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Enhancement of Compost Quality and Nutrient Retention Through Co-composting with Bamboo-derived Biochar

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Abstract: This research evaluates the efficacy of bamboo-derived biochar (BB) as a pivotal amendment for optimizing compost quality and nutrient retention. The study utilized BB produced via a Kon-Tiki kiln, a method selected to preserve the feedstock's biogenic integrity. Scanning Electron Microscopy (SEM) analysis confirmed that the resulting biochar possesses a highly developed micro and mesoporous network, a structural attribute critical for augmenting water retention, cation exchange capacity, and microbial habitat stability. When integrated into the composting matrix, the Bamboo Biochar enriched Compost (BBC) demonstrated superior physicochemical balance, characterized by a near-neutral pH (7.14) and an electrical conductivity of 3.79 dS/m. Crucially, the co-composting process yielded a robust nutrient profile that significantly exceeds typical values for conventional compost, with elevated concentrations of Nitrogen (1.09%), Phosphate (0.79%), and Potassium (1.18%), alongside secondary nutrients such as Calcium (4.31%) and Magnesium (1.27%). The analysis also highlighted substantial micronutrient retention, including Zinc (379.73 mg/kg), Manganese (543.17 mg/kg), Iron (1.73%), and Copper (55.6 mg/kg). While raw BB serves as a stable carbon sink (86.7% organic carbon), the BBC formulation achieved a functional equilibrium with a moderate organic carbon content (28.6%) and an optimized C:N ratio of 26.2, thereby fostering efficient microbial activity and compost maturity. Ultimately, these findings confirm that the synergy between the porous structure of bamboo biochar and the nutrient density of compost fosters a circular waste valorization approach, delivering a sustainable, high-quality soil amendment.

Keywords: Bamboo biochar, Co-composting, Nutrient retention, Physico-chemical properties, Soil amendment.

Introduction

Biochar, a carbon-rich material derived from organic biomass, is increasingly recognized as an environmentally sustainable strategy for organic waste management (Hien *et al*., 2017). Its capacity to ameliorate soil quality and mitigate environmental degradation has positioned it as a viable solution in both agriculture and conservation. Synthesized via pyrolysis, a process involving the thermal decomposition of organic matter under oxygen-limited conditions (Lehmann and Stephen, 2009), biochar enriches the soil matrix by supplying essential macronutrients and trace elements (Gaskin *et al*., 2008). Furthermore, its highly porous architecture provides a favorable habitat for soil microorganisms, thereby augmenting microbial activity and diversity (Thies and Rillig, 2009). Collectively, these attributes contribute to improved soil fertility and increased crop productivity, establishing biochar as a pivotal tool for sustainable farming.

Bamboo, a fast-growing and adaptable woody grass belonging to the Gramineae family, thrives abundantly across Asian nations (Hien *et al*., 2017) like Sri Lanka. Its economic and ecological potential is increasingly evident: according to a UNIDO (2016) report, Sri Lanka's bamboo cultivation spans approximately 5,166 hectares, valued at around Rs 220 million, with the Mahaweli Authority overseeing 2,500 hectares of this land. These figures highlight the untapped opportunities for expanding the country's bamboo sector. Further reinforcing this potential, a study by Amunugoda (2019) documented nearly 10,000 hectares of bamboo cultivation in Sri Lanka, featuring seventeen distinct species. Bamboo's high cellulose, hemicellulose, and lignocellulose content makes it a prime candidate for bioenergy applications. Its rapid growth cycle allows for annual harvesting of culms, positioning it as a sustainable feedstock for biochar production (Lathwal *et al*., 2023). This unique combination of renewable growth and chemical composition underscores bamboo's promise in advancing green energy solutions. Bamboo-derived biochar, in particular, offers distinct physicochemical advantages over hardwood variants, with its lighter, more porous structure enhancing water retention and facilitating optimal moisture balance and aeration within compost systems, effectively mitigating challenges posed by dense or adhesive organic materials (Fischer *et al*., 2012).

Compost itself is a valuable, readily available, inexpensive, and easy-to-prepare resource for improving soil and crop quality (Mulbah *et al*., 2023). It enriches soils with essential nutrients, enhances physicochemical properties, and binds soil particles to boost nutrient availability for plants (Meena *et al*., 2021). To further optimize this potential, incorporating biochar as a compost amendment has emerged as a recognized strategy, particularly for nutrient conservation. A global meta-analysis of 123 studies confirmed that biochar addition significantly mitigates the volatilization of ammonia and greenhouse gases (Xu and Xiong, 2025). While this reduction is often discussed in environmental terms, it implies a critical agricultural benefit: the retention of nitrogen and other volatile nutrients within the compost matrix. Specifically, bamboo-derived biochar (BB) has been extensively studied for this purpose. Research has consistently demonstrated that adding BB during co-composting reduces nitrogen loss by mitigating NH_3 volatilization (Awasthi *et al*., 2020; Zhang *et al*., 2021). These benefits are attributed to BB's excellent adsorption characteristics, which improve porosity and stimulate microbial activities that accelerate organic waste degradation (Awasthi *et al*., 2020; Ali *et al*., 2017). However, while the emission reducing mechanisms of biochar are well-documented, there is a need to translate these findings into practical application by optimizing the physicochemical quality of the final product using specific, locally available biomass.

Therefore, this study shifts the focus from emission monitoring to product quality optimization. The primary goal was to explore the potential of locally sourced *Bambusa vulgaris* for producing nutrient rich biochar amended compost, specifically aimed at enhancing nutrient retention. The study tested two specific hypotheses: (1) The inclusion of Bamboo Biochar as a porous absorbent is expected to improve the final physicochemical quality of the compost; and (2) Determining suitable mixing ratios where dry materials serve as the carbon source, fresh leaves/manure as nitrogen sources, and biochar as the adsorbent can optimize long-term nutrient management. To test these hypotheses, the research involved two phases: a BB production study and a subsequent field-scale composting heap experiment, with the following specific objectives:

To determine the pyrolysis yield and comprehensively physicochemically characterize the bamboo biochar for its suitability and role in enhancing the compost production process.

To determine the optimal mixing ratios of bamboo biochar and composting materials required for preserving nutrient integrity throughout the process.

To comprehensively evaluate the influence of bamboo biochar incorporation on the final physicochemical properties and overall quality of the resulting compost product.

Materials and Methods

Experiment 01: Production and Yield of Bamboo Biochar under controlled pyrolysis

This investigation focused on the production of bamboo biochar (Figure 1) using culms from the *Bambusa vulgaris* species. The study utilized mature stem samples, aged five years, based on reports that this species is widely used for biochar production (Alfei and Pandoli, 2024). The initial stage involved harvesting the bamboo culms, which were then air-dried for a week after collection from the local area in the Ampara district, Sri Lanka. To facilitate uniform processing and consistent pyrolysis, the air-dried bamboo was cut into smaller pieces and inspected to ensure it was thoroughly dried and devoid of impurities. The pyrolysis was conducted using a registered Kon-Tiki kiln. This process was carried out in a controlled, low-oxygen environment at a temperature of 600^0C for 4 hours. This temperature was selected based on findings demonstrating that biochar produced at 600^0C the highest surface area, a key factor influencing its porosity and adsorption capacity (Suthar *et al*., 2018; Inyang *et al*., 2010). After pyrolysis, the biochar was carefully cooled and collected to prevent contamination. The process yielded 45.8 kg of biochar from an initial 275 kg of air-dried bamboo culms. This mass conversion of approximately 17% is characteristic of efficient, high-temperature carbonization, which drives off volatile components and concentrates the stable carbon matrix.

Figure 1. Pyrolysis process using Kon Tiki Biochar Kiln: collection of bamboo culms (A), pyrolysis process at 600^0C using Kon Tiki Biochar Kiln (B), clean flames with minimal smoke emission (C) and bamboo biochar (D).

The process behind the Pyrolysis system using Kon Tiki Biochar Kiln

The Kon Tiki biochar kiln incorporated a precision-engineered design, optimizing biochar yield through systematic thermal decomposition while significantly curbing smoke emissions to reduce environmental impact. The production cycle commenced with precisely arranging bamboo culms within the kiln's burner chamber (Figure 1). Once combustion was initiated, heat was rapidly absorbed by the outer shield of the kiln, and the airflow was directed upwards in a controlled manner. This airflow system was crucial for maintaining consistent combustion by drawing air inward, which allowed the smoke to be contained and the temperature (600^0C) to be regulated inside.

The controlled airflow helped sustain the combustion process while minimizing smoke, which was evident from the clear flames observed inside the kiln and the minimal smoke emissions. This demonstrated how the kiln's design protected the burning process from external disturbances, allowing the system to function efficiently. Additionally, the upward movement of hot air within the kiln was not disrupted by external drafts, ensuring that the biochar production process continued uninterrupted, with the necessary heat maintained for the conversion of bamboo into biochar. This synergy of heat management and airflow control not only enhanced efficiency but also reduced environmental footprint, aligning with the kiln's goal of sustainable biochar production.

Experiment 02: Formulation of compost enriched with bamboo biochar

Incorporating biochar into compost was considered a relatively simple and straightforward process. It started with choosing high-quality biochar produced from bamboo culms. The following steps outlined the procedures employed to produce a blend of biochar compost (Figure 2) suitable for agricultural use. Firstly, a well-drained site was chosen for the creation of a compost heap, ensuring easy accessibility and a balance of sunlight for 4-6 hours and partial (60 %) shade. An area with dimensions of 3 feet in width, 6 feet in length, and 3 feet in height were defined, and the boundaries were marked. Locally sourced fresh and dry organic materials were gathered from the Batticaloa district, Sri Lanka. These materials were included glyricidia, Salvinia, Calotropis, Banyan, and groundnut as fresh green leaves, as well as poultry, goat, and cattle manure as animal manure components. Additionally, wood dust was also collected from the State Timber Corporation in Batticaloa, Sri Lanka.

After collecting the substrates, the animal manure underwent air drying until its moisture content was reduced to less than 15%. It was then mechanically crushed using a 40 mm sieve. The initial layer began with old compost serving as a base to foster a nutrient-rich environment for the decomposition of new organic materials and to promote optimal conditions for microbial activity. To achieve an ideal carbon to nitrogen (C/N) ratio of 25:1, the compost heap was layered with air dried leaf materials (392 kg), green leaves (235 kg), and animal manures (156 kg) by weight (w/w), building up to a height of 3 feet.

Following the placement of dried leaves at a height of 8 inches a top the old compost, animal manure was added in a layer measuring 3 inches. Fresh leaves and young plant branches were then arranged on top, reaching a height of 8 inches. Old compost was introduced at a rate of 50 grams/m^2 onto this layer. Continuing until the total height reached three feet, alternating layers of animal manure, fresh leaves, and dry leaves were added. Throughout this process, old compost was introduced every two layers within the heap, while wood dust was also included as a layer in between to ensure the appropriate balance of nutrients and microorganisms required for effective composting.

The prepared bamboo biochar was then strategically layered among these composting materials, incorporating alternating layers of biochar with fresh and dried organic materials. This layering approach is crucial for optimizing the internal structure, which enhances nutrient absorption and promotes microbial colonization, thereby facilitating efficient degradation of organic matter. As a general guideline for composting, adding 5-10% biochar by volume is typically recommended, though the optimal rate depends on the final application and target nutrient profile (CharGrow, 2023). Studies demonstrate that incorporating biochar significantly improves the composting process efficiency, for instance, Sánchez-García *et al.* (2015) found that biochar addition at 2-4% of the compost's total weight can shorten the composting timeline by up to 20 %. Furthermore, the inclusion of biochar is essential for preserving the final product's nutrient profile. For example, research on poultry manure compost showed that blending 10 % bamboo biochar reduced overall nitrogen loss by 12.59 % (Awasthi *et al*., 2020) and minimized the loss of volatile nitrogen compounds (ammonia, NH_3) by 9.2 % (Cheng *et al*., 2017), directly resulting in a more nutrient-rich final soil amendment.

Therefore, for our experimental study, we applied these findings by blending 39.15 kg of bamboo biochar into the total compost weight of 783 kg, achieving a 1:20 (w/w) ratio for accelerating the composting process. After establishing the compost heap, it was securely covered with black polythene, leaving a 10 inches gap from the bottom of the heap. Subsequently, the compost was manually turned three times at fifteen-day intervals using a shovel. This process aerated the pile, facilitated decomposition, and mitigated the development of unpleasant odors. Moisture levels and temperature were monitored at regular intervals throughout the composting period to assess microbial activity and decomposition progress. Measurements were taken using a digital thermometer and a moisture meter to ensure optimal conditions for effective composting. By carefully managing moisture and temperature levels, ensures a smooth composting process, yielding high-quality biochar-enriched compost suitable for agricultural applications. Ultimately, high-quality biochar compost was achieved within a span of three and a half months.

The analysis of the organic manures used in this experiment is presented in Table 1, revealing that poultry manure contains the highest percentages of N, P_2O_5, and K_2O.

Table 1. Analysis of organic manures

ANIMAL MANURES	N (%)	P_2O_5 (%)	K_2O (%)
Cattle manure	1.42	0.78	0.93
Poultry manure	3.14	2.16	1.36
Goat manure	1.13	0.37	0.84

To achieve a balanced compost heap with an optimal carbon-to-nitrogen (C: N) ratio of 25:1, specific quantities of different manures were carefully calculated and blended based on their nitrogen content. During the composting process, 80 kilograms of cattle manure, 40 kilograms of poultry manure, and 36 kilograms of goat manure were incorporated. This mix ensured that the nitrogen levels from each manure type complemented the carbon sources, creating an ideal environment for microbial activity and efficient decomposition. The proportions were tailored to meet the target ratio, accounting for the distinct nutrient profiles of each manure to optimize the composting outcome.

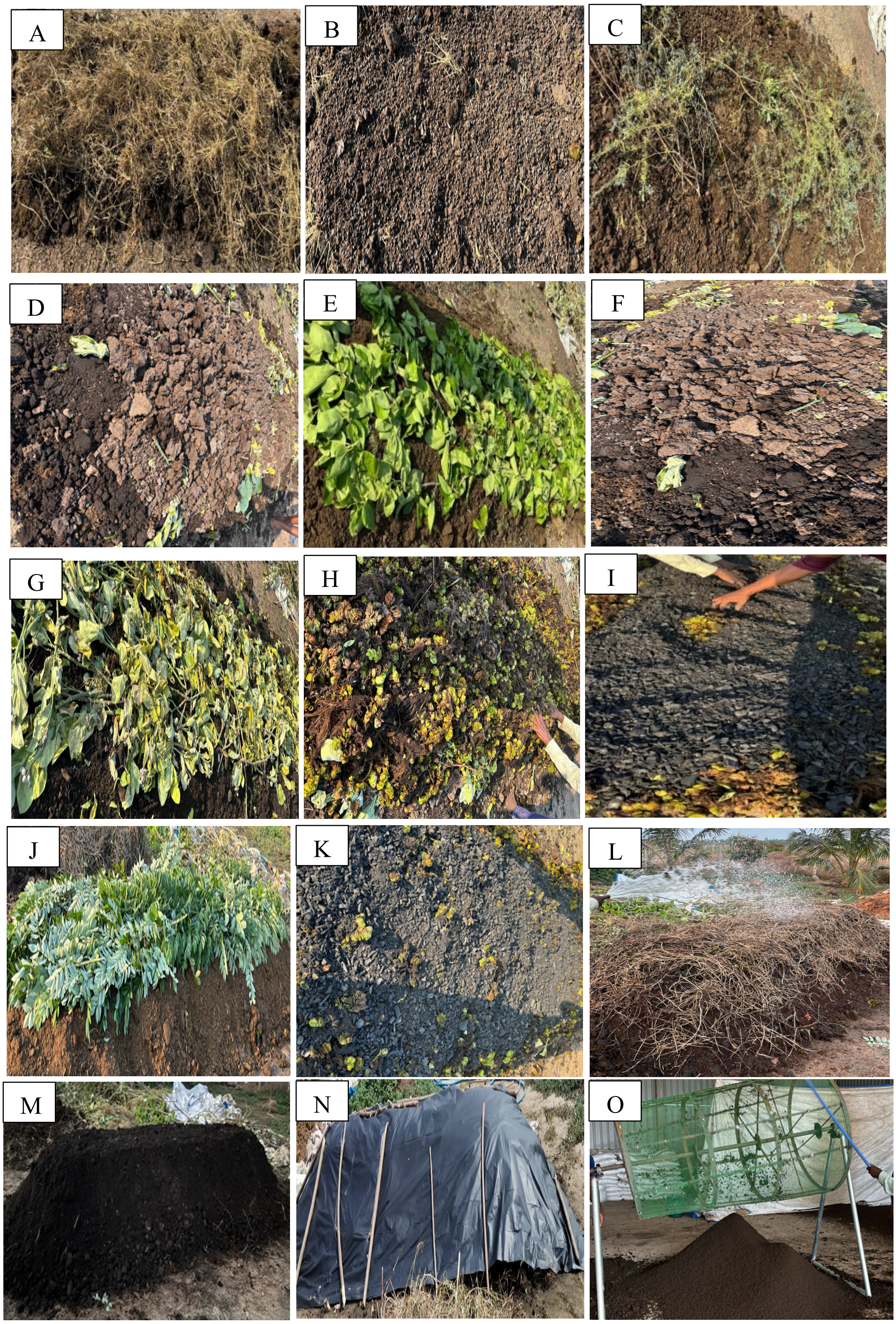

Figure 2. Images depicting the entire process of formulating compost enriched with bamboo biochar: Inclusion of dried leaves (A), addition of animal manure (B), incorporation of groundnut haulms (C), addition of cattle manure (D), inclusion of banyan leaves (E), addition of cattle manure (F), incorporation of Calotropis (G), addition of Salvinia (H), addition of bamboo biochar (I), inclusion of Gliricidia (J), addition of poultry and goat manure (K), inclusion of dried leaves and watering the pile (L), covering with old compost (M), covering with black polythene (N), biochar-enriched compost product (O).

Laboratory Analysis

The physical and chemical characteristics of bamboo biochar (BB) and bamboo biochar enriched compost (BBC) were examined, covering a range of parameters.

pH and Electrical Conductivity (EC)

The technique outlined by Jørgensen and Jensen (2009) was employed to ascertain the pH and EC of the prepared BB and BBC. pH levels were assessed using an OAKTON pH 700 benchtop pH meter, with a mixture of wet solids (BB and BBC) and de-ionized water at a ratio of 1:10 (w/v). The same solution was utilized for EC measurement using a benchtop OAKTON EC meter. After being vigorously shaken for 30 minutes on an open-air platform shaker (Thermo Fisher Scientific, USA), the solutions were left to settle for an hour before recording the pH and EC readings.

Assessment of Macro and Micro nutrients of BB and BBC

Total nitrogen and organic carbon concentrations were assessed using the protocols outlined by De and De (2006). Additionally, the total concentrations of phosphorus and potassium were analyzed using Inductively Coupled Plasma - Atomic Emission Spectrometry (ICP-AES) at the Central Soil and Fertilizer Testing Laboratory of the Horticultural Crops Research and Development Institute, Gannoruwa, Sri Lanka.

Secondary macro nutrients, including calcium (Ca) and magnesium (Mg), and micronutrients such as iron (Fe), manganese (Mn), copper (Cu), zinc (Zn), boron (B), sodium (Na), and silicon (Si) were analyzed in the Bamboo Biochar (BB) and Bamboo Biochar enriched Compost (BBC). The analysis was performed at the Central Analytical Laboratory of the Coconut Research Institute, Sri Lanka, using Inductively Coupled Plasma – Optical Emission Spectrometry (ICP-OES). To ensure accurate characterization, one representative sample of both BB and BBC were analyzed. Specifically, two hundred grams of the BB and BBC material, collected at the maturation stage, were submitted for this analysis.

SEM Analysis for biochar

To analyze structural changes in the bamboo biochar after pyrolysis, scanning electron microscopy (SEM) was used (Figure 3). A small sample of the biochar was submitted to the Department of Geology at the University of Peradeniya, Faculty of Science for this evaluation. The SEM technique provided high-resolution insights into microscopic transformations in the biochar's surface and internal structure.

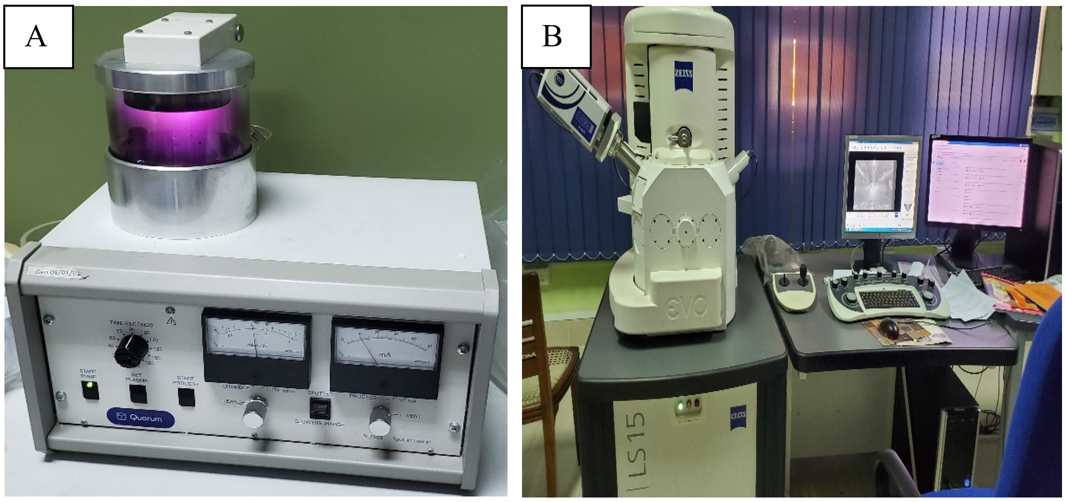

Figure 3. Preparing samples for SEM imaging: SEM Coater (A) and SEM unit (B).

The analysis was performed using a ZEISS EVO LS 15 SEM (manufactured in Germany), operated at an accelerating voltage of 20.00 kV. This allowed for precise imaging of the biochar's morphology, revealing details such as pore formation, surface texture, and other physical modifications resulting from the pyrolysis process.

Results and Discussion

Analysis of Physico-chemical properties

The analysis of physico-chemical properties (Table 2) provides a comparative assessment of the raw Bamboo Biochar (BB) and the final Bamboo Biochar Compost (BBC). To determine the specific value addition provided by the biochar amendment, the properties of BBC were benchmarked against established literature values for conventional compost and the Sri Lanka Standards Institution (SLSI) requirements. Notably, BB exhibits a markedly alkaline pH of 10.09, a property that enhances its capacity to elevate soil pH and improve nutrient availability, particularly in acidic environments. This alkalinity arises from the thermal decomposition of cellulose and hemicellulose during pyrolysis, a process that generates organic and phenolic acids contributing to elevated pH levels (Jia *et al*., 2013). Such properties align with studies demonstrating biochar's capacity to neutralize soil acidity, as its inherent pH often exceeds that of acidic soils, thereby fostering a more favorable microbial habitat (Jeffery *et al*., 2016). Zheng *et al*. (2013) further corroborate this, noting that biochar typically exhibits a broad pH range (6.52–12.64), underscoring its efficacy in mitigating soil acidification.

In contrast, BBC exhibits a neutral pH of 7.14, which enhances its versatility across diverse soil types and cropping systems. This neutrality arises from the integration of biochar with compost, a process that moderates the inherent alkalinity of raw biochar through organic matter decomposition and microbial activity. These findings align with research by Maso and Blasi (2008), who emphasized that stable compost should maintain a pH of 7 to 8.5 for safe agricultural use. Similarly, Biekre *et al.* (2018) observed pH levels of 7 to 8.1 in compost made from farm by-products, reinforcing the importance of pH neutrality for soil health and crop safety.

Table 2. Assessment of physico-chemical properties of BB and BBC.

CHARACTERISTICS	BB	BBC	SLSI REQUIREMENT FOR COMPOST	LITERATURE REPORTED VALUES/RANGES FOR COMPOST
1. pH (1:10 in water)	10.09	7.14	6.5 - 8.5	6.3-7.8 (Elsayed, 2012), 7.29 (Thidar *et al*., 2021)
2. EC (dS/m)	4.14	3.79	< 4	2.6-4.1 (Elsayed, 2012)
3. Total N (% by mass)	0.17	1.09	>1	0.95-1.68 (Elsayed, 2012), 1.25 (Thidar *et al*., 2021)
4. Total Phosphate content as P_2O_5 (% by mass)	0.65	0.79	> 0.5	0.27-1.13 (Elsayed, 2012), 1.62 (Thidar *et al*., 2021)
5. Total Potassium content as K_2O (% by mass)	3.81	1.18	> 1	0.27-2.11(Elsayed, 2012), 1.56 (Thidar *et al*., 2021)
6. Calcium (Ca %)	2.1	4.31		1.96 (Thidar *et al*., 2021)
7. Magnesium (Mg %)	0.7	1.27		0.62 (Thidar *et al*., 2021)
8. Organic Carbon (% by mass)	86.7	28.6	> 20	16.6-23.89 (Elsayed, 2012)
9. Moisture Content (% by dry mass)	26.3	23.2	< 25	20.39 (Thidar *et al*., 2021)
10. C: N Ratio	510	26.2	10-25	14.22:1 – 18.52:1 (Elsayed, 2012)

Bamboo biochar + Compost at a ratio of 1:20 (w/w)
SLSI: Sri Lanka Standards Institution.

In terms of electrical conductivity (EC), BB exhibits a higher EC of 4.14 dS/m compared to BBC, which has an EC of 3.79 dS/m. These values are within the range of 2.6–4.1 dS/m reported for compost produced from agricultural wastes (Elsayed, 2012) and also meet the SLSI requirement of less than 4. The elevated EC in BB suggests a stronger ionic exchange capacity, potentially enhancing nutrient availability for plant growth, however, its classification as slightly saline (Ghassemi, Jakeman, and Nix, 1995) may necessitate caution when used with salt-sensitive crops. In contrast, BBC's moderate salinity strikes a balance, reducing the risk of nutrient leaching while promoting nutrient retention in soil systems. This aligns with findings by Fischer and Glaser (2012) and Sánchez-Monedero *et al*. (2017), who demonstrated that biochar-compost blends improve nutrient conservation by stabilizing organic matter and enhancing soil cation exchange capacity, thereby supporting sustainable agricultural practices without exacerbating salinity stress.

The nutrient profile further distinguishes BB and BBC in agricultural applications. The BB typically exhibits a moderate nutrient profile, with a total nitrogen content of 0.17% and phosphate content of 0.65%, making it a viable soil amendment for enhancing fertility. However, research by Sahoo and colleagues (2021) demonstrated that pyrolysis temperature influences nutrient retention, as BB produced at 600°C showed a higher nitrogen concentration of 0.28%. This suggests that production conditions can alter its nutrient availability. Phosphorus dynamics in biochar also warrant attention. Studies by Jia *et al*. (2013) and Yao *et al*. (2013) propose that biochar rich in phosphorus could act as a slow-release fertilizer, gradually replenishing soil nutrients. However, they emphasize the importance of carefully managing application rates, timing, and frequency, as phosphorus naturally releases into the soil at a slow rate, a fact underscored by Hernández-Hernández (2015). The most striking feature of BB is its potassium content, averaging 3.81%. Potassium is indispensable for critical plant functions, including osmoregulation, stomatal regulation, and photosynthesis. These findings are reinforced by Hien *et al*. (2020), who reported potassium levels in BB ranging from 1.51% to 4.87%, consistently exceeding its nitrogen and phosphorus concentrations. Their findings align with the broader understanding that potassium in biochar supports drought resilience and nutrient uptake in crops, making it particularly valuable in nutrient-deficient soils.

Meanwhile, BBC contains a relatively higher nitrogen content (1.09%) with a C:N ratio of 26.2. Although this value is slightly above the typical range for compost derived from the SLSI requirement (10–25), the increase can be attributed to the incorporation of BB, which contains a very high proportion of organic carbon (86.7%). The additional carbon input from biochar elevates the overall C:N ratio. Nevertheless, this value still lies within the optimal range of 25:1–30:1 suggested by Pace *et al*. (1995) for promoting active microbial activity and nutrient cycling, and within the broader favorable range of 20:1–40:1 that supports effective composting. Maintaining such a balance is important, as C:N ratios below 20:1 can lead to carbon depletion before nitrogen is stabilized, causing ammonia emissions and unpleasant odors (Pace *et al*., 1995), while the natural decline in the C:N ratio during composting reflects carbon and nitrogen losses through microbial metabolism. Additionally, BBC's phosphorus (0.79%) and potassium (1.18%) levels create a nutrient-rich profile that promotes plant growth. The rise in phosphorus concentration over time may occur as phosphorus precipitates into a stable solid form that resists dissolving and leaching, as noted by Okoli *et al*. (2024). Studies by Godlewska *et al*. (2017) and Guo *et al*. (2020) further demonstrate that blending biochar with compost accelerates maturation and improves nutrient retention, enhancing its agricultural value.

Notably, the elevated organic carbon content (86.7%) observed in BB demonstrates its efficacy in carbon sequestration and soil quality enhancement, whereas its moisture retention capacity (26.3%) suggests utility in improving water holding properties within agricultural soils. Studies have demonstrated that BB pyrolyzed under optimal conditions (approximately 600°C) achieves a carbon mass fraction between 81.85% and 85.68% (Chaturvedi *et al*., 2024; Alfei and Pandoli, 2024), aligning with the material's role in climate mitigation strategies. Furthermore, Steiner *et al*. (2011) documented enhanced moisture absorption in compost systems amended with biochar, a trait that improves composting efficiency and process stability. While BBC exhibits a reduced organic carbon content (28.6%) compared to pure biochar, its capacity to retain soil moisture, stimulate microbial proliferation, and contribute to nutrient cycling remains significant. These attributes position BBC as a viable resource for advancing sustainable soil management practices, particularly in agricultural contexts where water conservation and microbial activity are critical to long-term productivity.

Additionally, the presence of 2.1% calcium (Ca) and 0.7% magnesium (Mg) highlights the role of BB in enhancing soil health and fertility. These levels are notably higher than the Ca (0.16%) and Mg (0.18%) concentrations documented by Suthar *et al*. (2018). Furthermore, BBC's calcium (4.31%) and magnesium (1.27%) content surpass typical values, directly supporting critical plant functions such as root growth, cell wall strength, and chlorophyll synthesis.

In summary, the integration of bamboo biochar into the composting matrix established a physicochemical synergy that effectively neutralized pH extremes and optimized the C:N ratio for microbial efficacy. This interaction mitigated the inherent limitations often associated with raw biochar application, such as potential salinity spikes, while simultaneously creating a reservoir for essential macro-nutrients like Nitrogen, Phosphorus, and Potassium. Consequently, the biochar-enriched formulation demonstrated superior agronomic stability and nutrient density when benchmarked against standard composts derived solely from agricultural residues. These findings corroborate the comparative standards reported by Thidar *et al*. (2021) and Elsayed (2012), confirming that the addition of biochar is a decisive factor in elevating the quality, nutrient efficiency, and long-term sustainability of compost beyond what is achievable with organic waste alone.

Micro-nutrient profile of BB and BBC.

The micronutrient composition of BB and BBC presented in Table 3 offers important perspectives on their potential as soil amendments, as both contain essential elements that support soil health and plant growth. BB's nutrient profile highlights substantial amounts of iron (Fe), zinc (Zn), manganese (Mn), copper (Cu), sodium (Na), boron (B) and silicon (Si) which collectively enhance soil nutrient availability. Specifically, the iron concentration in BB is 1.62%, which can help alleviate iron deficiencies, a common limitation in many soils. However, this value is significantly higher than that reported by Suthar *et al.* (2018). Iron plays a central role in chlorophyll synthesis and plant metabolic processes, and recent studies, such as Algethami *et al*. (2023), demonstrate that soil amended with 2% iron-modified biochar increases available iron content by 13.3%, directly boosting plant vitality.

In addition to iron, BB contains zinc at 96 mg/kg and manganese at 74 mg/kg, both of which are crucial for enzymatic function and photosynthesis. Zinc aids various enzyme activities that support plant structure, while manganese supports photosynthetic functions, directly affecting plant resilience and yield potential. Although the copper content in BB is relatively low at 22 mg/kg, it still plays an essential role in promoting physiological processes in plants. Sodium (0.36 %) and boron (27 mg/kg) further contribute to a balanced soil nutrient profile, making BB a well-rounded soil amendment that improves plant resilience against nutrient deficiencies and promotes higher crop yields. The Zn, Cu, and B levels in this BB were higher than those in biochar derived from *Bambusa vulgaris*, as reported by Orozco Gutiérrez *et al*. (2021). However, the sodium content is slightly lower than the 0.552% reported by Suthar *et al*. (2018) at a pyrolysis temperature of 600°C. These findings align with broader research indicating that biochar amendments improve soil quality and fertility over time, offering a sustainable strategy for agricultural management (Gao *et al*., 2022; Rasse *et al*., 2022).

In contrast, BBC offers a considerably intensified nutrient profile, which includes notably high levels of iron, manganese, and zinc, as well as substantial amounts of copper and boron. The notably high iron content in BBC serves a dual function by enhancing nutrient availability for plants and stimulating microbial activity essential for organic matter decomposition (Purakayastha *et al*., 2015). This iron level is slightly higher than the 1.30% reported for compost in the study by Thidar *et al*. (2021). Such properties make BBC particularly advantageous in intensively managed agricultural systems or soils suffering from nutrient depletion. By enhancing soil fertility and nutrient retention, BBC supports soil management practices, while its positive effects on microbial health further contribute to long-term soil ecosystem resilience (Lehmann *et al.,* 2011).

BBC also has significantly higher zinc and manganese concentrations compared to BB, with zinc at 379.73 mg/kg and manganese at 543.17 mg/kg. Zinc's elevated levels in BBC are valuable for promoting enzymatic functions and chlorophyll synthesis (Fischer and Glaser, 2012), which are critical for plant growth. The manganese concentration, while beneficial for photosynthesis, is quite high and should be monitored closely to prevent potential toxicity that could harm plants in some soil types (Zheng *et al*., 2013). Copper is present at 55.6 mg/kg in BBC, further supporting enzyme activity, and boron at 78.02 mg/kg enhances cell division and nutrient transport, vital for plant structure and growth (Gabhane *et al*., 2012). However, according to Thidar *et al*. (2021), the micronutrient composition of compost was reported as follows: zinc (Zn) at 0.01%, manganese (Mn) at 0.02%, and copper (Cu) at 0.03%.

One key advantage of BBC over BB is its notably low sodium content (0.3%), which reduces the risk of soil salinity, a common barrier to healthy plant growth. This feature makes BBC particularly advantageous for use in saline-prone regions or with crops sensitive to salt stress, as highlighted by Antonangelo *et al*. (2021). Furthermore, BBC's rich micronutrient profile, paired with its minimal sodium levels, positions it as an efficient organic fertilizer. A study by Gao *et al*. (2016) demonstrated that the use of woody biochar enhanced the soil's absorption of micronutrients, including iron, copper, zinc, and manganese. By enhancing soil microbial activity, boosting resilience to environmental pressures, and decreasing reliance on synthetic alternatives, BBC supports eco-friendly farming practices that prioritize long-term soil health (Bazrafshan *et al*., 2016).

Table 3. Micro-nutrient profile of BB and BBC.

PARAMETERS	BB	BBC
Zn (mg/kg)	96	379.73
Cu (mg/kg)	22	55.6
Mn (mg/kg)	74	543.17
B (mg/kg)	27	78.02
Fe (%)	1.62	1.73
Na (%)	0.36	0.3
Si (%)	0.32	0.19

Bamboo biochar + Compost at a ratio of 1:20 (w/w)

Moreover, silicon is regarded as a beneficial element (Leksikowati and Rachmawati, 2024) rather than a conventional macro or micronutrient. In this study, BB exhibited a higher silicon content (0.32%) compared to BBC, which contained 0.19%. This difference may be attributed to the natural accumulation of silica in bamboo (Umemura and Takenaka, 2014; Collin *et al*., 2013), during pyrolysis suggesting that bamboo can serve as an alternative silicon source in agriculture. It has been reported that bamboo culms store significant amounts of silica, which remains in the biochar after pyrolysis. This elevated silica content contributes to the structural stability, porosity, and cation-exchange capacity of BB (AU Synergy, 2025). When BB is incorporated into composting materials, the silicon is dispersed throughout the organic matrix, thereby reducing its measured concentration and potentially influencing its chemical availability and interactions with soil microbes (Wang *et al*., 2018). Nevertheless, silicon continues to support soil fertility and plant growth, and the lower concentration observed in BBC is primarily due to dilution and chemical interactions rather than a loss of its functional benefits.

SEM Analysis for Bamboo Biochar

Figure 4 displays high-resolution SEM (Scanning Electron Microscope) micrographs of BB, capturing intricate details of its porous architecture and heterogeneous surface morphology features critical for agricultural use. The images reveal surface topography characterized by protrusions, indentations, and thin-film layers in cross-sectional views (Cahyana *et al*., 2014). The visualized pore systems and irregular particle textures underscore the biochar's capacity to modulate soil chemistry, offering a foundation for understanding its role in sustainable nutrient management.

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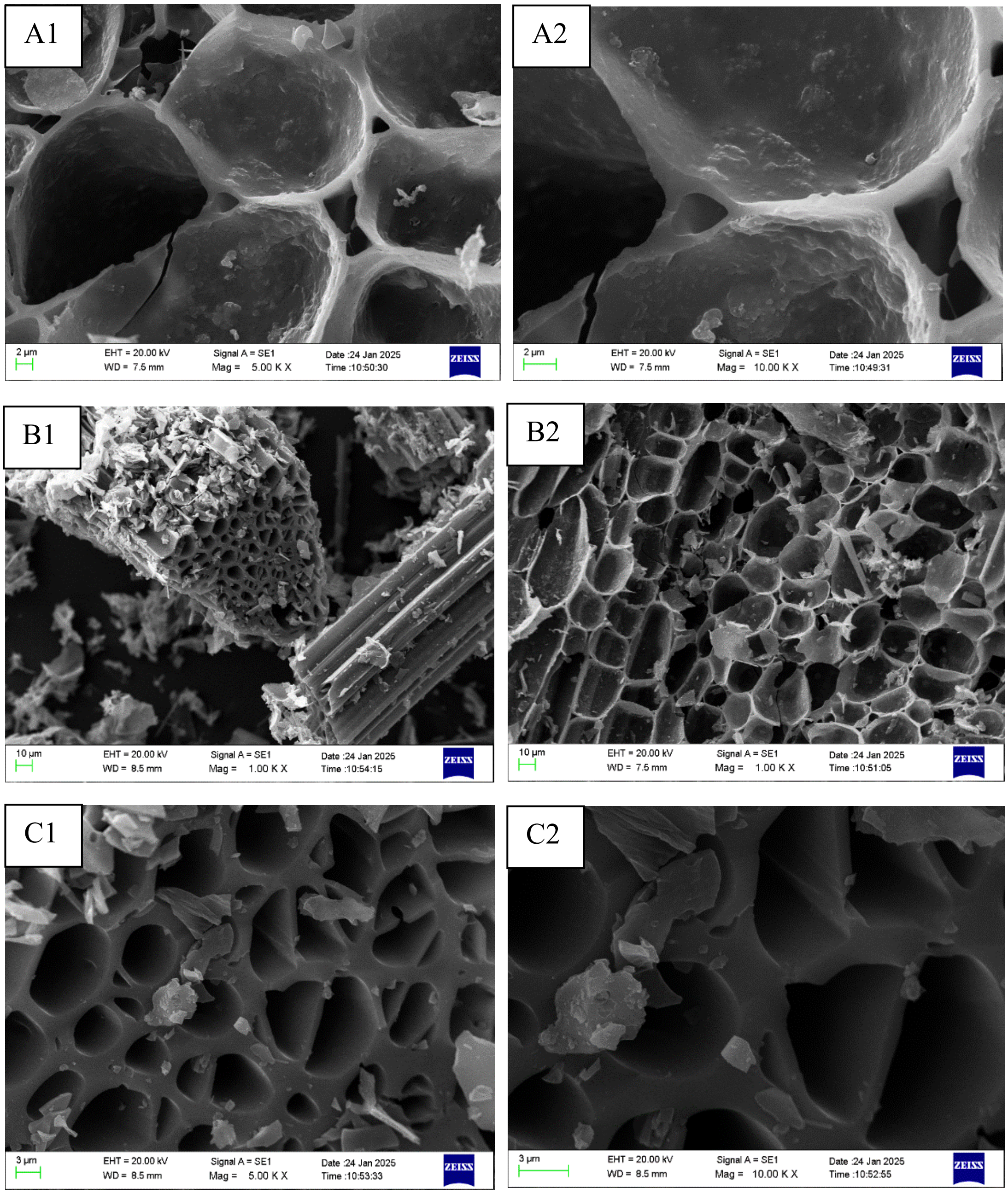

Figure 4. SEM micrographs of bamboo biochar: image of BB at 5.00 KX magnification with WD of 7.5 mm (A1), image of BB at 10.00 KX magnification with WD of 7.5 mm (A2), image of BB at 1.00 KX magnification with WD of 8.5 mm (B1), image of BB at 1.00 KX magnification with WD of 7.5 mm (B2), image of BB at 5.00 KX magnification with WD of 8.5 mm (C1) and image of BB at 10.00 KX magnification with WD of 8.5 mm (C2). Abbreviations: SEI, secondary electron imaging; WD, work distance.

Structural Characteristics of Bamboo Biochar

The initial scanning electron microscopy (SEM) images in Figure 4, captured at 5.00 KX (A1) and 10 KX (A2) magnification with a working distance of 7.5 mm, reveal a highly porous, honeycomb-like structure. This distinctive feature of bamboo-derived biochar results from the preservation of vascular bundles during pyrolysis. These observations align with findings by Sahoo *et al*. (2021), who demonstrated that biochar synthesized from bamboo biomass at varying pyrolysis temperatures exhibited smoother surface morphologies relative to counterparts derived from pigeon pea stalks. Moreover, the BB exhibited well-defined honeycomb-like pore structures with greater structural clarity than its precursor biomass. These interconnected porous networks have been found to greatly enhance key functional properties essential for environmental applications, such as adsorption capacity (Liao *et al*., 2013), water retention efficiency (Scott *et al*., 2014), and suitability as a habitat for microbial communities (Khodadad *et al*., 2010). Furthermore, research indicates that bamboo biochar's highly porous microporous structure enhances its adsorption efficiency, which is approximately ten times greater than that of traditional wood-derived biochar (Hua *et al*., 2009). These morphological characteristics underscore the material's efficacy in agricultural contexts, particularly through its capacity to enhance soil aeration and regulate hydrological dynamics within terrestrial ecosystems.

The secondary SEM micrographs, taken at 1 KX magnification with WD = 8.5 mm (B1) and WD = 7.5 mm (B2), depict a fractured morphology with distinct micro and meso porous networks, reflecting structural reorganization induced by pyrolysis. This microstructural evolution is accompanied by the preservation of tubular features, consistent with the inherent hierarchical arrangement of native bamboo fibers. This morphological retention aligns with previous findings by Inyang *et al*. (2016), who demonstrated that the directional structure of lignocellulosic biomass remains largely preserved in bamboo-derived biochar despite thermal degradation. The presence of multiscale porosity alongside fiber-aligned tubularity indicates a dual mechanism of partial carbonization and selective preservation of biogenic structures, which is crucial for preserving biochar's mechanical integrity while maximizing its reactive surface area.

The third-row images, captured at magnifications of 5.00 KX (C1) and 10 KX (C2) with a working distance (WD) of 8.5 mm, indicate distinct micro- and macropores across the biochar's surface. These structural features indicate a high surface area, a characteristic linked to enhanced cation exchange capacity (CEC) and the gradual release of vital nutrients like potassium, phosphorus, and micronutrients, as demonstrated in prior research (Tan *et al*., 2016). According to Liang *et al*. (2006), biochar exhibits greater resistance to decomposition and demonstrates superior absorption of ions and water compared to other organic materials owing to its significantly larger surface area. Variations in biochar feedstock composition further influence how significantly it modifies soil CEC, which plays a critical role in nutrient accessibility and moisture retention (Yadav *et al*., 2018). Notably, the biochar exhibits irregularly shaped surface particles, potentially mineral deposits or residual ash from pyrolysis. Such components may enhance its alkaline properties, offering liming benefits when applied to acidic soils (Taskin *et al*., 2019). This aligns with findings that alkaline biochar consistently elevates pH levels in both acidic and neutral soils, improving overall soil health (Buss *et al*., 2016). Together, these attributes of porous structure, nutrient retention, and pH modulation position BB as a versatile amendment for advancing sustainable farming practices and addressing environmental challenges like soil degradation.

Effect of Pyrolysis on Biochar Morphology

The development of BB's porous structure is significantly influenced by the temperature used during pyrolysis. Studies have shown that when pyrolysis occurs at higher temperatures (above 500°C), organic matter within the bamboo breaks down and vaporizes, creating more pores and boosting both the surface area and overall porosity of the biochar (Liu *et al*., 2017). Additionally, elevating the temperature during this process not only improves the crystallinity of minerals present in the biochar (Figure 4) but also drives the arrangement of carbon into more organized aromatic frameworks (Kim *et al*., 2012). These structural changes are directly tied to how the thermal breakdown is managed, which governs the porosity and surface properties of the final product. These characteristics, in turn, play a critical role in determining how effectively the biochar performs when applied to soil, such as in nutrient retention or pollutant adsorption.

Research by Sahoo *et al*. (2021) revealed that biochar produced at 600°C developed fragmented, crumbled pores, which interconnected to create a distinctive channel-like network (Figure 4, B1 and B2). This structural transformation was linked to the growth of stable aromatic carbon frameworks during pyrolysis. The study also highlighted that intense heat triggered the swift release of volatile substances and the decomposition of biomass, further shaping these porous channels (Figure 4, C1 and C2). These findings underscore the importance of carefully adjusting pyrolysis parameters, such as temperature and heating rate to engineer biochar with targeted physical features. By fine-tuning these conditions, scientists and engineers can design biochar optimized for specific uses, whether enhancing soil fertility, sequestering carbon, or filtering contaminants in environmental remediation projects.

Application in Agriculture

The structural properties inherent in BB specifically its highly porous nature and expansive surface area, remain critical in the final composite product. This structure serves as a powerful tool for bolstering microbial colonization and fostering healthier soil ecosystems. Research confirms that biochar creates an ideal, protected habitat for soil microbes, allowing them to thrive within its intricate network of pores (Prapagdee and Tawinteung, 2017). When soils are amended with a biochar-enriched product like BBC, studies consistently observe a surge in beneficial microbial populations (Castaño *et al*., 2019). These microbes are essential for accelerating the breakdown of organic matter and nutrient cycling, processes that are further optimized by the BBC's balanced pH and favorable C:N ratio. By acting as a stable microbial sanctuary while providing an optimal chemical environment, BBC enhances soil health, thereby amplifying its capacity to sustain agricultural productivity and ecological balance. The inherent nutrient stability, achieved through the synergy between the biochar's porous structure and the compost's organic matter, significantly reduces environmental losses via leaching compared to conventional soluble fertilizers. Positioning BBC as a strategic tool in precision agriculture, the blend minimizes the need for excessive chemical applications, thereby improving overall fertilizer efficiency and directly contributing to lowering farming costs while promoting sustainable soil health and protecting water systems (Andrey *et al*., 2020).

Conclusions

This study successfully demonstrated that the integration of bamboo biochar (BB) via co-composting creates a Bamboo Biochar-enriched Compost (BBC) with significantly superior agronomic utility compared to conventional organic waste compost. The research confirmed the synergistic benefits of this blend: the inherent physicochemical properties of BB mitigate the limitations of standalone biochar, such as nutrient imbalances and high alkalinity, by balancing the compost pH to a near-neutral 7.14 and establishing an optimal C:N ratio of 26.2. This enhanced stability fosters superior microbial activity and nutrient retention, leading to a final product with a robust profile, including 1.09 % Nitrogen, 0.79 % phosphate (P_2O_5), 1.18 % potassium (K_2O), and high levels of micronutrients (Zn:379.73 mg/kg). The ability of BBC to enhance both the effectiveness and nutrient efficiency of the final soil amendment validates its potential for use across various soil types. Ultimately, the co-composting of locally sourced bamboo culms into BBC provides a sustainable and flexible solution for waste valorization and long-term soil fertility management.

The structural and functional attributes of bamboo biochar, including its porous architecture and surface chemistry, play a pivotal role in determining its agricultural performance. Pyrolysis conditions, especially temperature, govern the development of biochar’s micro- and mesoporous networks, which enhance water retention, cation exchange capacity, and habitat provision for soil microorganisms. These morphological features, coupled with the retention of biogenic structures from feedstock, enable biochar to improve soil aeration, nutrient adsorption, and gradual nutrient release. When combined with compost, these properties are further enhanced, as the hybrid material benefits from both the physical structure of biochar and the nutrient-rich composition of compost. This integration not only addresses nutrient deficiencies but also mitigates challenges like soil degradation, offering a sustainable approach to enhancing soil fertility, resilience, and productivity across varied agroecological environments.

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