vigorous secondary combustion in the outer zone [20,30]. This secondary combustion of pyrolysis gases is intended to reduce particulate emissions and improve combustion efficiency, as reported for similar smokeless kiln systems in previous studies. However, emissions were not directly measured in the present work [9,10,21].

4.2. Physicochemical Properties and Carbon Stability

The proximate analysis results demonstrated substantial compositional transformation of corncob biomass following carbonization at 150 min. Fixed carbon content increased from 2.5–2.9% in the raw feedstock to 51–54% in the produced biochar, while volatile matter decreased from 80–83% to 15.74–16.68%, confirming effective devolatilization and carbon concentration under the applied carbonization conditions [23,34]. The substantial reduction in volatile matter and increase in fixed carbon during carbonization reflect the thermal degradation of lignocellulosic components, including hemicellulose, cellulose, and lignin, resulting in progressive devolatilization and enrichment of the carbonaceous fraction. This behavior is consistent with reported biomass transformation pathways during thermochemical conversion [50]. These values are consistent with those reported for agricultural-residue-derived biochars produced under slow carbonization at comparable temperatures [22,25]. The higher heating value increased correspondingly from 16–17 MJ·kg^{−1} to 22–24 MJ·kg^{−1}, reflecting improved energy density following carbonization [18,34].

The decrease in ash content from 15–18% in the raw feedstock to 9–11% in the produced biochar is less commonly observed than the concentration effect typically reported during carbonization. This reduction may be attributed to volatilization of thermally labile inorganic constituents, particularly alkali salts such as potassium chloride, which have been reported to volatilize at temperatures above 400 °C [41]. Minor physical losses during post-carbonization handling may also have contributed. However, as direct ash compo-

sition analysis was not conducted, this interpretation remains indicative and warrants verification in future studies.

Ultimate analysis confirmed progressive carbon enrichment, with carbon content increasing from 44–45% to 71–71.5%, accompanied by decreases in oxygen (43–44% to 24.4–25.4%) and hydrogen (5.8–6% to 3–3.5%) contents, reflecting deoxygenation and dehydration reactions characteristic of slow carbonization of lignocellulosic biomass [23,25]. Nitrogen and sulfur contents remained low and stable throughout carbonization, indicating minimal heteroatom impurities favorable for agricultural and environmental applications [28,31].

The atomic H/C ratio of approximately 0.55 and O/C ratio of approximately 0.27 indicate a moderately carbonized material with appreciable aromaticity and residual oxygen-containing functional groups. According to IBI classification criteria [19], H/C ratios below 0.7 and O/C ratios below 0.4 are associated with Class 1 biochar stability, suggesting sufficient structural recalcitrance for long-term carbon storage. These values are consistent with biochar produced from lignocellulosic feedstocks at 400–500 °C, where partial aromatization has occurred without complete graphitization [18,34]. The O/C ratio of approximately 0.27 indicates residual oxygen-containing functional groups that contribute to surface hydrophilicity and cation exchange capacity, analogous to surface properties reported for other biomass-derived biochars [50].

The surface and adsorption-related properties were consistent with the physicochemical characteristics described above. Bulk density values of 0.551–0.698 g·cm^{−3} reflect a lightweight porous carbon matrix typical of non-activated lignocellulosic biochar [14,32]. The moderately alkaline pH_{sol} (8.97–9.08) is consistent with ash-derived mineral content and within the range commonly reported for agricultural-residue-derived biochar [39,46]. The net negative surface charge (pH_{sol} > pH_{pzc}) in both production runs is attributable to deprotonated oxygen-containing functional groups, consistent with the O/C ratio and surface chemistry described above [18,39]. The measured CEC of 30 cmol kg^{−1} and the net negative surface charge observed under the tested conditions are within ranges reported for biochars considered effective for soil amendment applications. These characteristics are associated with an enhanced capacity to retain exchangeable nutrient cations and may contribute to improved nutrient retention in agricultural soils, particularly in smallholder production systems [51]. The iodine number values of 32.31–33.24 mg·g^{−1} are consistent with limited adsorption capacity relative to activated carbons and suggest modest pore development under the applied carbonization conditions, as expected for non-activated biochar produced at moderate temperatures, and are consistent with the macropore-dominated pore architecture observed via SEM in Section 3.4 [40,45]. The measured iodine number values are lower than those commonly reported for activated carbons and highly porous biochars specifically engineered for adsorption applications, which often exceed 100–300 mg g^{−1} depending on feedstock and activation conditions. This result suggests that the biochar produced under the present carbonization conditions possesses only modest adsorption capacity. Nevertheless, the material was developed primarily for carbon sequestration and potential soil amendment applications rather than for use as a commercial adsorbent. Therefore, the observed iodine number values remain consistent with the intended application of the biochar and indicate the presence of a limited but measurable pore network.

However, because ash composition was not directly characterized using techniques such as XRF or ICP analysis, the proposed volatilization mechanism remains speculative. Physical losses of fine mineral-rich particles during post-carbonization handling may also have contributed to the observed reduction in ash content. Therefore, the interpretation should be considered indicative and warrants verification through future ash composition analyses.

4.3. Soil Water Retention and Agronomic Implications

Although direct measurements of soil water retention, infiltration, field capacity, hydraulic conductivity, or crop response were not conducted, the physicochemical and structural characteristics of the produced biochar can be interpreted in relation to established mechanisms linking biochar properties to soil water dynamics and agronomic performance. Such interpretations are based on physicochemical characterization and literature-reported relationships between biochar properties and soil responses rather than direct experimental validation under the conditions of the present study [15,16,37,52].

The porous structure observed via SEM (Section 3.4), characterized by abundant open cavities and interconnected pore networks, is considered a primary determinant of biochar's capacity to improve soil water storage and infiltration. Meta-analytic evidence has reported mean improvements in soil water holding capacity of approximately 15% following biochar amendment, with more pronounced effects in coarse-textured soils [16,35]. The low bulk density values ($0.551\text{--}0.698\text{ g}\cdot\text{cm}^{-3}$) may contribute to improved soil porosity when incorporated into soil, as reported in previous studies [15,29]. The O/C ratio of approximately 0.27 indicates the presence of residual oxygen-containing functional groups that may contribute to surface hydrophilicity. However, the actual contribution of these functional groups to soil water retention requires direct soil-based validation [14,18]. Nevertheless, because BET surface area and pore size distribution analyses were not conducted, the relationship between the observed pore structure and potential water-retention behavior should be regarded as preliminary and inferred from previous studies.

The net negative surface charge and moderate capacity for electrostatic retention of cationic nutrients such as Ca^{2+} , Mg^{2+} , K^{+} , and NH_4^{+} , which is relevant for reducing nutrient leaching losses in tropical smallholder farming systems [16,44]. The EC of 1.6 dS/m indicates moderate soluble salt content within a range generally considered acceptable for direct soil application under typical application rates, though cumulative effects under repeated application should be evaluated under field conditions [31,37]. The moderately alkaline pH_{sol} ($8.97\text{--}9.08$) further suggests potential for soil pH buffering in acidic tropical soils, with associated benefits for nutrient availability and microbial activity [37,44].

The estimated carbon sequestration potential was consistent with values reported for agricultural-residue-based biochar systems [13,48]. The H/C ratio of approximately 0.55 supports the interpretation that a substantial fraction of sequestered carbon will persist in soil over extended timescales [18,48]. Life cycle assessment evidence further indicates that crop-residue biochar systems can achieve net negative greenhouse gas balances when accounting for avoided emissions, carbon sequestration, and energy co-benefits [13].

Beyond direct carbon sequestration, replacing open burning with biochar production may reduce emissions of CH_4 , N_2O , CO , and $\text{PM}_{2.5}$ according to previous studies. However, these emissions were not quantified in the present study and therefore remain a potential environmental benefit rather than an experimentally verified outcome, and may represent a dual mitigation pathway relevant to both national greenhouse gas inventories and local air quality management in Thailand [7,8,10]. Collectively, these characteristics position the produced biochar as a multi-functional material with relevance to climate mitigation, climate adaptation, and agronomic improvement within a climate-smart agriculture framework [6,15,48]. However, field-based experimental validation under site-specific soil and climatic conditions is required to quantify the magnitude of these effects.

4.4. Community-Scale Feasibility and Climate-Smart Agriculture

The results of this study demonstrate that the smokeless vertical charcoal kiln developed by EEEEC, Kasetsart University, can produce biochar from corncob residues under stable and reproducible thermal conditions at the community scale. The consistent internal

temperature profiles (415–435 °C) and acceptable yield ranges (23.33–28.33%) achieved across all production runs indicate that the system can deliver reliable performance under practical operating conditions without requiring sophisticated process control equipment or specialized technical expertise [24,30]. This operational simplicity is a critical consideration for community-level adoption in smallholder agricultural contexts, where technology accessibility, low capital cost, and ease of operation are primary determinants of uptake [24,27].

The run-to-run variability observed in biochar yield and bulk density, while consistent with expectations for manual batch carbonization systems, highlights the importance of standardizing feedstock preparation procedures, particularly corncob cutting length and packing density to improve product consistency at the community scale [24,30]. Jayakumar et al. [30] similarly emphasized that feedstock preparation and loading practices are among the most influential operational parameters affecting biochar quality consistency in low-cost kiln systems. Implementation of simple standardized operating procedures for feedstock preparation and kiln loading could therefore meaningfully reduce batch-to-batch variability without requiring additional capital investment.

The measured iodine number values (32.31–33.24 mg g^{−1}) indicate a measurable but relatively modest adsorption potential compared with activated carbons and highly porous biochar specifically engineered for adsorption applications, which commonly exhibit substantially higher iodine numbers. This result is consistent with the moderate carbonization temperatures employed in the present study and the absence of any physical or chemical activation process. Nevertheless, adsorption performance was not the primary objective of the production system evaluated here. Rather, the biochar was developed as a carbon-rich product for carbon sequestration and potential soil amendment applications. Therefore, the observed iodine number values should be interpreted within the context of the intended application of the material rather than as a limitation of overall biochar quality.

From an environmental perspective, the smokeless vertical charcoal kiln offers a demonstrably preferable alternative to open field burning of corncob residues, which currently represents the dominant residue management practice in many agricultural areas of Thailand [7,8]. By converting corncob residues into biochar through a controlled carbonization process, the system may offer environmental advantages over open burning. Previous studies have reported lower emissions of PM_{2.5}, CH₄, N₂O, and CO from improved kiln systems compared with uncontrolled residue burning. However, such emission reductions were not directly quantified in the present study while sequestering 0.189–0.203 t C per tonne of dry feedstock in a recalcitrant solid form [8,9,48]. This dual benefit emission avoidance, combined with carbon sequestration, is directly aligned with Thailand's national priorities for agricultural burning reduction and greenhouse gas mitigation and represents a practical pathway for smallholder farmers to contribute to both air quality improvement and climate change mitigation at the local level [7,8,10].

The biochar produced by this system exhibits physicochemical properties potentially relevant to soil amendment applications, including moderately alkaline pH, net negative surface charge, moderate CEC, and a macropore-dominated porous structure. These characteristics suggest potential relevance to soil–water and nutrient-related processes, particularly under conditions of increasing rainfall variability and water stress projected for agricultural systems in Southeast Asia. However, the magnitude of such agronomic effects must be confirmed through pot, mesocosm, or field-scale experiments [1,2,15]. The combination of agronomic potential and climate mitigation contribution positions community-scale biochar production as a viable climate-smart agriculture strategy that simultaneously addresses residue management, soil health, and greenhouse gas reduction objectives [6,15,46]. Methodological limitations and directions for future research are discussed in Section 4.5.

4.5. Methodological Limitations and Future Research Needs

Several limitations of the present study should be acknowledged, and directions for future research are identified accordingly.

First, each carbonization condition was evaluated with only two replicate runs ($n = 2$), which limits statistical confidence in comparisons between the 150 and 180 min treatments and precludes formal identification of an optimal carbonization duration. Although standard deviations were reported where possible, the small sample size limits the reliability of variance estimates and confidence intervals. Consequently, comparisons between treatments should be interpreted as indicative rather than statistically conclusive. Future studies should incorporate at least four to five independent replicates per treatment to enable formal statistical comparison and establish robust performance baselines for community-scale biochar production systems. The limited replication ($n = 2$ per condition) constrains the statistical generalizability of yield and property comparisons and does not fully capture the range of operational variability that may occur under community-scale production conditions. Therefore, the observed differences between carbonization durations should be regarded as preliminary and indicative rather than definitive. Future studies incorporating at least five independent replicates per treatment are recommended to establish robust performance baselines and enable formal statistical comparison.

In addition, temperature measurements were obtained from only two monitoring locations and therefore do not fully describe the internal temperature distribution within the kiln. Future studies should employ multi-point thermocouple arrays or thermal mapping approaches to better characterize temperature gradients and their influence on biochar quality consistency.

Third, quantitative emission characterization of the smokeless vertical charcoal kiln was not conducted in this study. Because PM_{2.5}, CO, CH₄, N₂O, and other gaseous emissions were not monitored during kiln operation, any discussion of emission reduction in this study should be interpreted as an inference based on the replacement of open burning and evidence from previous literature rather than direct experimental verification [9,21]. Such measurements are particularly important for evaluating the system against emission performance standards and for supporting regulatory recognition of smokeless kiln technologies within national agricultural burning reduction frameworks in Thailand [7,8]. Future studies should prioritize direct monitoring of PM_{2.5} and gaseous pollutants to provide quantitative evidence of emission performance and to verify the environmental benefits associated with the smokeless kiln design.

Fourth, surface area and pore size distribution of the produced biochar were not directly measured, as BET analysis and mercury intrusion porosimetry were not available within the scope of this study. Quantitative pore characterization would provide a more complete description of the material's structural properties and enable more precise interpretation of adsorption behavior and soil water retention potential [34,41]. Future characterization studies should incorporate these analyses alongside the proximate, ultimate, and surface property measurements reported here.

Fifth, the agronomic and hydrological implications discussed in Section 4.3 are derived from physicochemical characterization and literature-based interpretation rather than direct field measurements. Field-based experimental validation under site-specific soil and climatic conditions representative of smallholder farming systems in Thailand is required to confirm and quantify the effects of this biochar on soil water holding capacity, nutrient retention, crop productivity, and long-term soil health [15,16,35]. Pot or mesocosm experiments under controlled conditions would represent an important intermediate step prior to field-scale evaluation.

Sixth, the carbon sequestration estimates presented in Section 3.6 represent theoretical upper-bound values based on yield and elemental carbon content, and do not account for potential carbon losses during biochar handling, transport, field application, or post-application processes [13,48]. A full life cycle assessment incorporating the complete system boundary, including feedstock collection, kiln operation, biochar transport, soil application, and long-term carbon stability, would provide a more comprehensive and defensible evaluation of the net climate benefit of the community-scale biochar production system [13,24].

Seventh, this study evaluated only a single feedstock type (corn cob) and a single kiln design. Future research should assess the performance of the smokeless vertical charcoal kiln with alternative agricultural residue feedstocks commonly available in central Thailand, including rice husk, sugarcane bagasse, and cassava stems, to broaden the applicability of the findings and identify feedstock-specific optimization opportunities [22,30]. Comparative evaluation of biochar properties across feedstock types would also contribute to a more comprehensive understanding of the system's versatility for community-scale biomass management.

Eighth, BET surface area and pore size distribution analyses were not performed. Consequently, interpretations regarding adsorption-related functionality and pore-mediated water-retention mechanisms are based on qualitative SEM observations and should be considered preliminary.

Finally, the long-term stability of the produced biochar under field conditions—including resistance to biological and chemical degradation, changes in surface properties following soil incorporation, and persistence of carbon sequestration benefits over time was not evaluated in this study and represents an important area for future investigation [18,25,48].

4.6. Contribution to Sustainability

Taken together, the findings of this study contribute to sustainable development across three interconnected dimensions. Environmentally, the smokeless kiln reduces reliance on open-field burning, offering a pathway toward lower emissions of PM_{2.5}, CH₄, and N₂O while sequestering a measurable fraction of biomass carbon (0.189–0.203 t C per tonne of dry feedstock) in a stable solid form, directly supporting climate change mitigation and air quality objectives. Economically, the system's low capital cost, simple operation, and lack of dependence on specialized technical expertise make it accessible to resource-limited smallholder farmers, lowering the barrier to adoption relative to industrial-scale biochar technologies and enabling residue management without imposing a significant financial burden on rural households. Socially, community-level operation reduces smoke exposure for farmers and nearby residents relative to traditional open burning and uncontrolled kilns while fostering local ownership and capacity building around residue management, rather than relying on centralized or externally managed waste treatment infrastructure. By jointly addressing environmental performance, economic accessibility, and social acceptability, this study provides an integrated, quantifiable contribution to sustainability that extends beyond the material characterization of biochar itself, offering practical evidence relevant to sustainable agricultural development policy in Thailand and comparable smallholder farming contexts across Southeast Asia.

5. Conclusions

This study evaluated the performance of a community-scale smokeless vertical charcoal kiln for producing biochar from corn cob residues under practical operating conditions in central Thailand. The key findings and conclusions are summarized as follows:

The smokeless vertical charcoal kiln demonstrated stable and reproducible thermal behavior across all production runs, with internal temperatures consistently maintained within the slow carbonization regime (415–435 °C). Biochar yields of 23.33–28.33% were obtained, with the 150 min carbonization duration appearing to be the most promising condition among those evaluated, providing the highest observed yield within a shorter processing time under the tested conditions. However, because each treatment was evaluated using only two replicate runs, this observation should be considered preliminary and requires confirmation through experiments with a larger number of independent replicates. Run-to-run variability in yield and material properties was consistent with expectations for manual batch carbonization systems and did not preclude community-scale adoption.

The produced biochar exhibited physicochemical characteristics consistent with effective carbonization of lignocellulosic biomass, including high fixed carbon content (51–54%), elevated carbon concentration (71–71.5%), low volatile matter (15.74–16.68%), and moderately alkaline pH (8.97–9.08). Atomic H/C and O/C ratios of approximately 0.55 and 0.27, respectively, satisfy the International Biochar Initiative (IBI) Class 1 stability criteria and indicate a relatively stable carbon structure suitable for long-term carbon storage. The porous surface morphology observed by SEM, together with the net negative surface charge and moderate CEC (30 cmol kg^{−1}), suggests potential relevance for soil amendment applications. However, water-retention and nutrient-retention effects were not directly evaluated in the present study.

The estimated carbon sequestration potential of 0.189–0.203 t C per tonne of dry feedstock (0.693–0.743 tCO₂-eq) indicates a potential contribution to climate change mitigation through carbon sequestration. In addition, replacing open-field burning with smokeless biochar production may provide environmental benefits through carbon sequestration and the potential reduction in PM_{2.5}, CH₄, N₂O, and CO emissions reported in previous studies. However, these emissions were not directly measured in the present study.

Collectively, the results demonstrate that community-scale smokeless biochar production from agricultural residues is technically feasible and capable of producing a carbon-rich material with physicochemical properties potentially relevant to soil amendment applications and long-term carbon storage. The findings provide practical evidence supporting the adoption of low-emission biochar production systems in smallholder agricultural contexts across Southeast Asia.

Nevertheless, the agronomic, hydrological, and environmental implications discussed in this study are based primarily on material characterization and interpretation of previous literature rather than direct field measurements. Future research should therefore include field-scale validation of soil–water and crop productivity responses, direct quantification of emissions during kiln operation, comprehensive life cycle assessment of system-wide carbon impacts, quantitative pore characterization, and evaluation of alternative feedstocks to broaden the applicability of community-scale biochar production systems. Overall, by jointly demonstrating environmental performance, economic accessibility, and social relevance for smallholder communities, this study offers an integrated contribution to sustainable agricultural residue management, supporting progress toward the Sustainable Development Goals on climate action (SDG 13), responsible consumption and production (SDG 12), and sustainable agriculture (SDG 2).

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