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Improving Maize Tolerance to Salinity and Low Available Phosphorus Situation by Arbuscular Mycorrhizal Fungi and Potassium Silicate

Eman H. Abd El-Azeiz and **Riham M. N. Faiyad***

Soil Fertility and Plant Nutrition Research Department, Soils, Water and Environment Research Institute (SWERI), Agricultural Research Center (ARC), Giza, Egypt

SALINITY and low phosphorus availability have a detrimental effect on crop plants' growth and yield by restricting their physiological functions as abiotic stress situation. In accordance with the state's directives for sustainable agricultural development aimed at enhancing soil health and augmenting crop productivity while safeguarding the environment and human health, we have investigated the optimization of maize productivity, a vital oil and strategic crop, under abiotic stress conditions utilizing two ecologically sound methods: arbuscular mycorrhizal fungi (AMF) and potassium silicate (KS). Field experiments were carried out over the course of two growing seasons (2023–2024) to examine the impact of AMF and KS treatments on fodder maize growth and productivity in salt affected soil with low available phosphorus. Four treatments of arbuscular mycorrhizal fungi inoculation with different rates of phosphorus fertilizer [100% Phosphorus fertilizer recommended dose (74.4 kg P_2O_5 ha^{-1}) (100%PRD)(as control), 75%PRD+AMF, 50%PRD+AMF, and 0%PRD+AMF] were used as the main plots and three treatments of potassium silicate foliar application [without foliar application (KS0), 3ml $l.^{-1}$(KS1), and 6ml l^{-1} (KS2)] were used as the sub plots. Data showed that AMF generally works to mitigate the negative effects of salinity and soil-available phosphorus deficiency which results in increased yield productivity and high quality when compared to the control. The application of (75%PRD+AMF) produced the greatest values of all measured parameters in both vegetative and harvest periods. The treatment (75%PRD+AMF) application improved values of chl. a, chl. b, yield, protein and oil content of mature grains in the two growing respective seasons. Foliage potassium silicate (KS) application at varied rates has a significant impact on all parameters under consideration. The better foliage was 6ml l^{-1} (KS2) in contrast to the treatment KS0. Potassium silicate foliar application at 6ml.l^{-1} enhanced chl. a and chl. b as well as grain yield and its quality in the two consecutive growing seasons when compared to KS0. In general, the combination of 75%PRD+AMF application and KS foliar application at 6ml.l^{-1} concentration reduces the negative effects of salinity on maize under low available phosphorus soil conditions. In terms of soil, the combination of 75%PRD+AMF treatment and KS0 foliage resulted in the highest value of available phosphorus nutrient in the soil after harvest. While, the highest AMF spore's density per 100 grams of soil was achieved with the lowest phosphorus rate application (50%PRD) comparing with control (100% PRD). Economically, the combination of 75%PRD+AMF without KS foliar treatment is substantiated as a feasible alternative to current treatments for enhancing agricultural productivity and farmer income.

Keywords: Arbuscular mycorrhizal fungi, Potassium silicate, Salinity, Phosphorus, Maize.

1. Introduction

The ancient Egyptian lands are suffering from many problems resulting from various agricultural practices, and the situation could worsen as a result of climate change, that has a discernible effect on the agricultural sector as a whole (Hamada, 2023). As noted, salt stress, is one of the most significant and well-known of these problems, which has a detrimental and adversely impact on the soil and agricultural output (Vennam et al. 2024 and Melebari, 2025). Furthermore, most agricultural fields suffer from a deficiency of readily available phosphorus (AP), which is no less harmful than salinity (Dey et al. 2021). So, phosphate fertilizers are necessary to replenish the soil and provide plants with phosphorus. On the contrary, the excessive use of these fertilizers can be detrimental to the environment (Khan et al. 2023). It is recognized that salinity, particularly in semi-arid, and dry agricultural soils, increases the deficiency of available phosphorus that can severely impact plant growth, development, and productivity (Dey et al. 2021 and Farid et al. 2025).Consequently, it was imperative to use sustainable agriculture practices to enhance soil health and productivity, while also safeguarding the environment and facing the two previously abiotic stresses.

*Corresponding author e-mail: reham.nageb@yahoo.com
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This led us to use eco-friendly technologies in this research as arbuscular mycorrhizal fungi (AMF) and potassium silicate (KS).

Regarding arbuscular Mycorrhizal Fungi (AMF) (Glomus spp.), they are a symbiotic fungi that form a symbiotic relationship with most plant roots. They enter plant roots, create a highly branching root and hyphae network that resembles a tree (Akpode´ et al. 2024) and get their carbon from the host plant and improve the plant's roots' capacity to absorb and transfer nutrients (Silva et al. 2023). They are considered one of the most effective bio- stimulant for lessening the consequences of salt stress where they increase the host plant's ability to tolerate salinity by enhancing nutrient uptake, preserving ionic balance, enhancing photosynthetic efficiency, and promoting antioxidant production (Islam et al. 2023). Furthermore, they play a crucial role in alleviating P deficit in soil and plant through secretion of phosphatase enzyme that catalyze phosphorus releasing from soil and be available to plant (Mosaad et al. 2024 and Kazadi et al. 2022).

In connection with potassium silicate (KS), it is a plant bio stimulant whose use as an eco-friendly in order to increase plant growth and resilience to environmental challenges such as salinity, drought, and nutritional imbalances (Alayafi et al. 2022). It is a source of highly soluble silicon (Si) and potassium (K) (Rizwan et al. 2023). Under conditions of stress Si has the function of a buffer to maintain internal plant balances, control the biosynthesis of solutes and osmo-regulating chemicals, improve the uptake and transport of water, and stimulate the activity of antioxidant enzymes (Aboyousef et al. 2025 and Elmahdy et al. 2023). Furthermore, potassium is known to improve physiological functions such chlorophyll pigments, stomatal movement, and water status, as well as root length, vegetative growth, and osmoregulation. It has been demonstrated that potassium enhances ionic balance and antioxidant enzymes activity (Gomaa et al.2021).

The impact of these treatments was evaluated on maize (zea mays), a crucial strategic crop that ranks second after rice in Egypt and is one of the most extensively cultivated crops in the world (Tammam et al. 2022). During the period from 2019 to 2023, the average area cultivated with maize in Egypt was approximately 2.2 million feddan, with a total production of around 7.6 million tons (Saleh, 2025). Maize grain contains 72% starch, 10% protein, 5% oil, 2% sugar and 1% ash and it is considered as a relatively sensitive cereal crop (Abuzaid et al. 2025 and Ibrahim et al. 2023). Additionally, they are employed in a number of industries, including the production of feed for cattle and poultry as well as the oil sector (Lamlom et al., 2024).

Since Egypt imports about 75% of its maize needs each year, particularly fodder maize (Abdel Azim et al., 2024), The aim of this research was to use environmentally friendly methods for increasing fodder maize productivity and growth under abiotic stress conditions, like salinity and a lack of available phosphorus in the soil, in keeping with the nation's efforts to achieve sustainable agricultural development.

2. Materials and Methods

Tow filed experiments were conducted to investigate the effect of arbuscular mycorrhizal fungi (AMF) *(Glomus spp.)* and potassium silicate (KS) applications on maize (*Zea mays L.*) var. (cv. Yaqout single hybrid) growth and productivity in salt affected soil with low amounts of available phosphorus. This maize variety was selected due to its status as the first red hybrid in Egypt. It is characterized by its elevated productivity and high protein content, which makes it an excellent animal feed, and it remains under investigation to determine its complete agricultural potential.

2.1. Study location

During the two summer seasons of 2023 and 2024, the present study grown in a private farm (coordinates: 31°4'54"N, 31°24'4"E) located in Met Antar village, Talkha district, Dakahlia Governorate, Egypt.

2.2. Soil Sampling and Analyses

Before planting random disturbed soil samples were taken from the soil surface at the depth of (0-30 cm). According to Klute (1986), Page et al. (1982) and Walker et al. (2006), some properties and density of AMF Spores, respectively in the initial soil were pointed out in Table 1. After harvesting, surface soil samples at the same depth from each sub plot were collected to determine the available P (mg kg^{-1}). According to Walker et al. (2006), spores were collected from a 100 g sample of soil using the conventional wet screening and decantation procedure (45 µm and 1 mm mesh), and then counted using an Olympus SZ61 stereo microscope.

Table 1. Average values of some properties for the initial soil of the experimental site during the two growing seasons (2023/2024).

Particle size distribution (%)			Texture class	EC[1], dSm^{-1}	pH[2]	SSP[3]	SAR[4]	ESP[5]	Density of AMF Spores		
Sand	Silt	Clay	Clay	4.36	8.7		%		Spore 100 g^{-1} Soil		
29.36	20.13	50.51				60.80	8.71	10.38	7170		
Soluble ions (mmol L^{-1})								Available			Total
Soluble cations				Soluble anions				elements mg kg^{-1}			
Mg^{++}	Ca^{++}	Na^{+}	K^{+}	SO_4^{--}	Cl^{-}	HCO_3^{-}	CO_3^{--}	N	P	K	P
7.62	8.15	24.46	3.37	22.96	19.48	1.16	0.00	29.3	5.92	189.4	82.4

[1] Soil Electrical Conductivity (ECe) and soluble ions were determined in saturated soil paste extract.
[2] Soil pH was determined in soil suspension (1: 2.5).
[3] SSP: Soluble Sodium Percentage.
[4] SAR: Sodium Adsorption Ratio.
[5] ESP: Exchangeable Sodium Percentage.

2.3. Experiment description

Two field studies with three replicates were carried out utilizing a statistical split plot design. The Experiments included twelve treatments resulting from four treatments of arbuscular mycorrhizal fungi inoculation with different rates of phosphorus fertilizer and three treatments of potassium silicate foliar applications. The main plots comprised:100% Phosphorus fertilizer recommended dose (74.4 kg P_2O_5 ha^{-1}) (100% PRD) (as control), 75% PRD+AMF, 50% PRD+ AMF, and 0% PRD + AMF. The sub-main plots included potassium silicate foliar treatments [without foliar application (KS0), 3 ml. l^{-1} (KS1) and 6 ml. l^{-1} (KS2)].The experimental flowchart is presented in Fig 1. Maize grains (Yaqout single hybrid) and potassium silicate (K_2O_3Si) were purchased from the agricultural commercial market. Potassium silicate contains 25% silicon oxide (SiO_2) and 10% potassium oxide (K_2O). Before being sown, treatments which have AMF, maize grains were infected with AMF that bought from the microbiology department, SWERI, ARC using the rate of 2.4 kg. ha^{-1}. Grains of maize were sown on 1st of May during the two cultivated growing summer seasons. Thinning was done when the plant reached 15 cm in height, leaving one plants per hill. As advised by the Ministry of Agriculture and Land Reclamation (MALR), nitrogen was added as ammonium sulphate (20.5% N) at a rate of 288 kg N ha^{-1} and potassium sulphate (48% K_2O) at a rate of 60 kg K_2O ha^{-1}. Super phosphate fertilizer was added at a rate of 74.4 kg P_2O_5 ha^{-1} as the control treatment and other treatments were calculated and potted during the soil preparation. Potassium silicate treatments were applied to the plants three times at 30, 45 and 60 days after sowing, using freshly produced solutions. The percentage of potassium in potassium silicate was removed from the amount of potassium added to the ground.

2.4. Recorded Data

2.4.1. Growth Stage measurements

Plant samples were obtained from each sub plot at the greatest stage of vegetative growth (70 days after sowing) to evaluate some growth parameters as: plant height (cm), plant fresh weight (g $plant^{-1}$), plant dry weight (g $plant^{-1}$). Leaf area (cm^2) also calculated according to the following formula: Leaf Area = lamina length x maximum width x k (where k is the coefficient to be Computed that equal 0.75) (Musa et al., 2016). Chlorophyll a and b in levels (mg g^{-1} FWT) were assessed spectrophotometrically using 80% acetone in accordance with Nayek et al. (2014). Peroxidase (POD) and Catalase (CAT) activities were measured using a spectrophotometer in accordance with Alici and Arabaci, (2016), where the leaf sample (0.5 g) was frozen in liquid nitrogen and coarsely pulverized with a pestle in a cooled motor. The frozen powder was then added to 10 mL of phosphate buffer (pH 7.0). The homogenate was centrifuged at 15000 × g for 10 minutes at 4°C. The supernatant was utilized as an enzyme source for catalase (EC 1.11.1.6) and peroxidase (EC 1.11.1.7). Proline (µg.g^{-1} F.W) was extracted in 3% sulphosalicylic acid and was determined using a calorimetric method according to the method of Ábrahám et al. (2010).

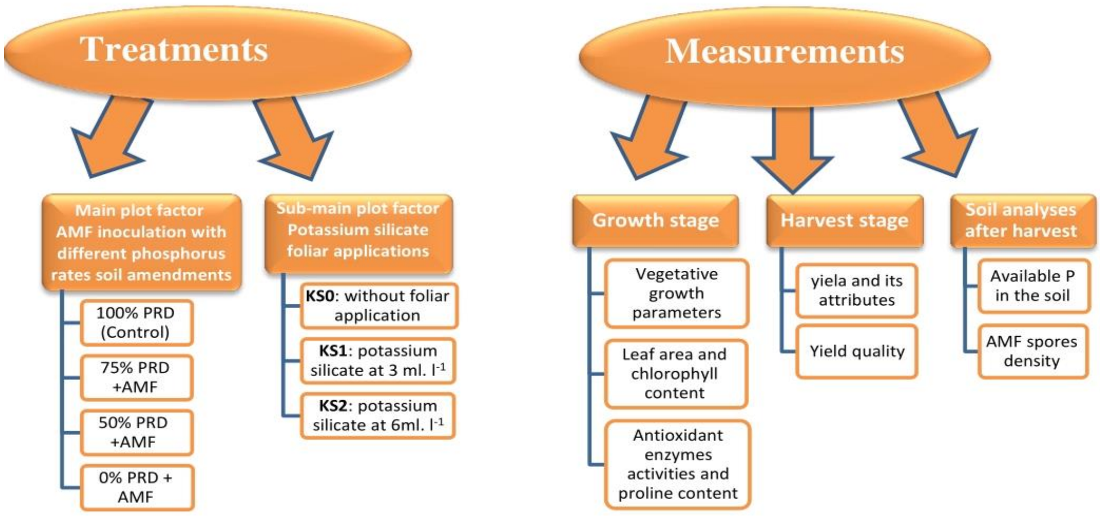

Fig. 1. The flowchart of the experiment

2.4.2. Harvest stage measurements

The following characteristics were obtained for random plants from each plot: cob length (cm), cob weight (g), 100 grain weight (g), and grain yield (ton ha^{-1}). The harvested grains were cleaned, crushed, and digested to evaluate the total amount of N, P, and K components. uptake of nutrients was calculated according to the following formula:

$$\text{Nutrients uptake in mature grains kg ha}^{-1} = \frac{\text{Nutrient concentration x grain yield kg ha}^{-1}}{100}$$

Protein content in maize grains was calculated as follows, in accordance with A.O.A.C. (1990): Protein percentage = grain N% ×5.75. According to A.O.A.C. (1995), oil was extracted utilizing a Soxhelt apparatus with petroleum ether serving as the solvent.

2.5. Economic evaluation

Using current market rates for different methods and products, total cultivation expenses and gross returns were calculated. To calculate net returns for each treatment, the total cost of cultivation was subtracted from the gross income per hectare.

Net return ($\$. ha^{-1}$)= Gross return ($\$. ha^{-1}$) - Cost of cultivation ($\$. ha^{-1}$)

Benefit cost ratio (BCR) was calculated treatment wise as below:

$$\text{Benefit Cost Ratio (BCR)} = \frac{\text{Gross return}}{\text{Cost of cultivation}}$$

The economic evaluation was conducted utilizing the methodology outlined by Ayalew et al. (2018) and CIMMYT (1988).

2.6. Statistical analyses

The outcomes of two years' worth of identical tests were combined for study. Significant differences in treatment means were identified at P 0.05 using the LSD test and Duncan's Multiple Comparisons Test (Snedecor and Cochran 1980). According to Gomez and Gomez (1984), Co-STATE Computer Software was used to statistically evaluate the data from the current investigation.

3. Results

3.1. Effect of AMF inoculation with different phosphorus rates and foliar KS applications during maize vegetative growth stage

Tables 2 and 3 illustrates how the presented results demonstrated a considerable impact of AMF inoculation with different phosphorus rates on the studied parameters of vegetative growth, leaf area, and chlorophyll content of maize under salinity and low available P conditions. In comparison to the control (100% PRD [phosphorus recommended dose], the treatment (75% PRD+ AMF) application recorded the highest levels of vegetative growth parameters, with relative increments 3.46 and 3.69 % for plant height, 4.61 and 4.69 % for fresh weight, 6.87 and 6.68% for dry weight, 3.83 and 3.86% for leaf area, 2.27 and 3.42% for chl. a, and 3.32 and 3.22% for chl. b in the two growing seasons, respectively. In addition to, as seen in Table 4, it raises activities of CAT by 5.62 and 5.62%, POD by 2.24 and 2.33% and proline content by 4.32and 4.68% in two successive growing seasons respectively comparing with control treatment.

Regarding to applying foliage KS using varying rates, it has a substantial impact on every parameter under investigation. Foliar application with 6 ml. l^{-1} (KS2) was better in comparison to the non-foliar application (KS0). Potassium silicate application at 6 ml. l^{-1} as indicated in Tables 2 and 3 raised the values of plant height by 5.18 and 4.97%, fresh weight by 1.92 and 1.65%, dry weight by 4.36 and 4.49 %, leaf area by 2.45 and2.52%, chl. a by 4.2 and 4.87%, and chl. b by 4.57 and 4.58% in maize leaves grown under salinity and low available P conditions in the two respective growing seasons, respectively. Also, the data recoded in Table 4 demonstrated that the application of KS at 6 ml. l^{-1} was superior, where the values in the two growing seasons raised by 4.94 and 5.22 % for CAT activity, 3.61 and 3.66% for POD activity and 6.90 and 5.77% for proline, respectively.

For the interaction, the combination of 75% PRD +AMF application and KS foliar application at 6 ml. l^{-1} concentration reduces the negative effects of salinity on maize under low available P soil conditions. Application of 75% PRD +AMF and KS2 treatment increases chlorophyll content during two resoective growing seasons with relative increments 9.95 &10.24% for chl. a and 8.92 & 8.64% for chl. b in comparing with the control. Also, it increases activities of CAT by 13.90 & 13.80 and POD by 3.50 & 3.61 % as well as raises proline accumulation by 6.76 and 7.32 % as compared to the control in two growing seasons, respectively.

Table 2. Effect of AMF inoculation with different phosphorus rates and KS foliar applications and their interactions on some vegetative growth parameters on maize under salinity and low available P conditions across the growing seasons of 2023 and 2024.

Treatments		Plant height, cm		Fresh weight, g. plant^{-1}		Dry weight , g. plant^{-1}	
		2023	2024	2023	2024	2023	2024
Main : AMF inoculation with different phosphorus fertilizer rates							
100% PRD (Control)		290.82^{b}	293.70^{b}	873.32^{b}	877.16^{b}	215.14^{b}	216.84^{b}
75% PRD +AMF		300.88^{a}	304.55^{a}	913.61^{a}	918.34^{a}	229.93^{a}	231.32^{a}
50% PRD +AMF		281.63^{c}	284.40^{c}	848.05^{c}	852.48^{c}	198.77^{c}	200.91^{c}
0% PRD + AMF		257.86^{d}	260.80^{d}	823.93^{d}	828.47^{d}	189.54^{d}	191.27^{d}
F test		***	***	***	***	***	***
Sub main :KS foliar applications							
KS0		275.14^{c}	277.95^{c}	855.93^{c}	861.21^{c}	203.42^{c}	205.10^{c}
KS1		283.83^{b}	287.86^{b}	865.83^{b}	870.66^{b}	209.30^{b}	210.84^{b}
KS2		289.41^{a}	291.78^{a}	872.42^{a}	875.46^{a}	212.30^{a}	214.32^{a}
F test		***	***	***	***	***	***
Interactions							
100% PRD	KS0	287.96^{cd}	290.16^{d}	862.42^{f}	866.66^{f}	209.24^{f}	210.68^{f}
	KS1	290.00^{cd}	294.30^{c}	876.00^{e}	880.33^{e}	215.52^{e}	218.52^{e}
	KS2	294.50^{bc}	296.66^{c}	881.55^{d}	884.50^{d}	220.66^{d}	221.33^{d}
75% PRD +AMF	KS0	294.88^{bc}	297.00^{c}	908.00^{c}	912.66^{c}	224.36^{c}	225.42^{c}
	KS1	300.56^{ab}	306.50^{b}	912.33^{b}	920.00^{b}	230.75^{b}	232.18^{b}
	KS2	307.20^{a}	310.15^{a}	920.52^{a}	922.36^{a}	234.68^{a}	236.36^{a}
50% PRD +AMF	KS0	277.50^{ef}	280.46^{f}	840.33^{i}	845.12^{i}	194.39^{h}	196.90^{i}
	KS1	282.26^{de}	285.33^{e}	848.33^{h}	852.00^{h}	200.12^{g}	201.10^{h}
	KS2	285.13^{de}	287.42^{de}	855.50^{g}	860.33^{g}	201.80^{g}	204.75^{g}
0% PRD + AMF	KS0	240.25^{h}	244.18^{i}	813.00^{l}	820.42^{l}	185.72^{j}	187.40^{l}
	KS1	262.50^{g}	265.33^{h}	826.66^{k}	830.33^{k}	190.83^{i}	191.56^{k}
	KS2	270.83^{g}	272.90^{g}	832.13^{j}	834.66^{j}	192.08^{i}	194.85^{j}
F test		***	***	***	***	**	**

Means within a row followed by a different letter (s) are statistically different at $p < 0.05$
PRD: phosphorus recommended dose, AMF: arbuscular mycorrhizal fungi, KS0: without foliar application, KS1: potassium silicate at 3 ml. l^{-1}, KS2: potassium silicate at 6ml. l^{-1}.

3.2. Effect of AMF inoculation with different phosphorus rates and foliar KS applications during maize harvest stage

Tables 5 and 6 shows the impact of AMF inoculation with different phosphorus rates and foliar KS applications on yield, yield components as well as yield quality in mature maize grains under salinity and low phosphorus availability conditions. Data indicated that the application of (75% PRD+ AMF) produced the highest values for cob length (23.09 and 26.96 cm), cob weight (238.00 and 240.90 g), 100 grain weight (44.35 and 46.06 g), and grain yield (8.48 and 9.08 ton ha^{-1}), respectively, when compared to the control. The same treatment increased grain yield in comparing with the control by 10.84 and 10.32 % in two respective growing seasons. Also, it had a significant effect on crop quality (protein, oil content, and nutrient uptake). In comparison to the control, the values of nutrient uptake increased by 21.90 &23.12 % for N, 17.80 & 17.02 % for P and 25.45 & 24.45% for K during the two growing seasons, respectively. As well as, the amount of protein during the two growing seasons increased by 9.96 and 11.62%, and oil by 4.45 & 4.36 % respectively.

In terms of KS foliage, applying potassium silicate at 6.0 ml. l^{-1} had a positive significant effect with relative increments 2.41 and 3.19% for 100 grain weight, 3.43 and 4.15% for grain yield, 12.58 and 12.81 % for N uptake, 9.81 and 9.76% for P uptake and 14.38 and 15.71% for K uptake. Additionally, KS2 treatment (6. ml. l^{-1}) raised protein by 8.90 and 8.32% and oil by 9.05 and 7.99% during the two respective growing seasons as compared to the KS0.

Table 3. Effect of AMF inoculation with different phosphorus rates and KS foliar applications and their interactions on leaf area and chlorophyll a, b content on leaves of maize under salinity and low available P conditions across the growing seasons of 2023 and 2024.

Treatments		Leaf area, cm^2		chlorophyll a, $mg.g^{-1}$ FWT		chlorophyll b, $mg.g^{-1}$ FWT	
		2023	2024	2023	2024	2023	2024
Main: AMF inoculation with different phosphorus fertilizer rates							
100% PRD (Control)		935.01^{b}	938.28^{b}	1.103^{b}	1.142^{b}	0.723^{b}	0.745^{b}
75% PRD +AMF		970.83^{a}	974.49^{a}	1.128^{a}	1.181^{a}	0.747^{a}	0.769^{a}
50% PRD +AMF		880.35^{c}	885.33^{c}	0.984^{c}	1.029^{c}	0.677^{c}	0.697^{c}
0% PRD + AMF		847.33^{d}	851.16^{d}	0.881^{d}	0.932^{d}	0.630^{d}	0.651^{d}
F test		***	***	***	***	***	***
Sub main: KS foliar applications							
KS0		896.93^{c}	900.81^{c}	1.001^{c}	1.042^{c}	0.678^{c}	0.699^{c}
KS1		909.29^{b}	912.56^{b}	1.025^{b}	1.074^{b}	0.695^{b}	0.716^{b}
KS2		918.92^{a}	923.57^{a}	1.046^{a}	1.097^{a}	0.709^{a}	0.731^{a}
F test		***	***	***	***	***	***
Interactions							
100% PRD	KS0	920.74^{e}	924.36^{f}	1.045^{e}	1.103^{e}	0.706^{e}	0.729^{e}
	KS1	936.19^{d}	940.50^{e}	1.129^{bc}	1.157^{c}	0.722^{d}	0.742^{d}
	KS2	948.12^{c}	950.00^{d}	1.136^{b}	1.166^{c}	0.742^{c}	0.765^{c}
75% PRD +AM	KS0	959.50^{b}	962.33^{c}	1.111^{d}	1.140^{d}	0.717^{d}	0.739^{d}
	KS1	972.50^{a}	975.14^{b}	1.124^{c}	1.189^{b}	0.755^{b}	0.778^{b}
	KS2	980.50^{a}	986.00^{a}	1.149^{a}	1.216^{a}	0.769^{a}	0.792^{a}
50% PRD + AMF	KS0	876.00^{f}	880.33^{i}	0.971^{g}	0.998^{h}	0.669^{g}	0.690^{g}
	KS1	880.75^{f}	884.50^{h}	0.968^{g}	1.020^{g}	0.679^{f}	0.699^{fg}
	KS2	884.31^{f}	891.17^{g}	1.014^{f}	1.071^{f}	0.684^{f}	0.703^{f}
0% PRD + AMF	KS0	831.50^{i}	836.24^{l}	0.875^{i}	0.927^{j}	0.622^{i}	0.641^{i}
	KS1	847.75^{h}	850.12^{k}	0.882^{hi}	0.933^{ij}	0.627^{i}	0.647^{i}
	KS2	862.75^{g}	867.13^{j}	0.887^{h}	0.937^{i}	0.643^{h}	0.665^{h}
F test		**	***	***	***	***	***

Means within a row followed by a different letter (s) are statistically different at $p < 0.05$

PRD: P recommended dose, AMF: arbuscular mycorrhizal fungi, KS0: without foliar application, KS1: potassium silicate at 3 ml. l^{-1}, KS2: potassium silicate at 6ml. l^{-1}

The combination of 75% PRD +AMF application and KS foliar application at 6 ml. l^{-1} concentration improves plant tolerance to salinity, promote plant growth and grain yield productivity by adapt maize plants to abiotic stress. Application of treatment 75% PRD + AMF in combination with KS2 raised grain yield by 15.52 and 15.19% , N uptake by 37.67 and 40.32 %, P uptake by 28.50 and 28.9 8% and K uptake by 41.48 and 40.19% in two growing seasons, respectively as compared to the control. Also, it increased protein and oil content by 19.18 & 21.80% and 7.61 & 7.78%, respectively.

3.3. Effect of AMF inoculation with different phosphorus rates and KS foliar applications on available phosphorous and density of AMF Spores in soil after harvesting

Available phosphorus (mg kg^{-1}) status and AMF spores density in the soil after maize harvesting were shown in Figs. 2 to 5 during the two growing seasons, respectively. It's clear that available P in the soil increased with application of 75% PRD+ AMF comparing with the control (100% PRD). For KS foliar application, KS0 treatment (without foliar) was the superior where it recorded the highest values of available phosphorus status in the soil post harvesting reflecting low P uptake related to reduced maize growth under stress condition. The interaction of 75% PRD +AMF application and no potassium silicate foliage recorded the highest value of the available phosphorus nutrient demonstrating role of AMF on soil P availability.

Table 4. Effect of AMF inoculation with different phosphorus rates and KS foliar applications and their interactions on antioxidant enzymes activities and proline content on leaves of maize under salinity and low available P conditions across the seasons of 2023 and 2024.

Treatments		CAT, mg $^{-1}$ protein		POD, mg $^{-1}$ protein		Proline, µg.g $^{-1}$ F.W	
		2023	2024	2023	2024	2023	2024
Main : AMF inoculation with different phosphorus fertilizer rates							
100% PRD (Control)		70.49^{b}	71.72^{b}	205.10^{b}	208.61^{b}	11.58^{b}	11.96^{b}
75% PRD +AMF		74.45^{a}	75.75^{a}	209.70^{a}	213.48^{a}	12.08^{a}	12.52^{a}
50% PRD +AMF		63.38^{c}	63.38^{c}	194.52^{c}	198.14^{c}	10.69^{c}	10.77^{c}
0% PRD + AMF		55.83^{d}	56.63^{d}	175.00^{d}	177.97^{d}	9.75^{d}	9.94^{d}
F test		***	***	***	***	***	***
Sub main : KS foliar applications							
KS0		64.27^{c}	64.92^{c}	192.10^{c}	195.41^{c}	10.72^{c}	11.10^{b}
KS1		66.78^{b}	67.39^{b}	197.10^{b}	200.65^{b}	10.90^{b}	11.07^{b}
KS2		67.45^{a}	68.31^{a}	199.05^{a}	202.58^{a}	11.46^{a}	11.73^{a}
F test		***	***	***	***	***	***
Interactions							
100% PRD	KS0	65.87^{e}	66.92^{e}	204.47^{d}	207.54^{f}	11.39^{c}	11.74^{c}
	KS1	72.07^{d}	73.30^{d}	205.39^{c}	208.88^{e}	11.44^{c}	11.83^{c}
	KS2	73.55^{c}	74.95^{c}	205.46^{c}	209.41^{d}	11.92^{b}	12.31^{b}
75% PRD +AM	KS0	74.05^{b}	75.61^{b}	208.32^{b}	212.28^{c}	11.96^{b}	12.41^{ab}
	KS1	74.28^{b}	75.50^{b}	209.17^{b}	213.14^{b}	12.14^{a}	12.55^{a}
	KS2	75.03^{a}	76.16^{a}	211.63^{a}	215.03^{a}	12.16^{a}	12.60^{a}
50% PRD + AMF	KS0	62.04^{h}	62.04^{h}	184.93^{g}	188.44^{i}	10.49^{g}	10.93^{e}
	KS1	63.62^{g}	63.62^{g}	198.49^{f}	202.26^{h}	10.63^{f}	10.16^{f}
	KS2	64.50^{f}	64.50^{f}	200.14^{e}	203.74^{g}	10.97^{d}	11.23^{d}
0% PRD + AMF	KS0	54.41^{k}	55.12^{k}	170.68^{j}	173.41^{l}	9.05^{i}	9.31^{h}
	KS1	56.36^{j}	57.15^{j}	175.35^{i}	178.33^{k}	9.41^{h}	9.73^{g}
	KS2	56.72^{i}	57.63^{i}	178.98^{h}	182.17^{j}	10.81^{e}	10.80^{e}
F test		***	***	***	***	***	***

Means within a row followed by a different letter (s) are statistically different at $p < 0.05$
PRD: P recommended dose, AMF: arbuscular mycorrhizal fungi, KS0: without foliar application, KS1: potassium silicate at 3 ml. l^{-1}, KS2: potassium silicate at 6ml. l^{-1}

Regarding to AMF spores density, the highest density was recorded by (50%PRD +AMF) application followed by (0% PRD+AMF), then (75% PRD+AMF) and 100% PRD was the lowest. While, potassium silicate has a non-significant effect on AMF spores density.

3.4. Economic evaluation

Table 7 shows the economics of maize as influenced by (AMF) inoculation with different phosphorus rates and KS foliar applications. The greatest total costs ($. ha^{-1}) were observed with fertilization treatment includes 75% PRD +AMF and KS2 then followed by treatment 50% PRD+AMF and KS2. The lowest total costs were recorded with 0% RPD+AMF and no foliage treatments comparing with the control (100% RPD and KS0). The highest gross return (2687.09 and 1922.81 $.$ha^{-1}$) of maize was mentioned with the combination of 75% PRD+ AMF and KS2 treatment followed by application of 75% PRD +AMF and KS1 applied treatment with gross return of 2677.41 and 1903.12 $. ha^{-1} during the two subsequent growing seasons. As for net return, the treatment 75% PRD+ AMF and KS0 was the highest, followed by the treatment 75% PRD+ AMF and KS1 in the first season with a margin of 0.57 $. ha^{-1}. While, the treatment 75% PRD +AMF and KS2 came in the second season with the highest net return with a difference of 6.79 $ from the treatment 75% PRD+AMF and KS1 that followed it. The highest B:C ratio (Benefit Cost Ratio) 1.726,1.733 were recorded from 75% PRD +AMF and no KS foliar treatment which was followed by 75% PRD +AMF and KS1treatment with 1.717, 1.726 B:C ratio (BCR) in both seasons. The combination of 75% PRD + AMF without KS foliar treatment is economically substantiated as a feasible alternative to current treatments for enhancing agricultural productivity and farmer income.

Table 5. Effect of AMF inoculation with different phosphorus rates and KS foliar applications and their interactions on yield and yield attributes of maize under salinity and low available P conditions across the growing seasons of 2023 and 2024.

Treatments		Cob length, cm		Cob weight, g		100 grain weight, g		Grain yield, $ton.ha^{-1}$	
		2023	2024	2023	2024	2023	2024	2023	2024
Main : AMF inoculation with different phosphorus rates									
100% PRD (Control)		22.17 ^{b}	24.15 ^{b}	223.26 ^{b}	225.74 ^{b}	43.16 ^{b}	44.11 ^{b}	7.65 ^{b}	8.23 ^{b}
75% PRD +AMF		23.09^{a}	26.96 ^{a}	238.00 ^{a}	240.90 ^{a}	44.35 ^{a}	46.06 ^{a}	8.48 ^{a}	9.08 ^{a}
50% PRD +AMF		21.45^{c}	22.68 ^{c}	199.06 ^{c}	201.92 ^{c}	41.25 ^{c}	42.23 ^{c}	7.52 ^{c}	7.91 ^{c}
0% PRD + AMF		19.93^{d}	21.04 ^{d}	185.85 ^{d}	188.50 ^{d}	39.5 ^{d}	40.20 ^{d}	7.21 ^{d}	7.32 ^{d}
F test		***	***	***	***	***	***	***	***
Sub main : KS applications									
KS0		21.09 ^{c}	22.96 ^{c}	206.65 ^{c}	209.39 ^{c}	41.50 ^{c}	42.38 ^{c}	7.57^{c}	7.96 ^{c}
KS1		21.78^{b}	23.87 ^{b}	211.49 ^{b}	214.33 ^{b}	42.19 ^{b}	43.34 ^{b}	7.74 ^{b}	8.15 ^{b}
KS2		22.11 ^{a}	24.29 ^{a}	216.48 ^{a}	219.07 ^{a}	42.50 ^{a}	43.73 ^{a}	7.83 ^{a}	8.29 ^{a}
F test		***	***	***	***	***	***	***	***
Interactions									
100% PRD	KS0	21.96^{f}	23.36^{f}	218.45^{f}	221.56^{f}	42.66^{f}	43.22^{f}	7.47^{g}	8.03^{g}
	KS1	22.15^{e}	24.25^{e}	223.53^{e}	225.53^{e}	43.20^{e}	44.32^{e}	7.69^{e}	8.25^{e}
	KS2	22.40^{d}	24.86^{d}	227.82^{d}	230.14^{d}	43.62^{d}	44.80^{d}	7.80^{d}	8.41^{d}
75% PRD +AM	KS0	22.83^{c}	26.52^{c}	233.75^{c}	236.82^{c}	43.96^{c}	45.16^{c}	8.33^{c}	8.89^{c}
	KS1	23.12^{b}	27.00^{b}	238.69^{b}	241.56^{b}	44.40^{b}	46.36^{b}	8.50^{b}	9.10^{b}
	KS2	23.33^{a}	27.36^{a}	241.56^{a}	244.33^{a}	44.70^{a}	46.66^{a}	8.63^{a}	9.25^{a}
50% PRD + AMF	KS0	21.23^{i}	22.30^{i}	193.97^{i}	196.30^{i}	40.48^{i}	41.90^{i}	7.40^{g}	7.72^{i}
	KS1	21.43^{h}	22.75^{h}	197.30^{h}	200.82^{h}	41.52^{h}	42.16^{h}	7.55^{f}	7.90^{h}
	KS2	21.70^{g}	23.00^{g}	205.91^{g}	208.66^{g}	41.76^{g}	42.63^{g}	7.62^{ef}	8.12^{f}
0% PRD + AMF	KS0	18.36^{l}	19.67^{l}	180.45^{l}	182.92^{l}	38.90^{l}	39.25^{l}	7.11^{i}	7.22^{k}
	KS1	20.42^{k}	21.50^{k}	186.46^{k}	189.42^{k}	39.66^{k}	40.52^{k}	7.24^{h}	7.35^{j}
	KS2	21.03^{j}	21.96j	190.66^{j}	193.18^{j}	39.94^{j}	40.83^{j}	7.30^{h}	7.41^{j}
F test		***	***	***	***	***	***	***	***

Means within a row followed by a different letter (s) are statistically different at $p < 0.05$
PRD: P recommended dose, AMF: arbuscular mycorrhizal fungi, KS0: without foliar application, KS1: potassium silicate at 3 ml. l^{-1} , KS2: potassium silicate at 6ml. l^{-1}

Table 6. Effect of AMF inoculation with different phosphorus rates and KS foliar applications and their interactions on NPK uptake, protein and oil content of maize grain under salinity and low available P conditions across the growing seasons of 2023 and 2024.

Treatments		Uptake (kg ha^{-1})						%			
		N		P		K		Protein, %		Oil, %	
		2023	2024	2023	2024	2023	2024	2023	2024	2023	2024
Main : AMF inoculation with different phosphorus rates											
100% PRD (Control)		153.92^{b}	170.18^{b}	22.92^{b}	25.65^{b}	146.20^{b}	169.08^{b}	11.55^{b}	11.88^{b}	5.84^{b}	5.97^{b}
75% PRD +AMF		187.63^{a}	209.54^{a}	27.00^{a}	30.02^{a}	183.43^{a}	210.43^{a}	12.70^{a}	13.26^{a}	6.10^{a}	6.23^{a}
50% PRD +AMF		138.22^{c}	150.14^{c}	20.66^{c}	21.45^{c}	129.45^{c}	139.^{39c}	10.56^{c}	10.90^{c}	5.08^{c}	5.22^{c}
0% PRD + AMF		116.24^{d}	122.14^{d}	17.90^{d}	19.08^{d}	96.98^{d}	105.81^{d}	9.25^{d}	9.58^{d}	3.96^{d}	4.05^{d}
F test		***	***	***	***	***	***	***	***	***	***
Sub main : KS foliar applications											
KS0		140.16^{c}	152.90^{c}	21.05^{c}	23.11^{c}	129.55^{c}	144.64^{c}	10.56^{c}	10.93^{c}	4.97^{c}	5.13^{c}
KS1		149.^{07b}	163.63^{b}	22.22^{b}	23.66^{b}	139.34^{b}	156.55^{b}	10.99^{b}	11.44^{b}	5.34^{b}	5.43^{b}
KS2		157.79^{a}	172.48^{a}	23.11^{a}	25.36^{a}	148.17^{a}	167.37^{a}	11.50^{a}	11.84^{a}	5.42^{a}	5.54^{a}
F test		***	***	***	***	***	***	***	***	***	***
Interactions											
100% PRD	KS0	144.60^{f}	158.18^{f}	21.88^{f}	24.09^{f}	139.68^{f}	159.00^{f}	11.10^{f}	11.33^{f}	5.78^{d}	5.91^{d}
	KS1	157.34^{e}	171.62^{e}	23.06^{e}	25.99^{e}	146.11^{e}	167.47^{e}	11.50^{e}	11.96^{e}	5.83^{d}	5.95^{d}
	KS2	166.97^{d}	180.79^{d}	23.85^{d}	26.90^{d}	152.88^{d}	180.81^{d}	12.08^{d}	12.36^{d}	5.92^{c}	6.06^{c}
75% PRD +AM	KS0	177.88^{c}	197.35^{c}	25.82^{c}	28.99^{c}	169.10^{c}	199.12^{c}	12.25^{c}	12.77^{c}	5.98^{c}	6.10^{c}
	KS1	190.90^{b}	209.32^{b}	27.12^{b}	30.02^{b}	183.60^{b}	209.30^{b}	12.65^{b}	13.23^{b}	6.12^{b}	6.24^{b}
	KS2	199.06^{a}	221.97^{a}	28.13^{a}	31.08^{a}	197.61^{a}	222.91^{a}	13.23^{a}	13.80^{a}	6.22^{a}	6.37^{a}
50% PRD + AMF	KS0	131.26^{h}	142.05^{h}	19.46^{h}	21.24^{h}	119.13^{i}	126.60i	10.18^{i}	10.58^{i}	4.39^{f}	4.51^{g}
	KS1	142.27^{g}	150.91^{g}	20.76^{g}	19.58^{j}	132.12^{h}	141.40^{h}	10.58^{h}	10.98^{h}	5.40^{e}	5.54^{f}
	KS2	148.20^{f}	157.53^{f}	21.79^{f}	23.54^{g}	137.16^{g}	150.21^{g}	10.93^{g}	11.16^{g}	5.47^{e}	5.62^{e}
0% PRD + AMF	KS0	111.01^{k}	114.04^{k}	17.06^{k}	18.19^{l}	90.28^{l}	93.86^{l}	8.74^{l}	9.09^{l}	3.91^{h}	4.00^{i}
	KS1	116.72^{j}	122.76^{j}	18.02^{j}	19.10^{k}	95.56^{k}	108.04^{k}	9.26^{k}	9.60^{k}	3.93^{h}	4.01^{i}
	KS2	127.26^{i}	129.64^{i}	18.69^{i}	20.01^{i}	105.12^{j}	115.58^{j}	9.78^{j}	10.06^{j}	4.04^{g}	4.14^{h}
F test		***	***	***	***	***	***	***	***	***	***

Means within a row followed by a different letter (s) are statistically different at $p < 0.05$
PRD: P recommended dose, AMF: arbuscular mycorrhizal fungi, KS0: without foliar application, KS1: potassium silicate at 3 ml. l^{-1} , KS2: potassium silicate at 6ml. l^{-1}

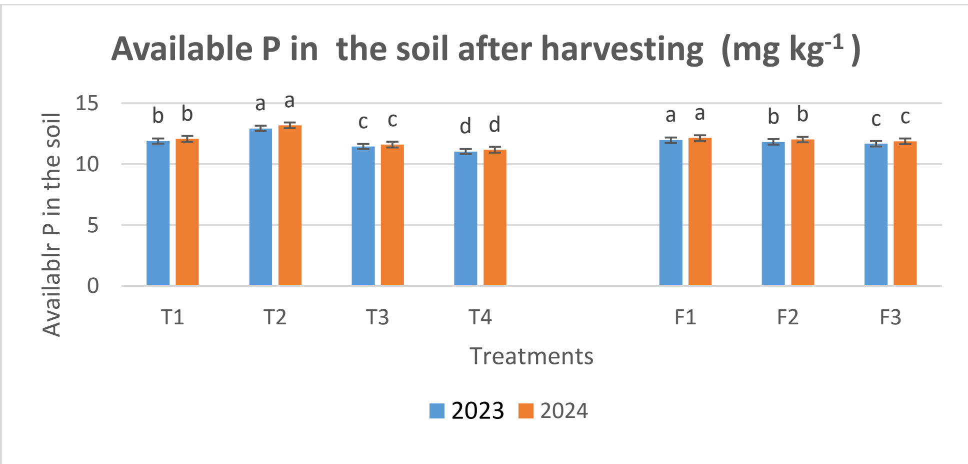

Fig. 2. Individual effect of AMF inoculation with different phosphorus fertilizer rates and KS foliar applications on soil's available P (mg kg^{-1}) after harvesting in both growing seasons of 2023 and 2024.

T1: 100% Phosphorus recommended dose (PRD), T2: 75% PRD+ arbuscular mycorrhizal fungi (AMF) , T3 :50% PRD +AMF , T4: 0% PRD+AMF F1: without foliar application, F2: potassium silicate at 3 ml. l^{-1}, F3: potassium silicate at 6ml. l^{-1}.

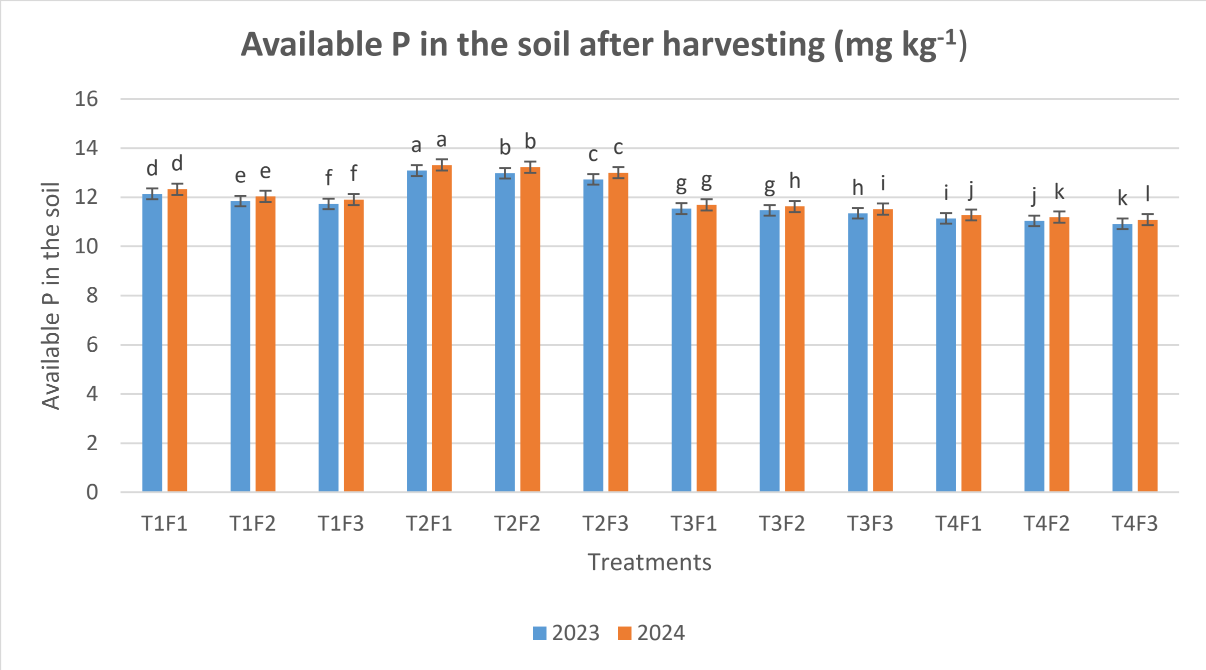

Fig. 3. Interaction effect of AMF inoculation with different phosphorus fertilizer rates and KS foliar applications on soil's available P (mg kg^{-1}) after harvesting in both growing seasons of 2023 and 2024.

T1F1: 100% Phosphorus recommended dose (PRD)+ without foliar application (KS0), T1F2: 100% PRD+ potassium silicate at 3 ml. l^{-1}(KS1), T1F3: 100% PRD+ potassium silicate at 6 ml. l^{-1}(KS2), T2F1: 75% PRD+ KS0, T2F2: 75% PRD+ KS1, T2F3 : 75% PRD+ KS2, T3F1: 50% PRD+ KS0, T3F2: 50% PRD+ KS1, T3F3: 50% PRD+ KS2, T4F1, 0% PRD+ KS0, T4F2: 0% PRD+ KS1, T4F3: % PRD+ KS2.

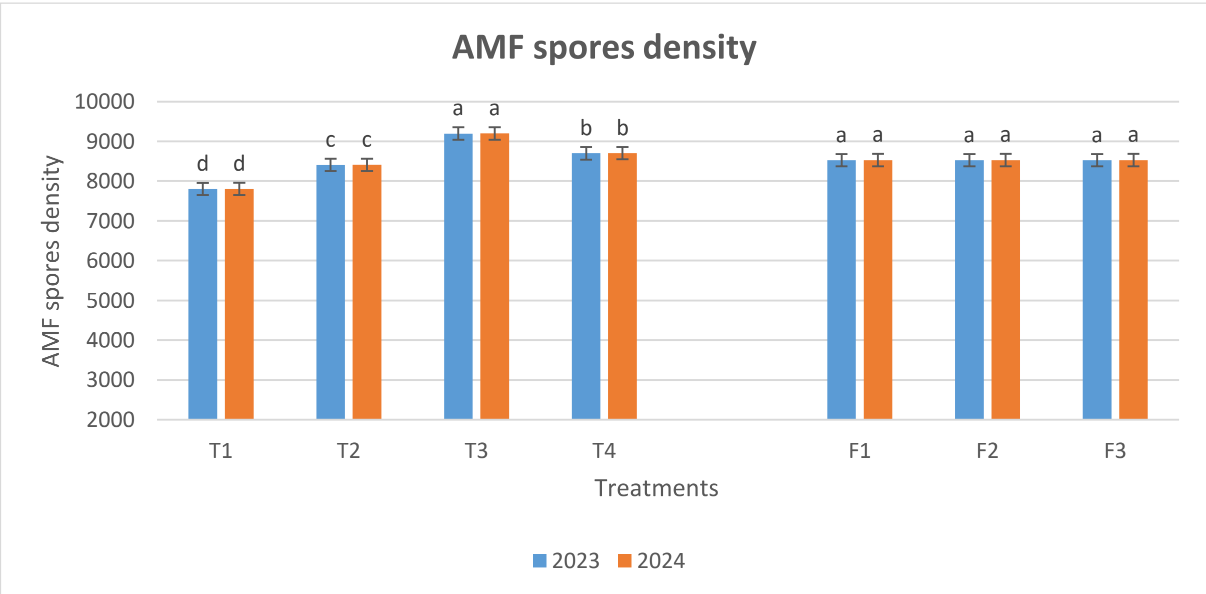

Fig. 4. Individual effect of AMF inoculation with different phosphorus fertilizer rates and KS foliar applications on soil's AMF spores density after harvesting in both growing seasons of 2023 and 2024.

T1: 100% Phosphorus recommended dose (PRD), T2: 75% PRD+ arbuscular mycorrhizal fungi (AMF), T3 :50% PRD +AMF , T4: 0% PRD+AMF F1: without foliar application, F2: potassium silicate at 3 ml. l^{-1}, F3: potassium silicate at 6ml. l^{-1}.

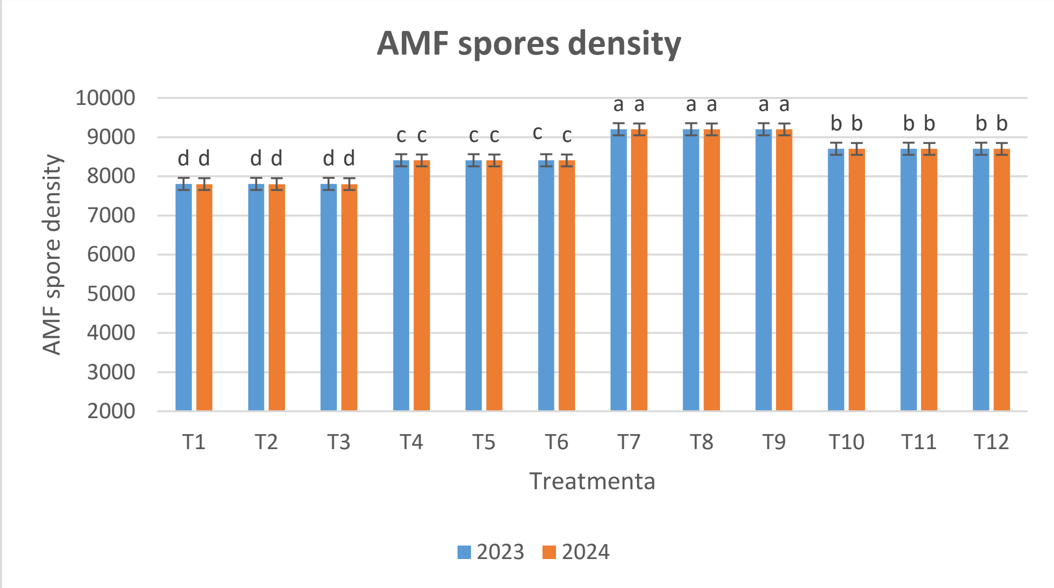

Fig. 5. Interaction effect of AMF inoculation with different phosphorus fertilizer rates and KS foliar applications on soil's AMF spores density after harvesting in both growing seasons of 2023 and 2024.

T1F1: 100% Phosphorus recommended dose (PRD)+ without foliar application (KS0), T1F2: 100% PRD+ potassium silicate at 3 ml. l^{-1}(KS1), T1F3: 100% PRD+ potassium silicate at 6 ml. l^{-1}(KS2), T2F1: 75% PRD+ KS0, T2F2: 75% PRD+ KS1, T2F3 : 75% PRD+ KS2, T3F1: 50% PRD+ KS0, T3F2: 50% PRD+ KS1, T3F3: 50% PRD+ KS2, T4F1, 0% PRD+ KS0, T4F2: 0% PRD+ KS1, T4F3: % PRD+ KS2.

Table 7. Economic analyses for maize crop due to response to AMF inoculation with different phosphorus rates and KS foliar applications under salinity and low available P conditions across the growing seasons of 2023 and 2024.

		Total costs ($ ha^{-1})		**Gross return ($ ha^{-1})**		**Net return ($ ha^{-1})**		**BCR (%)**	
		2023	**2024**	**2023**	**2024**	**2023**	**2024**	**2023**	**2024**
100% PRD	KS0	1534.57	1086.43	2496.77	1815.62	962.19	729.19	1.627	1.671
	KS1	1554.50	1097.98	2567.74	1841.87	1013.23	743.89	1.652	1.675
	KS2	1574.43	1112.68	2619.35	1859.37	1044.92	746.69	1.664	1.671
75% PRD +AMF	KS0	1539.58	1089.31	2658.06	1887.81	1118.48	798.50	1.726	1.733
	KS1	1559.50	1102.66	2677.41	1903.12	1117.91	800.46	1.717	1.726
	KS2	1579.43	1115.56	2687.09	1922.81	1107.66	807.25	1.701	1.724
50% PRD +AMF	KS0	1535.29	1086.54	2387.09	1688.75	851.80	602.20	1.555	1.554
	KS1	1555.21	1099.89	2435.48	1728.12	880.26	628.23	1.566	1.571
	KS2	1575.14	1112.79	2458.06	1776.25	882.91	663.45	1.561	1.596
0% PRD + AMF	KS0	1526.71	1081.00	2293.54	1579.37	766.83	498.37	1.502	1.461
	KS1	1546.63	1094.35	2335.48	1607.81	788.84	513.46	1.510	1.469
	KS2	1566.56	1107.25	2354.83	1620.93	788.27	513.68	1.503	1.464

First season, 2023

Base cost per ha equal 1517.41 $ included fertilizers (N and K) = 154.84 $, grains= 139.35$, soil service practices (rent, plowing, grasses removal, workers' wages and irrigation)= 1223.23$.
Treatments cost per ha included super phosphate fertilizer (100% PRD) =17.16 $, AMF= 9.29 $, KS1=19.93 $. and KS2=39.85 $.
Yield price ton ha^{-1}= 334.24 $.
$ equal almost 31 L.E.

Second season, 2024

Base cost per ha equal 1075$ included fertilizers (N& K) = 123 $, grains= 112$ soil service practices (rent, plowing, grasses removal, workers' wages and irrigation)= 840$
Treatments cost per ha included super phosphate fertilizer (100% PRD) = 11.43 $, AMF= 6.00$, KS1= 13.35 $and KS2= 26.25 $
Yield price ton ha^{-1}= 226.10 $.
$ equal almost 48 L.E.

PRD: P recommended dose, AMF: arbuscular mycorrhizal fungi, KS0: without foliar application, KS1: potassium silicate at 3 ml. l^{-1} , KS2: potassium silicate at 6ml. l^{-1}

4. Discussion

The present investigation looked at maize agronomical growth, physiological & biochemical response and productivity, as well as nutrients absorption, to explain the impact of AMF and KS in enhancing the tolerance of fodder maize plants (cv. Yaquot single hybrid) growing in salt affected soils with a low level of available phosphorus.

4.1. Effect of AMF inoculation with different phosphorus rates on maize growth performance and productivity

Arbuscular mycorrhizal fungi (AMF) are a commonly utilized symbiotic relationship to enhance plant development and increase plant tolerance to salinity and available phosphorus leakage (Abdul Wahab et al. 2023). On the other hand, Phosphorus is a key component of several biologically essential substances as nucleic acids and phospholipids (Umair et al. 2024). Previous detailed data in tables 2 to 6 showed that application of (75% PRD +AMF) treatment produced the outstanding effects during the stages of vegetative growth and harvest. These results may be attributed to the effective role of phosphorus and AMF in enhancing plant resistance to salinity and the soil's lack of available phosphorus. Mycorrhizal fungi symbiosis with maize plants positively affected on photosynthesis by improving the water status of the mycorrhizal plants, increasing stomatal conductance and leaf area (Thielicke et al. 2023). Furthermore, the increase in leaf area of mycorrhizal plants is attributable to an increase in cytokinin activity, which encourages cell division and expansion (Dastogeer et al. 2020). A significant increase in chlorophyll concentration in leaves was observed in the case of phosphorus and AMF treatment applications, and this may be due to the increased ability of plants to absorb more nutrients through the root network formed by mycorrhizae (Islam et al. 2023). Also, phosphorus in combination with AMF inoculant improved photosynthesis by raising synthesis of adenosine triphosphate (ATP), and even the ratio of ATP to ADP (adenosine diphosphate) in leaves by raising the N and P concentrations in leaves (Khan et al. 2023).

Under salinity and available phosphorus leakage the plant is exposed to oxidative stress due to production of reactive oxygen species (ROS). Plant cells have antioxidant enzymes as CAT and POD that become more active under stress conditions to scavenge or prevent ROS creation and defend cells from oxidative damage (Ibrahim et al. 2023).Furthermore , they create osmoprotectants as proline that prevents physiological dehydration, gets rid of reactive oxygen species, and keeps proteins and the cell membrane stable (Abdelraouf et al. 2023). As recorded in this work phosphorus and AMF inoculation treatments improved antioxidant enzymes activity and increased proline accumulation. These results are in harmony with that recorded by Ndiate et al. (2021). This can be explained by the symbiotic nature of the AMF connections, which leads to better ion balance maintenance in photochemical reactions in leaves under salinity, thus increasing the activity of antioxidant enzymes as a plant defense response (Abdul-Wahab et al. 2023). In addition, AMF inoculation cause a decrease in cellular osmotic potential and enhance proline accumulation under salt-affected soil stress (Dastogeer et al. 2020). The content of N, P, and K in maize grains significantly decreased due to salinity. The decrement in the phosphorus content was a result of the decreased phosphorus availability in the soil due to poorly soluble calcium phosphate compounds (Ouhaddou et al. 2023). While, phosphorus and AMF inoculation treatments recorded higher values of nutrients content in mature grains. This result can be explained as plant nutrient absorption is influenced by root development and nutrient availability in the root zone (Fall et al. 2023). When the plant inoculated with the AMF, nutrient absorption rises as a result of their penetration into the plant roots, generating a tree-like network of roots that allows the plant to grow its root system and improves nutrient absorption (Santana et al. 2023). AMF also maintain the internal phosphate content by generating phosphate within the hypha (Kazadi et al. 2022), in addition to their ability to collect massive amounts of ingested phosphorus compared to the roots, allowing for continual phosphorus flow in the roots (Etesami et al. 2021). In salt affected soils, mycorrhizal plants recorded a higher K accumulation than control, and this is may be advantageous because they preserve a high K/Na ratio and affect the cytoplasm's ionic balance or plants' Na efflux (Wang et al. 2021).

The aforementioned information makes it evident how AMF generally work to alleviate the detrimental effects of salinity and low available phosphorus conditions by raising proline accumulation, promoting antioxidant enzyme activity, supplying phosphorus that promote plant growth, and preserving the ionic stability required for chemical reactions and all of which are reflected in increased yield productivity with high quality comparing with the control.

4.2. Effect of KS foliar application on growth performance and productivity

As shown in Tables 2 to 6, applying foliage potassium silicate (KS) at varying rates has a substantial impact on every parameter under investigation. Foliar application with 6 ml. l^{-1} (KS2) was better in comparison to the non-foliar application (KS0). These outcomes could be explained by the effective role of potassium silicate in mitigating the negative effects of various abiotic stressors on plants where it serves as a source of silicon (biostimulant) and potassium (Aboyousef, et al. 2025). The favorable effects of Si on plant growth and development could be attributed to silica deposition in cell walls in the form of solid polymerized SiO_2 particles which provides mechanical strength and rigidity to plant tissues (Rizwan et al. 2023). Silicon foliage alters the cell wall's structure, improves the leaf's thickness and its rigidity (Alayafi et al. 2022). As well as, it balances nutrients uptake from the soil by plant under salinity stress (Elmahdy et al. 2023). Furthermore, silicon increases the activity of antioxidant enzymes such as CAT and POD, which help eliminate ROS (Gou et al. 2023) and increases the accumulation of proline, an osmoprotective compound under conditions of salinity and low phosphorus availability (Alayafi et al. 2022). Silicon has a beneficial effect on plant nutrient content due to its ability to reduce increases in plasma membrane permeability during stress, thus maintaining membrane selectivity for ion flux (Sharf-Eldin et al. 2023). Regarding to potassium, it enhances plants' ability to tolerate salt. This is due to its protective role in maintaining cell integrity, as it maintains osmotic pressure in the cytoplasm and enhances proline accumulation (Abdelraouf, et al. 2023). It also enhances the activity of antioxidant enzymes, reducing oxidative stress resulting from abiotic stress (Elmahdy et al. 2023). Furthermore, it regulates the metabolic processes necessary to maintain the efficiency of photosynthesis under salt stress conditions (Attia et al., 2022).

4.3. The interaction effect of AMF inoculation with different phosphorus rates and KS foliar applications on growth performance and productivity

In general, the combination of Mycorrhizal fungi inoculation with different phosphorus rates and potassium silicate application appear to improve maize's resilience to abiotic stressors, including salinity and phosphorus deficiency in the soil. Application of 75% PRD + AMF and KS2 treatment, at a concentration of 6 ml.l^{-1}, yielded the most favorable outcomes. AMF promoted root development, improved nutrient accessibility, and preserved ionic equilibrium, hence augmenting chlorophyll levels. Potassium silicate enhanced the activity of antioxidant enzymes and proline accumulation, hence augmenting the plant's tolerance to salinity and its capacity to mitigate phosphorus deficiency in the soil and all of which positively impacted growth and productivity. These results are in harmony with that recorded by Kazadi et al. (2022) and Islam et al. (2023).

4.4. Effect of AMF inoculation with different phosphorus rates and KS foliar applications on soil after harvesting

Despite the fact that inorganic phosphorus reacts with calcium dissolved in alkaline soil to form phosphate minerals which are low soluble in the soil and not readily available to plants (Souza Buzo et al. 2023), the results in figs. 2 to 5 show that, the rate of available phosphorus in the soil after harvest increased in all treatments compared to the rate before planting. This is owing to the presence of AMF, which facilitate soil phosphorus through the alkaline phosphatase enzyme and deliver it to the plant as part of their symbiotic connection, increasing the percentage of facilitated phosphorus in the soil (Ndiate et al., 2021). Regarding to AMF spores density, as indicated in the materials and methods section, the soil used in the experiment contains 7170 mycorrhizal spores per 100 g of soil. Despite this, a new inoculation was required to generate new AMF propagules capable of colonizing the established crop. The results showed that the highest AMF spores' density per 100 grams of soil was achieved with the lowest phosphorus rate (50% PRD) comparing with control (100% PRD). This is due to the fact that increasing the added phosphorus rate reduces the activity and reproduction of AMF. Furthermore, treatment 0% PRD+ AMF ranked second in terms of AMF spores' density where, the amount of available phosphorus in the experimental initial soil sample was less than what needed for optimal maize growth (under critical level of P concentration) and development, resulting in a substantial rise in AMF spores density as compared to using 100% of the suggested phosphorus. These results are in harmony with that recorded by Fall et al. (2023).

5. Conclusions

This research revealed the potential to enhance the resistance of maize plants and augment their yield and quality in salt affected soil with phosphorus deficiency using eco-friendly materials. The findings demonstrated that the application of 75% PRD + AMF yielded optimal outcomes during both the vegetative growth and harvest phases of maize plants, enhancing phosphorus availability in the soil and augmenting mycorrhizal population density, thereby improving soil health and bolstering the plant's resilience to abiotic stress in its two distinct forms examined in the study. The foliar application of potassium silicate (KS) demonstrated that the 6 ml l^{-1} (KS2) treatment was the most effective, mitigating the adverse effects of salt on maize plants and enhancing the activity of antioxidant enzymes, hence promoting growth and productivity. Consequently, it is advisable to applicate a combination of 75% PRD and AMF with foliage potassium silicate (KS2) treatment, due to its efficacy in alleviating the detrimental impacts of salinity and phosphorus deficiency on maize plants. It also attains elevated growth rates, productivity, nutritional absorption, and levels of oil and protein content. Economically, the combination of 75% PRD + AMF without KS0 foliar treatment is substantiated as a feasible alternative to current treatments for enhancing agricultural productivity and farmer income. In conclusion, we declare that the research achieved enhanced productivity through the use of eco-friendly sustainable materials. Finally, we hope further research that maximizes maize production while minimizing economic costs for sustainable agricultural development.

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