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Dynamics of Soil Sulfur Due to Application of Water Hyacinth Compost Based Biochar and Its Relationship with Sulfur Uptake and Sweet Corn Productivity in Inceptisol

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Abstract

Sulfur deficiency has become an emerging constraint in maize production due to reduced atmospheric deposition and intensive cropping practices. Organic amendments such as compost and biochar have the potential to improve sulfur availability through enhanced mineralization and nutrient retention. This study aimed to evaluate the dynamics of soil available sulfur following the application of water hyacinth compost and biochar, and to assess their effects on sulfur uptake and productivity of sweet corn grown on Inceptisol under pot conditions. The experiment was conducted from May to August 2025 using a randomized block design with seven treatments, consisting of a control, compost-only, biochar-only, and combined compost–biochar applications. Soil available sulfur was monitored periodically during plant growth, while sulfur uptake and ear weight were measured at harvest. The results showed that organic amendments significantly influenced soil sulfur dynamics, characterized by an increase in sulfur availability during early growth stages followed by a gradual decline toward harvest. Treatments combining compost and biochar maintained higher sulfur availability throughout the growing period, resulting in greater sulfur uptake and higher sweet corn ear weight compared with single amendments and the control. Among all treatments, the combined application of water hyacinth compost at 50 g pot^{-1} and biochar at 100 g pot^{-1} produced the highest sulfur uptake and the greatest ear weight. These findings indicate that integrating water hyacinth compost with biochar is an effective strategy for improving sulfur nutrition and sweet corn productivity on Inceptisol.

Keywords: Biochar; Organic Amendments; Nutrient Dynamics; Sweet Corn Productivity; Water Hyacinth Compost

1. Introduction

Sulfur (S) is an essential macronutrient that plays a fundamental role in plant physiological processes, including protein synthesis, enzyme activation, and chlorophyll formation (Narayan, 2022). Sulfur is also involved in nitrogen metabolism and the formation of sulfur-containing amino acids such as cysteine and methionine, which are critical for plant growth and crop yield (Narayan, 2022; Sharma, 2024). However, in many agricultural systems, sulfur availability can be limited due to soil leaching, reduced atmospheric deposition, or intensive cropping, leading to sulfur deficiency and reduced productivity (Sharma, 2024).

In sweet corn (*Zea mays saccharata*), adequate sulfur nutrition is increasingly recognized as essential for maximizing yield and grain quality. Direct sulfur application has been shown to enhance yield components such as grain number and weight, as well as improve amino acid balance within maize grain proteins (Wang et al., 2023). These findings highlight that sulfur availability in the soil must be managed effectively to sustain maize productivity.

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Organic amendments, such as compost and biochar, represent sustainable strategies to improve soil fertility and nutrient availability. Compost adds organic matter and nutrients to the soil, and its decomposition releases mineralized nutrients including sulfur, thereby enhancing soil nutrient pools (Agegnehu et al., 2016). Biochar, a carbon-rich material obtained through pyrolysis of biomass, can improve soil physical and chemical properties, increase nutrient retention, and moderate soil acidity, thus supporting long-term soil health and crop performance (Agegnehu et al., 2016). Studies have reported that combining biochar with compost can improve soil nutrient status and maize growth more effectively than applying each amendment alone (Agegnehu et al., 2016; Manolikaki & Diamadopoulos, 2019).

Despite these benefits, most research has focused on general soil fertility and nutrient dynamics such as nitrogen and phosphorus, while relatively few studies have specifically investigated how combined organic amendments influence sulfur dynamics in soil and its uptake by crops. Given the importance of sulfur for maize growth and the potential for organic amendments to modify soil nutrient supply, understanding the temporal dynamics of sulfur availability and uptake under biochar–compost treatments is particularly relevant in low-fertility soils such as Inceptisols.

Therefore, this study aims to quantify the soil sulfur dynamics following the application of water hyacinth compost and biochar, to evaluate their effects on sulfur uptake by sweet corn and to determine the relationship between soil sulfur availability and crop productivity. The findings are expected to provide insights into sustainable nutrient management strategies using locally available organic resources.

2. Materials and methods

2.1. Experimental Site and Duration

The experiment was conducted from May to August 2025 at the experimental field of the Laboratory of Soil Chemistry and Plant Nutrition, Faculty of Agriculture, Universitas Padjadjaran, Indonesia. Laboratory analyses for soil sulfur and plant sulfur uptake were carried out at the same laboratory.

2.2. Soil and Plant Materials

The soil used in this study was an Inceptisol, collected from the surface layer (0–20 cm), air-dried, homogenized, and sieved through a 2-mm mesh prior to use. Each experimental unit consisted of a plastic pot filled with 10 kg of air-dried soil. Sweet corn seeds were used as the test crop. Compost derived from water hyacinth and biochar were applied as soil amendments.

2.3. Experimental Design and Treatments

The experiment was arranged in a Randomized Block Design (RBD) with seven treatments and three replications. Blocking was applied to minimize the effects of environmental variability within the experimental area.

The treatments were as follows:

- T0: Control (no compost and no biochar)
- T1: Water hyacinth compost at 25 g pot^{-1}
- T2: Water hyacinth compost at 50 g pot^{-1}
- T3: Biochar at 25 g pot^{-1}
- T4: Biochar at 100 g pot^{-1}
- T5: Water hyacinth compost 25 g + biochar 25 g pot^{-1}
- T6: Water hyacinth compost 50 g + biochar 100 g pot^{-1}

The application rates were calculated based on the assumption that 1 ha of soil (0–20 cm depth) weighs approximately 2,000,000 kg, where 1 t ha^{-1} corresponds to 0.5 g kg^{-1} soil, equivalent to 5 g per 10 kg soil per pot.

2.4. Soil Amendment Application and Incubation

The required amounts of compost and biochar were thoroughly mixed with the soil according to the treatment design. The amended soils were incubated for 7–14 days at moisture content close to field capacity to allow stabilization of soil chemical reactions and initiation of organic sulfur mineralization prior to planting.

2.5. Planting and Crop Management

Sweet corn seeds were sown directly into the pots, and seedlings were thinned to one plant per pot after establishment. Soil moisture was maintained near field capacity through regular irrigation, with uniform watering across all treatments. Weed control was conducted manually, and pest or disease control was applied uniformly when necessary. No sulfur-containing mineral fertilizers were applied during the experiment to avoid interference with sulfur dynamics originating from the organic amendments.

2.6. Soil Sampling and Analysis

Soil samples were collected to determine available sulfur (SO_4^{2-}-S) at 0, 14, 28, 42, 56 days after planting (DAP) and at harvest. Soil pH was measured at the beginning and at the end of the experiment. Available sulfur was analyzed using standard sulfate extraction and determination procedures commonly employed in soil chemistry laboratories.

2.7. Plant Sampling and Sulfur Uptake

At harvest, plant tissue samples (above-ground biomass) were collected for sulfur analysis. Samples were washed with distilled water, oven-dried at 65–70 °C until constant weight, and finely ground. Plant sulfur concentration was determined in the laboratory, and sulfur uptake was calculated as:

Sulfur uptake (mg plant^{-1})=Sulfur concentration × Dry biomass

2.8. Yield Measurement

Sweet corn yield was assessed based on fresh ear weight per pot at harvest. All ears were harvested at the same physiological stage to ensure uniformity among treatments.

2.9. Statistical Analysis

Data were analyzed using analysis of variance (ANOVA) according to the Randomized Block Design at a 5% significance level. When significant differences among treatments were detected, mean separation was performed using Duncan's Multiple Range Test (DMRT) at $p \leq 0.05$.

3. Results and discussion

3.1. Soil Sulfur Dynamics

Analysis of variance (ANOVA) was conducted separately for each sampling time to evaluate the effects of compost, biochar, and their combinations on soil available sulfur (SO_4^{2-}-S). The ANOVA results indicated that treatment effects on soil available sulfur were statistically significant ($p \leq 0.05$) at all observation times, except at 0 days after planting (DAP), where initial differences reflected baseline amendment effects rather than plant-mediated processes.

Table 1 Soil available sulfur dynamics under different treatments (mg kg^{-1})

Treatment	0 DAP	14 DAP	28 DAP	42 DAP	56 DAP	70 DAP
T0 = Control	5.15 c	4.76 d	4.41 d	4.16 d	3.89 d	3.82 d
T1 = Compost 25 g pot^{-1}	7.59 b	9.50 c	8.20 c	7.03 c	6.23 c	5.57 c
T2 = Compost 50 g pot^{-1}	8.97 ab	12.53 b	10.80 b	9.18 b	7.98 b	7.19 b
T3 = Biochar 25 g pot^{-1}	6.49 bc	6.73 d	6.60 d	6.32 cd	6.01 c	5.80 c
T4 = Biochar 100 g pot^{-1}	7.28 b	7.62 cd	7.49 c	7.18 c	6.98 bc	6.76 bc
T5 = Compost 25 g + Biochar 25 g pot^{-1}	9.21 ab	12.00 b	11.12 b	10.00 b	9.22 ab	8.62 ab
T6 = Compost 50 g + Biochar 100 g pot^{-1}	10.51 a	13.99 a	13.00 a	11.79 a	10.80 a	9.99 a

Note: Values are mean ± standard error (SE). Means followed by different letters within the same column are significantly different at $p < 0.05$ according to Duncan's Multiple Range Test (DMRT).

Significant treatment effects became more pronounced at 14 and 28 DAP, coinciding with the early vegetative growth phase of sweet corn. This suggests that organic sulfur mineralization and sulfate release were most active during early growth stages. Similar temporal responses of soil nutrients following organic amendment application have been widely reported in amended agricultural soils, where nutrient availability peaks shortly after amendment incorporation and gradually declines due to plant uptake and stabilization processes.

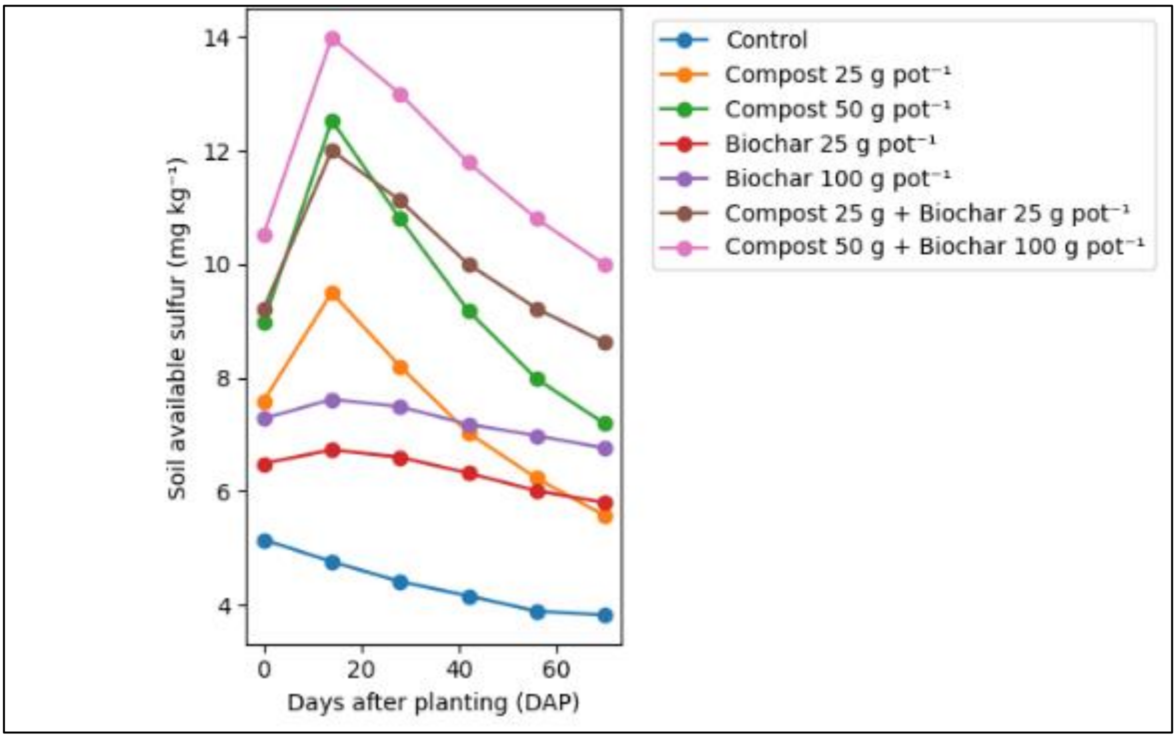

Figure 1 Dinamics of Soil Available Sulfur During Sweet Corn Growth

3.2. Temporal dynamics of soil available sulfur

The data presented in Table 1 and Figure 1 clearly demonstrate that soil available sulfur (SO_4^{2-}-S) varied significantly with both treatment and time after planting (DAP). Across all treatments, sulfur availability exhibited a consistent temporal pattern characterized by an increase during the early growth stage (14–28 DAP), followed by a gradual decline toward harvest (56–70 DAP). This trend was most pronounced in treatments receiving organic amendments, particularly those combining compost and biochar (T5 and T6). In the control treatment (T0), soil available sulfur decreased continuously from 5.15 mg kg^{-1} at 0 DAP to 3.82 mg kg^{-1} at 70 DAP. This monotonic decline indicates that, in the absence of external sulfur inputs, sulfate availability was governed primarily by plant uptake and limited mineralization of native soil organic sulfur. Such behavior is consistent with the understanding that sulfate is a transient pool in soil and is rapidly depleted when not replenished (Scherer, 2009).

3.3. Early sulfur peak under compost-based treatments

Treatments receiving water hyacinth compost alone (T1 and T2) showed a marked increase in soil available sulfur during the early growth stage. For example, in T2 (compost 50 g pot^{-1}), soil available sulfur increased from 8.97 mg kg^{-1} at 0 DAP to a maximum of 12.53 mg kg^{-1} at 14 DAP, before declining gradually thereafter. This early peak reflects rapid mineralization of organic sulfur supplied by the compost. According to Scherer (2009), more than 90% of soil sulfur exists in organic forms, and sulfate availability depends largely on microbial mineralization processes. The addition of compost introduces fresh organic substrates that stimulate microbial activity and enzymatic hydrolysis of ester-sulfate compounds, resulting in a temporary accumulation of sulfate in the soil solution. Similar early-stage sulfur mineralization patterns have been reported in studies examining organic residue decomposition and sulfur cycling (Nziguheba et al., 2006).

3.4. Biochar treatments and sulfur stabilization

In contrast to compost treatments, biochar-only treatments (T3 and T4) showed relatively stable sulfur concentrations over time. For instance, in T4 (biochar 100 g pot^{-1}), soil available sulfur ranged from 7.62 mg kg^{-1} at 14 DAP to 6.76 mg kg^{-1} at harvest, indicating a slower rate of sulfur depletion compared with compost-only treatments. This pattern suggests that biochar did not act primarily as a sulfur source but rather influenced sulfur dynamics indirectly by modifying soil physicochemical conditions. Biochar has been shown to improve soil structure, aeration, and nutrient retention, which can reduce nutrient losses and stabilize available nutrient pools (Agegnehu et al., 2016). Although direct sulfate adsorption by biochar is not always observed, the improved soil environment may help retain sulfate in the root zone and slow its decline over time.

3.5. Synergistic effects of compost–biochar combinations

The most pronounced and sustained sulfur availability was observed in the combined compost–biochar treatments (T5 and T6). In T6 (compost 50 g + biochar 100 g pot^{-1}), soil available sulfur reached 13.99 mg kg^{-1} at 14 DAP and remained relatively high at 9.99 mg kg^{-1} even at harvest. This treatment consistently maintained the highest sulfur levels at all observation times compared with other treatments. The data indicate a clear synergistic effect between compost and biochar. Compost served as the primary source of organic sulfur that was mineralized into sulfate, while biochar likely enhanced sulfur retention and moderated the rate of sulfur depletion. Similar synergistic improvements in nutrient availability and maize performance under combined biochar–compost application have been reported by Agegnehu et al. (2016) and Manolikaki and Diamadopoulos (2019). These studies suggest that integrating nutrient-supplying organic amendments with soil conditioners can improve nutrient use efficiency and sustain availability throughout the crop growth cycle.

3.6. Effects of Water Hyacinth Compost and Biochar on Sulfur Uptake by Sweet Corn

Sulfur uptake by plants represents the integrated response to soil sulfur availability, root absorption capacity, and plant physiological demand throughout the growing period. Unlike single-time soil measurements, sulfur uptake reflects the cumulative sulfur supply provided by the soil over the entire growth cycle and therefore serves as a reliable indicator of plant sulfur nutritional status. In soils receiving organic amendments, sulfur uptake is strongly influenced by the temporal dynamics of sulfate release from organic sulfur pools and by the soil's ability to retain available sulfur in the root zone.

In the present study, sulfur uptake varied markedly among treatments, as shown in Table 2. These differences closely mirrored the observed dynamics of soil available sulfur during the growing period. Treatments that maintained higher sulfate concentrations over time exhibited greater sulfur uptake, whereas treatments with limited sulfur availability showed substantially lower uptake. This pattern emphasizes the importance of sustained sulfur availability rather than short-term sulfur supply for optimizing sulfur nutrition in sweet corn grown on Inceptisol.

Table 2 Sulfur uptake by sweet corn at harvest under different applications of water hyacinth compost and biochar in Inceptisol

Treatment	**Sulfur uptake (mg plant^{-1})**
T0 = Control	74.30 ± 6.73 d
T1 = Compost 25 g pot^{-1}	127.17 ± 0.98 c
T2 = Compost 50 g pot^{-1}	160.47 ± 6.81 bc
T3 = Biochar 25 g pot^{-1}	101.10 ± 5.42 c
T4 = Biochar 100 g pot^{-1}	110.47 ± 1.27 c
T5 = Compost 25 g + Biochar 25 g pot^{-1}	185.77 ± 5.08 ab
T6 = Compost 50 g + Biochar 100 g pot^{-1}	225.97 ± 10.21 a

Note: Values are mean ± standard error (SE). Means followed by different letters within the same column are significantly different at $p < 0.05$ according to Duncan's Multiple Range Test (DMRT).

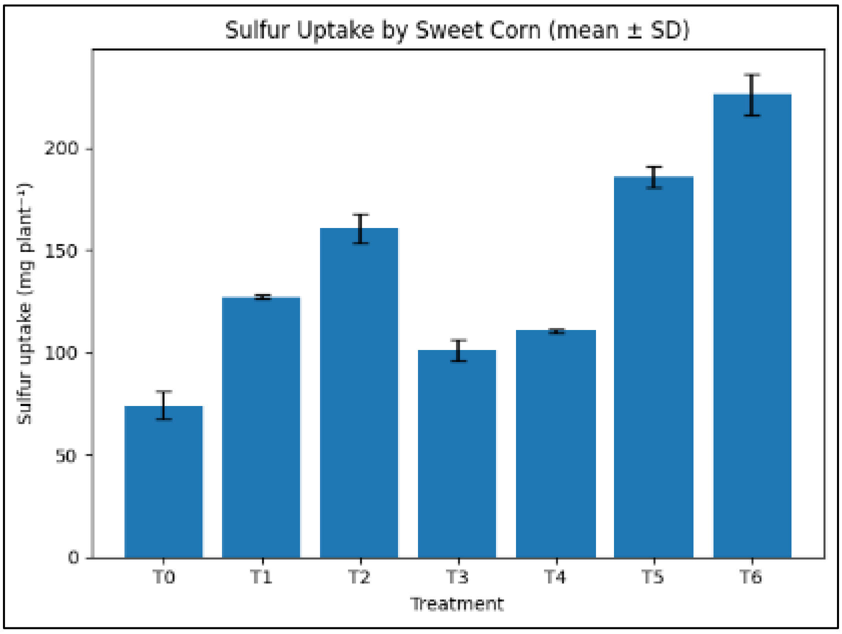

Figure 2 Sulfur uptake by sweet corn under different applications of water hyacinth compost and biochar in Inceptisol

Sulfur uptake by sweet corn responded strongly to the compost–biochar treatments (Table 2). The control (T0) produced the lowest S uptake (74.30 ± 6.73 mg plant^{-1}), indicating limited sulfate supply from native soil pools. This is expected because most soil sulfur is stored in organic forms, while plant-available sulfate represents a relatively small and dynamic pool that must be replenished through mineralization (Scherer, 2009). The highest uptake occurred in T6 (225.97 ± 10.21 mg plant^{-1}), followed by T5 (185.77 ± 5.08 mg plant^{-1}), demonstrating that combining compost and biochar was more effective than applying either material alone. Similar synergistic outcomes of combined biochar–compost application—improving soil nutrient status and crop performance relative to single amendments—have been reported in maize-based systems (Agegnehu et al., 2016; Manolikaki & Diamadopoulos, 2019).

Compost-only treatments (T1–T2) resulted in higher S uptake than the control, consistent with the mechanism that organic residues supply organic S which can be mineralized into sulfate and subsequently absorbed by plants. Sulfur release from organic residues is known to involve concurrent mineralization and immobilization, with net sulfate availability depending on residue quality and microbial demand (Nziguheba et al., 2006).

Biochar-only treatments (T3–T4) increased S uptake relative to the control but remained lower than compost and combined treatments. This pattern is consistent with biochar acting primarily as a soil conditioner (e.g., improved nutrient retention and overall soil chemical environment) rather than as a direct sulfur source. Evidence from tropical soils indicates that biochar and biochar–compost approaches can improve soil nutrient status and maize yield, supporting the observed direction of response in plant nutrient acquisition (Agegnehu et al., 2016).

3.7. Sweet Corn Yield Response to Water Hyacinth Compost and Biochar Application

Sweet corn productivity in this study was evaluated based on fresh ear weight at harvest as the primary yield parameter. Ear weight provides an integrative measure of plant growth and nutrient acquisition throughout the growing period. The effects of water hyacinth compost, biochar, and their combinations on sweet corn ear weight are presented in Table 3 and Figure 4, which summarize the mean values, variability among treatments, and overall yield response under the experimental conditions.

Table 3 Sweet corn ear weight under different applications of water hyacinth compost and biochar in Inceptisol

Treatment	Ear weight (g ear^{-1})
T0 = Control	185.0 ± 5.0 d
T1 = Compost 25 g pot^{-1}	267.7 ± 2.5 c
T2 = Compost 50 g pot^{-1}	315.0 ± 5.0 bc
T3 = Biochar 25 g pot^{-1}	235.0 ± 5.0 c
T4 = Biochar 100 g pot^{-1}	247.7 ± 2.5 c
T5 = Compost 25 g + Biochar 25 g pot^{-1}	345.0 ± 5.0 ab
T6 = Compost 50 g + Biochar 100 g pot^{-1}	401.7 ± 7.6 a

Note: Values are mean ± standard error (SE). Means followed by different letters within the same column are significantly different at $p < 0.05$ according to Duncan's Multiple Range Test (DMRT).

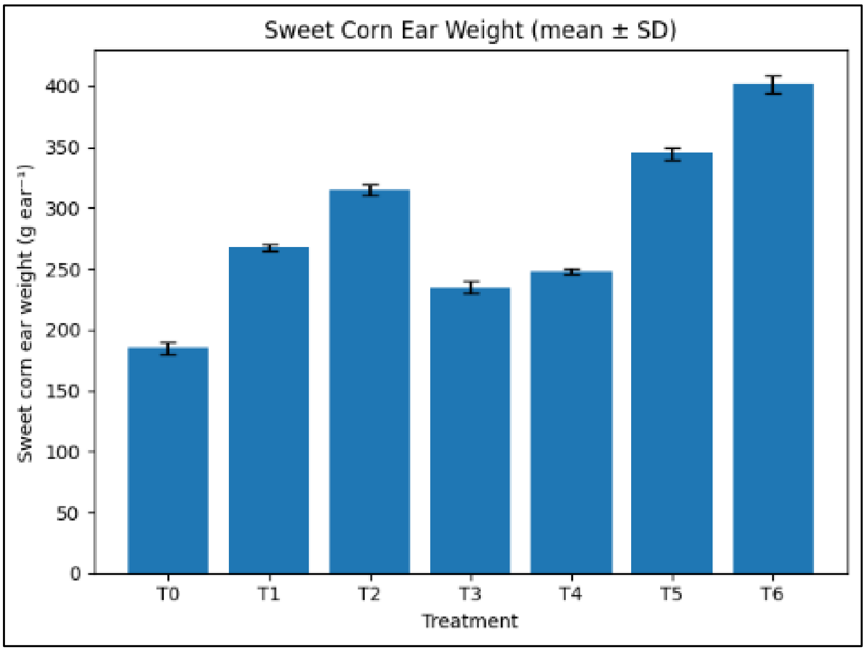

Figure 3 Sweet corn ear weight under different applications of water hyacinth compost and biochar in Inceptisol**.**

Sweet corn ear weight (Table 3; Figure 3) showed a clear response to organic amendment treatments, with the highest ear weight consistently recorded under T6 (Compost 50 g + Biochar 100 g pot^{-1}), followed by T5 (Compost 25 g + Biochar 25 g pot^{-1}), indicating that the combined application of compost and biochar was the most effective strategy for improving sweet corn productivity in this study. In contrast, the control treatment (T0) produced the lowest ear weight, confirming that native soil fertility and sulfur availability in the Inceptisol were insufficient to support optimal yield formation.

The superior performance of T6 can be attributed to the complementary roles of compost as a nutrient source and biochar as a soil conditioner that improves nutrient retention and the root environment, a mechanism that has been reported to enhance maize growth and yield under integrated organic amendment management (Mensah et al., 2018). Moreover, studies on maize nutrition have demonstrated that adequate sulfur supply plays a critical role in improving yield and yield components, particularly when sulfur interacts positively with nitrogen uptake and utilization efficiency (O'Leary et al., 1990; Carciochi et al., 2020). The higher ear weight observed under T6 is also consistent with evidence that improved sulfur nutrition can enhance kernel development and fresh maize quality, emphasizing the importance of sustained sulfur availability during critical growth stages (Jiang et al., 2024). Therefore, based on the yield data, T6

(Compost 50 g + Biochar 100 g pot^{-1}) can be identified as the best treatment for maximizing sweet corn ear weight under the experimental conditions.

4. Conclusions

The application of water hyacinth compost and biochar significantly influenced soil sulfur dynamics, sulfur uptake, and sweet corn productivity in Inceptisol under pot conditions. Organic amendments increased soil available sulfur during early growth stages and helped sustain sulfur availability throughout the growing period, which in turn enhanced sulfur uptake by plants. Sulfur uptake showed a strong positive relationship with soil available sulfur and was closely associated with increases in sweet corn ear weight.

Among all treatments, the combined application of compost and biochar consistently outperformed single amendments and the control in terms of maintaining soil sulfur availability, maximizing sulfur uptake, and improving yield. Based on the overall results, the best treatment was T6 (Compost 50 g + Biochar 100 g pot^{-1}), which produced the highest sulfur uptake and the greatest sweet corn ear weight. These findings indicate that integrating water hyacinth compost with biochar is an effective strategy for improving sulfur nutrition and sweet corn productivity on Inceptisols..

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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