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Original Research Article

The impact of biochar and arbuscular mycorrhizal inoculation on garden egg (*Solanum gilo* L.) performance

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Abstract

Garden eggs are an important vegetable, but often yield poorly due to soil fertility depletion. Biochar has gained interest in mitigating nutrient loss, while arbuscular mycorrhizal fungi (AMF) reportedly enhance plant nutrition. However, limited information exists on garden egg responses to biochar application and their interactions with mycorrhizal inoculation. Therefore, the effects of biochar and AMF inoculation on garden egg performance were investigated. In a 3 × 2 factorial field experiment during the 2021 and 2022 cropping seasons, biochar (0, 2.5, and 5 t/ha) and AMF inoculation (–AMF and +AMF) were evaluated in a randomised complete block design with three replicates. Garden egg (NHSg–3) seedlings were transplanted at 60 cm × 60 cm spacing. Data were subjected to ANOVA at $p < 0.05$. Applying 5 t/ha biochar and AMF inoculation resulted in a significant leaf area increase compared with their respective controls. Fruit yield was significantly higher with 2.5 t/ha biochar than other treatments. The AMF-inoculated plants had significantly higher fruit yield (726.40 kg/ha) than the untreated plants (644.17 kg/ha). Fruit yield for biochar and AMF interactions ranged from 436.50 (–AMF) to 854.53 kg/ha (+AMF inoculation) at 5 t/ha biochar. However, 5 t/ha biochar resulted in significantly higher weed biomass and lower microbial count, while 2.5 t/ha biochar +AMF and –AMF treatments gave 771.63 and 802.08 kg/ha fruit yields, respectively, enhanced microbial counts, and reduced weed biomass. Applying 2.5 t/ha biochar without AMF inoculation was considered adequate for good garden egg performance and improved soil conditions.

Keywords: garden eggs; biochar; AMF inoculation; weed biomass; microbial count.

INTRODUCTION

Garden egg (*Solanum gilo* L.) is an herbaceous vegetable crop that is intensively cultivated in tropical and subtropical regions of West and East Africa for its fruits and leaves, which are used for human consumption (Han et al., 2021). It is a popular crop in the region with increased high demand due to increasing awareness of its nutritional and health benefits in meeting the family's nutritional requirements (Mpanga et al., 2021). According to FAO (2022), the productivity of garden eggs is low in Nigeria compared with the world's average yield. This could be due to various factors such as the use of low-yielding and susceptible varieties, inadequate control of pests and diseases, limited access to inputs and markets, and lack of proper facilities for post-harvest handling and processing.

The limited use of mineral fertiliser due to its high cost and inability to significantly improve soil health contributes to low yields. Inorganic fertiliser is a synthetic fertiliser made with chemicals such as ammonium nitrate, urea, and superphosphate, which provide plants with the necessary nutrients for growth and development. However, persistent use of inorganic fertiliser can negatively impact soil health, plant growth and fruit quality. Feng et al. (2021) reported that excessive use of inorganic fertiliser can increase the accumulation of heavy metals in fruits and pose a health risk to consumers.

To address this issue, agricultural wastes have been introduced as a sustainable solution, with biochar as a bioprocess product particularly beneficial (D'Hose et al., 2020). Biochar improves soil physical and chemical properties, such as cation exchange capacity, pH, nutrient, and water retention, and promotes soil microbial communities (Wu et al., 2017). However, the level of biochar required to support crop productivity depends on the source of the material used, pyrolysis temperature, biotic interactions, and soil type. Yeboah et al. (2016) reported that maize cob biochar contains 49.1, 1.3, and 0.46% of C, N, and P, respectively. The availability of these nutrients would ensure improved plant growth. The combination of biochar with other soil amendments such as poultry manure to further improve crop yield has been reported (Mpanga et al., 2021). Another approach to improve crop productivity is the use of arbuscular mycorrhizal fungi (AMF) (Hristozkova and Orfanoudakis, 2023). Arbuscular mycorrhizal fungi are naturally occurring fungi that colonise the roots of many plant species and are directly involved in plant mineral nutrition (Hristozkova and Orfanoudakis, 2023). The symbiosis between AMF and plant roots can increase the uptake of less mobile nutrients such as phosphorus and reduce the stress caused by micronutrients such as zinc (Saboor et al., 2021). Arbuscular mycorrhizal fungi stimulate the production of growth-regulating substances, increase photosynthesis, improve osmotic adjustment under drought and salinity stresses, and increase resistance to pests and soil-borne diseases (Wahab et al., 2023). Most horticultural crops can establish this symbiosis with AMF, improving horticultural production (Zhu et al., 2022). However, there is limited information on the response of garden eggs to biochar and its interaction with AMF inoculation. Therefore, this study aimed to evaluate the effects of biochar, AMF inoculation, and their co-application on the growth and yield of garden eggs, weed biomass, and microbial population changes. The null hypotheses of this study stated that there is no significant difference between the control and applications of biochar, AMF, and their combinations on the growth and yield of garden egg, weed biomass, and soil microbes.

MATERIALS AND METHODS

The experimental study was conducted in 2021 and 2022 at the Department of Crop and Horticultural Sciences Research Field located along Parry Road, University of Ibadan, Ibadan, Oyo State, Nigeria. The coordinates of the location were 07°27′07″N, 03°53′29″E, and 190 m altitude. The site is situated within the Savannah agroecological zone of southwestern Nigeria. The site experiences an average annual rainfall of 1260 mm, with a bimodal pattern consisting of long and short rainy seasons between April to July and September to November, separated by a dry spell in August. The mean relative humidity is 75%, and the atmospheric temperature ranges between 25 to 30°C. The precipitation and temperature readings during the cropping periods in 2021 and 2022 were obtained from the National Aeronautics and Space Administration (NASA) Project's Data Access Viewer (DAV) and presented in Figure 1.

Experimental design, treatment and layout

The field experiment was a 3 × 2 factorial combination conducted in a randomised complete block design with three replicates. The first factor consisted of biochar applications (0, 2.5, and 5 t/ha), while the second factor consisted of arbuscular mycorrhizal fungi (without AMF and with AMF) at 10 g/plant. The AMF inoculation used for the study was *Glomus clarum*, while the biochar source was maize cob. The total experimental plot area occupied was 201.16 m^2, and each plot size was 240 cm × 180 cm. A 200 cm path separated the replications, while plots within replicates were demarcated with a one-metre pathway. Biochar application was carried out two weeks before transplanting at actual weights of 0 (control), 1.08, and 2.16 kg/plot, corresponding to the 0, 2.5, and 5 t/ha treatments, respectively, for each cropping season. The AMF was applied at 231.48 kg/ha for each cropping season. In the following season, the study was repeated for consistency.

The garden egg *Solanum gilo* L. variety (NHSg–3) was obtained from the National Horticultural Research Institute (NIHORT) in Ibadan, Nigeria. Seedlings were raised in a nursery tray in the screenhouse. Seeds were sown by making drills 15 cm apart, covered lightly with sand, and watered regularly until the seedlings were transplanted. During the first and

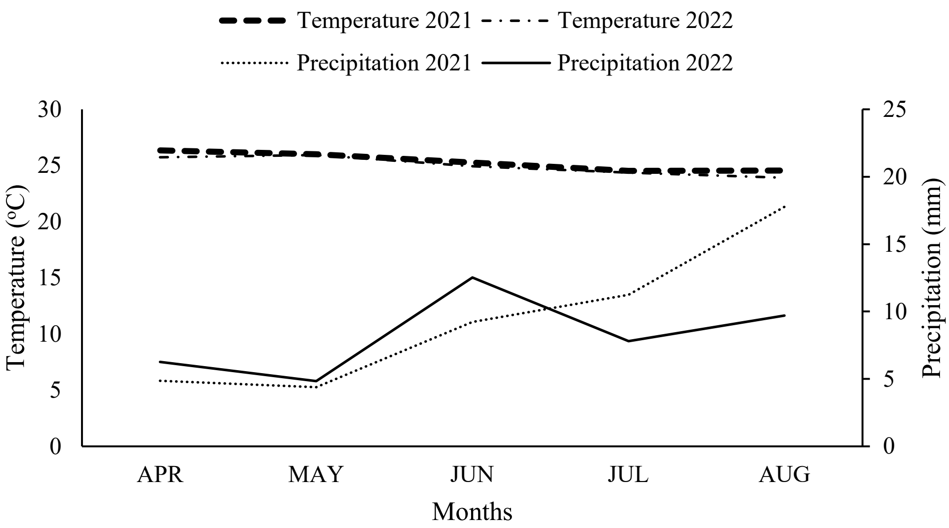

Figure 1. The precipitation and temperature readings during the periods of cropping in 2021 and 2022 (NASA Power, 2024)

second growing seasons, seeds were sown on the 16 of March 2021 and 22 of March 2022, while transplanting dates were 26 April 2021 and 1 May 2022, respectively. Seedlings were exposed to sunlight for a week before being transplanted to the field for seedling hardening. Transplanting was carried out in the evening, six weeks after sowing, when the seedlings were 15 cm tall. Adequate watering was performed before transplantation to maximise water uptake and ease of removal. The seedlings were watered immediately after transplanting in the morning and evening to minimise transplant shock. The seedlings were transplanted at 60 cm × 60 cm for the inter-row and intra-row, respectively. The experimental layout of the study is presented in Figure 2. Harvesting started from 14 June to 30 July 2021 and from 22 June to 5 August 2022 for the first and second cropping seasons, respectively.

Maize cob biochar

Biochar was produced at the Department of Crop and Horticultural Science and Department of Soil Resources Management, University of Ibadan, Ibadan, Nigeria from maize cobs. Maize cobs were chipped and pyrolysed using the common closed drum kiln production technique (Anika et al., 2021).

Field management

Arbuscular mycorrhizal fungus (AMF) was applied on the day of transplanting. Water was supplied artificially at intervals of 2 days for 2–3 weeks because of inconsistent rainfall. The source of irrigation water was a stream along Parry Road, University of Ibadan. Manual weeding was performed three times at 4, 8, and 11 weeks after transplanting (WAT) using a weeding hoe. Stem and leaf attacks, including fruit borers, were controlled by spraying Dichlorvos (DDVP) 1000 g/L EC organophosphate) at a rate of 10 mL in 5 L of clean

1 B_5N_0AMF	2 B_0N_1AMF	3 $B_{2.5}N_1AMF$	4 B_0N_0AMF	5 B_5N_1AMF	6 $B_{2.5}N_0AMF$	Rep 1
12 $B_{2.5}N_1AMF$	11 B_5N_1AMF	10 B_0N_0AMF	9 $B_{2.5}N_0AMF$	8 B_0N_1AMF	7 B_5N_0AMF	Rep 2
13 B_0N_0AMF	14 $B_{2.5}N_1AMF$	15 $B_{2.5}N_0AMF$	16 B_5N_1AMF	17 B_0N_1AMF	18 B_5N_0AMF	Rep 3

Figure 2. The experimental layout of the study. B_5N_0AMF = biochar at 5 tonnes/ha without the use of AMF; B_0N_1AMF = no biochar application with the use of AMF; $B_{2.5}N_1AMF$ = biochar at 2.5 tonnes/ha with the use of AMF; B_0N_0AMF = no biochar application and no use of AMF; B_5N_1AMF = biochar at 5 tonnes/ha with the use of AMF; $B_{2.5}N_0AMF$ = biochar at 2.5 tonnes/ha without the use of AMF

water contained in a 10 L-capacity Knapsack Sprayer. Harvesting was done every 5–7 days.

Data collection

Leaf area (cm²)

This was measured at 2, 4, 6, and 8 WAT using the formula LA = 0.641 (L × W); where LA is leaf area, L is the length of the leaf from the tip to the base of the leaf, and W is the width of the widest portion of the leaf. The length and width or breadth of leaves were measured using the metre rule, and the leaf area was calculated for each leaf sampled (Rivera et al., 2007).

Fruit yield per plant (kg)

The weight of the fruits per plant was measured using a Camry electronic weighing scale, model EK5350, made in China. The total yield per plant for each of the treatments was used to estimate the yield per hectare.

Dry weed biomass weight (kg)

Before each weeding operation, weed biomass from each treatment was measured by collecting the weeds within a 50 cm × 50 cm iron quadrant thrown twice at random on the field in each treatment. The collected weeds were air-dried for 14 days in the screenhouse located in the Department of Crop and Horticultural Science, University of Ibadan, Nigeria. The final weight (dry biomass) was determined using a Camry electronic weighing scale.

Soil microbial population

The determination of soil microbial population was performed before and after planting using the Standard procedure used in the serial dilution method for bacterial and fungal isolation (McPherson et al., 2018).

This analysis was conducted at the Soil Microbiology Laboratory in the Department of Soil Resources Management at the University of Ibadan, Nigeria.

All data collections during the 2021 trial were repeated for the 2022 experiment in the following season and the mean values are reported in the study.

Data analysis

The collected data on growth, yield, dry weed biomass and microbial parameters were subjected to analysis of variance using SAS version 9.4, and significant differences among means were compared using the Least Significant Difference (LSD) at $p < 0.05$.

RESULTS

Chemical and particle size analysis of the soil in the experimental site

The soil analysis results are presented in Table 1 along with the USDA (2020) critical range of soil testing requirements for garden eggs. The soil pH value was 6.98, total nitrogen was 0.2 g/kg, and organic carbon

Table 1. Particle size distribution and chemical properties of the experimental soil before cropping

Properties	Values	Critical range (USDA 2020)	Remarks
pH (1:1, H2O)	6.98	6.0–7.5	Neutral
Organic Carbon (g/kg)	1.82	1.00–5.00	Moderate
Total Nitrogen (g/kg)	0.2	0.1–0.5	Moderate
Available Phosphorus (mg/kg)	17.93	10.00–30.00	Moderate
Available Potassium (mg/kg)	700	100–400	Very high
Exchangeable Cations (cmol/kg)			
Ca	2.88	2.00–5.00	Low
Mg	1.07	0.5–1.5	Moderate
Na	1.35	0.1–0.5	Moderate
Exchangeable Acidity	0.9	0–2.00	Moderate
Extractable Micronutrients (mg/kg)			
Fe	18.81	4.00–20.00	High
Mn	73.36	4.00–40.00	High
Cu	1.02	0.2–2.0	Moderate
Zn	3.34	0.5–5.0	High
Particle size distribution (%)			
Sand	81	0–85	
Silt	12	0–85	
Clay	7	0–60	
Textural class (USDA)	Sandy loam		

Table 2. Effects of biochar and arbuscular mycorrhizal fungi inoculation on garden egg leaf area (cm²)

	2021 cropping (WAT)				2022 cropping (WAT)			
Treatments	**2**	**4**	**6**	**8**	**2**	**4**	**6**	**8**
Biochar application								
B0	20.88	41.92	125.00	192.92	58.32	105.72	214.63	370.08
B 2.5	28.63	62.71	131.13	178.22	74.17	117.72	349.31	560.58
B5	34.71	66.38	151.25	201.46	57.74	113.55	293.33	481.42
LSD	ns	ns	7.56	5.5	ns	ns	ns	ns
AMF inoculation								
N0 AMF	29.42	56.92	129.28	178.56	58.90	110.24	269.69	442.70
N1 AMF	26.72	57.08	142.31	203.17	67.92	114.42	301.83	498.69
LSD	ns	ns	1.058	1.022	ns	ns	ns	ns
Interactions								
B0 × N0 AMF	20.50	44.33	133.08	200.75	42.20	82.06	237.59	373.50
B0 × N1 AMF	21.25	39.50	116.92	185.08	74.45	129.39	191.68	366.67
B2.5 × N0 AMF	29.83	69.75	127.92	181.03	73.12	132.04	380.92	599.60
B2.5 × N1 AMF	27.42	55.67	134.33	175.42	75.21	103.40	317.71	521.57
B5 × N0 AMF	37.92	56.67	126.83	153.92	61.39	116.61	190.56	355.00
B5 × N1 AMF	31.50	76.08	175.67	249.00	54.09	110.48	396.11	607.83
LSD	ns	6.502	7.205	9.102	ns	ns	ns	ns

B_0 – Control (No Biochar); $B_{2.5}$– Biochar at 2.5 t/ha; $B_{2.5}$– Biochar at 5 t/ha; WAT – Weeks After Transplanting; N_0 AMF – Without Arbuscular Mycorrhizal Fungal; N_1 AMF – With Arbuscular Mycorrhizal Fungal; ns – Not significant.

was 1.82 g/kg. The available potassium was 0.2 mg/kg, and the textural class of the soil was sandy loam.

Effects of biochar and AMF inoculation on leaf area of the garden egg

The mean values of garden egg leaf area for each treatment throughout the 2021 and 2022 cropping seasons are presented in Table 2. At 2 and 4 weeks after transplanting (WAT) during 2021 cropping, biochar application did not have a significant ($p > 0.05$) effect on leaf area. However, there was an increase in leaf area with the increase in the level of biochar applications. At 6 and 8 WAT, biochar application had a significant effect on the garden egg leaf area. The plants treated with 5 t/ha biochar had a significantly higher leaf area than those treated with 0 t/ha biochar. However, the 2.5 t/ha biochar treatment did not differ significantly from the other treatments. During the 2022 cropping, the influence of biochar on the garden egg leaf area was not significant across the observation period. However, at 2, 4, 6, and 8 WAT, applying biochar at 2.5 t/ha gave plants with the highest leaf area values, while the lowest leaf area was in the control.

In both cropping seasons, the influence of AMF inoculation on leaf area was not significant but had higher values than the non-inoculated plants at 2 and 4 WAT. However, at 6 and 8 WAT, AMF inoculation had a significant ($p < 0.05$) effect on the garden egg leaf area, with AMF inoculation resulting in a higher leaf area compared with the absence of AMF in 2021. During the 2022 cropping, the AMF influence was not significant but had higher values than the non-inoculated throughout the observation period.

The trends observed for the interactions between biochar and AMF inoculation were similar for the two croppings of garden egg, except that the improvement was not significant during the 2022 cropping. At 2 WAT during the 2021 cropping, the differences in leaf area among treatments were not significant but ranged from 20.5 (control) and 37.92 (biochar at 5 t/ha × no AMF). The interactions between biochar and AMF inoculation differed significantly at 4 WAT. Across the levels of applications, interactions involving AMF inoculation had lower leaf area values compared with the non-inoculated plants, except for the 5 t/ha × AMF inoculation with the highest leaf area value. Biochar with AMF interactions did not improve garden egg leaf area compared with the non-inoculated treatments at 6 WAT, except at 5 t/ha biochar. At 8 WAT, both biochar application and AMF inoculation had significant effects on leaf area. The highest and lowest leaf areas observed were at 5 t/ha biochar with AMF inoculation (249.00 cm²) and biochar at 5 t/ha with no AMF treatment (153.92 cm²), respectively. The influence of biochar and AMF interactions was not significant during the 2022 cropping. At 2 and 4 WAT, the garden egg leaf areas were lowest in the control, while the highest values were at 2.5 t/ha biochar with AMF and biochar at 2.5 t/ha without AMF, respectively. At 6 and 8 WAT, the leaf areas were lowest by applying biochar at 5 t/ha without AMF and highest with biochar at 5 t/ha with AMF application.

Effects of Biochar and AMF inoculation on fruit yield of garden egg and dry weed biomass

Applying 2.5 t/ha of biochar produced a significantly ($p < 0.05$) higher fruit yield than the other treatments (control and 5 t/ha biochar) during the 2021 cropping (Table 3). The responses of garden egg to the application of biochar did not vary significantly for fruit yield during the 2022 cropping. However, the plants treated with 2.5 t/ha biochar gave 16.82% higher fruit yield than the 5.0 t/ha, while the lowest yield was observed in the control. Inoculation with AMF resulted in a significant ($p < 0.05$) increase in fruit yield (726.40 kg/ha) compared with the treatment without AMF inoculation (644.17 kg/ha) during the 2021 cropping season. The AMF-inoculated plant had 13.22% higher fruit yield than the non-treated plants during the 2022 cropping but the difference was not significant ($p < 0.05$). The interaction between biochar and AMF varied significantly for fruit yield. The combination of biochar at 2.5 t/ha × AMF inoculation resulted in a significant ($p < 0.05$) higher yield than the other treatment combinations. The variations in fruit yield for biochar × AMF interactions ranged from 360.33 kg/ha (5.0 t/ha without AMF inoculation) to 721.67 kg/ha (5.0 t/ha × AMF) during the 2022 cropping but were not significant. Biochar at 2.5 × without AMF treatment had a 3.80% higher and 1.50% lower yields than the 2.5 t/ha biochar × with AMF during the 2021 and the 2022 cropping seasons, respectively.

The results shown in Table 3 indicated that dry weed biomass varied among the biochar treatments in the 2021 and 2022 cropping seasons. During the 2021 cropping, the 5 t/ha biochar treatment resulted in a significantly ($p < 0.05$) higher dry weed biomass (3693.33 kg/ha) than the no biochar treatment (2653.33 kg/ha) and application of 2.5 t/ha biochar (2546.67 kg/ha). In the 2022 cropping, the 5 t/ha biochar had 20.39 and 20.58% higher weed biomass than the control and biochar at 2.5 t/ha, respectively. The presence of AMF also had a significant ($p < 0.05$) effect on reducing dry weed biomass (2831.11 kg/ha) than the plots without AMF (3097.78 kg/ha) in 2021. Similarly, the AMF-inoculated plot had 8.33% lower dry weed biomass than the uninoculated plot in 2022. The effect of biochar × AMF inoculation interaction was also found to be significant ($p < 0.05$) during the 2021 cropping. The plots treated with 2.5 t/ha biochar in combination with or without AMF inoculation were similar and had lower dry

Table 3. Effects of biochar and arbuscular mycorrhizal fungi inoculation on fruit yield and weed biomass (kg/ha) of garden egg during the 2021 and 2022 cropping seasons

Treatments	Total Yield		Total Dry Weed	
	2021	2022	2021	2022
Biochar application				
B0	623.55	529.17	2653.33	2596.67
B 2.5	786.84	650.42	2546.67	2590.33
B5	645.56	541.00	3693.33	3261.67
LSD	24.202	ns	1037.13	ns
AMF inoculation				
N0 AMF	644.17	532.94	3097.78	2938.67
N1 AMF	726.40	614.11	2831.11	2693.78
LSD	25.501	ns	264.67	ns
Interactions				
B0 × N0 AMF	693.89	593.00	2653.33	2330.67
B0 × N1 AMF	553.29	465.33	2653.33	2862.67
B2.5 × N0 AMF	802.08	645.50	2573.33	2850.00
B2.5 × N1 AMF	771.63	655.33	2520.00	2330.67
B5 × N0 AMF	436.50	360.33	4066.67	3635.33
B5 × N1 AMF	854.53	721.67	3320.00	2888.00
LSD	45.302	ns	502.32	1272.3

B_0 – Control (No Biochar); $B_{2.5}$– Biochar at 2.5 t/ha; $B_{2.5}$– Biochar at 5 t/ha; WAT – Weeks After Transplanting; N_0 AMF – Without Arbuscular Mycorrhizal Fungal; N_1 AMF – With Arbuscular Mycorrhizal Fungal; ns – Not significant at $p < 0.05$

Table 4. Microbial population colony changes in the soil as influenced by biochar and Arbuscular mycorrhizal fungi during the 2021 and 2022 cropping seasons

Treatments	Total bacteria count (× 10^4 cfu/g soil)		Total fungal count (× 10^6 cfu/g soil)	
	2021	2022	2021	2022
Biochar application				
Bf	3.00	1.00	0.80	0.20
B0	4.50	4.80	2.00	0.34
B 2.5	5.80	6.55	2.52	0.43
B5	3.90	3.60	1.50	0.22
LSD	0.52	1.46	0.35	0.07
AMF inoculation				
Bf	3.00	1.00	0.80	0.20
N0 AMF	4.63	4.20	1.84	0.32
N1 AMF	4.83	5.77	2.17	0.34
LSD	0.47	1.85	0.29	0.01
Interactions				
Bf	3.00	1.00	0.80	0.20
B0 × N0 AMF	4.50	3.80	2.00	0.30b
B0 × N1 AMF	4.50	5.80	2.00	0.37
B2.5 × N0 AMF	5.60	6.10	2.20	0.40
B2.5 × N1 AMF	6.00	7.00	2.83	0.46
B5 × N0 AMF	3.80	2.70	1.33	0.25
B5 × N1 AMF	4.00	4.50	1.67	0.20
LSD	2.12	0.82	1.46	0.71

bf = Before planting; B_0 – Control (No Biochar); $B_{2.5}$ – Biochar at 2.5 t/ha; $B_{2.5}$ – Biochar at 5 t/ha; WAT – Weeks After Transplanting; N_0 AMF – Without Arbuscular Mycorrhizal Fungal; N_1 AMF – With Arbuscular Mycorrhizal Fungal; ns – Not significant at $p < 0.05$

weed biomass compared to the other treatment interactions. The treatments at 5 t/ha combined with or without AMF inoculation had significantly higher dry weed biomass than the other treatment interactions. The plots treated with 5 t/ha biochar and AMF inoculation resulted in significantly lower dry weed biomass (3320.00 kg/ha) than the plots treated with biochar at 5 t/ha × without AMF (4066.67 kg/ha). During the 2022 cropping, dry weed biomass was significantly higher in the plots treated with 5 t/ha biochar × without AMF than 0 biochar × without AMF and biochar at 2.5 t/ha × AMF inoculation, while the other treatments were similar ($p < 0.05$).

Soil microbial population changes as influenced by biochar and AMF inoculation

Bacterial colonies as influenced by biochar, AMF, and their interactions before and after garden egg cultivation varied significantly during the 2021 and 2022 cropping seasons (Table 4). There was a significant ($p < 0.05$) increase in the bacterial colony count after garden egg cultivation compared with the assessment before planting. Biochar application at 2.5 t/ha significantly ($p < 0.05$) increased bacterial colonies more than the other treatments during the two cropping years. However, the highest biochar rate (5 t/ha) resulted in a significant decrease in the bacterial colonies by 13.33 and 25.00% compared to the control during the 2021 and 2022 cropping seasons, respectively. The bacterial population count under AMF inoculated or uninoculated treatments increased significantly ($p < 0.05$) compared to the population count before cultivation during both cropping years. However, the AMF inoculated treatment had 4.14 and 27.21% higher bacterial colonies than the uninoculated treatment during the 2021 and 2022 cropping seasons, respectively. Interactions between biochar and AMF treatments showed a significant ($p < 0.05$) increase in bacterial population in the soil treated with biochar at 2.5 t/ha × AMF inoculation compared to the biochar at 5 t/ha × no AMF but similar to the other treatments during the 2021 cropping. During the 2022 cropping, however, the inoculated treatment with biochar at 2.5 t/ha had a significantly higher bacterial population than the other treatments. The lowest counts of bacterial colonies were observed in the treatment with biochar at 5 t/ha × no AMF inoculation in both cropping years. Nonetheless, the values were 2.63 and

37.04% higher than those of the bacterial colonies before planting in 2021 and 2022, respectively.

Cultivating garden eggs improved the fungal colony counts compared to the observed colonies before planting in 2021 and 2022 (Table 4). Fungal populations had significant variations among the treatments. Biochar application at 2.5 t/ha significantly increased the fungal colony count compared to the other biochar treatments in both cropping years. However, the highest biochar rate (5 t/ha) significantly reduced the fungal population compared to the control during both cropping years. The inoculation with AMF significantly ($p < 0.05$) increased the number of fungal colonies compared to the uninoculated treatment during both cropping years. The biochar at 2.5 t/ha × AMF interaction significantly increased fungal colonies in the soil compared to biochar at 5 t/ha × no AMF in the 2021 cropping, while in the 2022 cropping, biochar at 2.5 t/ha × AMF inoculation had a significantly higher fungal colony than the other treatments.

DISCUSSION

The nutrients available in maize cob biochar possess large quantities of carbon and traces of N and P (Yeboah et al., 2016), indicating that the material can improve the soil's physical parameters and support plant growth. The effect of biochar on soil physical properties is achieved through improvement in soil bulk density, porosity, and soil water holding capacity (Abukari et al., 2022), This assertion would enhance the performance of the garden egg planted coupled with the minimum nutrient status of the soil, relative to the USDA (2020) soil fertility indicators for optimum growth reported.

The influence of biochar, AMF inoculation and their interaction on garden egg leaf area

The magnitude of leaf area coverage indicates the canopy structure and the exposed leaf surface area available for intercepting light by the plant for photosynthetic activities and promoting development (Digrado et al., 2020). The increase in garden egg leaf area with the application of 5 and 2.5 t/ha of biochar in 2021 and 2022, respectively, compared to the untreated plot confirms the positive impact of biochar on crop growth enhancement. Comparatively, a higher leaf area was observed at 2.5 t/ha than at 5 t/ha. Consequently, the higher level of biochar application improved the garden egg leaf area more effectively than the lower levels. This result is consistent with Yeboah et al. (2016), who reported that applying maize cob biochar enhances hybrid maize leaves more than untreated plants. The lower leaf area value observed at 2.5 t/ha relative to the control at 8 WAT could indicate earlier remobilisation of nutrients from the leaf in this treatment for the formation of fruits. However, the optimal level of biochar application for increasing leaf area was higher than previously reported. This variation could be attributed to differences in the crop planted, soil properties, and nutritional needs of the crops. The influence of biochar application as an amendment on soil properties in improving garden egg leaf area could have resulted in the noticeable yield difference at 2.5 t/ha of biochar compared with the control.

The growth response of the garden egg plant to AMF was also positive, although the magnitude of the difference was not substantial during both year croppings. The weaker response of garden eggs to AMF inoculation could be due to the AMF strain used not being adequately supportive to promote growth (Thanni et al., 2022). However, the findings of this study align with those of Djeugap et al. (2023), who reported that the contribution of AMF to improving potatoes was not significant. Nevertheless, the greater leaf area of the AMF-inoculated plant compared to the non-treated plant suggests that utilising AMF inoculation could be an effective strategy for enhancing the growth of crops such as garden eggs (Ejersa, 2021). The difference in leaf area could improve the plant's photosynthetic activities, leading to a higher crop yield (Muhie, 2022).

Similar trends for leaf area were observed for the interactions between biochar and AMF inoculation during the 2021 and 2022 cropping seasons, except that no significance among values in the second year was found. The interactions between biochar and AMF inoculation indicated that at each level of application, plants inoculated with AMF had a relatively smaller leaf area, except at 5 t/ha, where the difference was the most significant. The beneficial impact of the interactions between biochar and AMF inoculation has been reported for spinach (Jabborova et al., 2021). The suppressed effect of AMF inoculation could be due to the reliance of the AMF inoculum on plant roots for carbohydrates, which are essential for abundant colonisation and root infection by AMF (Ejersa, 2021; Hristozkova and Orfanoudakis, 2023). Afterwards, the AMF resumes its symbiotic role by supplying nutrients to the plant and conditioning the soil environment to promote better development. At higher levels of biochar application, the nutrients and soil physical conditions were likely to be adequate for promoting improved plant growth. Furthermore, the negative effect of using only biochar at a rate of 5 t/ha (without AMF) indicated unfavourable environmental conditions for optimal crop growth. The use of AMF inoculation is most appropriate under repressive conditions to promote optimal crop development.

The influence of biochar, AMF inoculation and their interaction on garden egg yield

The application of biochar increased the yield of garden eggs compared to the untreated plot in both cropping years. The increase in yield from biochar application conforms with the findings reported by Adeyemi et al. (2019) in maize. The yield difference resulting from the variation in biochar application levels could lead to improved growth. The enhancement of soil physical parameters by applying biochar could enhance the growth of adventitious roots, resulting in increased root metabolism and the crop's ability to extract available nutrients from the soil (Xiang et al., 2017). In addition, biochar application has been reported to enhance soil physical properties, thereby resulting in a significant increase in crop growth and yield (Premalatha et al., 2023). A positive correlation between leaf area and crop yield has been reported (Muhie et al., 2022). The larger the leaf area, the greater the surface area available for the photoactive leaves to translocate photosynthates, resulting in improved yield (Muhie, 2022). However, the higher yield observed from the application of 2.5 t/ha over 5 t/ha, despite lower leaf area coverage, could be a result of the high level of biochar application, which encouraged crop vegetative growth at the expense of yield. Furthermore, there have been reports of potential negative impacts of excessive biochar application on soil health, resulting in reduced crop yield (George, 2022).

The fruit yield increases in garden egg plants treated with AMF inoculation relative to the treatment without AMF inoculation during both years of cropping, substantiating the role of AMF inoculation in improving vegetable crop yield (Aggarwal et al., 2023; David-Rogeat et al., 2023). They reported the importance of AMF inoculation regarding its function as a soil conditioner (Muneer et al., 2020), biofertiliser, and bioprotectant (David-Rogeat et al., 2023; Wahab et al., 2023; Djeugap et al., 2023), thereby enhancing crop performance. The function of soil conditioners is achieved through the secretion of glomalin from their extraradical hyphae, thus improving the soil's structural quality (Muneer et al., 2020). The effects of AMF inoculation on garden eggs are consistent with Arcidiacono et al. (2023) findings, which showed that tomato nutrient uptake and yield were improved with AMF inoculation.

The effects of biochar with AMF inoculation interactions on garden egg yields were similar to the trend observed for leaf areas during the two cropping years, showing relatively lower yields in the inoculated plants, except at 5 t/ha. Reports have shown that the impact of AMF inoculation on crop growth is most significant when crops are growing under limiting, adverse, or stressed conditions (Ejersa, 2021; Wahab et al., 2023). Considering the soil nutrient status, the soil contains levels above the minimum values required for critical nutrients (N, P, and K) essential for garden egg production. Consequently, the contribution of biochar to soil physical parameters for improving yield is more pronounced compared to AMF inoculation, as demonstrated in the control and with 2.5 t/ha of biochar. However, the margin of the yield difference at 2.5 between the inoculated and non-inoculated plants was not significant. This result probably indicates a balance in the conditions for optimal crop growth. Therefore, the contribution of AMF inoculation was more efficient in promoting garden egg fruit yield compared to the native inoculum under the soil conditions necessary for optimal performance.

Weed dry biomass as influenced by biochar, AMF inoculation and their interaction

Weeds have detrimental effects on crop performance due to competition for above-ground and below-ground resources. Furthermore, the increase in dry matter indicates the level of competition for biomass accumulation with the available resources. The higher dry weed biomass observed at 5 t/ha indicates high competition between the crop and the weeds for the available resources during the two cropping years. The increase in weed biomass due to biochar application corroborates with the findings of Adeyemi et al. (2019), who reported that higher biochar application led to a further increase in weed dry weight. The competition for nutrients by the weeds, leading to biomass accumulation before their removal, could be responsible for the ultimately poor crop yield. The enhancement of soil conditions through biochar application to promote proper crop growth also stimulates weed development. A similar result was also obtained by Brozovic et al. (2021), who found that increasing biochar led to an increase in weed biomass and a decrease in yield in winter wheat. Weeds are known to have a higher competitive ability than crops for available resources, and enhancing the growing conditions for crops also improves weed performance (Zhang et al., 2022). Thus, this leads to a reduction in the impact of biochar on improving soil properties, which would have otherwise increased yields. Further reduction in dry weed biomass at 2.5 t/ha relative to the control implies a better competitive advantage for the crop in accessing available resources compared to treatments with a higher presence of weeds.

The reduction in dry weed biomass observed for the AMF-inoculated treatment during the 2021 and 2022 cropping seasons conforms with Akinrinola and Fagbola's (2021) investigation of weed growth in maize under AMF inoculation. It has been reported that AMF inoculation results in a reduction in weed biomass. The approach of AMF infection in suppressing weed was reported by Trinchera and Warren Raffa (2023). The strain of AMF to the weeds could be non-supportive or non-host species to the weeds, thus giving the crop an advantage over the weeds. This study showed that AMF inoculation reduced weed biomass and improved garden egg growth performance. This implies that AMF inoculation could be used as a potential strategy for improving crop performance with minimal threat to weed management. Yildirim et al. (2016) also reported the effect of AMF on weed control in sunflower production. The interaction of biochar with AMF inoculation had a considerable positive influence on dry weed biomass at 5 t/ha. This indicated that the improvement in soil health improved weed development. The increase in dry weed biomass at 5 t/ha biochar application in this study must have been responsible for the poor garden egg performance. Similarly, the lower dry weed biomass observed at 2.5 t/ha biochar, with or without inoculation, could explain the higher yield relative to the control. Furthermore, the higher dry weed biomass observed in the non-inoculated plot at 2.5 t/ha biochar suggests that the weeds are adapted to the environment and that the native inoculum supports their development relative to the introduced inoculum.

Effect of biochar, AMF inoculation and their interaction on soil microbial colonies

Garden egg planting enhanced bacterial and fungal populations compared to their initial levels during the 2021 and 2022 cropping seasons, indicating that the crop promotes an increase in microbial populations in the soil. This must have been achieved through the increase in soil organic matter resulting from the elongation of root growth in search of available nutrients. Biochar application also enhanced both bacterial and fungal populations with similar trends. However, the highest population increase observed at 2.5 t/ha of biochar in the 2 cropping implies a negative relationship between microbial population increase and dry weed biomass, but a positive relationship with fruit yield. A similar observation was reported by Jabborova et al. (2021), who confirmed that biochar increased the microbial activities of certain soil enzymes. The influence of biochar on soil microbes is related to the modification of soil physical and chemical properties provided by biochar, thus encouraging an increase in bacterial and fungal populations (Premalatha et al., 2023).

The trends observed for bacterial and fungal colonies during 2021 and 2022 are similar. The increase in bacterial and fungal populations in the AMF-inoculated treatments suggests improved conditions that promote microbial growth compared to the untreated plots. According to Akinrinola et al. (2022), an increase in microbial populations enhances the availability of nutrients such as nitrogen, phosphorus, and potassium, which are essential for plant growth and development. In addition, the improvement in root growth encourages an increase in both bacterial and fungal populations due to the presence of organic matter in the soil, which provides a favourable environment for growth (Zhang et al., 2018). Furthermore, higher levels of biochar application favoured weed biomass at the expense of the microbial population. The 2021 and 2022 results of this study are consistent with earlier investigations that have shown biochar and AMF to have positive effects on soil microbial communities. Premalatha et al. (2023) discovered that incorporating biochar into soil promotes microbial activity and accelerates the decomposition of soil organic matter. Similarly, Jabborova et al. (2021) reported that AMF inoculation can enhance the growth of beneficial soil microbes. These findings suggest that the combined application of biochar and AMF together can improve microbial population dynamics in soil. The increased nutrient availability facilitated by the introduced AMF inoculum and the favourable conditions for microbial growth provided by the biochar may account for the observed increase in microbial population alterations in the treatment with 2.5 t/ha of biochar with AMF inoculation. The higher number of fungal colonies observed in the 2.5 t/ha inoculated plot compared with the non-inoculated plot could be attributed to the combination of the introduced AMF inoculum (which most likely did not support the native weeds) and the indigenous or native inoculum. Furthermore, the results indicated that an increase in the bacterial population before and after planting in the control implies that cultivating the crop promotes the growth of native bacterial and fungal populations in the soil. The increase in the number of bacteria and fungi in the soil could be attributed to the presence of organic matter and the increased activity of plant roots (Moore et al., 2022), which release carbon compounds that promote the growth of native soil microbes. Thus, biochar's contribution to improving soil conditions for the native microbial population was appreciable in enhancing garden egg performance.

CONCLUSION

This study revealed that the sole application of 2.5 t/ha biochar improved leaf area, fruit yield, and soil microbial populations, while the application of 5 t/ha biochar improved leaf area but reduced fruit yield and soil bacterial and fungal populations. Sole AMF inoculation treatment also improved garden egg leaf area, yield, and bacterial and fungal populations but reduced dry weed biomass. Despite the higher growth and fruit yield observed by applying 5 t/ha biochar × with AMF inoculation weed biomass was increased, while bacterial and fungal colonies decreased. Applying biochar at 2.5 t/ha, with or without AMF comparatively improved of garden egg performance, reduced dry weed biomass, and enhanced soil bacterial and fungal populations. Consequently, 2.5 t/ha biochar without AMF inoculation was recommended for better soil health and improved garden egg performance

ETHICAL COMPLIANCE

The authors have followed ethical standards in conducting the research and preparing the manuscript.

CONFLICT OF INTEREST

The authors do not have any actual, potential or perceived conflict of interest to declare.

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