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Biochar–mycorrhiza synergy: A novel approach for calcareous soil rehabilitation and sorghum yield improvement in semi-arid dryland systems

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ABSTRACT

The potential of calcareous soils in semi-arid dryland areas is considerable; however, these soils face major constraints, including high pH, low organic matter content, and limited nutrient availability, which often result in low crop productivity. This study aims to evaluate the effectiveness of the integrated application of locally sourced organic biochar and arbuscular mycorrhizal fungi (AMF) inoculation in improving calcareous soil conditions and enhancing sorghum yield. The field experiment was conducted using a randomized complete block design (RCBD), involving seven types and dosages of biochar and two levels of mycorrhizal application. Biochar was applied prior to planting, while AMF was directly inoculated onto sorghum seeds. The results demonstrated that the combination of biochar and mycorrhiza significantly reduced soil pH from alkaline towards neutral, and increased organic carbon content, total nitrogen, available phosphorus, exchangeable potassium, and cation exchange capacity (CEC) compared to both the control and single-treatment groups. Furthermore, the integrated treatment also led to increases in dry biomass, plant N and P uptake, and sorghum grain yield. These improvements are associated with the release of organic acids from biochar, enhanced soil microbial activity, and the expansion of root absorption zones by mycorrhiza. Thus, the synergy between biochar and mycorrhiza has proven to be effective and sustainable for the rehabilitation of calcareous soils in semi-arid dryland environments.

Keywords: biochar, arbuscular mycorrhiza, calcareous soil, sorghum yield.

INTRODUCTION

One of the main challenges of semi-arid dryland areas in East Nusa Tenggara, aside from climatic factors, is that these regions are predominantly characterized by calcareous soils. The most prominent characteristics of calcareous soils include a shallow solum, low fertility due to limited soil nutrient content and low organic carbon levels (>2%), as well as an alkaline reaction, which restricts the availability of nutrients for plant growth. As a result, the productivity of dryland areas remains relatively low (Matheus, 2024). Nevertheless, calcareous soils possess significant potential for agricultural development due to their favorable physical properties, particularly their loose texture and good drainage capacity.

One promising approach to improving the productivity of calcareous soils is the utilization of biochar. Numerous studies have revealed that biochar serves as an important soil amendment, playing a significant role in enhancing the soil's water and nutrient retention capacity, reducing excessive pH (alkalinity), and improving cation exchange capacity (Abukari et al., 2022; Abujabhah et al., 2016). This is attributed to the fact that biochar contains carbon that is highly resistant to decomposition, allowing it to persist longer in the soil and function as an effective carbon sink (Wang et al., 2016; Kammann et al., 2017; Murtaza et al., 2023). The increase in soil carbon reserves is crucial for improving soil ecosystem functions and supporting climate change mitigation through long-term carbon sequestration (Lehmann et al., 2011; Woolf et al., 2010; Kammann et al., 2017; Murtaza et al., 2023). Thus, the addition of biochar not only improves the physical and chemical properties of the soil but also strengthens the role of soil as a sustainable carbon reservoir, particularly in calcareous soils (Zimmerman et al., 2011; Chen et al., 2017; Liu et al., 2013).

In addition, the presence of biochar also functions as a source of stable organic carbon, thereby improving soil structure and reducing nutrient losses through leaching (Murtaza et al., 2023; Dai et al., 2017; Agegnehu et al., 2016). Various studies have concluded that biochar amendments have superior capabilities in improving soil properties, including physical, chemical, and biological characteristics, compared to mineral amendments (Martinez et al., 2018; Mensah, 2015). Therefore, the addition of biochar not only improves the physical and chemical properties of the soil but also strengthens the role of soil as a sustainable carbon reservoir (Zimmerman et al., 2011; Chen et al., 2017; Liu et al., 2013).

In addition to biochar as a soil amendment, the presence of arbuscular mycorrhizal fungi also plays a vital role in improving soil quality and plant nutrition in calcareous soils. Mycorrhizal inoculation in calcareous soils can enhance nutrient uptake, stimulate the development of plant roots and hyphal networks, and increase plant tolerance to environmental stresses (Al-Silmawy et al., 2025; Güereña et al., 2015). Mycorrhizae have also been shown to contribute to the improvement of soil physical properties, particularly soil structure and aggregation, as well as to promote beneficial soil microbial activity, thereby creating more favorable conditions for plant growth in both dryland and calcareous soils (Mustafa et al., 2019; Güereña et al., 2015; Al-Silmawy et al., 2025).

Research on the individual potential of biochar and arbuscular mycorrhizal fungi has been extensively conducted (Al-Silmawy et al., 2025; Liang et al., 2023; Kammann et al., 2015; Biederman and Harpole, 2013; Liu et al., 2013). However, studies that synergize the application of biochar and mycorrhiza for the rehabilitation of calcareous soils in semi-arid regions remain limited. Therefore, it is necessary to conduct an investigation to evaluate the synergy between biochar application and mycorrhizal inoculation in improving the productivity of calcareous soils in dryland areas and enhancing sorghum yield.

MATERIALS AND METHODS

Study site description

The field experiment was conducted during the March–June 2023 growing season at the Experimental Farm of the State Agricultural Polytechnic of Kupang, located in Oesao Village, Kupang Tengah District, Kupang Regency (10°07′1.6″ S; 123°48′38.1″ E). The research site is characterized by clay-textured soil (71.25%), poor drainage, an alkaline soil pH of 7.71, and an organic carbon content of 2.17%.

Experimental design

The field experiment was arranged in a randomized complete block design (RCBD) with a factorial treatment structure. The first factor was the type and dosage of biochar, comprising seven treatments: (1) control/no amendment, (2) livestock manure biochar at 2 t ha^{-1}, (3) livestock manure biochar at 4 t ha^{-1}, (4) maize cob biochar at 2 t ha^{-1}, (5) maize cob biochar at 4 t ha^{-1}, (6) gliricidia pruning biochar at 2 t ha^{-1}, and (7) gliricidia pruning biochar at 4 t ha^{-1}. The second factor was mycorrhizal application, consisting of two levels: without mycorrhiza and with mycorrhiza. Each treatment combination was replicated three times, resulting in a total of 42 experimental units. Each experimental plot measured 1.2 × 4 m, with a 1 m buffer between plots. All treatment combinations were evaluated to assess their effects on soil chemical properties, nutrient uptake, and sorghum yield in calcareous dryland conditions.

The biochar utilized in this study was produced from locally sourced organic materials, specifically livestock manure, maize cobs, and gliricidia prunings, through pyrolysis at a temperature of 350 °C. The chemical characteristics of the resulting biochar are presented in Table 1.

In general, biochar derived from plant residues (such as maize cobs and gliricidia prunings) tends to exhibit higher organic carbon content and macronutrient levels (notably phosphorus and potassium) compared to biochar produced from livestock manure. These differences are attributable to the intrinsic properties of the feedstock

Table 1. Chemical properties of biochar

Biochar type	pH	C-org (%)	N	P(%)	K (%)
Livestock manure	8.92	46.39	0.26	0.20	4.37
Maize cob	7.85	66.87	0.32	0.32	6.65
Gliricidia pruning	7.65	59.65	0.28	0.28	5.38

materials and the pyrolysis process, which influence the formation of stable carbon fractions and the concentration of specific minerals. Consequently, each type of biochar demonstrates distinct advantages: livestock manure biochar is particularly effective in increasing soil pH, whereas maize cob and gliricidia biochars are more advantageous for enhancing organic carbon content and the availability of macronutrients. Therefore, plant residue-derived biochars are considered more suitable for improving the fertility of calcareous soils.

The arbuscular mycorrhizal fungi (AMF) inoculum used in this study was obtained from the Soil Biology Laboratory, Faculty of Agriculture, University of Nusa Cendana, Kupang, and consisted of a mixed culture of indigenous AMF species (*Glomus mosseae*, *Glomus fasciculatum*, and *Rhizophagus irregularis*) commonly found in calcareous soils of East Nusa Tenggara. The inoculum was prepared using a carrier-based system with sterilized vermiculite as the substrate, where vermiculite was autoclaved at 121 °C for 30 minutes, mixed with AMF spores and root fragments at a 1:1 (v/v) ratio, and incubated at 25±2 °C with 60–70% relative humidity for 4 weeks to allow spore germination and hyphal development before storage at 4 °C. The resulting inoculum contained approximately 50–80 spores per gram of carrier material with >85% viability, which was mixed with sterile distilled water (10 g inoculum per 100 ml water) and applied to sorghum seeds at a rate of 2 g inoculum per 100 seeds, ensuring uniform distribution of AMF spores on the seed surface before air-drying for 30 minutes prior to planting.

Research procedure

The experimental procedure commenced with the preparation of the field plots, which were uniformly tilled in accordance with the RCBD and the predetermined plot layout to ensure soil homogeneity prior to treatment application. Subsequently, biochar was applied at treatment-specific rates before sorghum sowing. The biochar was incorporated in furrows aligned with the designated planting distances and lightly mixed into the soil within the furrow area. Thereafter, AMF inoculum was thoroughly mixed with sorghum seeds prior to planting. The inoculated seeds were then sown directly into planting holes at a spacing of 80 × 40 cm, as specified in the experimental design.

Basal fertilization was applied at planting using P fertilizer (SP-36) and K fertilizer (KCl) at rates of 90 kg ha^{-1} and 60 kg ha^{-1}, respectively. Meanwhile, N fertilizer (urea) was applied at a total rate of 120 kg ha^{-1}, divided into two applications: 50% at 2 weeks after planting and the remaining 50% at 45 days after planting. During the growth period, weed control was performed manually to prevent nutrient competition, and irrigation was provided regularly to maintain optimal soil moisture for plant growth. All other maintenance practices were applied uniformly across all plots.

The sorgum plants were harvested at the predetermined maturity stage and according to established harvest criteria. All yield data were subsequently observed and analyzed based on the research parameters. Through this structured implementation process, it is expected that all treatments were applied consistently, thereby enhancing the validity and informativeness of the research findings.

Observed parameters

Soil samples were collected at the end of the experimental period for the analysis of soil chemical properties. The parameters assessed included: soil pH (measured using a pH meter in H_2O extract), organic carbon content (determined by the Walkley and Black method), total nitrogen (analyzed using the Micro Kjeldahl method), available phosphorus (Bray-2 method), exchangeable potassium, and cation exchange capacity (CEC) (both extracted with 1N NH4OAc). Plant samples were collected at the maximum vegetative stage (50 days after planting) to determine total nitrogen and total phosphorus content in plant tissues. For yield and yield component parameters, measurements were conducted for grain weight per plant (g/plant), 1000-grain weight (g), and sorghum yield per hectare (t/ha). All analyses and measurements were performed using standardized laboratory and agronomic procedures to ensure that the resulting data accurately and systematically represent the effects of the treatments.

Statistical analysis methods

Statistical analyses in this study were performed using analysis of variance (ANOVA) to evaluate the effects of treatments on each observed parameter. When significant differences were detected, post hoc comparisons were conducted using the least significant difference (LSD) test at a 5% significance level to distinguish among treatment means.

RESULTS AND DISCUSSION

Soil chemical properties

The results of the study indicate that the application of biochar in combination with mycorrhiza had a significant effect ($p<0.05$) on improving the chemical properties of calcareous soil at the end of the experiment. In general, all observed variables (soil pH, organic carbon, total nitrogen, available phosphorus, exchangeable potassium, and cation exchange capacity) showed improvements in soil chemical properties compared to the control, particularly in the treatment involving maize cob biochar at a rate of 4 t ha^{-1} combined with mycorrhiza. This finding confirms that the combination of these two soil amendments can synergistically enhance soil fertility quality. The effects of biochar type with and without mycorrhiza on soil chemical properties are presented in Figures 1–6. Each figure shows the comparison between treatments with and without mycorrhizal inoculation for specific soil parameters.

Soil pH alteration

The analysis of Figure 1, indicates that the application of various types of biochar, both approaches near-neutral pH values (7.56–7.59) in the lower-dose biochar treatment (2 t ha^{-1}). The most significant pH reduction was observed in the treatment combining maize cob biochar at a rate of 4 t ha^{-1} with mycorrhiza, reaching a pH of 7.44. Meanwhile, biochar treatments without mycorrhiza also resulted in a decrease in pH, although the effect was less pronounced compared to the combination with mycorrhiza. Although

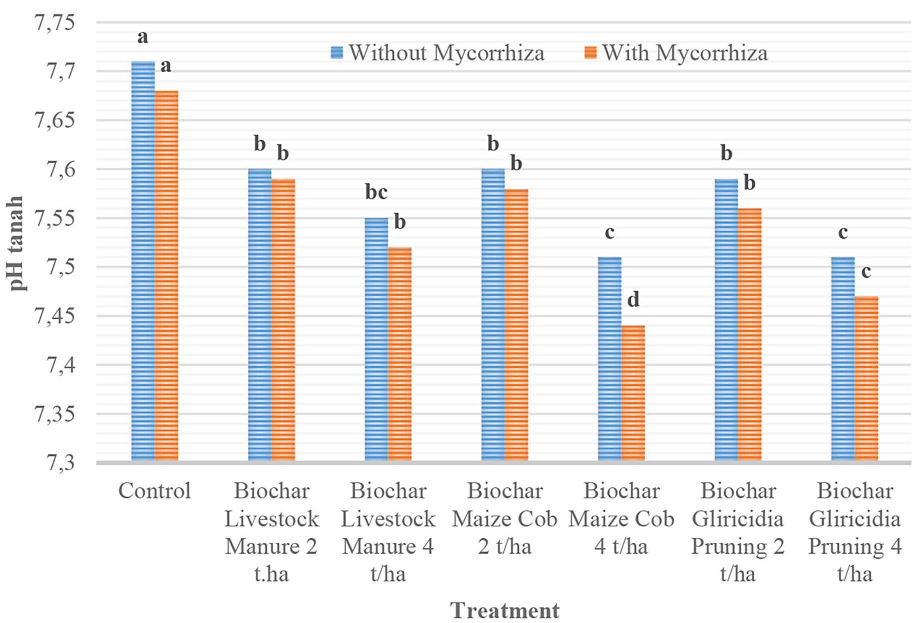

Figure 1. Soil pH (pH H_2O) under different biochar treatments with and without mycorrhiza [Bar chart showing pH values for each treatment, with separate bars for without mycorrhiza (blue) and with mycorrhiza (orange)]. Values followed by the same letter are not significantly different according to the LSD test at the 5% significance level

this reduction is relatively small, it has a highly important effect on calcareous soils, which are generally alkaline in nature (Shen et al., 2016).

This decrease is presumed to be associated with the presence of acidic functional groups such as carboxyl and phenolic groups, as well as organic acid compounds released from biochar, thereby increasing the concentration of H^+ ions in the soil (Dai et al., 2017). In addition, biochar plays a role in enhancing the soil's buffering capacity, which facilitates the neutralization of pH through the contribution of organic acids (Bruun et al., 2014b). The presence of mycorrhizae further amplifies this effect through root exudates and hyphal metabolites that are capable of dissolving basic cations and stimulating soil microbial activity, thus rendering the soil environment more reactive and supporting nutrient availability (Barrow and Hartemink, 2023; Ferrarezi et al., 2022; Chen et al., 2017).

A similar study was also reported by Ahmad et al. (2020), which demonstrated that biochar can reduce the pH of calcareous soils by 0.2–0.4 units, thereby increasing the availability of macro- and micronutrients. The results of the present study confirm that although biochar is often associated with increasing pH in acidic soils, in calcareous soils, its effect is instead a beneficial reduction in pH (Glaser et al., 2015). The addition of mycorrhizae, although not drastically lowering the pH, contributes to maintaining soil pH stability through its biological activity, thus ensuring that the soil environment remains optimal for sorghum growth (Yang et al., 2020). Therefore, it is evident that the synergy between biochar and mycorrhizae is more effective in lowering and stabilizing soil pH compared to single treatments.

Soil organic carbon content

The application of biochar from various sources significantly increased soil organic carbon (SOC) content compared to the control. In the control treatment, SOC levels ranged only from 2.17% to 2.20%, whereas treatments with biochar elevated these values to 2.48–2.68%. The highest increase was observed in the treatment with maize cob biochar at a rate of 4 t ha^{-1} combined with mycorrhiza, reaching 2.68% (Figure 2). The mycorrhizal treatment further enhanced this effect by increasing root exudates and rhizodeposition, thereby providing additional organic matter in the rhizosphere.

These findings confirm that biochar, particularly high-dose maize cob biochar combined with mycorrhiza, serves as a potential ameliorant for improving the chemical fertility of calcareous soils through increased SOC content. This increase not only augments the pool of organic matter but also acts as a source of stable carbon (recalcitrant carbon), thus contributing in the long term to the enhancement of soil organic matter reserves (Vahedi et al., 2022) and strengthening the function of sustainable soil ecosystems. The stable carbon in biochar originates from aromatic

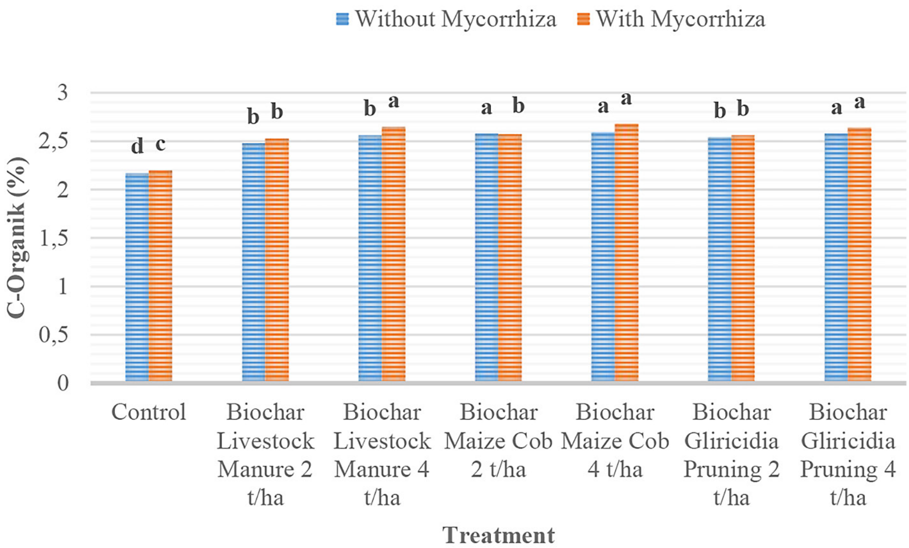

Figure 2. Soil organic carbon content (%) under different biochar treatments with and without mycorrhiza [Bar chart showing organic C values for each treatment, with separate bars for without mycorrhiza (blue) and with mycorrhiza (orange)]. Values followed by the same letter are not significantly different according to the LSD test at the 5% significance level

structures formed during pyrolysis, which are highly resistant to microbial activity (Abukari et al., 2022; Abujabhah et al., 2016).

The increase in SOC content following biochar application is primarily attributed to two main factors. First, biochar introduces stable carbon (recalcitrant carbon) that is resistant to microbial decomposition, allowing it to persist in the soil for extended periods. Second, the presence of biochar stimulates microbial activity, which subsequently accelerates the decomposition of organic matter and promotes the formation of more stable soil aggregates (Lehmann et al., 2011; Jeffery et al., 2015; Chen et al., 2017). In addition, biochar contributes to improving soil structure and enhancing water retention capacity, which in turn supports root growth and root exudation. The presence of mycorrhizae further amplifies the effects of biochar by increasing root exudation and microbial activity in the rhizosphere, thereby ensuring a more sustainable reserve of soil organic carbon (Abujabhah et al., 2016; Smith and Read, 2008)

Total nitrogen

The total nitrogen content in the control treatment was relatively low, at approximately 0.17%. The application of biochar, whether derived from livestock manure or maize cob, increased the total soil nitrogen (N-total) content to a range of 0.21–0.24%. The highest increase was observed in the treatment with maize cob biochar at a rate of 4 t ha^{-1} combined with mycorrhiza, reaching 0.24% (Figure 3).

These results indicate that biochar application can reduce nitrogen losses through leaching and volatilization, as the porous structure of biochar is capable of adsorbing ammonium (NH_4^+) and nitrate (NO_3^-) ions, thereby maintaining nitrogen availability in the soil (Murtaza et al., 2023). In addition, biochar creates a conducive microhabitat for soil microorganisms involved in the nitrogen cycle, such as nitrogen-fixing bacteria and organic matter decomposers, thus increasing soil N content. The increase in total nitrogen due to biochar application is consistent with the concept that biochar acts as a nitrogen reservoir while simultaneously slowing the mineralization cycle, resulting in more stable nitrogen in the soil (Clough et al., 2013).

The total soil nitrogen (N-total) content increased significantly in biochar treatments combined with mycorrhiza compared to the control.

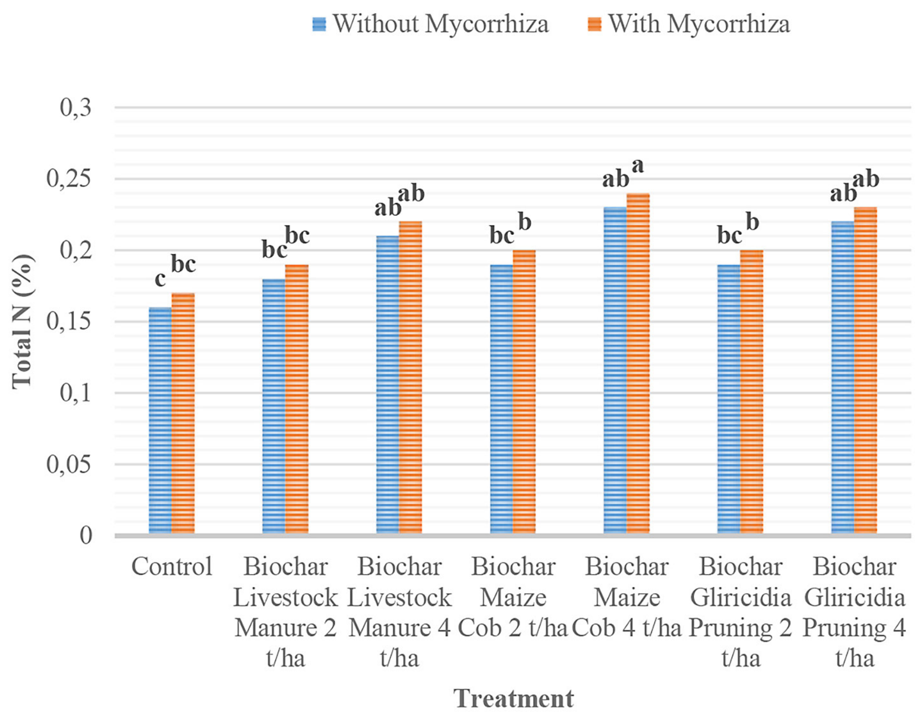

Figure 3. Total soil nitrogen content (%) under different biochar treatments with and without mycorrhiza. [Bar chart showing total N values for each treatment, with separate bars for without mycorrhiza (blue) and with mycorrhiza (orange)]. Values followed by the same letter are not significantly different according to the LSD test at the 5% significance level

The interaction between these two amendments plays an important role, as mycorrhiza functions to expand the root exploration area, enhance nitrogen uptake efficiency, and enrich nitrogen reserves in the rhizosphere through enzymatic activity (Mustafa et al., 2019; Hagemann et al., 2017). Several studies have also reported that the application of biochar together with mycorrhiza can increase N-total through increased microbial biomass and soil biological activity (Gul and Whalen, 2016). Biochar itself helps maintain nitrogen by improving CEC and soil porosity, thereby reducing nitrogen losses due to leaching (Chen et al., 2017; Bruun et al., 2014b; Vahedi et al., 2022). Meanwhile, mycorrhiza also improves nitrogen utilization efficiency through the expansion of the root system and interaction with nitrogen-fixing bacteria (Yang et al., 2020; Bruun et al., 2014b).

Available phosphorus

The results of this study consistently demonstrate that the available phosphorus (P-available) content increased significantly in the biochar treatments compared to the control. In the control treatment, the P-available value was only 6.45 ppm, whereas in the treatment with maize cob biochar at a dose of 4 t ha^{-1} combined with mycorrhiza, the value reached 8.11 ppm (Figure 4).

This increase in phosphorus (P) is particularly important because calcareous soils generally have limited phosphorus availability due to the binding of phosphate by calcium in the form of poorly soluble Ca-phosphate (Matheus et al., 2024; Abukari et al., 2022). The application of biochar enhances phosphorus availability (P-available) through the release of P from its ash and by improving soil pH towards a more moderate range, thereby facilitating the decomposition of P-Ca complexes (Liang et al., 2023).

Exchangeable potassium

In the control treatment, the K-dd value was only 54.05 ppm, while the application of maize cob biochar at a dose of 4 t ha^{-1} combined with mycorrhiza was able to increase K-dd to 73.91 ppm. This increase is primarily attributed to the ash content of maize cob biochar, which is rich in potassium (K) (approximately 6.65%), as well as the porous and negatively charged structure of biochar, thereby providing a greater contribution to nutrient availability compared to biochar from other sources.

Figure 5 shows that exchangeable potassium (K-dd) levels increased sharply in biochar treatments, particularly those derived from maize cobs. This increase is primarily influenced by two factors. First, biochar ash contains potassium that can be released directly into the soil. Second, the presence of biochar improves CEC, enabling the soil to better retain K^+ ions and reduce potassium losses due to leaching (Rogovska et al., 2014; Rogovska

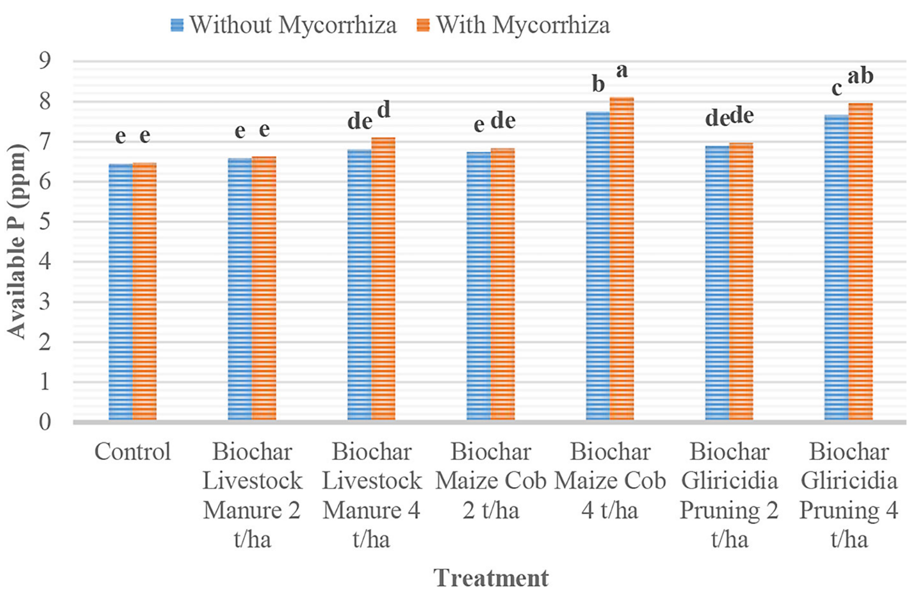

Figure 4. Available phosphorus (ppm) under different biochar treatments with and without mycorrhiza [Bar chart showing available P values for each treatment, with separate bars for without mycorrhiza (blue) and with mycorrhiza (orange)]. Values followed by the same letter are not significantly different according to the LSD test at the 5% significance level

et al., 2016). The characteristics of plant residue-derived biochar, which is rich in potassium, make it more effective in enriching the availability of this element compared to other types of biochar (Liang et al., 2023; Glaser et al., 2015).

Cation exchange capacity (CEC)

The results of the study indicate that the soil CEC increased significantly from 17.13 me/100 g in the control to 29.42 me/100 g in the treatment with maize cob biochar at 4 t ha^{-1} combined with mycorrhiza (Figure 6). This increase underscores the role of biochar as an additional source of cation exchange sites, attributed to its large surface area and the presence of negatively charged functional groups (Glaser et al., 2015; Biederman and Harpole, 2013). Furthermore, the ash content of biochar also contributes basic cations that enrich the soil nutrient reserves. Mycorrhiza further enhances this effect by maintaining soil aggregate stability and stimulating microbial activity, thereby enabling the soil system to more sustainably retain essential nutrients (Matheus et al., 2024).

This increase in CEC is particularly relevant in calcareous soils, which generally possess low charge due to the dominance of $CaCO_3$ (Matheus et al., 2024). Biochar, as a stable organic material, improves colloidal charge, nutrient retention, and nutrient availability, as reported by Bruun et al. (2014a) in dry and sandy soils. The study by Glaser et al. (2015) also confirms that increasing biochar dosage is positively correlated with higher CEC. Thus, the synergy between biochar and mycorrhiza creates optimal conditions, wherein biochar provides cation binding sites and mycorrhiza enhances soil biological activity, collectively improving nutrient retention capacity and supporting sorghum productivity in calcareous dryland soils.

Dry biomass and plant uptake of N and P nutrients

Plant growth and productivity are fundamentally determined by the plant's ability to utilize nutrients available in the soil. Alterations in soil chemical properties resulting from the application of biochar and mycorrhizae not only affect the soil's physicochemical conditions but also have a direct impact on biomass accumulation and the uptake of essential nutrients by plants. In this context, dry biomass reflects the cumulative outcome of vegetative growth, while nitrogen (N) and phosphorus (P) uptake indicate the efficiency of utilization of key macronutrients essential for plant development. Therefore, the analysis of dry biomass as well as N and P uptake in sorghum serves as a critical indicator for assessing the extent to which biochar treatments, either applied singly or in combination with mycorrhizal inoculation, can

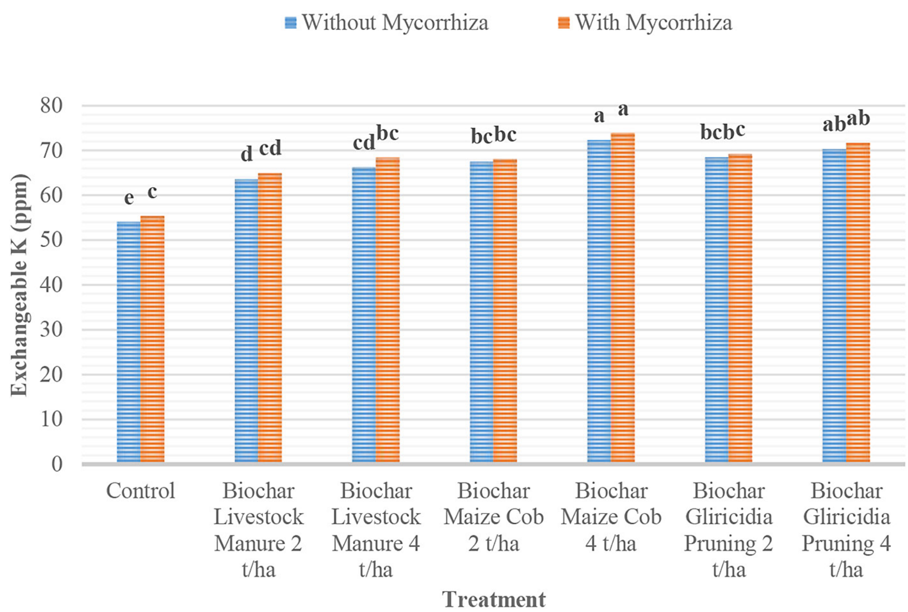

Figure 5. Exchangeable potassium (ppm) under different biochar treatments with and without mycorrhiza. [Bar chart showing exchangeable K values for each treatment, with separate bars for without mycorrhiza (blue) and with mycorrhiza (orange)]. Values followed by the same letter are not significantly different according to the LSD test at the 5% significance leve

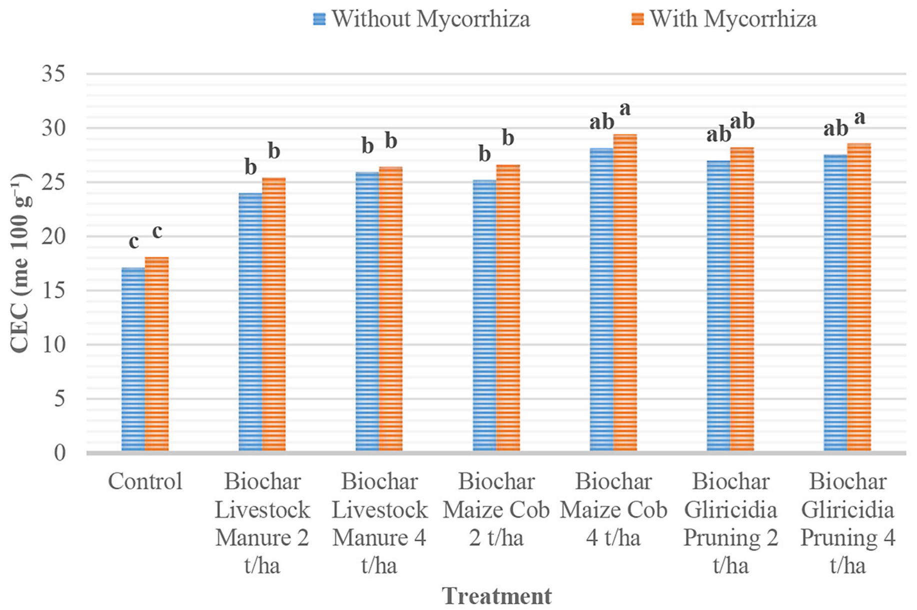

Figure 6. Cation exchange capacity (me 100 g^{-1}) under different biochar treatments with and without mycorrhiza. [Bar chart showing CEC values for each treatment, with separate bars for without mycorrhiza (blue) and with mycorrhiza (orange)]. Values followed by the same letter are not significantly different according to LSD test at 5% significance level

enhance nutrient use efficiency and support plant productivity in calcareous dryland soils. The results of the analysis of dry biomass and nutrient uptake are presented in Figures 7–9.

Plant dry biomass

The results of the study consistently demonstrate that the application of biochar increases the dry biomass weight of sorghum compared to the control. Plants in the control treatment produced only 69.43 g plant^{-1} of dry biomass (without mycorrhiza) and 73.18 g plant^{-1} (with mycorrhiza), whereas the combination of maize cob biochar at a rate of 4 t ha^{-1} and mycorrhiza was able to produce a dry biomass of 85.79 g plant^{-1} (Figure 7).

The synergy between biochar and mycorrhiza has been proven to exert a positive effect on increasing plant dry biomass. This occurs because biochar improves soil porosity and water-holding capacity, thereby creating soil conditions that are more conducive to root development (Agegnehu et al., 2016; Purakayastha et al., 2015). Simultaneously, mycorrhiza functions to expand the nutrient absorption zone through its external hyphal network, which is capable of reaching soil areas inaccessible to roots (Abujabhah et al., 2016). The combination of these two treatments results in a greater increase in dry biomass compared to the application of either biochar or mycorrhiza alone.

Plant nitrogen uptake

Nitrogen uptake consistently exhibited a significant increase in all biochar treatments compared to the control. In the control treatment, nitrogen uptake was only 2.15% without mycorrhiza and 2.40% with mycorrhiza, whereas the application of maize cob biochar at a rate of 4 t ha^{-1} resulted in the highest values, namely 3.17% without mycorrhiza and 3.34% with mycorrhiza (Figure 8).

The increase in nitrogen uptake indicates that biochar serves as an environmental amendment that supports soil nitrogen availability, while mycorrhizae contribute by expanding the root exploration area, thereby enhancing N uptake. Biochar derived from cattle manure and maize cobs demonstrates high effectiveness due to its content of decomposable organic nitrogen, which provides a sustainable source of N for plants (Cayuela et al., 2014). Mycorrhizae play a role in improving the efficiency of N absorption through the expansion of the hyphal system, which can access N from areas beyond the reach of roots, as well as by increasing the activity of enzymes involved in nitrogen assimilation (Clough et al., 2013). This increase in nitrogen uptake is crucial for supporting vegetative growth and sorghum productivity in dryland areas, as N is a macronutrient essential for protein and chlorophyll synthesis.

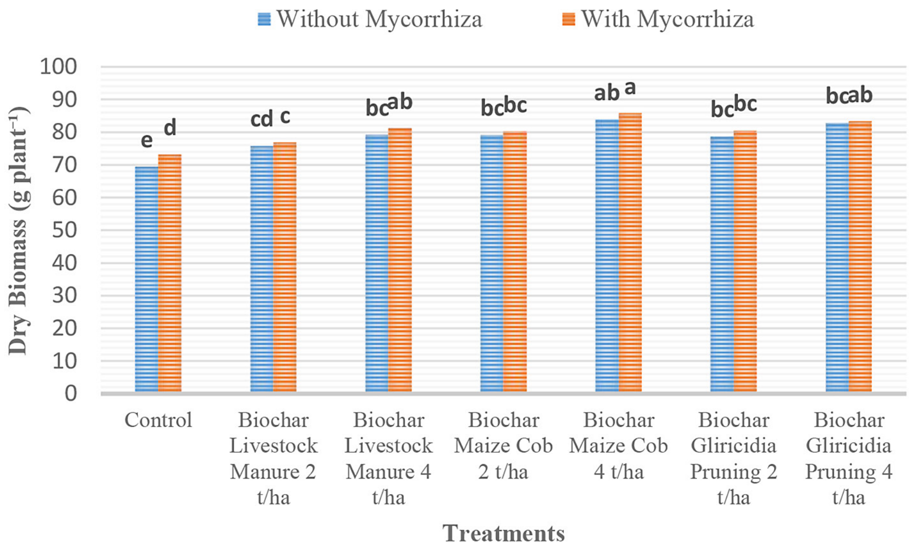

Figure 7. Dry biomass (g plant^{-1}) of sorghum under different biochar treatments with and without mycorrhiza. [Bar chart showing dry biomass values for each treatment, with separate bars for without mycorrhiza (blue) and with mycorrhiza (orange)]. Values followed by the same letter are not significantly different according to the LSD test at the 5% significance level

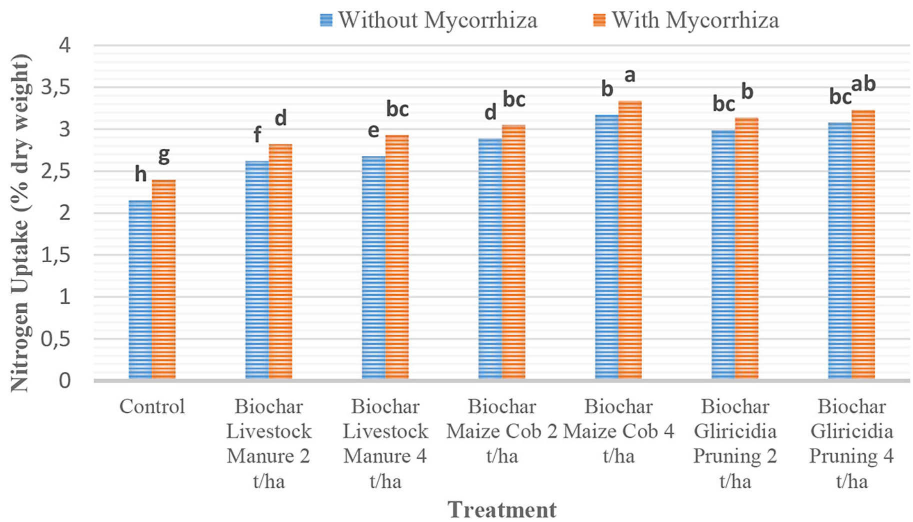

Figure 8. Nitrogen uptake (% dry weight) of sorghum under different biochar treatments with and without mycorrhiza. [Bar chart showing nitrogen uptake values for each treatment, with separate bars for without mycorrhiza (blue) and with mycorrhiza (orange)]. Values followed by the same letter are not significantly different according to the LSD test at the 5% significance level

Plant phosphorus uptake

The data on phosphorus uptake exhibited a pattern similar to that of nitrogen, wherein the biochar treatments consistently resulted in higher values compared to the control. In the control treatment, phosphorus uptake was only 1.07% without mycorrhiza and 1.24% with mycorrhiza, while the highest increase was observed in the maize cob biochar treatment at 4 t ha^{-1} combined with mycorrhiza, reaching 2.61% (Figure 9). This increase is attributed to the ability of biochar to improve soil reaction and provide available phosphorus, as well as the role of mycorrhiza in solubilizing bound phosphorus through the secretion of organic acids (Shen et al., 2016; Mukherjee and Lal, 2013). Maize cob biochar demonstrated high effectiveness in enhancing phosphorus uptake due to its content of decomposable organic phosphorus, which can be released into the soil solution, and its high adsorption capacity, which reduces phosphorus fixation

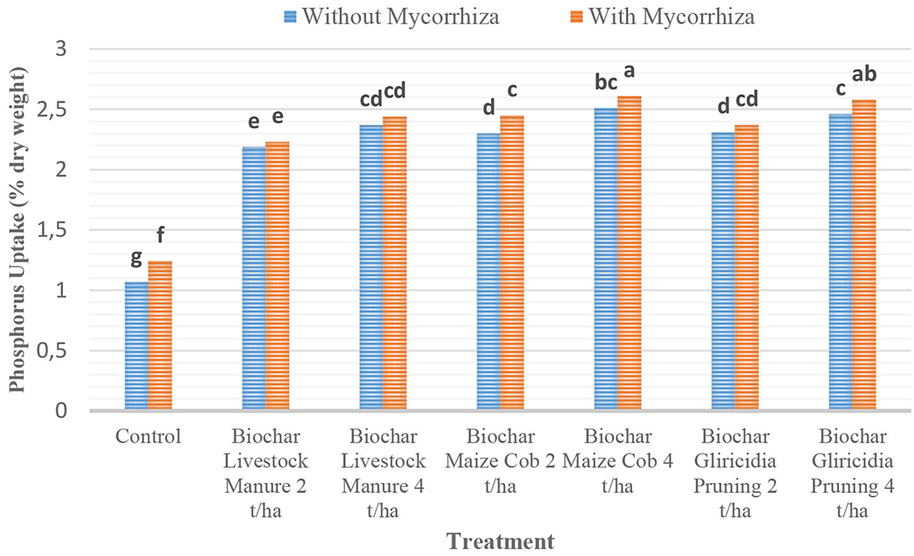

Figure 9. Phosphorus uptake (% dry weight) of sorghum under different biochar treatments with and without mycorrhiza. [Bar chart showing phosphorus uptake values for each treatment, with separate bars for without mycorrhiza (blue) and with mycorrhiza (orange)]. Values followed by the same letter are not significantly different according to the LSD test at the 5% significance level

by calcium in calcareous soils (Al-Wabel et al., 2013; Rajapaksha et al., 2014).

Mycorrhizae play a crucial role in enhancing phosphorus (P) availability by expanding the hyphal network, which can access P from soil areas that are inaccessible to plant roots, as well as through the secretion of organic acids such as citric and oxalic acids that solubilize P bound in soil minerals (Yang et al., 2020). This increase in P uptake demonstrates the potential of biochar and mycorrhizae to address P deficiency in dry soils, which is a common issue in calcareous lands where P is often bound by calcium and thus becomes unavailable to plants (Abukari et al., 2022; Shen et al., 2016). The synergy between biochar and mycorrhizae creates optimal conditions in which biochar supplies additional P and reduces fixation, while mycorrhizae enhance the efficiency of P uptake by sorghum plants.

Yield and yield components

In addition to influencing soil properties and vegetative growth, the application of biochar and mycorrhizae also exerts a significant effect on sorghum yield and its yield components. Parameters such as grain weight per plant, 1000-grain weight, and overall yield serve as indicators of the effectiveness of these treatments in enhancing productivity on calcareous dryland soils.

Grain weight per plant

The application of biochar had a significant effect on the grain weight per sorghum plant compared to the control. The best result was obtained with maize cob biochar at a rate of 4 t ha^{-1} combined with mycorrhiza, reaching 50.57 g per plant (Figure 10).

This increase in grain weight indicates that the combination of biochar and mycorrhiza is capable of improving nutrient availability and extending the grain filling period, thereby significantly increasing grain weight (Rogovska et al., 2016). Maize cob biochar demonstrated high effectiveness due to its ability to provide balanced nutrients and improve soil conditions that support the generative development of plants (Glaser et al., 2015). Mycorrhiza plays a role in enhancing nutrient uptake efficiency during the generative phase, thus supporting optimal grain formation and filling. Therefore, the integration of these two treatments makes a substantial contribution to improving sorghum yield components through enhanced nutrient availability and uptake efficiency.

Thousand-grain weight

A significant increase in the thousand-grain weight of sorghum was observed across all biochar treatments, with the lowest values recorded in the control (24.41 g without mycorrhiza and 26.08 g with mycorrhiza) and the highest in the

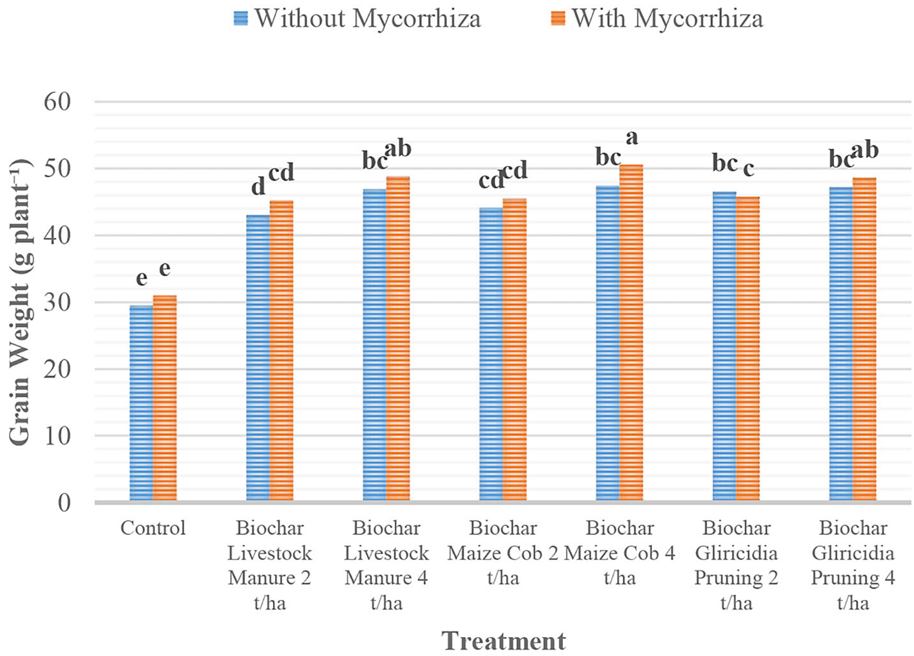

Figure 10. Grain weight per plant (g plant^{-1}) of sorghum under different biochar treatments with and without mycorrhiza. [Bar chart showing grain weight values for each treatment, with separate bars for without mycorrhiza (blue) and with mycorrhiza (orange)]. Values followed by the same letter are not significantly different according to the LSD test at the 5% significance level

combination of maize cob biochar at a rate of 4 t ha^{-1} with mycorrhiza (36.47 g). This increase in grain weight indicates an improvement in seed quality, which is closely related to the enhanced availability of macronutrients, particularly nitrogen and phosphorus, in the soil (Shen et al., 2016) (Figure 11).

Maize cob biochar plays a crucial role in providing a more balanced nutrient supply while simultaneously improving soil structure, thereby supporting optimal plant growth and development (Al-Wabel et al., 2013). On the other hand, mycorrhizal inoculation has been proven to enhance nutrient uptake efficiency and increase plant resilience to environmental stresses, which ultimately has a positive impact on yield and its components. The combination of biochar and mycorrhiza results in a higher thousand-grain weight compared to other treatments. These findings reinforce the synergistic benefits of applying both amendments simultaneously.

Sorghum yield per hectare

Sorghum yield (t ha^{-1}) exhibited a consistent increase, in line with other yield components. In the control treatment, yield reached only 2.54 t ha^{-1} without mycorrhizal inoculation and 2.76 t ha^{-1} with mycorrhizal inoculation. In contrast, the application of maize cob biochar at a rate of 4 t ha^{-1} in combination with mycorrhizae resulted in the highest yield, reaching 3.92 t ha^{-1}, representing an increase of approximately 42% compared to the control. This improvement underscores the synergistic effectiveness of biochar and mycorrhizae in enhancing sorghum productivity on calcareous dryland soils (Figure 12).

The observed increase in crop yield is closely associated with improvements in soil chemical properties, such as elevated levels of organic carbon, total nitrogen, available phosphorus, exchangeable potassium, and cation exchange capacity. Collectively, these changes contribute to enhanced nutrient uptake efficiency by plants (Bruun et al., 2014a; Kammann et al., 2017). Maize cob biochar plays a crucial role in providing a balanced nutrient supply and improving soil structure, thereby supporting optimal plant growth and development (Al-Wabel et al., 2013). On the other hand, the application of mycorrhizae has been proven to increase nutrient uptake efficiency and plant resilience to environmental stress, which is particularly important for maintaining productivity on marginal lands (Al-Silmawy et al., 2025; Murtaza et al., 2023; Neina, 2019).

Thus, the integration of biochar and mycorrhizae not only significantly enhances sorghum

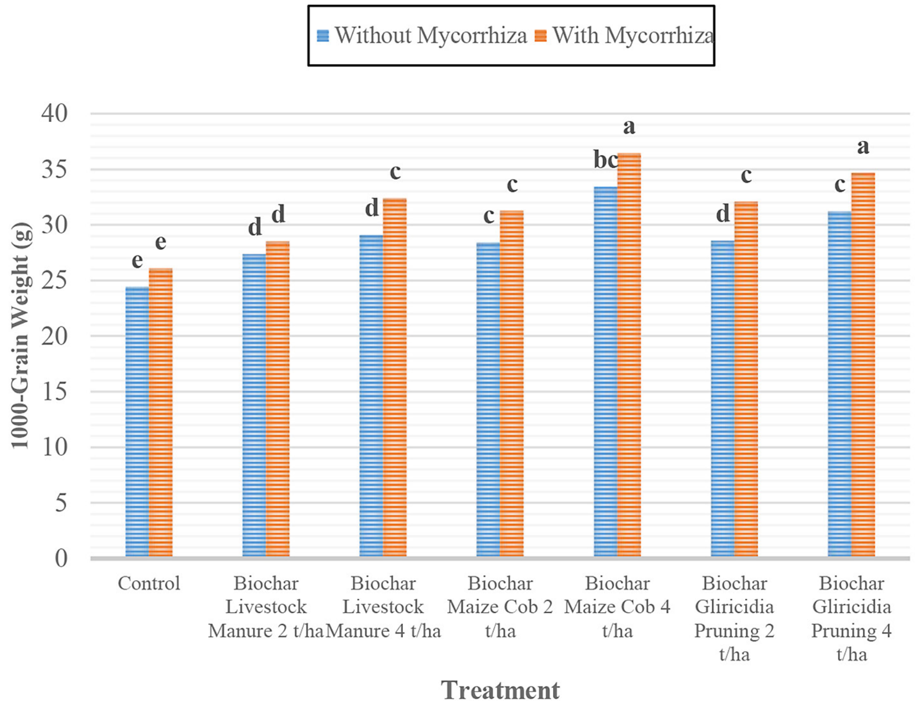

Figure 11. 1000-grain weight (g) of sorghum under different biochar treatments with and without mycorrhiza. [Bar chart showing 1000-grain weight values for each treatment, with separate bars for without mycorrhiza (blue) and with mycorrhiza (orange)]. Values followed by the same letter are not significantly different according to the LSD test at the 5% significance level

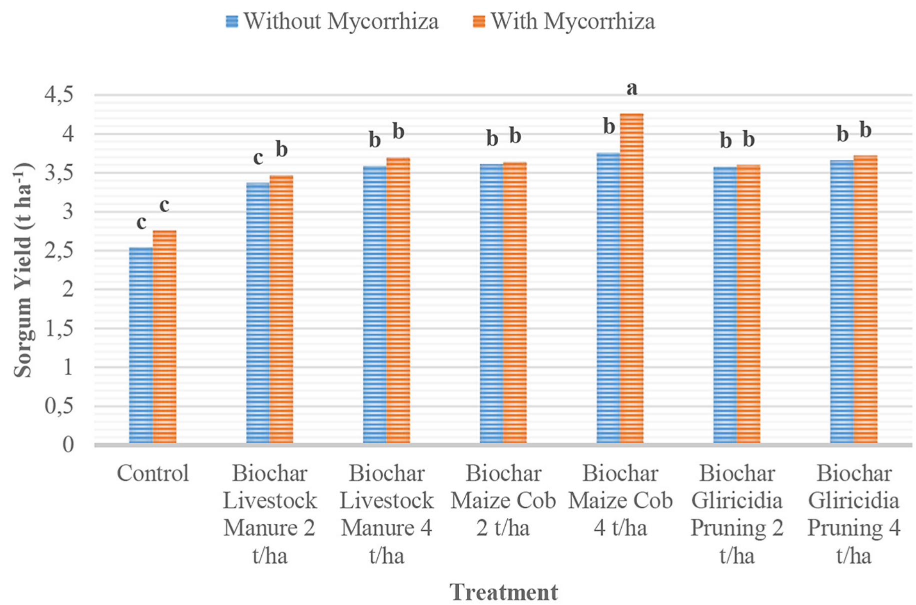

Figure 12. Sorghum yield (t ha^{-1}) under different biochar treatments with and without mycorrhiza [Bar chart showing yield values for each treatment, with separate bars for without mycorrhiza (blue) and with mycorrhiza (orange)]. Values followed by the same letter are not significantly different according to the LSD test at the 5% significance level

yield, but also establishes a more sustainable and adaptive production system in semi-arid dryland environments. The synergy between these two soil amendments serves as a key strategy for optimizing crop productivity and resilience in marginal land ecosystems. This integrated approach has been shown to significantly increase dry biomass, nitrogen and phosphorus uptake, grain weight per plant, and overall yield compared to the control. The observed improvements in productivity are supported by enhancements in soil chemical properties, such as increased CEC, available phosphorus, and exchangeable potassium, all of which contribute to more efficient nutrient uptake and plant growth. The combined application of biochar and mycorrhizae not only improves nutrient availability, but also enhances the physical and biological quality of the soil, thereby supporting plant tolerance to environmental stress. These findings underscore the importance of integrating both amendments for the sustainable management of calcareous soils, and highlight the need for further research on optimal application rates, biochar types, local mycorrhizal species, and technology adoption strategies at the farmer level.

CONCLUSIONS

The results of this study indicate that the combination of maize cob biochar at a rate of 4 t ha^{-1} with mycorrhizal inoculation is the most effective treatment for enhancing sorghum productivity on calcareous dryland soils. This treatment was proven to increase dry biomass, nitrogen and phosphorus uptake, grain weight per plant, and total yield compared to the control. The observed increase in productivity is closely associated with improvements in soil chemical properties, particularly CEC, available phosphorus, and exchangeable potassium, all of which collectively support nutrient uptake efficiency and plant growth. The synergy between biochar and mycorrhiza not only enhances nutrient availability but also improves the physical and biological quality of the soil, thereby strengthening plant resilience to environmental stress. These findings underscore the importance of integrating both amendments in the sustainable management of calcareous soils, while also opening opportunities for further research regarding optimal application rates, appropriate biochar types, local mycorrhizal species, and technology adoption strategies at the farmer level.

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REFERENCES

1. Abujabhah, I. S., Bound, S. A., Doyle, R., Bowman, J. P. (2016). Effects of biochar and compost amendments on soil physico-chemical properties and the total community within a temperate agricultural soil. *Applied Soil Ecology*, *98*, 243–253. https://doi.org/10.1016/j.apsoil.2015.10.021
2. Abukari, A., Ibrahim, A., Abukari, A. (2022). Biochar application effects on soil properties and crop productivity in semi-arid regions: A review. *Journal of Arid Environments*, *198*, 104–115. https://doi.org/10.1016/j.jaridenv.2022.104115
3. Agegnehu, G., Bass, A. M., Nelson, P. N., Bird, M. I. (2016). Benefits of biochar, compost and biochar–compost for soil quality, maize yield and greenhouse gas emissions in a tropical agricultural soil. *Science of the Total Environment*, *543*, 295–306. https://doi.org/10.1016/j.scitotenv.2015.11.054
4. Al-Silmawy, A. A., Al-Hamadani, H. J., Al-Maliki, G. M. (2025). Evaluating the interaction of mycorrhizal fungi, Azotobacter, and biochar in enhancing cucumber productivity and soil health. *Applied Soil Ecology, 185*, 104–115. https://doi.org/10.1016/j.apsoil.2024.104115
5. Al-Wabel, M. I., Al-Omran, A., El-Naggar, A. H., Nadeem, M., Usman, A. R. (2013). Pyrolysis temperature induced changes in characteristics and chemical composition of biochar produced from conocarpus wastes. *Bioresource Technology, 131*, 374–379. https://doi.org/10.1016/j.biortech.2012.12.165
6. Barrow, C. J., Hartemink, A. E. (2023). The effects of pH on nutrient availability depend on both soils and plants. *Geoderma*, *430*, 116–125. https://doi.org/10.1016/j.geoderma.2023.116125
7. Biederman, L. A., Harpole, W. S. (2013). Biochar and its effects on plant productivity and nutrient cycling: A meta-analysis. *Global Change Biology Bioenergy*, *5*(2), 202–214. https://doi.org/10.1111/gcbb.12037
8. Bruun, S., Harmer, S. L., Bekiaris, G., Christel, W., Zuin, L., Hu, Y.,..., Jensen, L. S. (2014a). The effect of different biochars on soil carbon pools and microbial communities in a sandy soil. *Soil Biology and Biochemistry, 76*, 1–10. https://doi.org/10.1016/j.soilbio.2014.04.011
9. Bruun, S., Harmer, S. L., Bekiaris, G., Christel, W., Zuin, L., Hu, Y.,..., Jensen, L. S. (2014b). The effect of different biochars on soil carbon pools

and microbial communities in a sandy soil. *Soil Biology and Biochemistry*, *76*, 1–10. https://doi.org/10.1016/j.soilbio.2014.04.011

10. Cayuela, M. L., Sánchez-Monedero, M. A., Roig, A., Hanley, K., Enders, A., Lehmann, J. (2014). Biochar and denitrification in soils: When, how much and why does biochar reduce N2O emissions? *Scientific Reports*, *3*(1), 1–7. https://doi.org/10.1038/srep01732
11. Clough, T. J., Condron, L. M., Kammann, C., Müller, C. (2013). A review of biochar and soil nitrogen dynamics. *Agronomy, 3*(2), 275–293. https://doi.org/10.3390/agronomy3020275
12. Dai, Z., Zhang, X., Tang, C., Muhammad, N., Wu, J., Brookes, P. C., Xu, J. (2017). Potential role of biochars in decreasing soil acidification-a critical review. *Science of the Total Environment*, *581*, 601–611. https://doi.org/10.1016/j.scitotenv.2016.12.169
13. Ferrarezi, R. S., Morgan, K. T., Zotarelli, L., Boman, B. J. (2022). Substrate pH influences the nutrient absorption and rhizosphere microbiome of Huanglongbing-affected grapefruit plants. *Frontiers in Plant Science*, *13*, 856–870. https://doi.org/10.3389/fpls.2022.856870
14. Glaser, B., Lehmann, J., Zech, W. (2015). Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal: A review. *Biology and Fertility of Soils*, *35*(4), 219–230. https://doi.org/10.1007/s00374-002-0466-4
15. Gul, S., Whalen, J. K. (2016). Biochemical cycling of nitrogen and phosphorus in biochar-amended soils. *Soil Biology and Biochemistry*, *103*, 1–15. https://doi.org/10.1016/j.soilbio.2016.08.001
16. Güereña, D. T., Lehmann, J., Thies, J. E., Enders, A., Karanja, N., Neufeldt, H. (2015). Partitioning the contributions of biochar properties to enhanced biological nitrogen fixation in common bean (Phaseolus vulgaris). *Biology and Fertility of Soils*, *51*(4), 479–491. https://doi.org/10.1007/s00374-014-0990-z
17. Hagemann, N., Joseph, S., Schmidt, H. P., Kammann, C. I., Harter, J., Borch, T.,..., Behrens, S. (2017). Organic coating on biochar explains its nutrient retention and stimulation of soil fertility. *Nature Communications*, *8*(1), 1–11. https://doi.org/10.1038/s41467-017-01123-0
18. Jeffery, S., Verheijen, F. G., van der Velde, M., Bastos, A. C. (2015). A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. *Agriculture, Ecosystems & Environment*, *144*(1), 175–187. https://doi.org/10.1016/j.agee.2011.08.015
19. Kammann, C., Ippolito, J., Hagemann, N., Borchard, N., Cayuela, M. L., Estavillo, J. M.,..., Wrage-Mönnig, N. (2017). Biochar as a tool to reduce the agricultural greenhouse-gas burden: Knowns, unknowns and future research needs. *Journal of Environmental Engineering and Landscape Management*, *25*(2), 114–139. https://doi.org/10.3846/16486897.2017.1319375
20. Kammann, C., Schmidt, H. P., Messerschmidt, N., Linsel, S., Steffens, D., Müller, C.,..., Conte, P. (2015). Plant growth improvement mediated by nitrate capture in co-composted biochar. *Scientific Reports, 5*(1), 1–13. https://doi.org/10.1038/srep11080
21. Lehmann, J., Rillig, M. C., Thies, J., Masiello, C. A., Hockaday, W. C., Crowley, D. (2011). Biochar effects on soil biota–a review. *Soil Biology and Biochemistry, 43*(9), 1812–1836. https://doi.org/10.1016/j.soilbio.2011.04.022
22. Liang, C., Zhu, X., Fu, S., Méndez, A., Gascó, G., Paz-Ferreiro, J. (2023). Biochar and biochar-compost as soil amendments: Effects on peanut yield, soil properties and greenhouse gas emissions in tropical North Queensland, Australia. *Agriculture, Ecosystems & Environment*, *213*, 72–85. https://doi.org/10.1016/j.agee.2015.07.027
23. Liu, X., Zhang, A., Ji, C., Joseph, S., Bian, R., Li, L.,..., Zheng, J. (2013). Biochar's effect on crop productivity and the dependence on experimental conditions—a meta-analysis of literature data. *Plant and Soil*, *373*(1–2), 583–594. https://doi.org/10.1007/s11104-013-1806-x
24. Martinez MM, Ortega R, Janssens M FP. (2018). Use of organic amandements in table grape: Effect on plant root system and soil quality indicators. *J Soil Science Plant Nutrion. 18*(1), 100–112. http://dx.doi.org/10.4067/S0718- 95162018005000501
25. Matheus, R., Kantur, D., Levis, L.R. (2024). Using soil amendments and mycorrhiza to improve chemical properties of degraded calcareous soil and yield of Sorgum in dryland. *Journal of Degraded and Mining Lands Management. 11(3)*, 5673–5681, https://doi.org/10.15243/jdmlm.2024.113.5673
26. Mensah Ak. (2015). Role of revegetation in restoring fertility of degraded mined soils in Ghana. *Int J. Biodivers Conserv*. *7*(2), 57–80. https://doi.org/10.5897/IJBC2014.0775
27. Mukherjee, A., Lal, R. (2013). Biochar impacts on soil physical properties and greenhouse gas emissions. *Agronomy, 3*(2), 313–339. https://doi.org/10.3390/agronomy3020313
28. Murtaza, G., Ahmed, Z., Usman, M., Tariq, W. (2023). Biochar-soil-plant interactions: A cross talk for sustainable agriculture under changing climate. *Frontiers in Plant Science*, *14*, 1–15. https://doi.org/10.3389/fpls.2023.001234
29. Mustafa, A., Naveed, M., Abbas, T., Saeed, Q., Hussain, A., Zahir, Z. A.,..., Minggang, X. (2019). Application of biochar in soil fertility and plant nutrition. In *Biochar for environmental management* 301–322. Routledge.

30. Neina, D. (2019). The role of soil pH in plant nutrition and soil remediation. *Applied and Environmental Soil Science*, 1–9. https://doi.org/10.1155/2019/5794869
31. Purakayastha, T. J., Kumari, S., Pathak, H., Sarkar, B., Singh, B. (2015). Characterization of biochar and biochar-amended soil: A review. *Biology and Fertility of Soils, 51*(4), 403–415. https://doi.org/10.1007/s00374-015-0989-0
32. Rajapaksha, A. U., Vithanage, M., Ahmad, M., Kim, K. R., Chang, J. Y., Lee, S. S., Ok, Y. S. (2014). Enhanced sulfamethazine removal by steam-activated invasive plant-derived biochar. *Journal of Hazardous Materials*, *290*, 43–50. https://doi.org/10.1016/j.jhazmat.2015.02.046
33. Rogovska, N., Laird, D., Cruse, R., Fleming, P., Parkin, T., Meek, D. (2014). Impact of biochar on manure carbon stabilization and greenhouse gas emissions. *Soil Science Society of America Journal*, *75*(3), 871–879. https://doi.org/10.2136/sssaj2010.0274
34. Rogovska, N., Laird, D., Cruse, R., Trabue, S., Heaton, E. (2016). Germination tests for assessing biochar quality. *Journal of Environmental Quality*, *41*(4), 1014–1022. https://doi.org/10.2134/jeq2011.0103
35. Shen, J., Li, C., Mi, G., Li, L., Yuan, L., Jiang, R., Zhang, F. (2016). Maximizing root/rhizosphere efficiency to improve crop productivity and nutrient use efficiency in intensive agriculture of China. *Journal of Experimental Botany*, *64*(4), 1181–1192. https://doi.org/10.1093/jxb/ers342\
36. Singh, B. P., Cowie, A. L., Smernik, R. J. (2012). Biochar carbon stability in a clayey soil as a function of feedstock and pyrolysis temperature. *Environmental Science & Technology, 46*(21), 11770–11778. https://doi.org/10.1021/es302545b
37. Smith, S. E., Read, D. J. (2008). *Mycorrhizal symbiosis*. Academic Press.
38. Vahedi, R., Gorbani, M., Rasouli-Sadaghiani, M. H. (2022). Biochar and biochar-compost as soil amendments: Effects on peanut yield, soil properties and greenhouse gas emissions in tropical North Queensland, Australia. *Agriculture, Ecosystems & Environment, 213*, 72–85. https://doi.org/10.1016/j.agee.2015.07.027
39. Wang, J., Xiong, Z., Kuzyakov, Y. (2016). Biochar stability in soil: Meta-analysis of decomposition and priming effects. *Global Change Biology Bioenergy*, *8*(3), 512–523. https://doi.org/10.1111/gcbb.12266
40. Woolf, D., Amonette, J. E., Street-Perrott, F. A., Lehmann, J., Joseph, S. (2010). Sustainable biochar to mitigate global climate change. *Nature Communications*, *1*(1), 1–9. https://doi.org/10.1038/ncomms1053
41. Yang, Y., Zhao, Y., Gao, C., Lu, H., Zhu, L., Chen, X.,..., Yu, X. (2020). Biochar improves soil quality and N2-fixation and reduces net ecosystem CO2 exchange in a dryland crop rotation. *Journal of Cleaner Production, 244*, 118–130. https://doi.org/10.1016/j.jclepro.2019.118130
42. Zimmerman, A. R., Gao, B., Ahn, M. Y. (2011). Positive and negative carbon mineralization priming effects among a variety of biochar-amended soils. *Soil Biology and Biochemistry*, *43*(6), 1169–1179. https://doi.org/10.1016/j.soilbio.2011.02.005