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Biochar-enriched compost and foliar application of banana stem sap on soil fertility, nutrient availability against Al^{3+} toxicity, and sweet corn yield in acidic soil

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ABSTRACT

In tropical soils, inadequate nutrient availability, exacerbated by high concentrations of iron (Fe) and aluminum (Al) ions, significantly limits sweet corn yield by interfering with the nutrient uptake. This study tested the hypothesis that applying biochar-enriched compost (BEC), together with foliar application of banana stem sap (BSS), would enhance soil fertility and nutrient utilization compared to chemical fertilizers alone. Two consecutive pot experiments were conducted using four BEC levels (T_1: control with 100% recommended chemical fertilizers; T_2: 5 t/ha; T_3: 10 t/ha; T_4: 15 t/ha) and three BSS frequencies (F_1: no spray; F_2: two sprays; and F_3: three sprays), arranged in a factorial randomized complete block design with three replications. Application of 15 t/ha BEC significantly improved soil properties, increasing pH by 1.79 units, potassium by 362%, calcium by 230%, magnesium by 253%, and cation exchange capacity by 80%, while reducing exchangeable Al^{3+} by 96% and soil acidity by 67%, compared to the control. Corn yield and biomass increased by 10.54% and 7.84%, respectively, with BEC and by 9.24% and 7.75% with the highest BSS frequency. In conclusion, the combination of 15 t/ha BEC and three foliar applications of BSS significantly improves sweet corn productivity and soil fertility in acidic soils.

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KEYWORDS
Acid soil; banana stem sap; compost; soil chemical properties; exchangeable acidity and corn yield

Introduction

Sweet corn (*Zea mays* L. var. *saccharata*), a high-sugar maize variant, is prized globally as a premium cereal crop due to its sweetness and nutritional profile (Subaedah, Edy, and Mariana 2021). It exhibits adaptability across diverse soil types and climatic zones (Chauhan, Solomon, and Rodriguez 2013). However, in tropical regions such as Malaysia, sweet corn production remains constrained, with yields averaging merely 5.6 t/ha over approximately 11,000 ha of cultivation. This limitation largely stems from inherent soil challenges, including strongly acidic pH ($\leq$ 5), low soil organic matter (SOM) content, limited cation exchange capacity (CEC), and restricted nutrient availability (Ch'ng et al. 2019).

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Tropical soils characteristically suffer from rapid decomposition of added OM, leaving only a minor fraction stabilized in the soil matrix (Glaser, Lehmann, and Zech 2002; Rabileh et al. 2015). Compounding this, high concentrations of iron (Fe) and aluminum (Al) in these soils readily form insoluble complexes with the essential nutrients such as calcium (Ca), magnesium (Mg), and phosphorus (P), thereby further reducing nutrient availability and impairing crop growth (Radin et al. 2018).

To address these limitations, organic amendments like composts and manures have been extensively utilized and consistently demonstrated benefits for enhancing soil fertility and crop productivity (Oueriemmi, et al. 2021). Compost, in particular, through its porous structure and nutrient richness, augments SOM content, water-holding capacity, CEC, and aggregation (Fidelis and Rajashekhar Rao 2017). The quality and functionality of composts are closely tied to their feedstocks (Hannet, et al. 2021). Composts produced from banana pseudostems, spent mushroom substrate, and poultry manure have shown considerable promise in improving soil chemical properties, raising soil pH, optimizing the C:N ratio, enhancing CEC, and increasing overall nutrient density (Islam, et al. 2021). Moreover, compost derived from banana residues tends to be alkaline ($pH \geq 10$), making it effective for neutralizing acidic soils.

Parallel to soil-applied amendments, foliar fertilization represents an effective strategy to circumvent the limitations of nutrient uptake through roots in acidic soils plagued by Al toxicity. In this context, banana pseudostem sap has garnered interest as a foliar input due to its rich content of mineral nutrients such as nitrogen (N), P, potassium (K), Ca, Mg, zinc (Zn), and boron (B) and a wide array of phytochemicals including amino acids, phenolics, flavonoids, and organic acids (Islam, et al. 2022). These compounds play pivotal roles in plant metabolic processes and stress tolerance. Studies have reported that foliar application of banana stem sap (BSS), particularly when enriched, significantly enhances nutrient uptake, photosynthesis, biomass accumulation, and grain yield of sweet corn grown on nutrient-depleted, acidic soils (Islam, et al. 2023). Thus, BSS acts as both a supplier of essential mineral nutrients and a source of bioactive compounds, offering a holistic means to improve plant performance under challenging soil conditions. Its value is further underlined by findings that banana residues, including sap, are naturally high in K, Ca, and Mg and contain phytochemicals that support robust plant development (Islam, et al. 2022).

Complementing compost and foliar approaches, biochar has emerged as a potent soil amendment, chiefly recognized for its liming effect that can substantially raise soil pH (Jeffery et al. 2011). When applied to low-fertility soils, biochar enhances nutrient retention and availability through its high surface area and adsorption capacity (Liu, et al. 2017). Both compost and biochar, owing to their elevated CEC and strong binding affinity, effectively reduce the bioavailability of toxic Al and Fe ions in acidic soils, thereby mitigating their deleterious effects on plant roots (Sasmita et al. 2017). Consequently, foliar application of nutrient solutions becomes even more critical in such soils where root-based uptake is limited, with BSS potentially acting synergistically when applied in this manner (Dong, et al. 2022).

While numerous studies have evaluated compost and biochar separately for their effects on acidic soil fertility, including improvements in exchangeable cations, CEC, soil pH, and reductions in Al toxicity (Lin et al. 2012; Agegnehu et al. 2016; Mensah and Frimpong 2018), findings consistently highlight increased nutrient availability and crop yields alongside diminished exchangeable acidity (Major et al. 2010; Jeffery, et al. 2015; Pandit, et al. 2018). Similarly, foliar application of BSS has shown promise in enhancing growth and productivity in various crops such as cowpea and cabbage (Ding et al. 2016; Fernando and Karunarathna 2020), with the beneficial effects attributed to key phytochemicals like glutamic acid and aminobenzoic acid (Miranda, Maycock, and Ventura 2015; Zhang, et al. 2017; Deng, et al. 2020).

However, despite these individual findings, there remains a conspicuous gap in research exploring the combined use of biochar-enriched banana stem compost and foliar banana sap applications for simultaneously alleviating soil acidity, reducing Al toxicity and improving sweet corn productivity in tropical acidic soils. Such an integrated approach holds potential to synergistically enhance soil physical properties (e.g., moisture retention), neutralize soil pH, reduce Al^{3+} toxicity, elevate CEC, and promote nutrient uptake. The rapid absorption of nutrients *via* foliar-applied banana sap could further bolster corn growth and yield. We hypothesized that the alkaline properties (pH $\geq$ 10) of banana stem compost addition to biochar would reduce soil acidity and improve nutrient availability, while foliar application of BSS would directly address plant nutrient deficiencies, collectively leading to superior crop performance under these challenging conditions. While previous studies have examined biochar, compost, or banana pseudostem sap individually, the novelty of this study lies in evaluating their combined use. We tested biochar-enriched compost together with foliar banana pseudostem sap as an integrated approach to simultaneously improve soil fertility, reduce Al^{3+} toxicity, and enhance nutrient uptake and yield in acidic tropical soils.

Therefore, this study aimed to investigate the combined effects of biochar-enriched compost and foliar application of BSS on improving soil fertility, mitigating Al^{3+} toxicity and enhancing sweet corn yield in acidic tropical soils.

Materials and methods

Soil collection and preparation

The soil used in this study was collected from the topsoil of Bukit Expo, University Putra Malaysia. Soil collection location of the present study was geographically positioned at latitude, 2°59′22.6″ N and longitude, 101°42′82.2″ E. The location detail and a Figure can be found in the publication of Islam, et al. (2021). After a week of air-drying, the soil was cleaned to remove the unwanted materials. Subsequently, the air-dried samples were milled to <2 mm particle size and mixed entirely. The initial soil textural properties included sand at 66.5%, silt at 12%, and clay at 21.5% indicating sandy clay loam, where the average bulk density was 1.42 g cm^{-3}. The initial soil samples were analyzed for characterization using the same methods as those used for post-harvest soil, and the results are presented in the below section. Zannah et al. (2016), characterized the soil as Ultisol, having a highly weathering tendency. Additionally, the deficiency of Ca, Mg, and P, as well as the toxicity of Al, is significant in soils with low pH (4.94) studied in Malaysia (Shamshuddin et al. 2011).

Preparation of pot with soil, compost, and biochar

The compost was gathered at a moisture content of 25%, generated from a mixture of 25% banana stems, 50% spent mushroom substrate, and 25% poultry litter through an aerobic co-composting process. The details can be found in the previous publication of the senior author (Islam, et al. 2021). The empty fruit bunch biochar (EFB) from oil palms was sourced from a reputable biochar manufacturer (Pyrochar Tech Sdn Bhd, Petaling Jaya, Selangor, Malaysia) and produced at a temperature of 450 °C. The compost used in this study was fully matured, as indicated by stable temperature (~32 °C) after 79 days, advanced carbon degradation, fine particle size, odorless appearance, and a high germination/toxicity index (126%). The details are reported in Islam, et al. (2021). The soil, compost, and biochar (20% v/v of the compost for enhancement) were completely mixed and moistened to approximately 30% using tap water. Before planting, corn seeds were soaked in water and treated with the fungicide Thiram for 10 h to promote effective germination. The physicochemical characteristics of compost and soil were analyzed separately.

BSS collection, preparation, and analysis

The banana stems were collected from the banana plant garden in UPM (2°48′16.1″ N and 101°30′10.99″ E), Selangor, Malaysia. The banana stem was clean and washed properly with fresh tap water. It was cut into small (30–35 cm) flakes and unwrapped the leaf sheath. The freshly separated leaf sheath was then passed through the mechanical crusher (ESM Machinery, J.B., Sdn, Bhd, Malaysia) twice. The resulting BSS was filtered using a muslin cloth. Approximately 10 liters of sap extracted from the banana stem was poured into an airtight container and preserved in the refrigerator at 5 °C for foliar application (Islam, et al. 2022). The macro- (N, P, K, Ca, and Mg) and micro (Zn, Cu, and Mn)-elements available in the BSS were analyzed using Inductively Coupled Plasma Spectroscopy (Optima 8300, PerkinElmer Corporation, Norwalk, Connecticut, USA), as indicated in the above section.

Characteristics of the soil, compost, banana pseudostem sap, and biochar

The initial characteristics of the soil, compost, banana pseudostem sap, and biochar used in the pot experiment are summarized below. The soil had a pH of 4.98, with exchangeable acidity and exchangeable aluminum (Al) concentrations of 0.52 cmolc kg^{-1} and 0.32 mg L^{-1}, respectively. The OM content was 1.35%, with 0.91% organic carbon (OC). Total nitrogen (TN) was measured at 0.08% and the CEC was 3.53 $cmol^{+}$ kg^{-1}. Available P content in soil was 0.007 g kg^{-1}, with Ca, Mg, and K concentrations of 0.69, 0.12, and 0.14 $cmol^{+}$ kg^{-1}, respectively.

The compost exhibited a highly alkaline pH of 10.0 and an electrical conductivity (EC) of 3.33 dS m^{-1}. It contained 27.06% OC and 24.30% TC. The TN content was 1.61% and the CEC was 31.1 $cmol^{+}$ kg^{-1}. Available P was 8.40 g kg^{-1}. The compost also had the elevated levels of exchangeable cations: Ca at 14.96 g kg^{-1}, Mg at 3.94 g kg^{-1}, and K at 14.14 g kg^{-1}. Copper (Cu), manganese (Mn) and zinc (Zn) concentrations were 64.6, 786, and 659 mg kg^{-1}, respectively. Banana pseudostem sap had a pH of 5.41 and an EC of 6.48 dS m^{-1}. The TN content was 0.425% and available P was 0.93 g L^{-1}. Calcium, Mg, and K contents were 6.03 mg L^{-1}, 83.41 mg L^{-1}, and 1.93 g L^{-1}, respectively. Copper concentration was recorded at 2.51 mg L^{-1}. On the other hand, biochar showed a pH of 8.36 and contained 51.5% TC and 1.20% TN. Available P was 1.95 g kg^{-1}, with Ca, Mg, and K concentrations of 34.8 cmol (±) kg^{-1}, 32.6 cmol (±) kg^{-1} and 132 cmol (±) kg^{-1}, respectively.

Treatments, design, and crop management

The pot experiment was conducted over two consecutive seasons in a glasshouse at the Land Management Department, Faculty of Agriculture, University Putra Malaysia. It examined four levels of biochar-enriched compost (BEC), including sole chemical fertilizers as the control (5 tons per ha, 10 tons per ha, and 15 tons per ha), along with three frequencies of foliar application of BSS (BSS—no spraying, twice, and thrice). The study employed a factorial design with three replications, utilizing a divided pot plan within a randomized block design. Fertilizers and amendments were applied based on a hectare of soil, with soil bulk density measured at 20 cm depth (1.42 g cm^3) corresponding to a total of 2.84 million kg of soil per hectare. Biochar-enriched compost or specified amounts of chemical fertilizers (P_{60}-K_{90} kg per hectare) were applied in plastic pots (72 cm × 48 cm × 42 cm) containing 100 kg of soil. Each pot was treated with 250, 500, or 750 g of BEC based on the treatment group. Two sweet corn seedlings (sweet corn 592, an F1 hybrid from Leckat) were cultivated from four sprouted seeds in each pot. The control treatment utilized 100% of the recommended chemical fertilizers (N_{120} P_{60} K_{90} kg per hectare), including urea, TSP, and MoP, as the Malaysian Agricultural Research and Development Institute (MARDI) prescribes. Only 50% of the recommended N (N_{60} kg per hectare) was applied in the amendment treatments. Fertilizers were reapplied in both growth cycles according to the specified rates, while organic amendments were applied only once before the study commenced. Triple superphosphate (TSP) and muriate of potash (MoP) were added during the final preparation of the pots, while urea was used in two applications at 10 and 30 days after sowing (DAS) for all treatments. Foliar applications of BSS (15% aqueous solution) mixed with detergent powder (2 g per 10 L of sap) were given at 15 and 30 DAS for F_2 treatments and at 15, 30, and 45 DAS for F_3 treatments, with each plant receiving about 50 mL of sap per application. The minimal concentration was added to help the spray stick to the leaf surface, while also having pesticidal effects aimed at controlling the corn armyworm and aphid eggs. Irrigations were provided through the built-in tap water channel of the glasshouse. Sweet corn cobs were harvested at the fresh edible stage, 68 days after planting.

Soil sampling for chemical analysis

Soil samples were collected from three different spots in each pot at a depth of 20 cm using a hand auger after the second corn cycle. These samples were then air-dried at room temperature for 10 days. Once dried, the samples were ground and sieved through a 2-mm mesh for chemical analysis. The pH of the air-dried samples was measured using a digital pH meter (HI 2211, Hanna Instrument, Inc., 270 George Washington Highway, Smithfield, RI 02917, USA) at a soil-to-water ratio of 1:2.5 (w/v) after 24 h of shaking (Ismail, Shamshuddin, and Omar 1993). The EC was determined from the same extract using a digital EC meter (Hanna 2300). Total soil carbon (C) and nitrogen (N) content were analyzed with a Leco TruMac CNS auto-analyzer (Islam, et al. 2021). Available P was measured by a UV-visible spectrophotometer at 882 nm, following the extraction method (Bray and Kurtz 1945). Exchangeable K, Ca, Mg, and CEC were determined using the ammonium acetate leaching method at pH 7.0 (Cottenie 1980), with readings taken by an Atomic Absorption Spectrophotometer (AAS) (A Analyst 800, PerkinElmer, Norwalk, CT, USA). Exchangeable acidity and Al^{3+} were measured according to the method outlined by Rowell's (1994) method.

Determination of total nutrient content in grain and plant samples

Nutrient content was analyzed in plant samples collected after the second season's harvest. Total N in the leaves and cobs was measured using the previously mentioned analyzer, while P, K, Ca, and Mg levels were determined using an AAS following the double dry ashing method (Cottenie 1980). Phosphorus content was measured using the auto-analyzer with the yellow method. The total nutrient utilization was calculated by summing the cumulative nutrient utilization from both the leaves and cobs, based on the following equation.

$$\text{Nutrient utilization} = \frac{\text{Concentration of nutrients } (\%) \times \text{dry matter } (\text{g})}{100}$$

Data collection on fresh cob and biomass yield

The data on agronomic parameters, that is, fresh cob yield (g pot^{-1}) estimated by electric balance. After harvesting the above-ground section of plants, including cob, was dried in an oven at 70 °C until stable weight and the equation was determined (Islam, et al. 2023):

$$\text{Dry matter} = \frac{W_1 - W_2}{W_1} \times 100$$

Where W_1 is the initial weight and W_2 means the weight after drying.

Statistical analysis

The data collected for this investigation were analyzed using ANOVA with a factorial Randomized Complete Block Design (RCBD), as described in SAS Institute Inc. (2013). The two experimental runs had no notable difference, so the average data from both seasons was merged and displayed. The nutrient content, utilization, and post-harvest soil measures shown below are all based on the second season's crop. The treatment means for all data points were compared using Tukey's Honest Significant Difference (HSD) test at a 5% probability level.

Language editing compliance

For language clarity and improvement of grammar, we used ChatGPT (OpenAI GPT-4, June 2025 version) to assist in rephrasing sections of the manuscript text. This tool was employed solely to enhance readability and did not contribute to the scientific content, analysis, or interpretation of results.

Results

Effect of BEC and BSS spraying on fresh cob and biomass yield

The application of BEC and BSS foliar sprays significantly influenced sweet corn productivity across both seasons ($p \leq 0.05$), though their interaction effect was not significant ($p \geq .05$) (Table 1). Cob yield and dry biomass increased consistently with higher rates of BEC. The maximum cob yield was recorded in T_4 (15 t ha^{-1} BEC), with values ranging from 465 (second season) g to 479 g pot^{-1} (first season). This treatment outperformed all others, showing a 10.53% increase in mean cob yield relative to the control (T_1: 100% recommended chemical fertilizer only). The T_3 (10 t ha^{-1}) also showed a substantial increase (6.08%) over the control. Conversely, the lowest yield was observed in T_1 and T_2 treatments, indicating the limited benefit of compost at lower application rates.

Dry biomass followed a similar trend, with T_4 producing the highest biomass (165 g pot^{-1} on average), followed by T_3 (146 g pot^{-1}), whereas T_2 yielded the lowest biomass (126 g pot^{-1}).

Table 1. Effects of different rates of compost and banana stem sap on the growth and yield of sweet corn in two consecutive seasons.

	Cob yield (g per pot)			Dry biomass (g per pot)		
Treatments	1st season	2nd season	Mean	1st season	2nd season	Mean
Compost (T)						
T_1	378 c	343 c	360	140 ab	167 b	153
T_2	442 b	412 b	427	113 c	139 c	126
T_3	463 ab	443 ab	453	124 b	166 b	146
T_4	479 a	465 a	472	145 a	186 a	165
Foliar frequency (F)						
F_1	419 b	404 b	411	128 b	157 b	142
F_2	432 b	416 b	424	130 b	163 b	146
F_3	471 a	427 a	449	134 a	173 a	153
Anova						
T	***	***	–	***	***	–
F	***	*	–	***	*	–
T x F	ns	ns	–	ns	ns	–

Mean values in a column that has identical letters for various rates of BEC and leaf spray frequency of BSS show no significant difference ($p \geq .05$). Here, four levels of BEC amendment were T_1: control (100% recommended chemical fertilizer), T_2: 5 tons per hectare (ha), T_3: 10 tons per ha, T_4: 15 tons per ha) and three foliar BSS were F_1: no spraying, F_2: 2 times spraying and F_3: 3 times spraying.

The frequency of BSS foliar application also significantly affected crop performance. The F_3 treatment (three sprays) produced the highest mean cob yield (449 g pot^{-1}), representing a 9.24% increase compared to F_1 (no spray). Similarly, F_3 led to the highest mean dry biomass (153 g pot^{-1}), reflecting a 7.75% improvement over F_1 (Table 1).

BEC amendment and BSS spraying effect on nutrient utilization by sweet corn

The application of BEC enhanced N and P utilization in sweet corn grown in acidic soil, whereas the frequency of BSS foliar application did not influence the uptake of these nutrients ($p > .05$) (Table 2). Across compost treatments, N and P uptake showed a clear increasing trend with the higher rates of BEC. The highest N utilization (1.76 g per 100 g dry weight) was observed in T_4 (15 t ha^{-1} BEC), representing a 7.31% improvement over the control (T_1: 1.40 g per 100 g). The lowest N uptake occurred in T_2 (5 t ha^{-1} BEC), suggesting that suboptimal amendment rates may suppress N utilization. Similarly, P utilization peaked in T_4 (209 mg per 100 g dry weight), which was 19.4% higher than the T_1 treatment (175 mg per 100 g). The minimum P uptake was recorded in T_2 (101 mg per 100 g), again indicating the ineffectiveness of low compost rates in facilitating P acquisition.

BEC amendment and BSS spraying effect on K, Ca, and Mg utilization

Significant interactive effects between BEC application rates and the frequency of BSS foliar spraying were observed for the uptake of K, Ca, and Mg by sweet corn (Table 2; Figures 1–3). Potassium utilization increased with both compost amendment and foliar application frequency of BSS. The highest K uptake (1.40 g per 100 g dry weight) was recorded in the T_4 treatment (15 t/ha BEC), while the lowest (0.49 g per 100 g) was observed in T_2 (5 t/ha). Foliar spray frequency had a clear effect: increasing from F_1 (no spray) to F_3 (three sprays) raised K uptake from 0.78 to 0.98 g per 100 g (a 25.6% increase). The interaction effects were most notable at higher BEC levels, where the combination of T_4 and F_3 yielded the maximum K uptake (Figure 1).

Calcium utilization also increased substantially with BEC rate and BSS foliar frequency. The T_4 treatment (15 t/ha BEC) led to the highest Ca uptake (541 mg per 100 g), while the lowest was observed in the control (T_1: 67.5 mg per 100 g). Among foliar treatments, F_3 resulted in the highest Ca uptake (319 mg per 100 g), showing a 19.5% increase over F_1 (267 mg per 100 g). The

Table 2. Effects of the compost and foliar frequency of banana stem sap on total nutrient utilization by sweet corn plants (Season 2).

Treatments	N (g 100g^{-1} DW)	P (mg100g^{-1} DW)	K (g100g^{-1} DW)	Ca (mg100g^{-1} DW)	Mg (mg100g^{-1} DW)
Compost (T)					
T_1	1.40 b	175 b	0.60 c	67.5 d	5.48 d
T_2	1.13 c	101 c	0.49 d	189 c	35.3 c
T_3	1.64 a	176 b	0.97 b	361 b	53.7 b
T_4	1.76 a	209 a	1.40 a	541 a	82.0 a
Foliar frequency of BSS (F)					
F_1	1.44 a	162 a	0.78 c	267 b	38.2 c
F_2	1.48 a	165 a	0.84 b	282 b	42.6 b
F_3	1.54 a	168 a	0.98 a	319 a	51.7 a
ANOVA					
T	***	***	***	***	***
F	ns	ns	***	***	***
T × F	ns	ns	*	*	**

The mean value following the same small letter within the column of the different levels of the BEC and foliar frequency of BSS are not significantly different by the Tukey test at $p \geq .05$. Here, four levels of BEC amendment were T_1: control (100% recommended chemical fertilizer), T_2: 5 tons per hectare (ha), T_3: 10 tons per ha, T_4: 15 tons per ha, and three foliar BSS were F_1: no spraying, F_2: 2 times spraying, and F_3: 3 times spraying. DW elaborates dry weight.

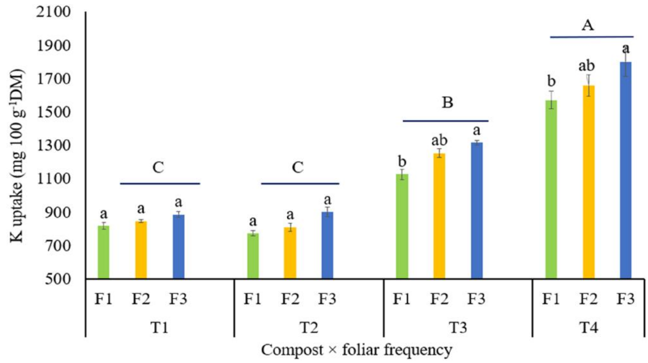

Figure 1. Two-way interaction of biochar augmented compost and leaf level spray frequency of sap on K utilization by corn (*Zea mays* L. var. *saccharata*). Average values with error bars followed by different lowercase letters within leaf level spray frequency and the different uppercase letters within biochar augmented compost denote significant variations ($p \leq .05$). Here, four levels of BEC amendment were T_1: control (100% recommended chemical fertilizer), T_2: 5 tons per hectare (ha), T_3: 10 tons per ha, T_4: 15 tons per ha and three foliar BSS were F_1: no spraying, F_2: 2 times spraying and F_3: 3 times spraying.

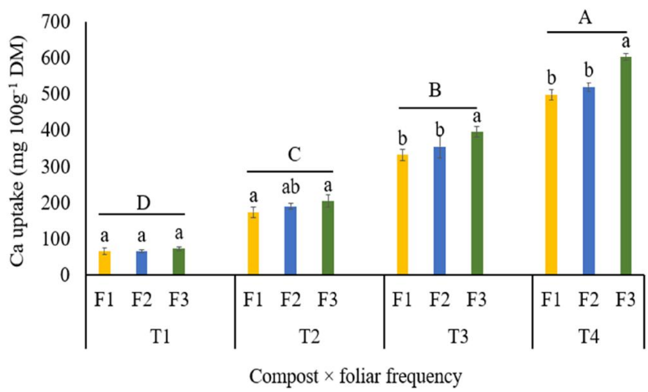

Figure 2. Two-way interaction of biochar augmented compost and leaf level spray frequency of sap on Ca utilization by corn (*Zea mays* L. var. *saccharata*). Average values with error bars followed by different lowercase letters within leaf level spray frequency and the different uppercase letters within biochar augmented compost denote significant variations ($p \leq .05$). Here, four levels of BEC amendment were T_1: control (100% recommended chemical fertilizer), T_2: 5 tons per hectare (ha), T_3: 10 tons per ha, T_4: 15 tons per ha and three foliar BSS were F_1: no spraying, F_2: 2 times spraying and F_3: 3 times spraying.

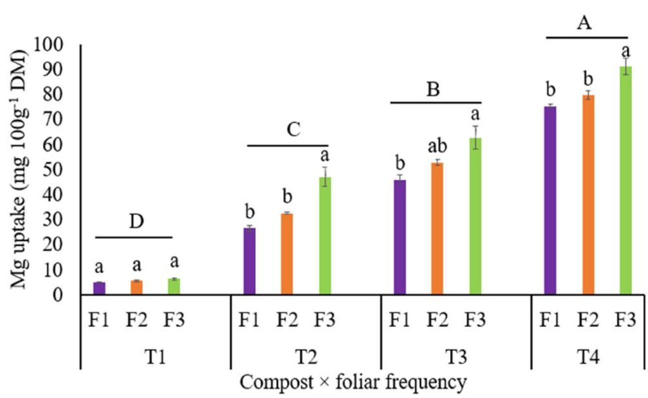

Figure 3. Two-way interaction of biochar augmented compost and leaf level spray frequency of sap on Mg utilization by corn (*Zea mays* L. var. *saccharata*). Average values with error bars followed by different lowercase letters within leaf-level spray frequency and the different uppercase letters within biochar augmented compost denote significant variations ($p \leq .05$). Here, four levels of BEC amendment were T_1: control (100% recommended chemical fertilizer), T_2: 5 tons per hectare (ha), T_3: 10 tons per ha, T_4: 15 tons per ha and three foliar BSS were F_1: no spraying, F_2: 2 times spraying and F_3: 3 times spraying.

interactive effect was particularly evident in the T_4F_3 treatment combination, where Ca uptake was approximately eight times (701% higher) than the control T_1F_1, highlighting the strong synergistic impact of compost and repeated BSS application (Figure 2).

Magnesium utilization followed a similar trend. The T_4 treatment yielded the highest Mg uptake (82.0 mg per 100 g), compared to only 5.48 mg per 100 g in T_1. Foliar spraying also played a significant role, with Mg uptake rising from 38.2 mg (F_1) to 51.7 mg per 100 g (F_3), indicating a 35.4% improvement. The interaction of T_4 and F_3 yielded the highest Mg accumulation, with uptake nearly 15 times higher than in T_1F_1. Notably, increased spray frequency resulted in Mg utilization gains of 33% in T_2, 77% in T3, and 36% in T_4 relative to their respective F_1 treatments (Figure 3).

Influence of BEC amendment and BSS spraying on soil chemical properties

pH and EC

A significant increase in pH ($p \leq .05$) was observed with higher compost application rates. However, the interaction between compost and foliar-applied BSS did not significantly affect pH (Figure 4). The highest pH value, 6.42, was recorded in pots treated with the maximum compost dose of 15 tons per hectare, while the lowest pH, 4.63, was found in pots treated only with chemical fertilizers. The pH increased by 0.72, 1.21, and 1.79 units with compost applications of 5, 10 and 15 tons per ha, respectively, compared to pots treated with chemical fertilizers. A similar pattern was observed in soil EC, where compost applications of 5, 10, and 15 tons per ha yielded statistically similar results ($p \leq .05$) but were higher than those in pots treated with chemical fertilizers alone.

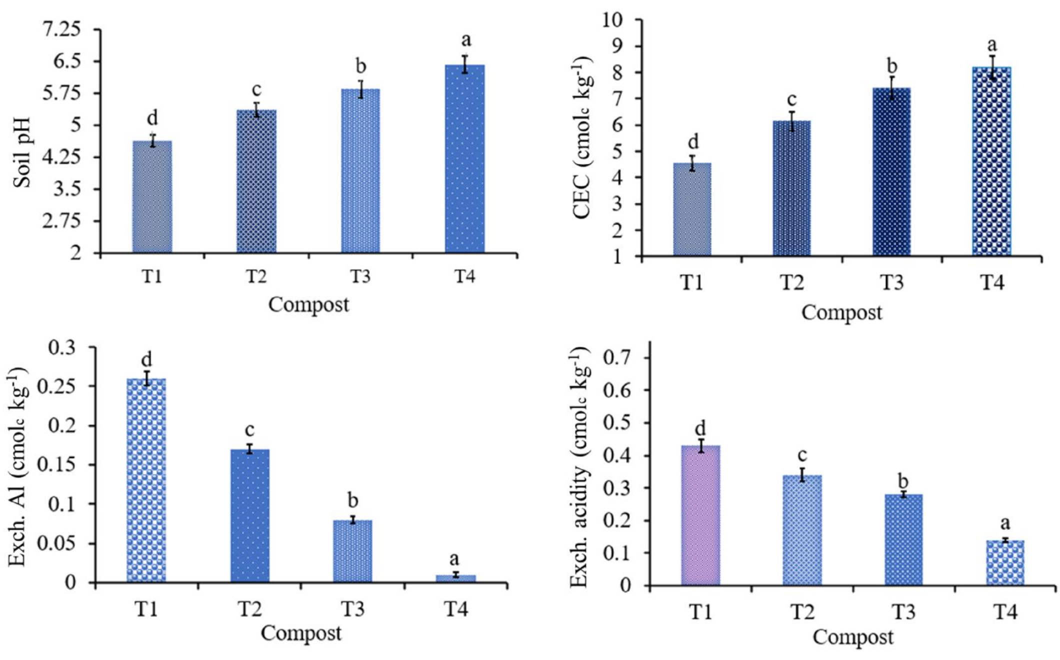

Figure 4. Effect of biochar-augmented compost on soil pH, cation exchange capacity, Al^{3+} and exchangeable acidity. The average values with error bars sharing different lowercase letters within dissimilar levels denote significant variations due to biochar-enriched compost ($p \leq .05$). Here, four levels of BEC amendment were T_1: control (100% recommended chemical fertilizer), T_2: 5 tons per hectare (ha), T_3: 10 tons per ha, T_4: 15 tons per ha and three foliar BSS were F_1: no spraying, F_2: 2 times spraying and F_3: 3 times spraying; $cmol_c\ kg^{-1}$ means centimole of charge per kg of soil.

Table 3. Effects of the biochar-enriched compost and foliar level banana stem sap application on acidic soil properties under sweet corn (*Zea mays* L. var. *saccharata*) cultivation.

Treatments	EC (μSm^{-1})	Total C (%)	Total N (%)	Available P (mg kg^{-1})	Exch. K $cmol_c\ kg^{-1}$	Exch. Ca $cmol_c\ kg^{-1}$	Exch. Mg $cmol_c\ kg^{-1}$
Compost (T)							
T_1	114 b	0.86 d	0.023 d	5.83 d	0.08 c	1.22 d	0.19 c
T_2	136 a	1.26 c	0.034 c	7.92 c	0.15 b	2.72 c	0.46 b
T_3	144 a	1.45 b	0.084 b	10.15b	0.34 a	3.53 b	0.63 a
T_4	151 a	1.62 a	0.100 a	14.34a	0.37 a	4.03 a	0.67 a
Foliar Frequency of BSS sap (F)							
F_1	135 a	1.27 a	0.062 a	9.50 a	0.23 a	2.85 a	0.49 a
F_2	137 a	1.30 a	0.063 a	9.53 a	0.23 a	2.84 a	0.48 a
F_3	137 a	1.33 a	0.064 a	9.64 a	0.24 a	2.93 a	0.49 a
Anova							
T	**	**	**	**	***	***	***
F	ns	ns	ns	ns	ns	ns	ns
T x F	ns	ns	ns	ns	ns	ns	ns

The mean value of similar letters within the column of the various compost and leaf level spray magnitudes do not differ significantly ($p \geq .05$). Here, four levels of BEC amendment were T_1: control (100% recommended chemical fertilizer), T_2: 5 tons per hectare (ha), T_3: 10 tons per ha, T_4: 15 tons per ha) and three foliar BSS were F_1: no spraying, F_2: 2 times spraying and F_3: 3 times spraying.

C, N, and available P

Increasing rates of compost application significantly affected the concentrations of total carbon (C), N, and available P in the soil after the cropping ($p \leq .05$; Table 3). Results showed that neither the frequency of leaf-level spray of BSS alone nor its interaction with compost suggestively influenced the concentrations of C, N, and available P. The highest concentrations were observed with 15 tons per ha of compost (T_4): C at 1.62%, N at 0.1%, and available P at 14.3 mg kg^{-1}. In contrast, the lowest concentrations were found in soils treated with only chemical fertilizers (T_1), with C at 0.86%, N at 0.023%, and available P at 5.83 mg kg^{-1}. The application of 15 tons per ha compost resulted in an 88.4%, 335%, and 146% increase in C, N, and P concentrations, respectively, compared to soils treated solely with the chemical fertilizers.

Exchangeable K, Ca, Mg, and CEC

Incorporating compost at increasing rates significantly enhanced the levels of exchangeable K, Ca, and Mg in the post-harvest soil ($p \leq .05$; Table 3). The frequency of foliar application and its interaction with compost rates did not affect exchangeable K, Ca, Mg, or CEC in post-harvest soil. The highest exchangeable K value (0.375 cmolc kg^{-1}) was found in soil treated with 15 tons per ha compost, while the lowest value (0.073 cmolc kg^{-1}) was recorded in soils treated with only chemical fertilizers. Similarly, significant variations ($p \leq .05$) in Ca and Mg concentrations were observed with different compost applications. Specifically, 15 tons per ha compost resulted in increases of 362% (from 0.073 to 0.375 $cmol_c\ kg^{-1}$), 230% (from 1.22 to 4.03 $cmol_c\ kg^{-1}$), and 253% (from 0.19 to 0.67 $cmol_c\ kg^{-1}$) in K, Ca, and Mg levels, respectively, compared to chemical fertilizers alone. The CEC value ranged from 4.5 to 8.1 $cmol_c\ kg^{-1}$ soil, while the highest CEC was recorded in T_4 and the lowest in control (T_1) treatment (Figure 4). These increases in K, Ca, and Mg were also reflected in the CEC, which showed an 80% increase with the 15 tons per ha compost application compared to control treatment (Figure 4).

Exchangeable Al and acidity

Increasing rates of compost application significantly reduced exchangeable Al^{3+} and exchangeable acidity (Figure 4) of soil. The application of 15 tons per ha compost resulted in the lowest values for exchangeable Al^{3+} (0.01 $cmol_c\ kg^{-1}$) and exchangeable acidity (0.14 $cmol_c\ kg^{-1}$). In contrast, the highest values for Al^{3+} (0.26 $cmol_c$ kg^{-1}) and acidity (0.43 cmolc kg^{-1}) were found in soils treated with the chemical fertilizers. The compost applications of 5 tons per ha, 10 tons per ha, and 15 tons per ha reduced Al^{3+} toxicity by 35%, 69% and 96%, respectively, compared to chemical fertilizers. Similarly, exchangeable acidity decreased by 21%, 35%, and 67% with these compost doses compared to chemical fertilizers (Figure 4).

Relationship between the cob yield and soil chemical properties by the BEC

The associations linking cob yield and soil chemical properties have been assessed through Pearson's correlation analysis (Figure 5). The study revealed a significant positive correlation between cob yield and exchangeable cations and CEC ($r = 0.98^*$). Conversely, exchangeable Al^{3+} and exchangeable acidity demonstrated significant negative correlations with exchangeable Ca ($r = -0.96^*$). Moreover, soil pH and CEC had strong negative correlations with exchangeable Al^{3+} ($r = -0.99^{**}$) and exchangeable acidity ($r = -0.99^*$). These results indicate that compost application increased soil pH and CEC, reduced Al toxicity, improved nutrient utilization, and enhanced corn yield (Figure 4).

Discussion

BEC on fresh cob and biomass yield

Compost not only improves the soil's nutrient retention but also provides essential nutrients. By increasing the CEC, compost helps to retain vital nutrients such as N, P, and K, which are important for plant growth. The application of the BEC and foliar spraying of BSS is significantly attributed to improved nutrient availability, enhanced soil water retention capacity (data not presented here), and reduced Al toxicity that enhanced crop productivity. These changes in turn influenced soil pH, as depicted in Figure 4. It is crucial to recognize the close relationship between nutrient availability and optimal soil pH for achieving optimal crop growth. According to the results, applying different amounts of compost treated with biochar greatly increases corn productivity during both growing seasons. The co-compost used in this study generated from banana stems, unused mushroom substrates, and poultry litter had alkaline properties and was nutrient-enriched (Section "Preparation of pot with soil, compost, and biochar"). In light of Ultisols' crop production limitations, this combination proved to be quite congenial in increasing plant growth. Particularly, as compared to the usage of chemical fertilizers, the addition of BEC at a rate of 15 tons per ha (T_4) led to a significant increase (by 12.86%) in cob production and dry biomass production by 11.37% (Table 1). These results are consistent with the findings of Agegnehu, Srivastava, and Bird (2017), which found that utilizing compost and inorganic fertilizers rather than chemical fertilizers increased maize yields by 10–29% on acidic soils. Additionally, Glaser, Lehmann, and Zech (2002) demonstrated a 26% increase in maize yield with the application of 10 tons per ha^{-1} of compost compared to the control group (no compost application). The better growth and production of sweet corn were probably made possible by the underlying mechanism for these soil improvements and greater mineral nutrient utilization from compost (Islam, et al. 2024). According to Pandit, et al. (2020), the applied compost had a plentiful supply of basic cations and the presence of Ca^+ ions efficiently neutralized the pH of the soil, greatly lowering acidity. This phenomenon was caused by enhanced nutrient availability, leading to better growth and cob yield.

Foliar spraying of BSS on corn growth and yield

The application of BSS as a foliar spray significantly enhanced fresh cob and biomass yields (Table 1). This improvement can be attributed to the sap's rich mineral content, particularly K, Ca, and Mg (Islam, et al. 2022). Notably, the highest frequency of sap application (F_3) resulted in average increases of 9.24% in cob yield and 7.75% in biomass compared to untreated plants across both growing seasons. These gains may be due to the stomatal absorption of nutrients through the leaf, which has been shown to enhance yield and biomass. This also aligns with the findings of Pangaribuan et al. (2019), who reported improved sweet corn yields with the combination of soil amendments and foliar sap applications. Furthermore, Brankov, et al. (2020) documented a 17–32% increase in maize yield from foliar applications of amino acid-rich organic fertilizers. Our previous research also supports these findings, confirming that BSS contains amino acids that promote plant growth and development (Islam, et al. 2022).

Interaction effects of BEC and foliar application of BSS on nutrient uptake

The study examined how compost and foliar banana pseudostem sap affect nutrient uptake in sweet corn. A higher compost dose (15 t ha^{-1}) decreased N uptake by 7%. However, it significantly increased P, K, Ca, and Mg uptake by 92%, 679%, and 1490%, respectively, compared to the chemical fertilizer. When combined with three foliar sprays applied at 15, 30, and 45 days after sowing, the higher compost dose further increased K, Ca, and Mg uptake by 120%, 843%, and 1823%, respectively, compared to chemical fertilizers. The synergistic effect of BEC and BSS may have enhanced nutrient availability in the soil and improved foliar absorption, leading to a significant increase in nutrient uptake (Manolikaki and Diamadopoulos 2019) even if those changes did not immediately translate into higher yield. This could be because improved soil structure, increased biochar adsorption, and stomatal hydration could have more immediate effects on nutrient absorption (Noack, McBeath, and McLaughlin 2010) than on overall plant growth, which also depends on processes like photosynthesis, root development, and reproduction. These findings are consistent with previous research showing the positive effects of combined compost and foliar applications on nutrient uptake in crops like sweet corn (Bojórquez-Quintal et al. 2017; Sumalan, et al. 2020). Therefore, the significant interaction in nutrient uptake but not yield could reflect these complex and differentiated responses to the treatments.

Improvement in soil fertility

The application of BEC, particularly derived from banana stems significantly altered soil properties, enhancing nutrient utilization and corn yield (Table 3 and Figures 1–3). In this study, applied compost was alkaline (pH $\geq$ 10) and, when enriched with biochar, effectively raised the pH and EC of acidic soils (Kalemelawa, et al. 2012). Of the treatments, 15 tons per ha compost application resulted in increased pH by 1.44 and 1.79 units (from 4.98 to 6.42 and from 4.63 to 6.42) related to the initial soil and the sole chemical fertilizer-treated soil. Equivalent evidence was recorded by Agegnehu, et al. (2015) what they reported 2.5 units higher soil pH from individual effects of compost in tropic soil. $H+$ ion exchange and decomposition of compost likely produced phenolic and humic compounds, which raised soil pH by consuming protons (Sayara et al. 2020). The elevated pH that was found may also have been caused by the particular adsorption of humic substances and organic acids *via* ligand exchange processes onto the hydrated surfaces of Al and Fe oxides (Hue, Craddock, and Adams 1986).

The BEC significantly improved the soil fertility status in the post-harvest soil by improving the soil organic C, N, available P, exchangeable K, Ca, Mg, and CEC. The higher levels of soil OC, N, available P, exchangeable K, Ca, Mg, and CEC were some of the major elements that made this improvement obvious (Tables 3 and Figure 4). It is significant to note that the compost utilized in this study was alkaline in nature and contained a higher amount of K, principally as a result of the inclusion of banana stems as a major component in its composition. Exchangeable Ca concentrations in the final soil were consistently 5–11% higher than exchangeable K concentrations. This indicates that Ca, released from the enriched compost, engaged in an exchange with K, potentially leading to the leaching of K from the soil. As a result, the concentration of K in the surface soil was comparatively lower. However, the application of enriched compost consistently led to an increase in K, Ca, and Mg by 414%, 230%, and 253%, respectively. Consequently, the cations density in soil influenced the higher CEC over control (Table 3 and Figure 2). These results are consistent with those of Agegnehu et al. (2016) studies which likewise found increased CEC values, mostly because of the density of soil exchangeable cations. The surface characteristics of biochar also contribute to the adsorption and retention of released nutrients from the compost, thus enhancing the soil's nutrient density (Wood, Adams, and Wood 2005). In many studies, applying stabilized compost with diversified functional groups in soil increased CEC at a high dose (Adugna 2016; Sayara et al. 2020). This study noted an 80% higher CEC from the increased application of BEC. Similar results concerning the increase of CEC were recorded by Agegnehu et al. (2016). Another study (Bass et al. 2016) explored the CEC value from 6.56 to 10.68 $cmol_c\ kg^{-1}$ with the amendment of co-composted biochar in tropical soil. The accumulation of negative-charged substances such as carboxyl and/or phenolic hydroxyl generated from biochar-augmented compost could be the cause of an increase in CEC (Diacono and Montemurro 2010).

The organic amendment had a significant influence on the reduction of Al toxicity, especially in acidic soil. In this study, the increasing rate of BEC has decreased exchangeable Al^{3+} and exchangeable acidity (Figure 2). Compared to chemical fertilizers, the compost at a higher dose (15 tons per ha) reduced exchangeable Al^{3+} and acidity by 96% and 67%, respectively. The existence of higher Ca concentration in the added compost could replace the absorbed H^+ from the soil colloidal surface. This may increase the base saturation, effectively neutralizing soil acidity (Wood, Adams, and Wood 2005). These findings were aligned with those (Opala 2017) who have shown a negative correlation between soil pH and CEC with exchangeable Al^{3+}. Besides, soil pH and Ca are positively correlated (Figure 5). However, with the increased soil pH, exchangeable Al^{3+} may have converted to insoluble Al hydroxides and at the same time improved nutrient utilization by the sweet corn plants, finally leading to an increased yield of sweet corn.

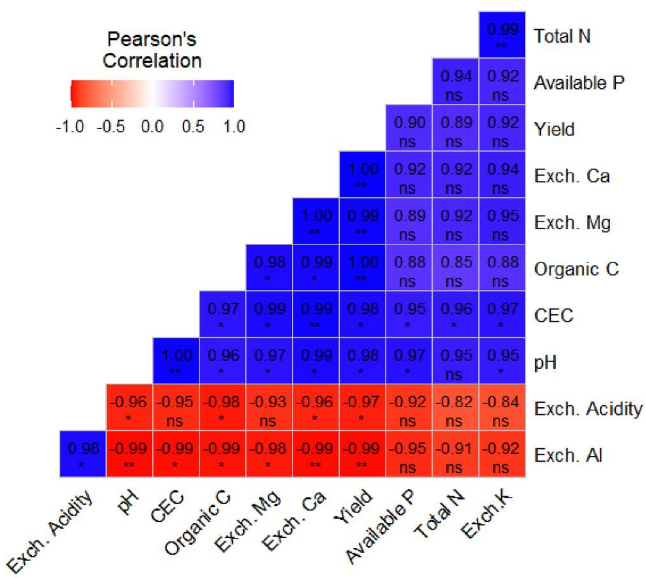

Figure 5. Correlation between sweet corn cob yield and interrelated soil chemical properties under biochar-enriched compost and foliar sap treatments. Here, ns = non-significant.

Although the interaction of BEC × BSS was significant for nutrient uptake (K, Ca, Mg), it was not significant for yield. This might suggest that the combined treatments enhanced nutrient acquisition more directly than final cob production. Yield formation depends on additional physiological processes such as photosynthesis, root development, and reproductive growth, which may have masked the short-term translation of higher nutrient uptake into yield gains (Amthor 2025).

In this study, cob yield showed very strong positive correlations with exchangeable Ca, Mg, K, and CEC ($r > 0.9$), and strong negative correlations with exchangeable Al^{3+} and acidity. While these findings feature the role of improved soil fertility in enhancing crop productivity, it is important to note that such strong correlations may partly reflect collinearity among soil chemical properties rather than direct causation. Exchangeable Ca, Mg, and K are inherently interrelated through cation exchange processes, while their collective influence is also reflected in CEC. Thus, the observed relationships likely represent both synergistic improvements in soil fertility and statistical interdependence among these parameters. Future research using multivariate statistical approaches (e.g., principal component analysis, path analysis, or structural equation modelling) would help disentangle these interrelationships and better quantify the individual contribution of each soil property to yield improvements.

Whereas earlier research has largely tested biochar, compost, or banana pseudostem sap in isolation, the recent work demonstrates the combined benefits of BEC and foliar BSS sprays. This dual strategy simultaneously improved soil chemical properties (pH, CEC, base cations) and mitigated Al^{3+} toxicity at the soil level, while enhancing nutrient uptake directly at the plant level *via* foliar pathways. Such a holistic approach to overcoming both soil acidity constraints and plant nutrient deficiencies is, to the state-of-the-art knowledge, the first of its kind. This positions the integrated use of biochar-enriched compost and banana sap as a novel and promising management option for sustaining sweet corn productivity in acidic tropical soils.

While this study was conducted under controlled pot conditions, field trials are being planned to validate the combined use of biochar-enriched compost and banana sap under the realistic agronomic settings. Although biochar is generally stable, the long-term effects on nutrient retention, Al^{3+} toxicity, and sap-derived nutrients require multi-year field evaluation to confirm the durability and broader applicability of this approach.

Conclusion

This study confirmed that biochar-enriched compost (BEC) can raise soil pH and CEC while substantially reducing exchangeable Al^{3+} in acidic soils. The enriched compost, naturally rich in base cations, released higher levels of K, Ca, and Mg, thereby improving soil fertility and supporting better nutrient utilization. When applied at 10–15 t ha^{-1}, either alone or combined with foliar applications of banana pseudostem sap (BSS), BEC enhanced soil properties and significantly increased sweet corn yield. The co-application of BEC and BSS thus represents a promising management option for improving crop productivity under acidic soil constraints. Future work should include field trials across diversified crops, such as rice and legumes, to test the broader applicability of this approach under variable agronomic conditions and to assess its long-term benefits for reducing chemical fertilizer dependence and supporting sustainable agriculture. Future field trials should also incorporate cost–benefit analyses to evaluate the economic feasibility of using biochar-enriched compost and banana sap as farmer-managed inputs.

Author contributions

MSI, MKA, and SK conceptualized the study; MSI, MKA, and SK contributed to methodology; MSI, MKA, and SK carried out formal analysis; MSI, MKA, MFK, and SK investigated the study; MSI, MKA, SB, MZR, and SK

contributed to resources; MSI, MKA, MZR, MFK, and SK performed manuscript draft preparation; MSI, MKA, and SK contributed to review and editing. The authors reviewed and approved the final manuscript before submission.

Disclosure statement

No potential conflict of interest was reported by the authors.

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