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Discovery Agriculture

To Cite:
Ricwuskebnde AT, Dantani AM, Maigida DT. Effect of Arbuscular Mycorrhizal Fungi on physiological growth of maize in Northern Guinea Savanna soil. *Discovery Agriculture* 2025; 11: e6da3107 doi: https://doi.org/10.54905/disssi.v11i23.e6da3107

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Peer-Review History
Received: 12 November 2024
Reviewed & Revised: 16/November/2024 to 02/April/2025
Accepted: 04 April 2025
Published: 09 April 2025

Peer-Review Model
External peer-review was done through double-blind method.

Discovery Agriculture
pISSN 2347-3819; eISSN 2347-386X

Effect of Arbuscular Mycorrhizal Fungi on physiological growth of maize in Northern Guinea Savanna soil

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ABSTRACT

Many factors scale the effect of arbuscular mycorrhizal fungi (AMF) on crops' growth with a possibility of negative impact under some growing conditions. The effect of phosphorus application rates and soil moisture regimes on mycorrhizal maize's physiological functions and growth was evaluated in this factorial study. Samples were either inoculated with AMF or not, supplied with 30, 60 or 90 kg P_2O_5 ha^{-1}, and irrigated at 50% or 100% field capacity (FC). The maize variety used was SAMMAZ-16. The plants were destructively sampled at 4 weeks after sowing (WAS), 8 WAS and 12 WAS during which per cent root colonization (determined only at 8 and 12 WAS), evapotranspiration, water use efficiency and biomass were determined. The determined data were subjected to analysis of variance and Duncan's Multiple Range Test was used as a tool for means separation at $\alpha = 0.05$. The results of the experiment showed that per cent root colonization by AMF in the inoculated pots was 62.22% at 8 WAS and 71.33% at 12 WAS. Under 100% FC, inoculated maize plants consistently achieved similar biomass production to non-inoculated plants that received 50% or higher P_2O_5. AMF inoculation tended to reduce the water use efficiency of the plants in low P_2O_5 application rates (30 and 60 kg P_2O_5 ha^{-1}) and moisture regime (50% FC). It is therefore concluded that AMF inoculation can be deleterious to the productivity of SAMMAZ-16 when both phosphorus and soil water simultaneously limit the crop growth.

Keywords: Maize; Arbuscular mycorrhizal fungi; Phosphorus application; soil water regime; Biomass accumulation; Water use efficiency.

1. INTRODUCTION

Savanna biomes are characterized by C3 trees and C4 grasses that constantly compete for limited growth resources (Sankaran, 2019). In the northern guinea savanna (NGS) of Nigeria, phosphorus is a major growth-limiting factor for many staples grown.

This is because the soils of the region are rich in sesquioxides which easily form complexes with phosphorus ions thereby limiting their availability for plant uptake (Chude et al., 2011). To alleviate this phosphorus-limiting growth condition, a high amount of phosphorus fertilizer is added which raises environmental concerns. However, studies have shown that arbuscular mycorrhizal fungi (AMF) may present an environmentally sustainable option for optimal phosphorus uptake by plants.

It is widely known that Arbuscular Mycorrhizal Fungi (AMF) can complement the phosphorus and water uptake of its plant symbionts in return for the carbon it obtains for respiration (Duan et al., 1996; Lehmann and Rillig, 2015; Mitra et al., 2019). This resource mobilization through the hyphal pathway promotes the growth and physiological functions of the plants (Calvo-Polanco et al., 2016; Quiroga et al., 2017). Abiotic factors may, however, modulate the effect of AMF on plant symbionts, sometimes resulting in growth suppression (Klironomos, 2003; Johnson and Graham, 2013). The degree of root colonization by AMF has shown an antagonistic trend with phosphorus availability in several studies (Liu et al., 2016; Aliyu et al., 2019).

In tomatoes, prolonged drought stimulated more root colonization in a study by (Bitterlich et al., 2018). However, intensive root colonization of plants' roots by AMF resulted in a negative growth response. Johnson et al., (1997) postulated that AMF can act as a parasite in a mycorrhizal symbiosis in certain growth conditions where the plant gets less than its C cost. Under such parasitic conditions, mycorrhizal symbiosis becomes deleterious to the plant symbionts. Even so, there remains a paucity of knowledge on the multi-factor effect of abiotic stressors on arbuscular mycorrhizal symbiosis as it relates to crop productivity in the Nigerian NGS.

Considering that global climate change is characterized by a simultaneous change in many environmental factors, it is necessary to build a robust understanding of combined environmental factor interaction effects on the development of mycorrhiza and the consequences on plants in the savanna ecologies which are prone to climate vagaries. Therefore, this study was designed to track at the interval, the effect of AMF-maize symbiosis on physiology and biomass accumulation of the maize plants, under phosphorus and soil water variations in the NGS of Nigeria.

2. MATERIALS AND METHODS

Site Description, Soil Sampling and Preparation

Disturbed soils were collected from a phosphorus depleted (1.7 mg kg^{-1}) field, air-dried, sieved through 4 mm mesh and sterilized at 110^{o} C for 90 min in that sequence. The field (11^{0} 09′ 96.5″ N, 7^{0} 37′ 96.2″ E) is located in the Northern Guinea Savanna of Nigeria. The soil is loam, with sand, silt and clay contents of 56.8, 28.3 and 14.9% respectively. The soil is classified based on USDA Soil Taxonomy as Typic Haplustalf. The soils contain; 5.80 g of organic carbon, 1.12 g of total nitrogen, 1.70 mg of phosphorus, 0.40, cmol of potassium and 0.40 cmol of sodium; per unit kilogram of soil. The electrical conductivity of the soils was 0.4 dS m^{-1} while pH (H_2O) and pH (CaCl) were 6.07 and 5.63 respectively.

Experimental Procedure

The experiment had three factors; Arbuscular Mycorrhiza Fungi (AM) at two levels (addition and no addition), Irrigation (I) at two levels (50 and 100% of field capacity) and Phosphorus (P) at three levels (30, 60 and 90 kg ha^{-1} P_2O_5). The 4mm sterile soil was repacked into cylindrical pots at a bulk density of 1.44 Mg m^{-3} in two layers of 3.5 kg each. Thirty grams (30g) of *Glomus mosseae* inoculum sourced from Soil Microbiology Laboratory, University of Ibadan was mixed with the upper layer to introduce AMF to the pots and an additional 10 g of the inoculum was placed in sowing holes during sowing to ensure adequate root colonization.

A maize variety called SAMMAZ-16 obtained from the institute for Agricultural Research was used as the test crop. Plants were irrigated at the full soil moisture at field capacity for the first 2 weeks after sowing (WAS) to ensure proper seedling development. Volumes of water for irrigation were estimated from the following relations:

$$V_{FC} = \pi r^2 Z (\theta_{FC} - \theta_{PWP}) \quad (1)$$

The volume of water (cm^3) for irrigating at 100% FC at any instance other than the first irrigation

$$V_{100} = \pi r^2 \sum_{i=1}^{n} z_i (\theta_{FC} - \theta_i) \quad (2)$$

The volume of water (cm^3) for irrigating at 50% FC at any instance

$$V_{50} = 0.5\pi r^2 \sum_{i=1}^{n} z_i (\theta_{FC} - \theta_i) \quad (3)$$

Where V_{FC}, V_{100} and V_{50} are the volumes of water for irrigating to FC on the first day of sowing, 100% FC at any instance other than first irrigation and 50% FC respectively. D is the total depth of soil in the pot, d_i is the depth of the i^{th} soil layer and r is the radius of the cylindrical pot all measured in cm, θ_i is moisture content of i^{th} soil layer at the instant of watering, θ_{FC} is the volumetric moisture content at field capacity and θ_{PWP} is the volumetric moisture content at permanent wilting point all in cm^3/ cm^3.

Evapotranspiration between irrigation intervals from each pot was quantified as the difference in moisture content of the soils at a designated irrigation regime and the moisture of the soil at the instant of irrigation (θ), multiplied by the soil depth (Z);

ET (mm) in experimental units maintained at 100% FC = Z ($\theta_{FC.}$ - θ) (4)

ET (mm) in experimental units maintained at 50% FC = Z ($0.5\theta_{FC.}$ - θ) (5)

Where;

$$\theta = \frac{(\theta_1+\theta_2+\cdots+\theta_n)}{n} \quad (6)$$

Here, 1, 2...n are integers that represent the layers of the soil whose moisture is measured.

120 kg/ha of N and 60 kg/ha of K was applied to all treatment groups while single superphosphate (20% P_2O_5) was applied to treatments according to their respective P-rates.

Data Collection

Destructive sampling was done at the 4th, 8th and 12th week after sowing (WAS). Three replicates (36 experimental units) were sampled destructively at each sampling.

Percentage root colonization

Fresh root bits were collected in the 8th and 12th week and stored in 50% ethanol in vials. Percentage root colonization (%RC) was determined using the protocol described by (Brundrett et al., 1994).

Total biomass

Above- and below-ground biomasses were collected by destructive harvests at the 4th, 8th and 12th week and oven-dried to constant masses except for the fine roots that were collected at 8th and 12th week and stored in vials for determination of root colonization. The sum of the oven-dried roots and shoot tissues was considered as the total biomass.

Water use efficiency (WUE)

WUE was calculated as units of total biomass yield (Y) divided by the units of water consumed by the crop (ETa) to produce that yield Ibragimov et al., (2007) at weeks 4, 8 and 12.

$$WUE = \frac{Y}{ET_a} \quad (7)$$

Statistical Analyses

The data were subjected to analysis of variance (ANOVA) and Duncan's Multiple Range Test (DMRT) was used for the means separation. Windows compatible Statistical Analysis System SAS, (1996) was used for all the statistical analyses.

3. RESULTS

Effect of Inoculation on Root Colonization by AMF

Root colonization by AMF was 62.22% at 8 WAS and 71.33% at 12 WAS (Table 1). Phosphorus application rate did not alter the per cent root colonization at 8 WAS. However, %RC was highest with 30 and 60 kg ha^{-1} P_2O_5 application which had statistically comparable %RC at 12 WAS. Irrigation regimes had no effect on %RC in this study.

Effect of AMF inoculation, Phosphorus and Irrigation on Physiology and Biomass of Plant

Evapotranspiration (ET)

The result of the volume of water evapotranspired during the experimentation is shown in (Table 1). At 8 and 12 WAS, ET did not differ between AMF-inoculated and non-inoculated plants. With regards to the main effect of phosphorus levels, ET increased with an

increase in P rate (P = 0.0003) at 8 WAS but was not statistically different at 12 WAS. Maintaining the soil at 50% FC significantly reduced cumulative ET by 13.6% at 8 WAS (P < 0.0005). At 12 WAS, however, plants growing on the soil that was maintained at 50% FC evapotranspired 26.5% less water than those irrigated at 100 % FC (P < 0.0005). While samples that received 90 and 60 kg P_2O_5 ha^{-1} applications under full irrigation evapotranspired the highest and second highest depth of water respectively, samples that received 30 kg P_2O_5 ha^{-1} under full irrigation evapotraspired the lowest and statistically similar water to those samples that received 30, 60 and 90 kg P_2O_5 ha^{-1} applications under 50 % FC at 8 WAS (Figure 1).

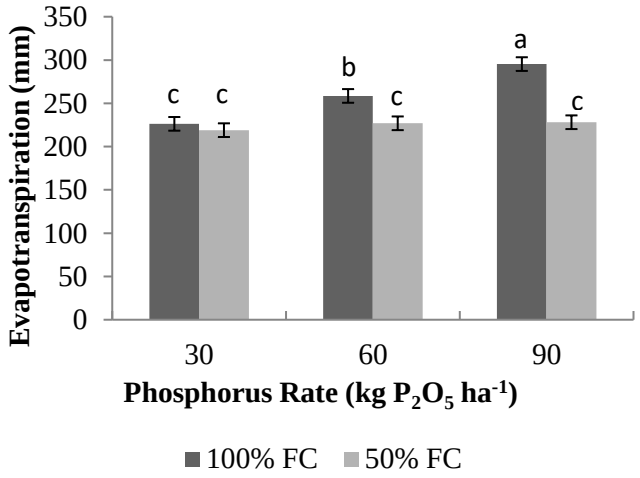

Figure 1 Interaction of Phosphorus and Irrigation on Evapotranspiration of plants at 8 WAS.
Means of Evapotranspiration (±SE) are shown and values with the same letter(s) are not significantly different (two-way ANOVA, DMRT, P < 0.05, n = 36)

Table 1 Effect of AMF inoculation, Phosphorus and Irrigation on Physiological Parameters of Plant

Treatment	% RC		Evapotranspiration (mm)		Biomass (g pot^{-1})			Water Use Efficiency (g mm^{-1})		
	8 WAS	12 WAS	8 WAS	12 WAS	4 WAS	8 WAS	12 WAS	4 WAS	8 WAS	12 WAS
Mycorrhiza (AMF)										
Inoculated	62.22a	71.33a	244.44	462.82	4.70	29.69	51.24a	0.052	0.121	0.111a
Non-inoculated	0.00b	0.00b	240.24	478.29	5.58	27.09	45.81b	0.061	0.112	0.097b
LOS	***	***	NS	NS	NS	NS	**	NS	NS	**
SE±	1.130	1.270	4.574	11.781	0.430	0.900	1.061	0.0050	0.0050	0.0041
Phosphorus, P (kg P_2O_5 ha^{-1})										
30	62.00	73.00a	222.61c	457.64	3.51b	21.48c	34.37b	0.039b	0.097b	0.076b
60	62.00	78.00a	242.71b	473.24	5.03b	30.01b	54.12a	0.055b	0.124a	0.116a
90	61.32	63.00b	261.72a	480.79	6.88a	33.37a	57.07a	0.075a	0.128a	0.120a
LOS	NS	**	***	NS	**	***	***	**	**	***
SE±	2.764	3.266	5.601	13.453	0.530	1.104	1.332	0.0060	0.0060	0.0040
Irrigation, I (% FC)										
100	59.34	72.88	260.02a	542.42a	-	34.37a	55.64a	-	0.133a	0.258
50	65.12	69.78	224.66b	398.69b	-	22.41b	41.41b	-	0.099b	0.254
LOS	NS	NS	***	***	-	***	***	-	***	NS
SE±	2.266	2.546	4.575	10.974	-	0.893	1.082	-	0.0052	0.0091

AMF x P	NS	NS	NS	NS	NS	*	**	NS	NS	**
AMF x I	NS	NS	NS	NS	-	***	NS	-	**	NS
P x I	NS	NS	**	NS	-	NS	NS	-	NS	NS
AMF x P x I	NS	NS	NS	NS	-	*	NS	-	NS	NS

Means followed by the same letter(s) within the same column under the same factor are not significantly different at 0.05 level of probability as determined by DMRT, LOS = level of significance, * = Significant at 0.05 level of probability, ** = Significant at 0.01 level of probability, *** = Significant at 0.001 level of probability, NS = Not significant at 0.05 level of probability, "-" signifies that data were not available, SE = Standard error, WAS = weeks after sowing.

Plant biomass

The effect of treatments on the biomass accumulation of the plants is shown in (Table 1). Although, plant biomass was not different at both 4 WAS and 8 WAS, AMF-inoculated plants significantly accumulated 12% more biomass than non-inoculated plants at 12 WAS ($P = 0.002$). Compared to 90 kg P_2O_5 ha^{-1} application, 30 and 60 kg P_2O_5 ha^{-1} applications produced statistically similar but significantly lower biomass at 4 WAS ($P = 0.001$). Plant biomass significantly increased for each increase in P_2O_5 level at 8 WAS ($P < 0.0005$). At 12 WAS, both 90 and 60 kg P_2O_5 ha^{-1} produced statistically similar but higher biomass than 30 kg P_2O_5 ha^{-1} application ($P < 0.0005$). Maintaining the soil at 50% FC significantly reduced plant biomass by 34.8% at 8 WAS ($P < 0.0005$) and 25.6% at 12 WAS ($P < 0.0005$).

There was a significant interaction between AMF inoculation, phosphorus and irrigation on total biomass at 8 WAS ($P = 0.011$) (Figure 2). Biomass was generally highest in plants that were amply watered regardless of their inoculation status except for non-inoculated plants that received 30 kg P_2O_5 ha^{-1} which produced statistically similar and lowest total biomass in both soil water conditions. Increasing the doses of P_2O_5 significantly improved biomass accumulation of the plants in soil that was maintained at 50% FC regardless of the inoculation status.

The interaction of AMF inoculation and phosphorus on plant biomass was significant at 12 WAS ($P = 0.0019$) (Figure 3). The biomass of inoculated plants was higher than that of non-inoculated plants in 60 and 90 kg P_2O_5 ha^{-1} application rates. However, the highest biomass was observed in inoculated plants with 60 kg P_2O_5 ha^{-1} application which was statistically similar to that of inoculated plants that received 90 kg P_2O_5 ha^{-1}. The biomass of inoculated and non-inoculated plants was the same and lowest with 30 kg P_2O_5 ha^{-1} application.

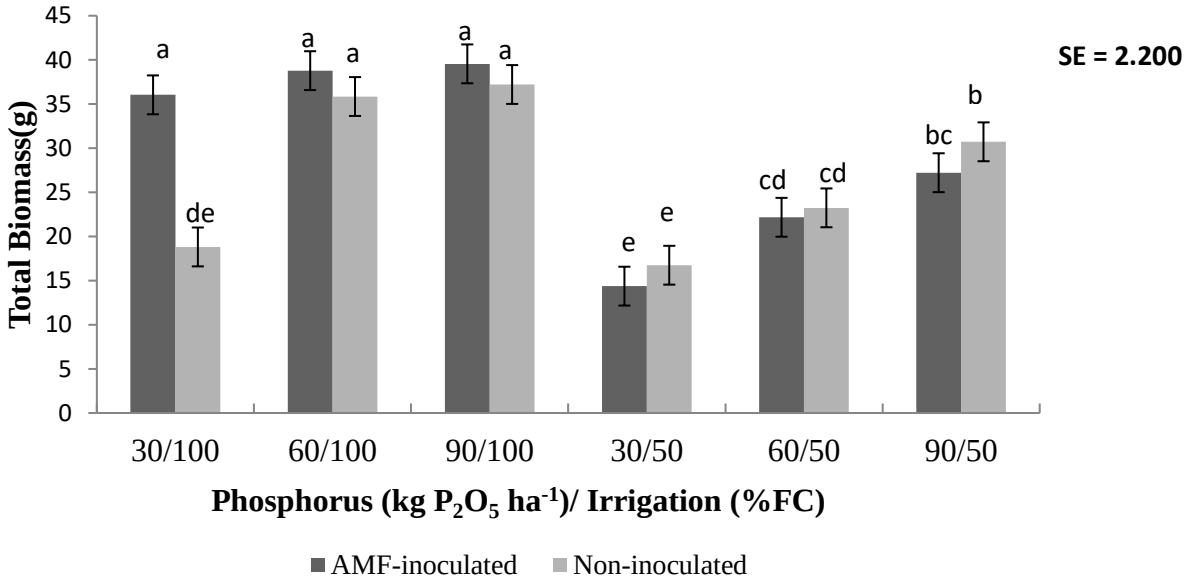

Figure 2 Interaction of AMF inoculation, phosphorus and irrigation on total biomass at 8 WAS

Means of total biomass (±SE) are shown and values with the same letter(s) are not significantly different (three-way ANOVA, DMRT, $P < 0.05$, $n = 36$).

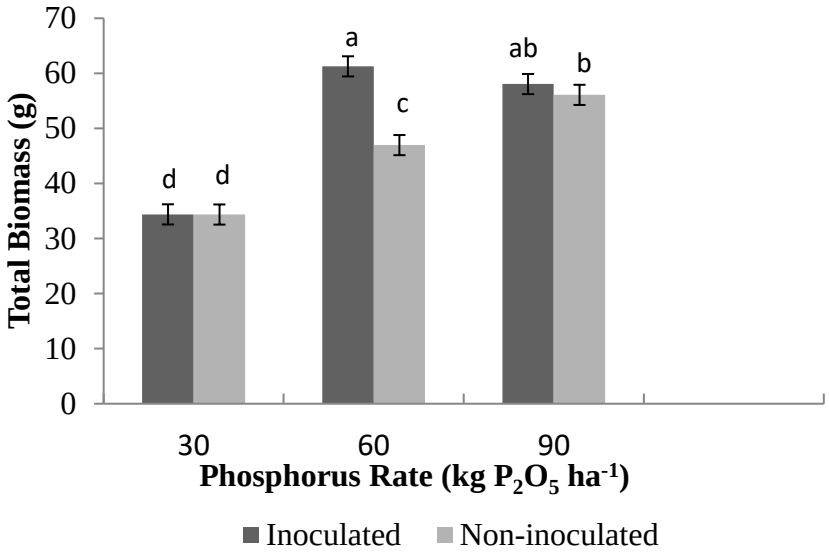

Figure 3 Interaction of AMF inoculation and phosphorus on total dry biomass of plants at 12 WAS.
Means of total biomass (±SE) are shown and values with the same letter(s) are not significantly different (two-way ANOVA, DMRT, $P < 0.05$, $n = 36$).

Water use efficiency

The results of water use efficiency (WUE) are shown in (Table 1). Inoculation with AMF did not significantly influence the amount of total dry matter accumulated (total biomass) per unit amount of water applied to produce that yield, quantified as WUE at 4 and 8 WAS. However, WUE of inoculated plants was 14.4% higher than that of non-inoculated plants at 12 WAS ($P = 0.009$). Compared to 90 kg P_2O_5 ha^{-1} application rates, 30 and 60 kg P_2O_5 ha^{-1} applications produced statistically similar but lower WUE at 4 WAS ($P = 0.001$). Water use efficiency of plants supplied with 90 and 60 kg P_2O_5 ha^{-1} was statistically at par and significantly higher than those supplied with 30 kg P_2O_5 ha^{-1} at 8 WAS ($P = 0.0011$) and 12 WAS ($P < 0.0005$). Irrigating plants at 50% FC significantly reduced WUE by 25.6% at 8 WAS ($P < 0.0005$) but no statistical difference was detected in WUE at 12 WAS with regard to the water treatment.

Mycorrhizal inoculation and phosphorus application interacted significantly on WUE at 12 WAS ($P = 0.028$) (Figure 4). The study shows that inoculated plants had higher WUE than non-inoculated plants that had similar P_2O_5 treatment only with 90 kg P_2O_5 ha^{-1} application. When 60 kg P_2O_5 ha^{-1} was applied, AMF-inoculated plants had significantly lower WUE than non-inoculated plants. Water use efficiency of the AMF-inoculated plants was higher than the non-inoculated plants when 100% of soil water at field capacity was supplied but was statistically similar to that of non-inoculated plants when soil was maintained at 50% of water at field capacity at 8 WAS (Figure 5).

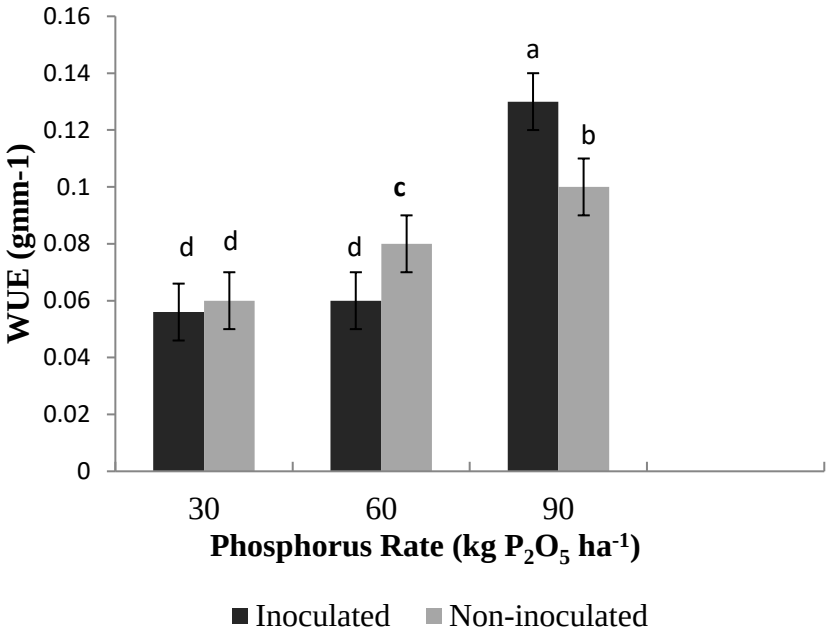

Figure 4 Interaction of AMF inoculation and phosphorus on WUE of plants at 12 WAS.
Means of WUE (±SE) are shown and values with the same letter(s) are not significantly different (two-way ANOVA, DMRT, $P < 0.05$, n = 36).

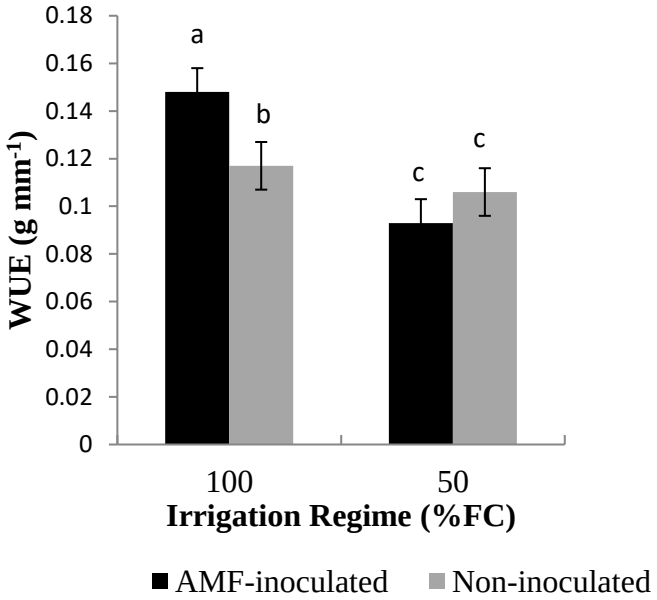

Figure 5 Interaction of AMF inoculation and Irrigation on water use efficiency of plants at 8 WAS.
Means of WUE (±SE) are shown and values with the same letter(s) are not significantly different (two-way ANOVA, DMRT, $P < 0.05$, n = 36).

4. DISCUSSION

Effect of AMF inoculation, Phosphorus and Irrigation on Plant Physiological and growth Responses

Evapotranspiration

Evapotranspiration (ET) of inoculated samples was not different from that of non-inoculated samples at both 8 and 12 WAS where ET was quantified. This result may lend credit to the assertion by Read, (1992) that water supply to plants through the hyphal pathway

may not be sufficient enough to significantly alter the rate of transpiration, but may just be adequate to maintain the physiological functions of the plant when hydraulic conductivity of the soil begins to limit uptake at the root surface. It is obvious in the result that increasing phosphorus application rate or irrigating at full soil moisture at FC induced higher ET than when lower phosphorus or less than water requirement was given to plants (Figure 1). This can be linked to the plant size effect likely brought about by more favourable P nutrient availability, dissolution and/or fluxes which can enhance better root interception and uptake thereby promoting the growth of the plants with implication for higher transpiration through the larger surface.

Plant biomass

The improvement in biomass accumulation of the plants due to inoculation with AMF at 12 WAS could be attributed to the advantages that the inoculated plants derived from hyphal proliferation during growth. The consistent similar or even higher biomass of inoculated plants given 30 or 60 kg P_2O_5 ha^{-1} compared to inoculated plants given 90 kg P_2O_5 ha^{-1} (Figure 3) observed under amply water condition is more likely due to the functional role of AMF in resources uptake than optimum P response to growth performance. This is because 60 kg P_2O_5 ha^{-1} application consistently accumulated lower biomass than 90 kg P_2O_5 ha^{-1} application in non-inoculated plants at both 8 and 12 WAS. In addition, even plants given 90 kg P_2O_5 ha^{-1} manifested P deficiency symptoms during the experimentation and this deficiency was more obvious in non-inoculated plants than in inoculated plants.

It is not unlikely that the hyphal length/density of treatment supplied with 60 kg P_2O_5 ha^{-1} was higher and equilibrated P uptake by plants in soils given 60 and 90 kg P_2O_5 ha^{-1} or even increased P uptake in soils given 60 kg P_2O_5 ha^{-1} application rate above that of those plants with 90 kg P_2O_5 ha^{-1} application rate. Although shoot P concentration at various sampling phases was not determined in this study, higher yield of inoculated than non-inoculated plants is often linked to higher shoot P concentration in several other studies (Polanco et al., 2016; Aliyu et al., 2019). However, Gavito et al., (2000) observed an increase in biomass of AMF-inoculated plants even when the shoot P concentration was lower than that of the non-inoculated plants, suggesting that biomass accumulation can be modulated by factors other than the nutrient uptake capacity of the plant.

This study singled out plant available water capacity which had a highly significant quadratic relationship with plant biomass ($R2 = 0.305$, $P = 0.001$) at 8 WAS (Data not shown). With this, it becomes necessary to infer that the improved growth of plants by AMF observed in this study is at least, partly directed at hyphal-mediated modification in the soil's hydro-physical properties in favour of plant available water even when AMF-enhanced plant nutrient uptake is not considered as a critical factor. The better performance in biomass of inoculated plants than non-inoculated plants with lower doses of P_2O_5 other than 90 kg P_2O_5 ha^{-1} application has very useful socio-economic and environmental implications in the Agricultural landscape. In economic terms, the opportunity cost associated with the application of 50% or more quantity of phosphorus fertilizer could simply be the creation of an enabling environment that encourages root colonization by AMF.

From the perspective of environmental sustainability, the amount of carbon dioxide that would have been released to the atmosphere during the manufacture and transportation of phosphorus fertilizers from the industry to the farm could be reduced by half if AMF which is an ecosystem-friendly biofertilizer is used. Under the amply watered condition, AMF-inoculated plants showed no reduction in biomass accumulation even at the lowest phosphorus level (30 kg P_2O_5 ha^{-1}) unlike the non-inoculated counterparts. Moreover, non-inoculated plants that were supplied with higher doses of phosphorus (60 and 90 kg P_2O_5 ha^{-1}) accumulated comparable biomass to the inoculated counterparts.

This indicates that low application of phosphorus fertilizers in combination with AMF inoculation can achieve similar optimization of biomass of the plants as high application of phosphorus fertilizers under adequate soil water scenario. The result also reveals the detrimental effect of water deficit on the crop regardless of inoculation status. Plants recorded lower biomass in soils that were maintained at 50% FC. The water stress-induced growth suppression could be due to perturbation in the physiological functions of the plants to cope with limiting soil moisture. Plants adjust stomatal opening based on soil moisture availability and stomatal conductance cannot be affected without a proportionate consequence on the growth of the plants (Blum, 2009).

Water use efficiency

The interplay between the total biomass production of a plant and evapotranspiration of the plant (ET) determines the outcome of water use efficiency (WUE). In this study, the highest WUE was recorded in inoculated plants supplied with 90 kg P_2O_5 ha^{-1} at 12 WAS. This could be linked to the ability of hyphae to supply additional phosphorus to the plants, and the influence that phosphorus nutrients

would have on the opening and closing of stomata with consequent effects on the physiological functions of the plants as suggested by (Safir et al., 1971). Another possibility could be the positive effect of AMF hyphae on the hydro-physical condition of the soil. However, with lower doses of P_2O_5 applications other than 90 kg P_2O_5 ha^{-1}, inoculated plants had lower WUE than- or comparable WUE to - non-inoculated plants.

As obligate biotrophs, AMF survives by the carbohydrate it gains from its plant partner in return for the resources it delivers through the hyphal pathway (Smith and Read, 2008). With limiting phosphorus nutrient in the soil, it was likely that AMF was taking more resources out of proportion than the P nutrient it delivered to the plants, or the biomass accumulated did not compensate for the energy expended in supplying the fungal hyphae with carbohydrates. This parasitic or neutral scenario can lead to corresponding retardation or stagnation in the biological growth of the AMF-inoculated plants hence, a reduction or invariable performance in WUE compared to the non-inoculated plants. This is particularly true if both AMF-inoculated and non-inoculated plants were transpiring at the same rate. Indeed, AMF inoculation did not alter the ET of the plants in this study. The regulation of stomatal opening by plants to cope with water deficit can limit plant growth (Blum, 2009).

Therefore, a cut in total biomass due to reduced evapotranspiration when deficit irrigation water was applied is the likely reason for the decrease in WUE in this study. Why inoculated plants had higher WUE than the non-inoculated plant at 8 WAS when both were supplied with 100% of their soil water at field capacity may not be unconnected to the additional advantages that hyphae may have garnered for the AMF-inoculated plants. The hyphae of AMF can explore more soil volume than root hairs for nutrients and water because of their relatively smaller diameter than root hairs (Smith and Read, 2008). The additional resources acquired through the hyphal pathway is capable of stimulating more growth thereby creating more surface and by extension, more stomata which can induce more influx of atmospheric carbon. The water use efficiency of a plant could be implicated by this "plant size effect".

5. CONCLUSION

This study evaluated the effect of AMF on the physiological parameters of a maize variety called SAMMAZ-16 under varying phosphorus and soil moisture levels in Nigerian Alfisols. It was observed that AMF-inoculated plants consistently achieved similar biomass production to non-inoculated plants that received greater than or equal to 50% higher phosphorus fertilizer. Phosphorus and water limiting conditions in the soil-AMF-plant system produced mutually exclusive positive feedback responses on plant biomass, while simultaneous low phosphorus nutrient and water stress exhibited undesirable responses on the plants' biomass. This presents very useful economic and environmental health implications. Can the benevolent arbuscular mycorrhizal fungi substitute or reduce phosphorus fertilizer application whose sources are fast depleting and its continuous application is increasingly becoming a threat to environmental health?

Can some combination of multi-factor environmental stressors phase out or nullify certain productivity-enhancing potentials and ecosystem services of AMF in the Nigerian savanna ecology? Ample and carefully designed, and integrated ecosystem manipulation experiments that would provide inputs for meta-analysis are required to address these. Such studies should among other things, seek to investigate the feedback mechanisms of the multi-factor effect of environmental changes on the photosynthetic quantum yield of plants, soil-plant nutrients and water relations, energy partitioning within plant system, plant surface-atmosphere gas exchange, hyphal density/length, and glomalin related soil protein (GRSP). Research at the field scale should also consider the economic analysis of AMF inoculation in crop productivity. This way, AMF inoculation can be incorporated into integrated soil fertility and conservation management system to boost crop production while avoiding environmental degradation and health concerns in the NGS.

Acknowledgement

We thank Prof. Ado Yusuf for providing technical advice on the handling of the mycorrhizal fungi, its inoculation and quantification of root colonization by the mycorrhizal fungi. We as well, appreciate Mrs. Juliana Mutuah for preparing the specimen and providing guidance during the determination of root colonization. The authors have no further declaration what so ever.

Informed consent

Not applicable.

Conflicts of interests

The authors declare that there are no conflicts of interests.

Ethical approval

Not applicable.

Funding

The study has not received any external funding.

Data and materials availability

All data associated with this study are present in the paper.

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