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EFFECTS OF PYROLYSIS TEMPERATURE AND RETENTION TIME ON THE PHYSICOCHEMICAL PROPERTIES OF CORN COB-DERIVED BIOCHAR FOR SUSTAINABLE SOIL MANAGEMENT

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Abstract

Corn cobs are an abundant agricultural residue with considerable potential for conversion into biochar as a sustainable soil amendment. This study evaluated the effects of pyrolysis temperature and retention time on the physicochemical properties of corn cob-derived biochar to determine the optimum production conditions for sustainable soil management. A 3 × 3 factorial experiment arranged in a Completely Randomized Design (CRD) with three replications was conducted using three pyrolysis temperatures (300, 400, and 500°C) and three retention times (1, 2, and 3 h). The produced biochar was characterized for biochar recovery, pH, organic matter, total nitrogen, and macro- and micronutrient contents. Analysis of variance (ANOVA) revealed significant effects of pyrolysis conditions on most biochar properties. The highest biochar recovery (42.67%) was obtained at 500°C for 2 h, indicating the most efficient biomass conversion. All biochar samples were strongly alkaline (pH 9.31–9.98), suggesting their suitability for ameliorating acidic soils. Biochar produced at 300°C for 3 h contained the highest organic matter (47.02%) and nitrogen (2.35%), whereas 500°C for 2 h yielded the highest phosphorus (20.45%) and calcium (1.28%) concentrations. The greatest potassium (3.09%) and sulfur (0.70%) contents were obtained at 500°C for 1 h, while 400°C for 1 h produced the highest available iron (1.73%). Magnesium and manganese contents were only minimally affected by the pyrolysis treatments. Overall, pyrolysis at 500°C for 2 h provided the best balance between biochar recovery, carbonization efficiency, and nutrient enrichment, making it the optimum condition for producing high-quality corn cob-derived biochar. The optimized biochar shows considerable potential as a climate-smart soil amendment for improving soil fertility, enhancing nutrient-use efficiency, and promoting sustainable agricultural production.

INTRODUCTION

Biochar is a carbon-rich material produced through the pyrolysis of biomass under oxygen-limited conditions. Owing to its ability to improve soil fertility, enhance nutrient retention, increase water-holding capacity, and sequester carbon, biochar has gained considerable attention as a sustainable soil amendment for climate-smart agriculture. Its physicochemical properties, which determine its effectiveness in agricultural and environmental applications, are strongly influenced by the feedstock used and pyrolysis conditions, particularly temperature and retention time (Li et al., 2023; An et al., 2025; Loc et al., 2025).

Corn cobs are among the most abundant agricultural residues generated in maize-producing countries, including the Philippines. Converting this biomass into biochar provides an environmentally sound approach to agricultural waste valorization while producing a value-added material for improving soil quality. Corn cob-derived biochar is characterized by high carbon content, porous structure, and chemical stability, making it suitable for enhancing nutrient retention, soil productivity, and carbon sequestration (Drané et al., 2023; Tang et al., 2025).

Pyrolysis temperature and retention time are recognized as the major factors governing biochar quality. Increasing pyrolysis temperature generally enhances carbonization, aromaticity, surface area, and alkalinity while reducing volatile matter. Likewise, longer retention time promotes more complete decomposition of lignocellulosic materials, resulting in improved pore development and carbon stability. However, excessive heating may reduce biochar yield and alter nutrient availability through volatilization and mineral transformation (Li et al., 2023; Loc et al., 2025; Tang et al., 2025).

Although numerous studies have examined the influence of pyrolysis conditions on biochar production, limited information is available on optimizing pyrolysis temperature and retention time for corn cob-derived SMART biochar intended for sustainable soil management. Establishing the optimum production conditions is essential for maximizing biochar quality and enhancing its agronomic value.

Therefore, this study evaluated the effects of different pyrolysis temperatures (300, 400, and 500°C) and retention times (1, 2, and 3 h) on the physicochemical properties of corn cob-derived SMART biochar. Specifically, it determined the individual and interactive effects of these factors on biochar quality and identified the optimum pyrolysis condition for producing nutrient-rich biochar suitable for sustainable agricultural and environmental applications.

MATERIALS AND METHODS

The study was conducted at the Biochar Production and Soil Science Laboratories, College of Agriculture, Isabela State University, Philippines. Corn cobs were collected from maize-producing farms in Alfonso Lista, Ifugao, and used as the feedstock for biochar production.

The collected corn cobs were cleaned to remove adhering soil and foreign materials, air-dried, and oven-dried at 105°C until constant weight. The dried cobs were cut into uniform sizes to facilitate homogeneous heating during pyrolysis and stored in clean, dry containers prior to processing.

Biochar was produced under oxygen-limited conditions using a controlled pyrolysis reactor. The feedstock was subjected to three pyrolysis temperatures (300, 400, and 500°C) combined with three retention times (1, 2, and 3 h) after the desired temperature was attained. After pyrolysis, the reactor was allowed to cool naturally under oxygen-limited conditions. The resulting biochar was collected, weighed, ground, passed through a 2-mm sieve, and stored in airtight polyethylene containers for laboratory analyses.

The experiment was arranged in a 3 × 3 factorial Completely Randomized Design (CRD) with three replications. Factor A consisted of pyrolysis temperatures (300, 400, and 500°C), while Factor B consisted of retention times (1, 2, and 3 h), resulting in nine treatment combinations.

The biochar samples were characterized for biochar yield, pH, organic matter, total nitrogen, and macro- and micronutrient contents (P, K, Ca, Mg, S, Fe, and Mn) following standard laboratory procedures. Biochar pH was determined using a biochar-water suspension with a calibrated pH meter, while total nitrogen was analyzed using the Kjeldahl method. Macro- and micronutrients were determined using standard extraction and instrumental analytical techniques.

Data were subjected to analysis of variance (ANOVA) for a 3 × 3 factorial experiment in a Completely Randomized Design. Treatment means were compared using Tukey's Honest Significant Difference (HSD) test at the 5% probability level.

RESULTS AND DISCUSSSION

Biochar Recovery

Table 1 shows the weight of biochar, uncooked substrates, and percent recovery of corn cob-derived biochar as affected by pyrolysis temperature and retention time. Pyrolysis conditions significantly influenced biomass conversion, particularly the amount of uncooked feedstock remaining after carbonization. The highest biochar yield (6.40 kg) and percent recovery (42.67%) were obtained at 500°C for 2 h (T6), followed by 400°C for 1 h (T2) with a recovery of 42.47%. In contrast, the lowest recovery (36.47%) was recorded at 400°C for 3 h (T8). The moderate coefficients of variation for biochar yield (11.70%) and recovery (11.69%) indicate acceptable experimental variability.

Table 1. Weight of Biochar Product, Weight of Uncooked Substrates, and Percent Recovery of Corn Cob Biochar as Influenced by Pyrolysis Temperature and Retention Time

TREATMENT		Weight of Biochar Product (kg)	Weight of Uncooked Substrates (kg)	Percent Recovery (%)
T_1	300 °C, 1 hour	6.13	1.20 a	40.87
T_2	400 °C, 1 hour	6.37	0.40 c	42.47
T_3	500 °C, 1 hour	5.57	0.04 d	37.13
T_4	300 °C, 2 hours	6.20	0.70 b	41.33
T_5	400 °C, 2 hours	6.23	0.03 d	41.53
T_6	500 °C, 2 hours	6.40	0.02 d	42.67
T_7	300 °C, 3 hours	5.87	0.20 cd	39.13
T_8	400 °C, 3 hours	5.47	0.02 d	36.47
T_9	500 °C, 3 hours	6.00	0.01 d	40.00
CV (%)		11.70	30.25	11.69

Means with common letters are not significantly different with each other using Tukeys's HSD at 1% level

The amount of uncooked substrate decreased markedly with increasing pyrolysis temperature and retention time. The greatest amount of uncarbonized material was observed at 300°C for 1 h (1.20 kg), whereas only 0.01–0.04 kg remained under treatments exposed to 500°C or longer heating periods. These results indicate that higher temperatures and longer residence times promoted more complete thermal degradation of cellulose, hemicellulose, and lignin, thereby improving carbonization efficiency. Similar observations were reported by Adekanye *et al.* (2022), Odiki *et al.* (2023), and An *et al.* (2025), who found that increasing pyrolysis severity enhanced biomass conversion while reducing residual feedstock.

The interaction between pyrolysis temperature and retention time further demonstrated that efficient biochar production depends on balancing both process variables. Higher temperatures compensated for shorter residence times, whereas lower temperatures required longer heating to achieve complete carbonization. Although prolonged heating minimized unconverted biomass, excessively long retention periods may reduce biochar recovery because of increased volatilization losses (Loc *et al.*, 2025; Tang *et al.*, 2025). Overall, 500°C for 2 h provided the optimum combination of biochar recovery and carbonization efficiency, making it the most suitable condition for producing high-quality corn cob-derived biochar.

pH, Organic matter and Nitrogen Content of Corn Cob Biochars

Table 2 shows the pH, organic matter, and nitrogen contents of corn cob-derived biochar produced under different pyrolysis temperatures and retention times.

Table 2. pH, organic matter and nitrogen contents of Corn Cob Biochar as Influenced by Pyrolysis Temperature and Retention Time

TREATMENT	pH	Organic Matter (%)	Nitrogen (%)
300 °C, 1 hour	9.58 d	35.98 e	1.80 e
400 °C, 1 hour	9.31 e	37.28 d	1.86 d
500 °C, 1 hour	9.71 c	44.12 b	2.21 b
300 °C, 2 hours	9.98 a	42.46 c	2.12 c
400 °C, 2 hours	9.72 c	38.08 d	1.90 d
500 °C, 2 hours	9.71 c	37.02 de	1.85 de
300 °C, 3 hours	9.88 b	47.02 a	2.35 a
400 °C, 3 hours	9.87 b	32.67 f	1.63 f
500 °C, 3 hours	9.82 b	42.53 c	2.13 c
CV (%)	0.21	0.96	0.96

All biochar samples were strongly alkaline, with pH values ranging from 9.31 to 9.98, indicating their potential for ameliorating acidic soils. The highest pH (9.98) was obtained at 300°C for 2 h (T4), while the lowest (9.31) occurred at 400°C for 1 h (T2). The low coefficient of variation (0.21%) indicates excellent analytical precision. Although pyrolysis temperature had only a slight influence on pH, increasing retention time generally resulted in more alkaline biochar due to greater decomposition of organic acids and enrichment of ash-forming minerals such as calcium, magnesium, and potassium. Similar findings were reported by Adekanye et al. (2022) and An et al. (2025), who attributed the alkaline nature of biochar to the accumulation of basic cations during pyrolysis.

Significant differences were likewise observed in the organic matter and nitrogen contents of the biochar. The highest organic matter (47.02%) and nitrogen (2.35%) contents were recorded at 300°C for 3 h (T7), whereas the lowest values (32.67% organic matter and 1.63% nitrogen) occurred at 400°C for 3 h (T8). These results indicate that the response of biochar composition depended on the interaction between pyrolysis temperature and retention time rather than on either factor alone. Moderate pyrolysis conditions favored the retention of organic matter and nitrogen, while prolonged heating at intermediate temperatures appeared to enhance the volatilization of nitrogen-containing compounds. Similar observations were reported by Li et al. (2023) and Odiki et al. (2023), who noted that nutrient retention in biochar is governed by the balance between carbonization and thermal degradation.

Overall, the interaction between pyrolysis temperature and retention time significantly affected the physicochemical quality of corn cob biochar. While 300°C for 2 h produced the most alkaline biochar, 300°C for 3 h yielded the highest organic matter and nitrogen contents, indicating its suitability for producing nutrient-rich biochar. These findings demonstrate that optimizing both temperature and retention time is essential for maximizing biochar quality and its potential application as a sustainable soil amendment for climate-smart agriculture (Loc et al., 2025; Tang et al., 2025).

Nutrient Contents of Corn Cob Biochar

Table 3 shows the available phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), iron (Fe), and manganese (Mn) contents of corn cob-derived biochar produced under different pyrolysis temperatures and retention times. Significant differences were observed among treatment combinations for phosphorus, potassium, calcium, sulfur, and iron, whereas magnesium and manganese varied only slightly, indicating that these nutrients were less responsive to the pyrolysis conditions evaluated. The low coefficients of variation for most parameters indicate high analytical precision and reliability.

Table 3. Nutrient contents Corn Cob Biochar as Influenced by Pyrolysis Temperature and Retention Time

TREATMENT	Available Phosphorus (%)	Available Potassium (%)	Available Calcium (%)	Available Magnesium (%)	Available Sulfur (%)	Available Iron (%)	Available Manganese (%)
300 °C, 1 hour	16.69 h	2.33 g	0.95 h	2.07	0.64 b	1.50 c	0.10
400 °C, 1 hour	18.76 c	2.31 g	1.01 f	2.13	0.60 e	1.73 a	0.10

500 °C, 1 hour	19.53 b	3.09 a	1.10 d	2.06	0.70 a	0.81 i	0.09
300 °C, 2 hours	17.47 f	2.64 d	0.99 g	1.93	0.54 g	1.22 g	0.09
400 °C, 2 hours	19.54 b	2.44 e	1.17 b	2.09	0.61 d	1.69 b	0.10
500 °C, 2 hours	20.45 a	2.37 f	1.28 a	2.21	0.60 e	1.17 h	0.10
300 °C, 3 hours	17.84 g	2.31 g	1.16 c	2.01	0.54 g	1.43 d	0.10
400 °C, 3 hours	17.43 g	2.98 b	1.08 e	1.89	0.63 c	1.30 f	0.09
500 °C, 3 hours	17.51 e	2.88 c	1.17 b	2.00	0.58 f	1.37 e	0.09
CV (%)	0.04	0.33	0.25	26.36	0.32	0.40	0.03

Higher pyrolysis temperatures generally increased the concentrations of phosphorus, potassium, and calcium because thermal decomposition concentrated mineral constituents within the biochar ash fraction. The highest phosphorus (20.45%) and calcium (1.28%) contents were obtained at 500°C for 2 h (T6), while the greatest potassium concentration (3.09%) occurred at 500°C for 1 h (T3). In contrast, sulfur and iron responded differently to increasing temperature. Sulfur was highest at 500°C for 1 h (0.70%) but declined with prolonged heating because of volatilization, whereas iron reached its maximum concentration at 400°C for 1 h (1.73%), suggesting that moderate temperatures favored iron availability while excessive heating promoted the formation of less soluble mineral forms. Magnesium (1.89–2.21%) and manganese (0.09–0.10%) remained relatively stable across treatments, indicating their high thermal stability during pyrolysis.

The interaction between pyrolysis temperature and retention time demonstrated that nutrient enrichment depended on optimizing both processing variables. Moderate retention time (2 h) at 500°C produced the highest phosphorus and calcium concentrations, whereas 500°C for 1 h maximized potassium and sulfur retention. Conversely, prolonged heating generally reduced the availability of sulfur and iron because of volatilization and mineral transformation. Overall, the results indicate that 500°C for 2 h provided the most favorable balance between carbonization and nutrient enrichment, producing biochar with high concentrations of essential macronutrients while maintaining stable levels of magnesium and manganese. These findings agree with previous studies showing that pyrolysis temperature and residence time regulate mineral concentration, nutrient availability, and the agronomic quality of biochar through ash enrichment and thermal transformation processes (Li *et al.*, 2023; An *et al.*, 2025; Loc *et al.*, 2025; Tang *et al.*, 2025).

CONCLUSION

The present study demonstrated that pyrolysis temperature and retention time significantly influenced the physicochemical properties of corn cob-derived biochar. Higher temperatures and longer retention times enhanced biomass carbonization by reducing unconverted feedstock, with 500°C for 2 h producing the highest biochar recovery (42.67%). All biochar samples were strongly alkaline (pH 9.31–9.98), indicating their potential for ameliorating acidic soils and improving soil chemical properties.

The interaction between pyrolysis temperature and retention time significantly affected nutrient composition. Biochar produced at 300°C for 3 h contained the highest organic matter (47.02%) and nitrogen (2.35%), whereas 500°C for 2 h yielded the greatest phosphorus (20.45%) and calcium (1.28%) concentrations. The highest potassium (3.09%) and sulfur (0.70%) contents were obtained at 500°C for 1 h, while 400°C for 1 h produced the highest available iron (1.73%). In contrast, magnesium and manganese contents remained relatively stable across the different pyrolysis conditions.

Overall, 500°C for 2 h provided the best balance between biochar recovery, carbonization efficiency, and nutrient enrichment, making it the optimum condition for producing high-quality corn cob-derived biochar. The findings demonstrate that optimizing both pyrolysis temperature and retention time is essential for maximizing biochar quality and supporting the sustainable utilization of agricultural residues.

The optimized corn cob biochar developed in this study has considerable potential as a climate-smart soil amendment for improving soil fertility, nutrient-use efficiency, and sustainable crop production. Future studies should evaluate its long-term agronomic performance under greenhouse and field conditions, assess its carbon sequestration potential, and further characterize its physicochemical properties, including surface area, pore structure, cation exchange capacity, and elemental composition, to support large-scale production and commercialization.

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Author Contributions

Artemio A. Martin Jr. conceptualized and designed the study, supervised the research, interpreted the results, and prepared and revised the manuscript. Ronvan P. Ribuca conducted the laboratory and experimental work, collected and analyzed the data, and assisted in manuscript preparation. Both authors reviewed, approved, and agreed to the final version of the manuscript.

Conflict of Interest

The authors declare that they have no conflict of interest regarding the publication of this manuscript.