

Comparative Evaluation of Cation Exchange Capacity Among Ten Feedstock-Based Biochars for Soil Amendment Application

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DOI: 10.29322/IJSRP.16.09.2026.p17726
<https://dx.doi.org/10.29322/IJSRP.16.09.2026.p17726>

Paper Received Date: 26th August 2026
Paper Acceptance Date: 25th September 2026
Paper Publication Date: 30th September 2026

Abstract- Biochar's (BCs) suitability as a soil amendment depends strongly on its cation exchange capacity (CEC), which governs nutrient retention in acidic, weathered tropical soils. This study evaluated and compared the CEC and associated chemical properties (pH, organic matter, total N, P, and K) of biochar produced from ten locally available feedstocks: Rice Hull (BC1), Oil Palm Empty Fruit Bunch (BC2), Coconut Shell (BC3), Water Hyacinth (BC4), Banana Pseudostem (BC5), Cacao Pod Husk (BC6), Bamboo (BC7), Corn Cob (BC8), Cassava Stem (BC9), and Rubber Wood (BC10). All feedstocks were pyrolyzed under identical conditions (350–400°C temperature, 1.2–1.3 hours) in a fabricated drum pyrolytic chamber to isolate feedstock type as the primary variable. Resulting BCs were alkaline (pH 8.79–10.69) and varied widely in organic matter (5.55–17.38%), total N (0.09–0.69%), total P (2,207.95–25,411.61 mg/kg), and total K (5,635.81–65,740.52 mg/kg). CEC ranged more than threefold across feedstocks, from 7.999 cmol/kg (BC3) to 26.626 cmol/kg (BC1), with BC5 (26.168 cmol/kg), BC6 (22.311 cmol/kg), and BC2 (21.428 cmol/kg) also ranking high. When grouped by feedstock nature, fruit/processing waste biochars showed the most consistently high CEC, while woody/lignocellulosic biochars showed the widest internal range, driven by (BC3) notably low value. These findings confirm feedstock type as the dominant determinant of biochar CEC and nutrient content, and identify fruit and agricultural processing residues particularly BC1, BC5, BC6, and BC2 as the most promising feedstocks for producing high-CEC biochar for soil amendment in tropical agricultural systems.

Index Terms- Biochar, Cation Exchange Capacity (CEC), Feedstock, Pyrolysis, Soil Amendment

I. INTRODUCTION

Soil degradation, nutrient depletion, and declining organic matter content remain persistent challenges in sustainable agricultural production. Among the various soil amendment strategies developed to address these concerns, biochar has emerged as a promising material due to several studies reporting a wide range of effects of biochar on physical and chemical soil properties and functions, and on plant growth [1]. It is also had a greater effect on microbial diversity (both bacterial and fungal), with more diverse bacterial populations in medium and coarse textured soils, while fungal diversity increased in fine textured soils [2]. Biochar, a carbon-rich substance produced through the pyrolysis of organic materials under limited oxygen conditions, has gained increasing attention as a sustainable soil amendment due to its potential to enhance soil health, improve agricultural productivity, and mitigate climate change [3]. [4].

One of the most critical properties determining biochar's effectiveness as a soil amendment is its Cation Exchange Capacity (CEC). CEC reflects a materials capability to hold and exchange cations such as calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), and potassium (K^{+}) in exchangeable and plant-available form [5], [6], making it a key indicator of a biochar's capacity to improve nutrient retention and reduce nutrient leaching. BC with higher CEC is generally considered more beneficial for enhancing soil fertility, particularly in highly weathered or sandy soils with inherently low nutrient-holding capacity.

However, the physicochemical properties of BC are strongly influenced by the type of feedstock and temperature used in its production [5] [7]. In many studies, increasing pyrolysis temperature, decreases biochar CEC [8] most likely due to significant degree of organic matter decomposition [9]. Meanwhile, reported results from several studies confirmed that feedstock type has a crucial impact on BC properties, both on general characteristics and features important for expected longevity in soil. A general overview of BC properties showed that, depending on feedstock type, the ash content can be different and was remarkably higher in BC originating from

cut green grass and kitchen wastes. High ash content in these BCs corresponded with higher CEC values, which was also observed in previous studies [10].

Thus, this study aims to assess the chemical properties specifically CEC of BC produced from ten different feedstocks, all processed under the same pyrolysis temperature. By isolating feedstock type as the primary variable, this study seeks to determine which biochar types exhibit the most favorable properties for use as a soil amendment, with particular emphasis on their nutrient retention potential as reflected by CEC. The findings are expected to provide practical guidance for selecting feedstock-appropriate biochar for soil fertility improvement, particularly in agricultural contexts requiring cost effective and locally sourced amendment options.

II. MATERIALS AND METHODS

Feedstock Collection and Preparation

Ten locally available biomass materials were used as feedstocks for biochar production: rice hull, oil palm empty fruit bunch, coconut shell, water hyacinth, banana pseudostem, cacao pod, bamboo, corn cob, cassava stem, and rubber wood. In order to prevent the growth of mold and maintain the same level of humidity in the biomasses, which is crucial for a successful pyrolysis process, the input materials were air-dried before the pyrolysis.

Biochar Production

BC was produced from each feedstock through pyrolysis using a vertical 55-gallon steel drum serves as the primary pyrolysis chamber, equipped with small, adjustable air inlets near the base and a modest top vent to regulate oxygen ingress and promote slow carbonization. Sundried feedstock was chopped into pieces approximately 2–5 cm, then loaded loosely in the drum to prevent compaction and allow gas flow. The pyrolysis process attained the temperature about 350 to 400 °C. The process continues for 1.2 to 1.3 hrs. All ten feedstocks were processed under identical pyrolysis conditions to isolate feedstock type as the primary variable influencing the resulting BC properties. The produced BCs were allowed to cool, then collected and stored appropriately prior to laboratory analysis.

Biochar Properties Analysis

Biochar properties were determined on air-dried material with a particle diameter smaller than 2 mm and were analyzed at the Soil and Plant Analysis Laboratory (SPAL) at the department of Soil Science, College of Agriculture, Central Mindanao University, Musuan, Maramag, Bukidnon, and in the soil laboratory of the Provincial Research Development and Innovation Office (PRDIO) of the provincial government of Agusan del Sur, located at Governor D.O. Plaza, Government Center, Patin-ay, Prosperidad, Agusan del Sur. The pH was measure using the Potentiometric Method at a 1:5 biochar-to-water ratio, with pH meter. Exchangeable cations for CEC were extracted with modified ammonium acetate (NH₄OAc) method at pH = 7.0 (Chapman, 1965). The total nitrogen (%) was determined through Modified Dumas dry combustion method [36]. The total phosphorus and total potassium (%) were prepared through nitric-perchloric acid digestion method [37]. The Heanes Wet Oxidation Method was used to determine the Organic Matter Content (%) of the biochar defined by PCARRD (1991).

Data Analysis

All collected data obtained from the chemical analysis of the ten BCs were organized and compared using descriptive statistics. Given that a single measurement was obtained per BC for each parameter, no inferential statistical analysis was performed. Instead, comparisons among BCs were made descriptively, supported where applicable by reference to values reported in existing literature.

III. RESULTS

A. Chemical Properties of Biochar from Different Feedstocks

Across ten feedstocks (Table 1.), pH values ranged from 8.79 to 10.69, exhibited alkaline reaction; BC1 recorded the lowest pH (8.79), while BC5 recorded the highest (10.69), and the remaining eight feedstocks clustered closely within a narrower alkaline range of 10.13 to 10.66, indicating that most feedstocks produced biochar of similarly high alkalinity under the pyrolysis conditions used in this study (400°C). Organic matter (OM) content varied more widely among feedstocks, ranging from 5.55% (BC8) to 17.38% (BC2). With BC2, BC7 (15.53%), and BC6 (13.75%) recording the top three (3) highest OM values, while BC8 (5.55%) and BC1 (7.42%) recorded the lowest, suggesting differences in the extent of carbon retention or volatilization among feedstock types during pyrolysis. Moreover, total nitrogen ranged from 0.0868% (BC5) to 0.6881% (BC6). BC6, BC1 (0.6645%), and BC4 (0.6218%) recording comparatively higher N content, while BC5, BC9 (0.1604%), and BC10 (0.1536%) recorded the lowest. Meanwhile, the total phosphorus concentrations ranged from 2,207.95 mg/kg (BC3) to 25,411.61 mg/kg (BC6), with BC6 and BC2 (25,375.80 mg/kg) recording markedly higher P levels compared to the rest of the feedstocks, while BC3 recorded the lowest by a substantial margin. Finally, total K concentrations showed the widest range among all parameters measured, from 5,635.81 mg/kg (BC1) to 65,740.52 mg/kg (BC5) more than a tenfold difference with BC5 K content particularly notable, exceedingly even the next-highest feedstocks, BC6 (57,361.15 mg/kg) and BC2 (56,806.83 mg/kg), by a considerable margin.

Table 1. Selected Chemical Properties of Biochar from Ten Different Feedstocks

Feedstock	pH	OM (%)	Total N (%)	P (mg/kg)	K (mg/kg)	CEC (cmol/kg)
Rice Hull	8.79	7.42	0.6645	8616.92	5635.81	26.626
Oil Palm EFB	10.63	17.38	0.4102	25375.8	56806.83	21.428
Coconut Shell	10.54	10.41	0.1663	2207.95	10976.37	7.999
Water Hyacinth	10.3	13.56	0.6218	17183.85	28234.09	19.454
Banana Pseudostem	10.69	14	0.0868	7082.1	65740.52	26.168
Cacao Pod	10.13	13.75	0.6881	25411.61	57361.15	22.311
Bamboo	10.32	15.53	0.2837	3903.88	7134.68	17.791
Corn Cob	10.49	5.55	0.273	16092.25	33481.61	12.545
Cassava Stem	10.43	6.55	0.1604	11692.29	20322.84	14.323
Rubber Wood	10.66	6.46	0.1536	9732.14	15898.63	16.791

B. Cation Exchange Capacity Across Biochar Types

As shown in Figure 1, CEC among the ten biochar types ranged from 7.999 cmol/kg (BC3) to 26.626 cmol/kg (BC1), representing more than a threefold difference across feedstocks. BC1 recorded the highest CEC (26.626 cmol/kg), closely followed by BC5 (26.168 cmol/kg), a difference of less than 0.5 cmol/kg between the two top-performing feedstocks. BC6 (22.311 cmol/kg) and BC2 (21.428 cmol/kg) followed, both exceeding the 20.4 cmol/kg threshold used to classify the high CEC tier. A distinct moderate tier followed, comprising BC4 (19.454 cmol/kg), BC7 (17.791 cmol/kg), BC10 (16.791 cmol/kg), and BC9 (14.323 cmol/kg). All falling within the 14.2–20.4 cmol/kg range. Notably, this tier shows a fairly even, stepwise decline across its four members, in contrast to the sharper drop-offs observed elsewhere in the ranking. BC8 (12.545 cmol/kg) and BC3 (7.999 cmol/kg) fell into the low CEC tier, with BC3 trailing the rest of the dataset by a considerable margin. Its CEC value is less than a third of rice hull's and roughly 4.5 cmol/kg lower than the next-lowest feedstock (BC8).

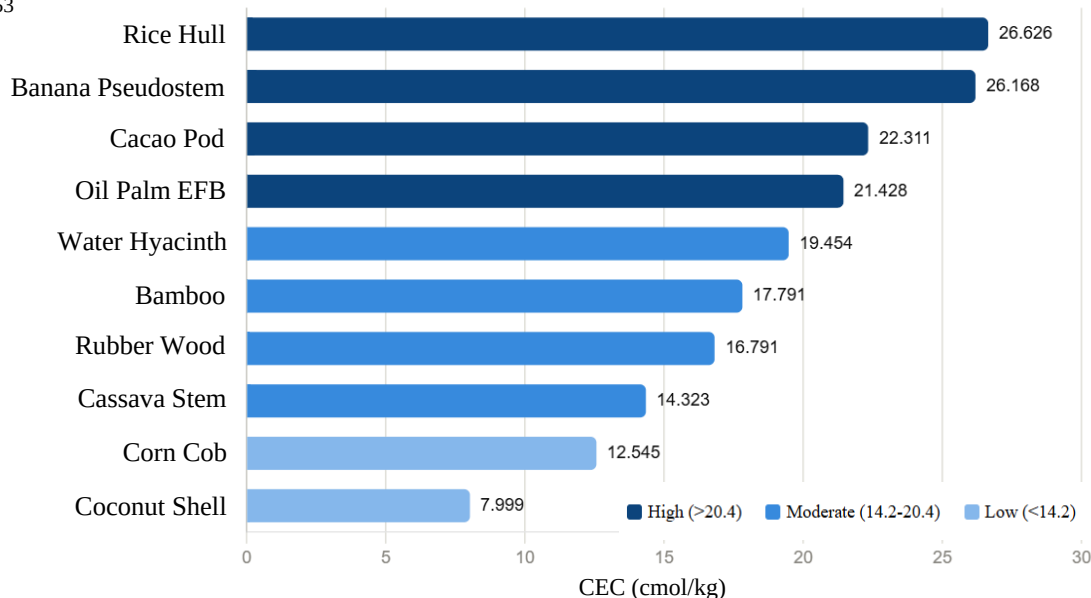


Figure 1. Cation exchange capacity (CEC) of biochar produced from ten different feedstocks, ranked from highest to lowest. Bars are shaded by CEC tier: high (>20.4 cmol/kg), moderate (14.2–20.4 cmol/kg), and low (<14.2 cmol/kg).

C. Cation Exchange Capacity in Relation to Feedstock Classification

Figure 2 presents the cation exchange capacity (CEC) of the ten biochar feedstocks, grouped according to feedstock nature into four categories: agricultural residues (BC1, BC9, BC8), fruit/processing waste (BC5, BC6, BC2), woody/lignocellulosic materials (BC7, BC10, BC3), and aquatic/herbaceous biomass (BC4). When examined by group, the fruit/processing waste category showed the most consistently high CEC values across its members (21.43–26.17 cmol/kg), while the woody/lignocellulosic group displayed the widest internal range (7.99–17.18 cmol/kg), driven largely by the low value of BC3 relative to BC7 and BC10. The agricultural residue group showed a similar spread, with BC1 CEC roughly double that of BC8 (12.55 cmol/kg) despite both being crop residues. BC4, the sole representative of the aquatic/herbaceous group, recorded an intermediate CEC value (19.45 cmol/kg).

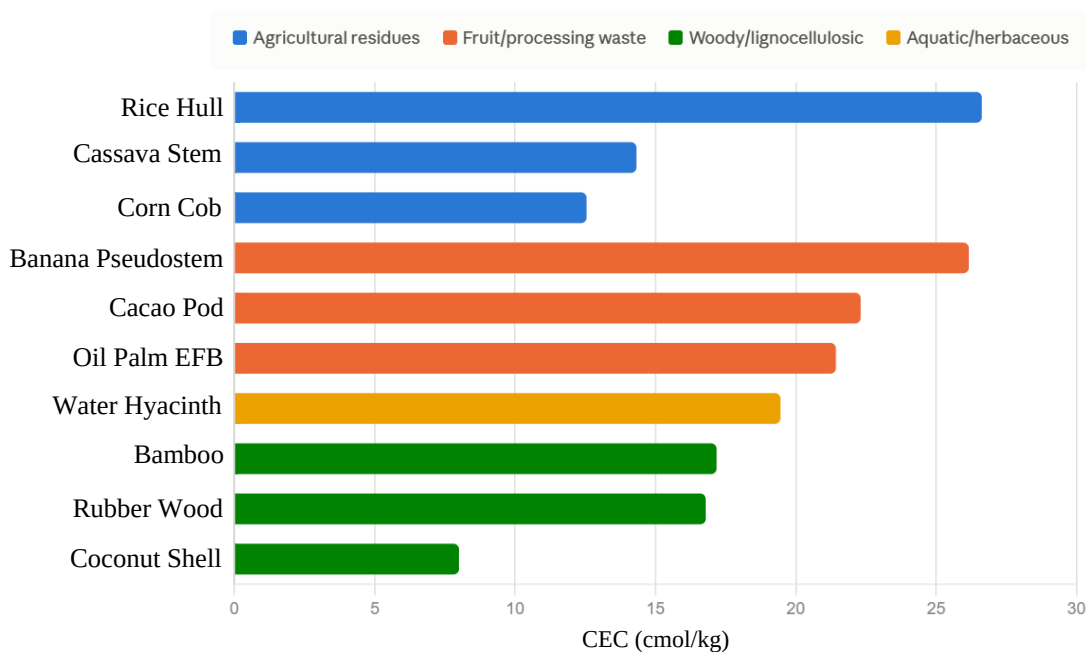


Figure 2. Cation exchange capacity (CEC) of ten feedstock-based biochars, grouped by feedstock nature (agricultural residue, fruit/processing waste, woody/lignocellulosic, aquatic/herbaceous).

IV. DISCUSSION

A. Chemical Properties of Biochar from Different Feedstocks

(Table 1) shows a pattern that is theoretically coherent with the two recognized sources of biochar alkalinity. At low pyrolysis temperatures, alkalinity derives predominantly from organic anions and surface oxygen-containing functional groups, whereas inorganic carbonates and base-cation oxides become dominant above approximately 500 °C [11],[12]. The uniformly alkaline reaction recorded here therefore reflects the combined contribution of residual organic functionality and ash-borne base cations, and the observed range sits comfortably within the 6.5–10.8 interval reported across the literature for slow-pyrolysis biochars [9]. Practically, biochars of this alkalinity carry appreciable liming value, a property of direct relevance to the acidic, highly weathered soils that dominate humid tropical agriculture [13].

The position of BC1 as a clear outlier merits particular attention. Although rice hull is a high-ash feedstock, its ash is dominated by amorphous silica rather than by base-cation carbonates, so its acid-neutralizing capacity is disproportionately low relative to its total ash content. [14] reported precisely this behavior, with rice hull biochar consistently the lowest-pH char across a 400–800 °C series despite high ash, and [15] similarly found rice hull biochar to have both the lowest pH and the lowest exchangeable base cations when compared directly with BC2 and wood biochars. The present finding therefore replicates a well-documented compositional anomaly and confirms that total ash content is an unreliable proxy for biochar alkalinity.

The OM values recorded here are consistent with the incomplete carbonization expected at 400 °C. BCs produced in the 300–450 °C window occupy a transitional zone characterised by high volatile matter and only partially aromatised carbon [16], [17], [18], [19]. The magnitude of feedstock differences in OM is conventionally attributed to biopolymer composition: hemicellulose decomposes at approximately 220–315 °C and cellulose at 315–400 °C, whereas lignin degrades slowly across 160–900 °C and yields the largest solid residue [20]. It is notable, however, that the present dataset only partly conforms to this expectation. Bamboo, a highly lignified feedstock, retained high OM (15.53%), yet rubber wood which was also lignified, retained among the lowest (6.46%), while the highest values were recorded for the fibrous fruit-processing residues oil palm EFB and cacao pod. This suggests that at a single, relatively low pyrolysis temperature, lignin content alone is insufficient to predict OM retention, and that ash dilution and feedstock density or particle geometry also mediate the outcome [21].

Nitrogen concentrations behaved as feedstock-controlled, as the literature predicts. Biochar total N is governed principally by the N concentration of the parent biomass, moderated by progressive volatilization of N as NH₃ and HCN as temperature rises [22], [23]. Low-temperature pyrolysis retains a comparatively high proportion of feedstock N, which explains why the N-rich residues in this study, cacao pod (0.6881%), rice hull (0.6645%) and water hyacinth (0.6218%) produced the most N-enriched biochars, whereas the structurally simple, N-poor banana pseudostem, cassava stem and rubber wood produced the least. An important qualification is that much of the N remaining in a 400 °C char has already been converted into heterocyclic pyridinic, pyrrolic and quaternary forms of low short-term bioavailability [24]; total N should therefore not be interpreted as a measure of fertilizer N value. Moreover [25], characterizing a closely comparable set of Cameroonian agricultural residues, likewise identified cocoa pod husk as the most N-, P- and base-cation-rich of eight biochars, corroborating the ranking obtained here.

Phosphorus and potassium, being non-volatile, are conserved in the ash fraction and therefore track the mineral composition of the feedstock almost directly. Cacao pod and oil palm biochars recorded markedly elevated P (25,411.61 and 25,375.80 mg/kg), while banana pseudostem recorded an exceptional K concentration (65,740.52 mg/kg). Both observations have direct precedent: [26], documented that banana pseudostem biochar has a very high ash content overwhelmingly dominated by potassium, and cacao pod husk biochar has been shown to function as a concentrated K source and to reduce phosphorus fixation in acid tropical soils [27]. Conversely, coconut shell biochar recorded the lowest P by a wide margin, consistent with the general finding that low-ash, highly lignified woody feedstocks yield nutrient-poor biochars that may induce rather than relieve nutrient limitation [28], [29]. These distinctions carry practical weight because the two nutrients behave differently after application: K in biochar is highly soluble and released in a rapid initial flush, whereas P is far less soluble and released only slowly [30]. Banana pseudostem, cacao pod and oil palm EFB biochars are thus best regarded as immediate K amendments and slow-release P amendments, and the broad agreement of these results with the meta-analytical conclusion that feedstock class is the single most influential determinant of biochar nutrient status [31], [21] reinforces the case for matching feedstock to the specific nutrient deficiency being targeted.

B. Cation Exchange Capacity Across Biochar Types

Theoretically, the values shown in (Figure 1) are consistent with the mechanism by which exchange capacity develops in biochar. Negative surface charge in biochar arises principally from deprotonated carboxylic and phenolic groups, which are abundant in incompletely carbonized material and are progressively destroyed by dehydration and deoxygenation as pyrolysis temperature increases, [9] [32] demonstrated this directly, recording CEC of approximately 52 cmol/kg for 250 °C biochar but only 16–21 cmol/kg for 400–650 °C biochars from the same feedstocks, and reporting a strong linear relationship between volatile matter and total surface acidic functional groups ($R^2 = 0.88$). [33] similarly found CEC to peak at 400 °C across nine biochars and to decline at 550 and 650 °C. The values obtained in the present study fall squarely within the range those authors report for 400 °C material, indicating that the pyrolysis temperature selected here was well suited to producing biochar with functional exchange capacity rather than merely high surface area.

Comparison with the wider literature nevertheless reveals both agreement and genuine tension. The very low CEC of coconut shell biochar aligns closely with established findings that highly lignified; low-ash woody feedstocks yield biochars with limited exchange capacity. [28] reported markedly lower potential CEC and exchangeable cations for Eucalyptus wood biochars than for manure-based chars, and [34] recorded CEC as low as 1.3 cmol/kg for eucalyptus sawdust biochar against 72 cmol/kg for coffee husk. The high CEC of rice hull biochar, by contrast, sits uneasily beside [14], who found rice hull biochar to have the lowest CEC as well as the lowest pH in their series. One plausible reconciliation is that the two properties are decoupled in silica-rich material: the same low ash alkalinity that suppresses rice hull pH also leaves its residual acidic surface functionality undissipated, so a feedstock can simultaneously be weakly alkaline and comparatively strongly exchanging. The present study's finding that rice hull recorded both the lowest pH and the highest CEC is internally consistent with that interpretation, though it requires direct spectroscopic confirmation.

C. CEC in Relation to Feedstock Classification

Grouping the ten biochars by feedstock nature produced a clear ordering of group means alongside marked within-group heterogeneity. The most comprehensive synthesis available concluded that crop and grass-based biochars possess higher cation exchange capacities than other biochars and that feedstock is the single most influential production parameter for biochar properties. [31] and [28] reported lower potential CEC and exchangeable cations for wood-based biochars than for non-woody chars, and [34] recorded an order-of-magnitude separation between low-ash woody feedstocks and herbaceous residues. [25], found that biochar physicochemical properties varied greatly according to residue origin, with cacao pod husk among the richest in nitrogen, phosphorus and exchangeable bases. The present classification therefore reproduces a robust and repeatedly documented pattern, and offers a practical corollary, where the objective of biochar application is to improve nutrient retention, fruit and processing residues represent the most reliable feedstock class, whereas highly lignified woody residues are the least dependable.

The within-group variation, however, is as analytically important as the between-group ordering, and it qualifies the utility of classification by feedstock nature. The woody group spanned more than nine cmol/kg and the agricultural residue group more than fourteen, so that membership of either class was a poor predictor of an individual biochar's CEC. This is not surprising once the underlying mechanism is considered: 'feedstock nature' is a morphological and provenance-based category, whereas CEC is determined by lignin-to-holocellulose ratio, ash chemistry and the resulting density of surface functional groups [20], [9]. Coconut shell and bamboo are both classed as woody yet differ substantially in lignification and ash content, and rice hull and corn cob are both cereal residues yet differ fundamentally in ash mineralogy. [21], reached a comparable conclusion, finding that biochar properties varied more with feedstock than with production temperature but that the variation did not resolve neatly into conventional biomass categories. Feedstock class is thus best understood as a coarse screening heuristic, not a substitute for characterization of the individual biochar.

Two limitations constrain the inferences that can be drawn from this classification. First, with three members in each of three groups and only one in the fourth, no formal test of between-group differences is warranted, and the intermediate position of water hyacinth cannot be generalized to aquatic and herbaceous biomass as a class; the substantially higher CEC reported for water hyacinth biochar produced at 350 °C, and [35] indicates that this category is at least as temperature-sensitive as the others. Second, because feedstock nature co-varies with ash content, lignin content and nutrient status, the grouping cannot isolate the causal driver of the observed differences. Resolving that question would require characterization of biopolymer composition and surface functional group density alongside CEC, ideally across a wider feedstock set and at more than one pyrolysis temperature.

ACKNOWLEDGMENT

The author would like to express his sincere gratitude to the Provincial Government of Agusan del Sur for its unwavering support throughout the course of this study. Deep appreciation is extended for the financial assistance provided under its scholarship program, which made the conduct of this research possible. The author is also grateful to the personnel of PGAS-EDS, for their unwavering support, patience, and understanding.

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