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Effect of mycorrhizal fungi inoculation, phosphate fertilisation and gypsum percentage on the uptake of nutrients in sorghum (*Sorghum bicolor* L.)

Ahmed Maath Ahmed, Raghad Qasim Kadhim, Sahar N Mousa, Hiba Mohammed Youssef, Hudhaifa Maan AL-Hamandi* & Mohammed Jarullah Farhan

Department of Soil Science and Water Resources, College of Agriculture, Tikrit University, Tikrit 21006, Iraq

***Correspondence:** Hudhaifa Maan AL-Hamandi, hudhaifaalhamandi@tu.edu.iq

Abstract

This study examined the individual and interactive effects of arbuscular mycorrhizal fungi (AMF) inoculation, phosphorus (P) fertilisation and gypsum levels on nutrient uptake and growth of *Sorghum bicolor* L. in gypsiferous soils under pot conditions. A factorial experiment was conducted with two gypsum levels (5 % and 25 %), four P rates (0, 80, 160 and 240 kg P ha^{-1}) and two AMF treatments (with and without inoculation). The AMF inoculation significantly enhanced nitrogen (N), P and potassium (K) concentrations and uptake at both 30 and 80 days after emergence, with higher relative increases at early stages. The N uptake increased by 76.85 % and 21.78 %, P uptake by 93.9 % and 38.4 % K uptake by 66.66 % and 31.55 % at 30 and 80 days, respectively. The AMF also increased Fe and Zn concentrations at 80 days by 28.37 % and 19.5 %. Phosphorus fertilisation improved macronutrient accumulation, with the highest N, P and K uptake at 240 kg P ha^{-1}, particularly under 5 % gypsum. Moderate P levels (80–160 kg P ha^{-1}) were optimal for Fe and Zn concentrations. High gypsum content (25 %) reduced both macro and micronutrient uptake compared with 5 % gypsum. Significant two- and three-way interactions among AMF, P and gypsum were observed, with the combination of AMF inoculation, 240 kg P ha^{-1} and 5 % gypsum resulting in the highest macronutrient uptake. Soil available P decreased in AMF treatments, likely due to increased plant uptake. These findings suggest that integrating AMF inoculation with appropriate P fertilisation under moderate gypsum conditions enhances nutrient acquisition efficiency in sorghum grown on gypsiferous soils.

Keywords: arbuscular mycorrhizal fungi; gypsiferous soils; Sorghum bicolor; soil fertility; sustainable agriculture

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Introduction

Soil fertility is an essential element in sustainable agricultural production as it represents the soil's ability to provide plants with adequate nutrients for normal growth and development (1). Yet, increased levels of intensive cultivation, salinity build-up and imbalanced use of fertilisers have resulted in a continuous degradation in the soil, particularly in arid and semi-arid lands (2). In such environments, suboptimal physico-chemical soil conditions may hinder nutrient availability and their efficient uptake by plants (3). Sorghum (*Sorghum bicolor* L.) is an important cereal crop known for its tolerance to drought and salinity. However, its productivity in many soils is constrained by limited phosphorus (P) availability due to the binding of P with calcium and other cations in calcareous or gypsum-rich soils (4). Arbuscular mycorrhizal fungi (AMF) also contribute to enhancing nutrient acquisition by increasing the root absorptive area and the bioavailability of P and micronutrients (5), as well soil structure stability, biological fertility (6). On the other hand, soil amendment with gypsum and phosphate fertilisation, beneficial to plant and soil development may disrupt ionic balance and nutrient bioavailability leading to reduced efficiency of the mycorrhizal symbiosis (7).

It is critical to comprehend the interactive effects of AMF inoculation, phosphate fertilisation and gypsum level that will facilitate nutrient assimilation enhancing sorghum performance in resource-poor and saline environments. Objective The specific objectives of this research are to: 1) investigate individual and interactive effects of AMF inoculation, phosphate fertilisation and gypsum level on the nutrient uptake and growth performance of sorghum; 2) evaluate how different levels of gypsum affect phosphorus availability and efficacy of mycorrhizal colonisation in the rhizosphere; 3) develop integrated soil fertility management strategies suitable for arid to semi-arid agroecosystems.

Materials and Methods

Fungal inoculum preparation

The primary fungal inoculum was sourced from the Department of Soil Science and Water Resources, College of Agriculture, University of Tikrit. The inoculum was in the form of *Rhizophagus mosseae* spores on an inert carrier. The presence of fungal propagules (infective units) was checked by wet sieving, decanting technique according to (8). Spores were extracted using a series of sieves with different mesh sizes and observation under the light microscope confirmed the presence of 302 spores g^{-1}. inoculation. Furthermore, the inoculum was confirmed to be free of pathogenic fungi and other contaminating organisms by examining it under a microscope.

Soil preparation and analysis

To study the effects of inoculation with AMF and P fertilisation in relation to the growth of *S. bicolor*, an experiment was carried out using two soils with contrasting gypsum content in pot trials. The soils were obtained from two locations in the experiment field of the College of Agriculture, Tikrit (5 and 25 % gypsum). All samples were air-dried and sieved through a 2 mm sieve. Prior to the experiment, selected physical, chemical and microbiological properties of the soils were analysed. The results of these analyses are presented in Table 1.

Table 1. Selected physicochemical and biological properties of the soils prior to planting

No	Parameters	Method	References
1	Soil Texture	Pipette method	(9)
2	Soil pH	pH-meter	(9)
3	Electrical Conductivity (EC) $dS \cdot m^{-1}$	EC-meter	(9)
4	Cation Exchange Capacity (CEC) $cmol \cdot kg^{-1}$	Methylene Blue method	(9)
5	Calcium Carbonate Content ($CaCO_3$) $mmol.L^{-1}$	Titration method with hydrochloric acid	(9)
6	Calcium Sulfate (Gypsum) Content $mmol.L^{-1}$	Dilution method	(10)
7	Organic Matter	Wet digestion method	(11)
8	Available Nitrogen	Micro-kjeldahl method	(12)
9	Available Phosphorus	Ammonium molybdate and ascorbic acid method	(13)
10	Available Potassium	Extracted using $CaCl_2$ solution	(14)
11	Soluble Cations and Anions (Na^+, Mg^{+2}, Ca^{+2}, Cl^-, SO_4^{+2}, CO_3^-, HCO_3^-)	Titration or using a flame photometer	(12)
12	Total bacteria count CFU gm^{-1}	Dilution plate method on nutrient agar medium	(12)
13	Total Fungi count CFU gm^{-1}	Dilution plate method on Rose bengal agar	(14)

Experimental treatments and implementation in an agricultural trial

A factorial pot experiment was conducted during the spring growing season at the College of Agriculture, Tikrit University. The experiment was arranged in a randomised complete block design (RCBD) and included three experimental factors:

1. Biofertiliser application using AMF, with two levels: Without inoculation (Vesicular-arbuscular mycorrhizae (VAM)-), With inoculation (VAM+).
2. Chemical Phosphorus Fertilization using triple superphosphate (TSP) at four application rates: (0, 80, 160 and 240) kg P ha^{-1}.
3. Gypsum Amendment applied at two rates: 5 and 25 % (by soil weight).

The interplay of the three factors produced 16 treatment combinations, each replicated six times, culminating in a total of 96 plastic pots (experimental units) with a soil capacity of 15 kg per pot.

Experimental procedures

Soil samples were collected from various locations within the gypsiferous soils at the College of Agriculture. The gypsum content was determined to identify two soils with gypsum levels of 5 % and 25 %, respectively, which were selected for use in the study. The soils were Include: root colonisation %, method used and sampling time sieved and sub-samples were taken for physical, chemical and biological analyses (Table 2). The soil was thoroughly aerated for 15 days to ensure complete volatilisation of toxic formalin residues before being filled into the pots.

Phosphorus fertiliser was applied at the four aforementioned levels as a single pre-planting dose using triple superphosphate as the source.

Nitrogen (N) and potassium (K) fertilisers were also applied. Urea (46 % N) was used as the N source at a rate of 280 kg N ha^{-1}, was split into two applications: the first at planting and the second after the first harvest (30 days after emergence). Potassium was supplied in the form of potassium sulfate (K_2SO_4, 43 % K) at a rate of 200 kg K ha^{-1}, also applied in two splits: one before planting and the other one month after planting.

Mycorrhizal inoculum (50 g per pot) was applied by first removing the topsoil layer, then distributing half of the inoculum onto the lower soil layer. The remaining half was mixed with the upper soil layer before reapplying it to the pot.

Sorghum seeds (*S. bicolor*) were sown at a rate of 20 seeds per pot on March 17, 2024. Field capacity was estimated and irrigation was carried out using the gravimetric method when 50 % of the available water was depleted.

The experiment was terminated at two growth stages: 30 and 80 days after emergence.

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Table 2. Physiochemical and biological properties of the soils prior to planting

Sl. No.	Parameters	Gypsum percentage in soil	
		First 5 %	Second 25 %
1	Electrical conductivity (EC) $dS \cdot m^{-1}$ (1 : 1)	2	3.3
2	Soil pH (1 : 1)	7.25	7.85
3	Cation exchange capacity (CEC) $cmol \cdot kg^{-1}$	8.94	4.93
4	Soluble cations and anions (1 : 1)		
5	Calcium mmol. L^{-1}	13	18
6	Magnesium mmol. L^{-1}	7	5.6
7	Sodium mmol. L^{-1}	1.3	2.3
8	Sulfate mmol. L^{-1}	2	2.2
9	Bicarbonate HCO_3 mmol. L^{-1}	19	20.5
10	Carbonate CO_3 mmol. L^{-1}	1.7	2,2
11	Organic Matter gm. kg^{-1}	13	5
12	Gypsum gm. kg^{-1}	50	250
13	Lime gm. kg^{-1}	185	175
14	Available nitrogen mg. kg^{-1}	21.5	17.8
15	Available phosphorus mg. kg^{-1}	7.12	5.1
16	Available potassium mg. kg^{-1}	106.23	90
17	Available iron mg. kg^{-1}	1.21	1.10
18	Available zinc mg. kg^{-1}	0.35	0.29
19	Typic calcigypsids soil series		
20	Sand kg^{-1} soil	525	540
21	Gilt kg^{-1} soil	275	260
22	Clay kg^{-1} soil	210	200
23	Soil texture	Sandy clay loam	
24	Total bacteria count CFU g^{-1}	10^6 *6	10^6* 3
25	Total fungi count CFU g^{-1}	10^4* 5	10^4* 2

Measured parameters in agricultural experiment

Nutrient content determination (Zinc (Zn), iron (Fe), K and P, N:A 0.2 g sample of dried plant material (shoots) was digested using concentrated sulfuric and perchloric acids following the procedure described by previous researchers (15).

Nitrogen was determined using a steam distillation unit (Micro-Kjeldahl method) as outlined by (12). Phosphorus determined using the ascorbic acid method and measured spectrophotometrically according to earlier reports (16). Potassium measured using a flame photometer, described by previous researchers (17).

Iron and Zn measured using an atomic absorption spectrophotometer, as described previously (9), conducted in the laboratories of Department of Chemical Engineering, College of Engineering, Tikrit University.

Statistical analysis

The collected data were statistically analysed using the Statistical Analysis System (SAS) software package (SAS Institute, 1989–96). Treatment means were compared using the least significant difference (LSD) test at a probability level of $p = 0.05$.

Results and Discussion

Nitrogen concentration and uptake in the vegetative part of sorghum

The data presented in Fig. 1 and 2 demonstrated that inoculation with arbuscular mycorrhiza fungi (AMF) significantly increased N concentration in the vegetative tissues of sorghum at both early and later growth stages. At the seeding stage and heading stage, sorghum treated with AMF under 25 % gypsum showed increases of 9.6 % and 11.5 %, respectively; Sorghum was more sensitive to AMF inoculation at the seedling stage. This stimulation probably results from better availability to the plants of main nutrients, including N, P and K, aided by association with AMF (18).

Nitrogen concentration was also significantly influenced by P fertilisation at both growth stages, with higher concentrations observed during the early growth stage. This agrees with a previous study where nutrient concentrations were found to decrease due to dilution once the biomass increases in the later ages (19). The increased N-uptake by the application of P might be ascribed to increasing root development and higher nutrient absorption ability (20). On the other hand, 25 % application of gypsum significantly decreased N contents compared with 5 % application, which might result from negative effects of higher levels of gypsum on nutrient availability in root zones and lower subsoil (with low OM and paucity of reserve nutrients) (21).

The interactions between AMF and P fertilisation indicated that the highest N contents was obtained in inoculation treatment with 240 kg P ha^{-1}, which showed synergistic effect at nutrient deficient soil (20). Analogously, the application of AMF and AM with 5 % gypsum showed higher N concentration when compared to the other sequences, confirming their positive function in a low nutrient system. A significant three-way interaction (AMF × P × gypsum) was also observed, resulting in the highest N concentrations 3.98 % and 3.85 %) at day 30 and day 80 respectively when both inoculated with AMF, supplied with a concentration of additional P at 5 % gypsum rate. As shown in Fig. 3 and 4, AMF inoculation significantly promoted N uptake by increasing 76.85 % at early stage and 21.78 % at later stage. This increment was the result of a combination between greater dry matter gain and N percentage from inoculated plants, highlighting the importance of AMF to enhancing nutrient uptake especially at pre-vegetative stage (22).

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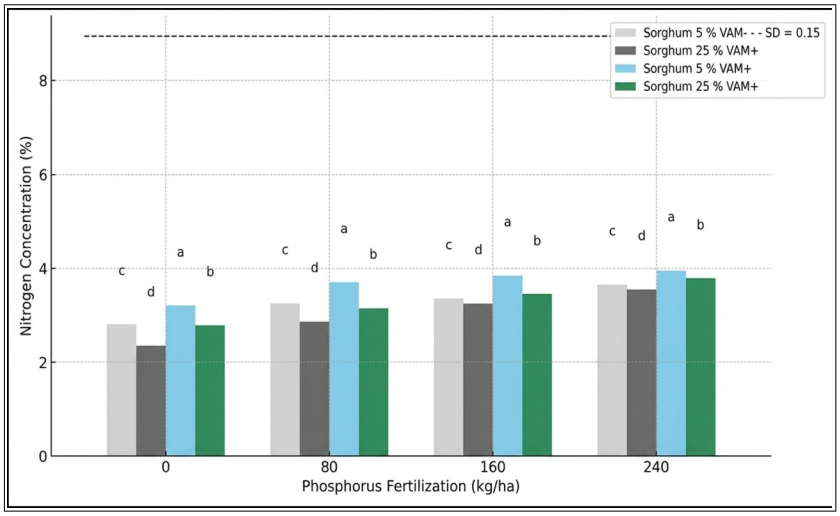


Fig. 1. Effect of inoculation with mycorrhizal fungi, phosphate fertilisation, gypsum concentration and their interaction on leaf N (%) 30 days.

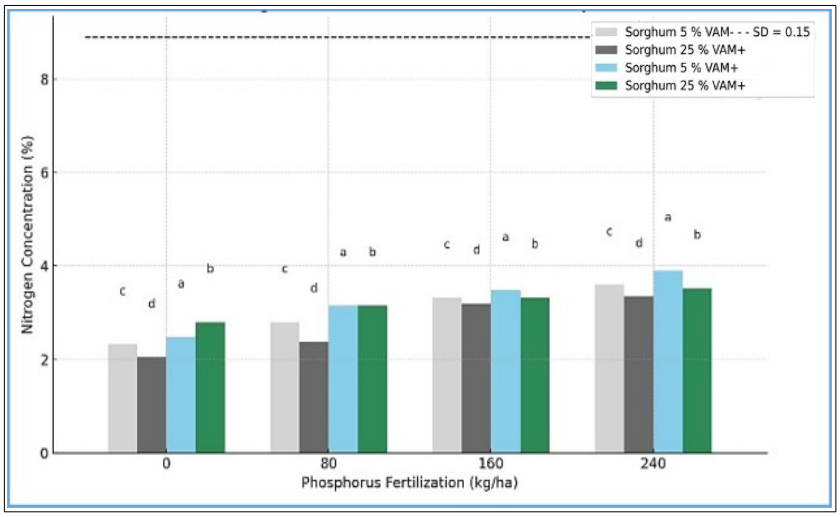


Fig. 2. Effect of mycorrhizal fungi inoculation, fertiliser phosphate, gypsum content and their on N concentration (%) in vegetative part after 80 days.

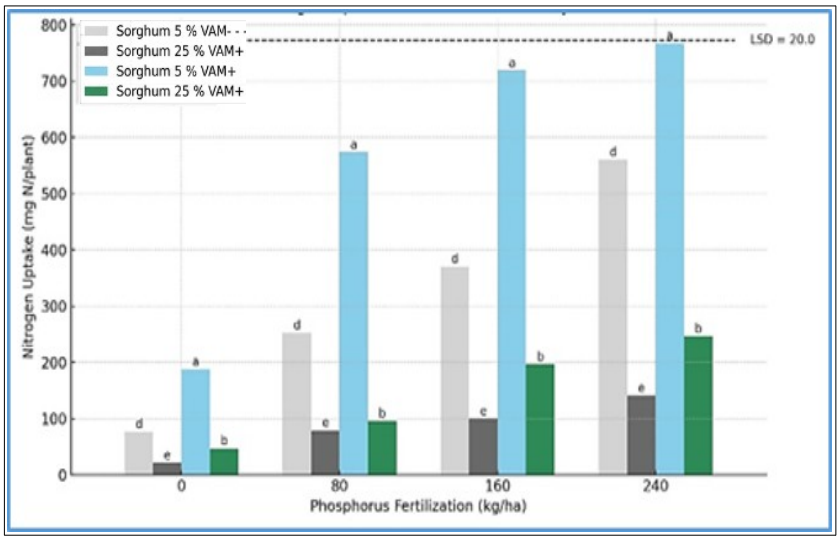


Fig. 3. Effect of mycorrhizal fungi inoculation, phosphate fertilisation and gypsum level (%) and their interaction on the N uptake through the dry vegetative mass in *Sorghum bicolor* L. (mg N plant $^{-1}$) at 30 days.

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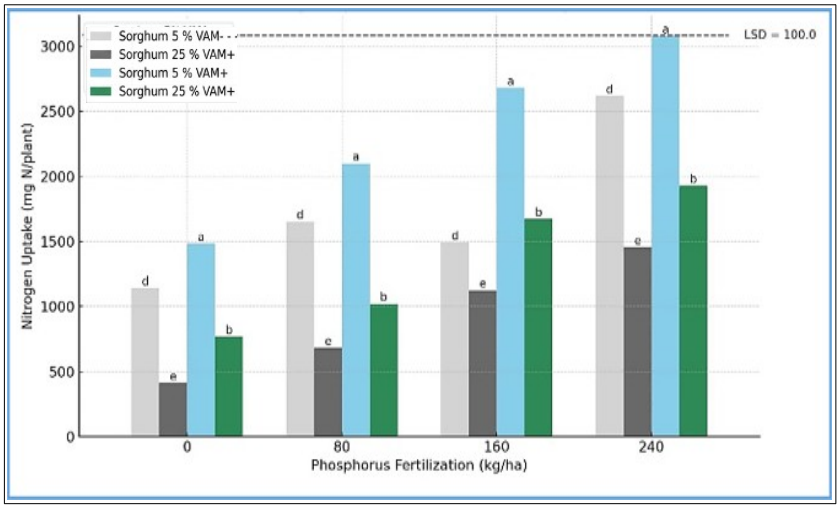


Fig. 4. Effect of the inoculation with mycorrhizal fungi, phosphate fertilisation, gypsum percentage and their interaction on N absorbed in dry vegetative mass of *Sorghum bicolor* (g root) after 80 days.

Phosphorus uptake and concentration in sorghum shoots

Inoculation with AMF significantly enhanced P concentration in sorghum shoots at both early and mid-vegetative stages (Fig. 5 and 6). This implies a higher degree of sensitivity to AMF colonisation in vegetative stages, primarily with respect to nutrient uptake efficiency and specifically P (a relatively immobile and commonly limiting macronutrient) (23).

In both stages, P fertilisation also induced a substantial increase in shoot P concentration, despite a dilution effect with increasing plant biomass. The observed response reflects the low native P availability in soil studied (Table 2) and the high sorghum P demand at early growth stages (24). The results are consistent with the physiological significance of AMF and P application in improving P uptake and above-ground biomass accumulation in P-limited soil.

Application of gypsum at the high level had a significant effect in reducing shoot tissue P content compared to lower levels (5 %). This reduction can be attributed to increased calcium (Ca^{2+}) activity in the soil solution resulting in P precipitation and depletion of bioavailable forms (21). Phosphorus fertilisation in combination with AMF inoculation greatly promoted P uptake. Except for the P concentration in AMF inoculation at 30 days after sowing, which were higher (0.40 %) at a high rate of kg P ha^{-1} than lower values (0.36 % – 80 days), this reflects additional synergistic interactions between rates and times of P application to plant growth in soil with nutrient limitation was observed when other NPK nutrients are limiting factors prior to SOT addition (18). A + B Triple interaction (NSAN × gypsum) The AMF × gypsum combination had the best results at 5 % gypsum, but the triple interaction (AMF × gypsum fertilisation) resulted in highest P concentration at both growth stages (0.40 and 0.38 %). The AMF inoculation contributed to total P uptake enhancement by 93.9 % in early growth and 38.4 % in the late stage, which were mainly due to increased root colonisation and hyphal foraging ability (23). Increased P fertilisation could enhance P uptake solely by stimulating root development deeper and denser under low ameliorated conditions of gypsum soils in which the available soil P content is very low.

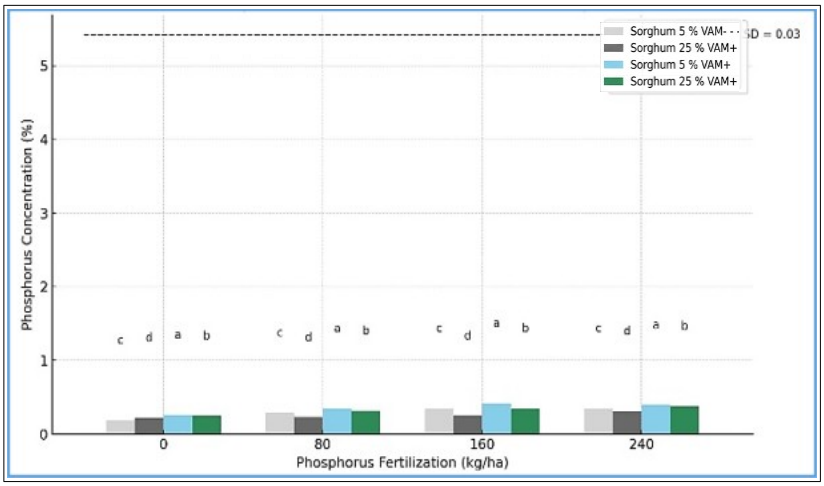


Fig. 5. The effect of inoculation with mycorrhizal fungi, phosphate fertilisation, gypsum percentage and their interaction on the P concentration (%) in the vegetative part 30 days.

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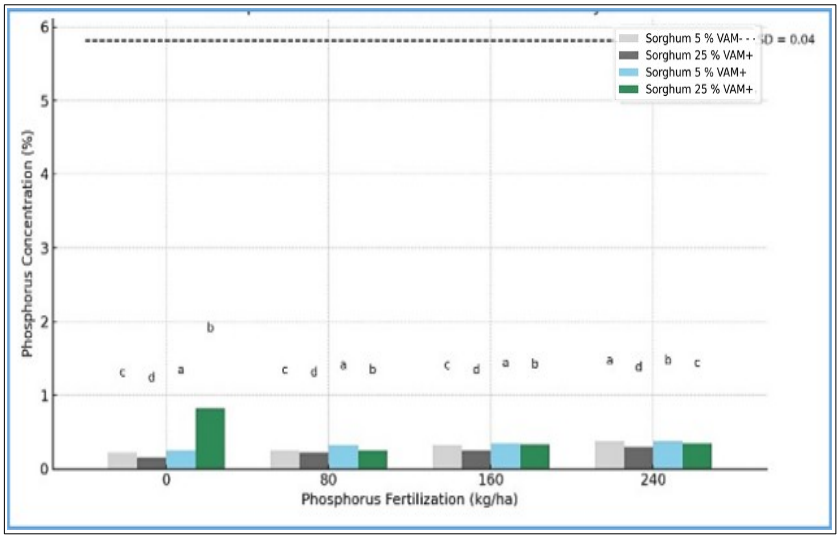


Fig. 6. The effect of inoculation with mycorrhizal fungi, phosphate fertilisation, gypsum percentage and their interaction on the P concentration (%) in the vegetative part 80 days.

Increment of rates of phosphate fertiliser significantly improved P uptake in sorghum. High gypsum level (25 %) had a negative impact on phosphorus utilisation by seedlings and it decreased 75.20 % and 51.25 % in the early and late growth stage, respectively compared to those in low gypsum (5 %) (Fig. 7 and 8). This is related to reduced soil fertility and lower available phosphorus at high gypsum. AMF inoculation was found to enhance phosphate uptake, especially at higher levels of phosphorus application. Maximal absorption was found at 240 kg P ha^{-1} with AMF and higher amounts in control (52.85 mg P plant $frequency^{-1}$ on the 30 day and 280.28 mg P plant $frequency^{-1}$ after eighty days of emergence) showing AMF plants respond better to phosphorus application in low nutrient soil (22).

Additionally, AMF combined with 5 % gypsum showed superior P uptake across both growth stages, while the dual interaction of phosphate fertilisation and gypsum confirmed the highest uptake at 240 kg P ha^{-1} and 5 % gypsum. The triple interaction (AMF × P fertilisation × gypsum) was also significant, with the best performance recorded at 240 kg P ha^{-1} + AMF + 5 % gypsum.

Potassium concentration and uptake in sorghum shoots

Mycorrhizal inoculation significantly enhanced K concentration in sorghum shoot tissues at both early growth stages, with increases of 5.92 % and 10.35 %, respectively (Fig. 9 and 10). This enhancement is associated with the involvement of extra radical hyphae in nutrient uptake, the enhanced growth has been partially linked to role of contributing factor with supplementary mineral mobilisation from AMF-induced extra radical hyphae under low mineral supplies (25). Increased K levels during stage 1 indicated better absorption in the early growth stage. Phosphorus fertilisation also had a significant positive effect on K concentration, this improvement may be attributed to the extensive extraradical hyphal network of AMF, which enhances nutrient uptake from the soil (26). These results are in accordance with the concomitant hatch and fertiliser interaction effect on dicot hair nutrient uptake as reported previously (18).

Phosphorus fertilisation increased K concentration of sorghum shoots remarkably by the promotion of root biomass and depth, thus increasing water and nutrient uptake efficiency including and for K (25). On the other hand, high gypsum (25 %) reduced K more than that of low gypsum (5 %) probably due to the higher Ca^{+2} in the rhizosphere which may reduce nutrient availability and plant growth under calcareous soil conditions (27).

There was a positive interaction between AMF inoculation and P application. The largest K content in AMF-inoculated + 240 kg P ha^{-1} was observed with 2.66 % and 2.58 %, at 30 and 80 days after emergence, respectively. This indicates an increased AMF activity under P-enriched but nutrient-deficient soil (28). The interaction of AMF with gypsum was observed to have the highest K concentration at 5 % gypsum inoculated with AMF (AMF + gypsum, 2.55 % and 2.40 %) in both stages located at a moderate gypsum level is however favourable for the colonisation of AMF (20). Similarly, P × gypsum interaction had the highest K content at 240 kg P ha^{-1} and 5 % gypsum, possibly owing to root development and enhanced nutrient uptake under low-gypsum condition. The three-way interaction (AMF × P × gypsum) was also significant, in which the greatest levels of K were attained with 5 % gypsum, AMF inoculum and 240 kg P ha^{-1} supplementation effects and indicating evidence for synergism between AMF and P in improving nutrient uptake under moderately gypseous conditions (29).

AMF inoculation also significantly improved the total shoot K uptake in sorghum, with increases of 66.66 % at stage one and 31.55 % at stage two. The greater improvement observed during the early growth stage suggests enhanced root responsiveness and mycorrhizal efficiency under nutrient-limited soil conditions (18) (Fig. 11 and 12).

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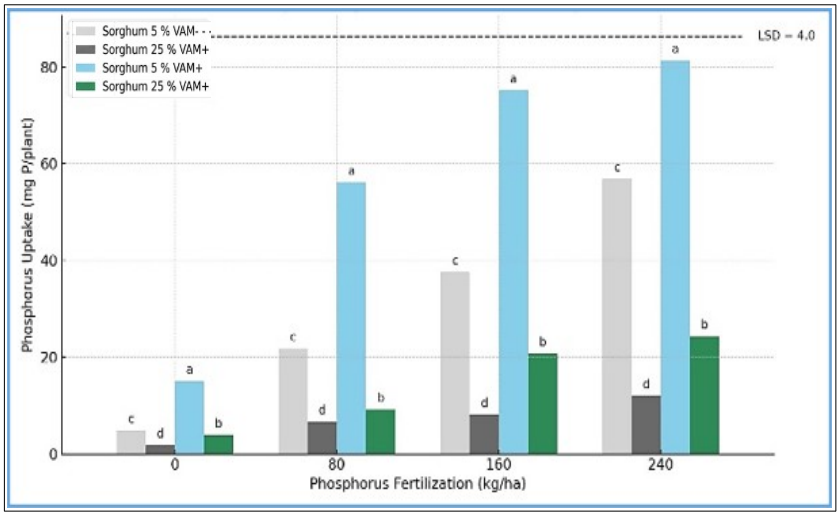


Fig. 7. The effect of inoculation with mycorrhizal fungi, phosphate fertilisation, gypsum percentage and their interaction on the amount of P absorbed in the vegetative part of *Sorghum bicolor* (mg P. plant^{-1}) after 30 days.

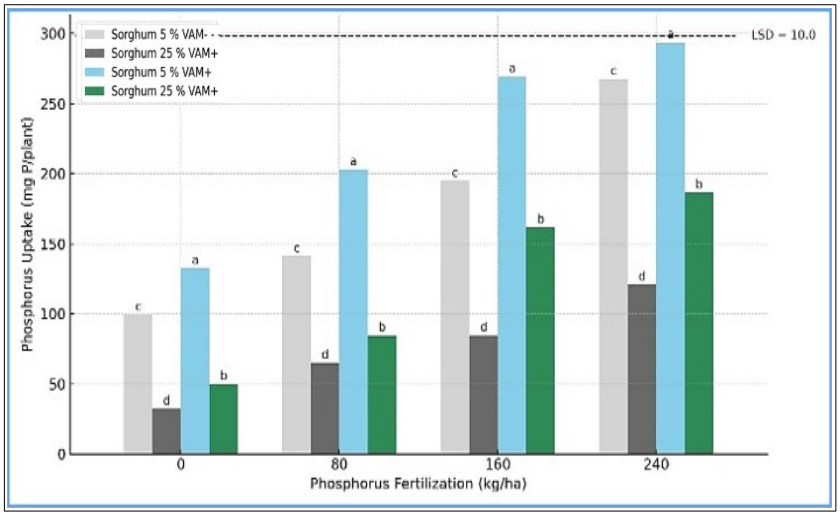


Fig. 8. The effect of inoculation with mycorrhizal fungi, phosphate fertilisation, gypsum percentage and their interaction on the amount of P absorbed in the vegetative part of *Sorghum bicolor* (mg P. plant^{-1}) after 80 days.

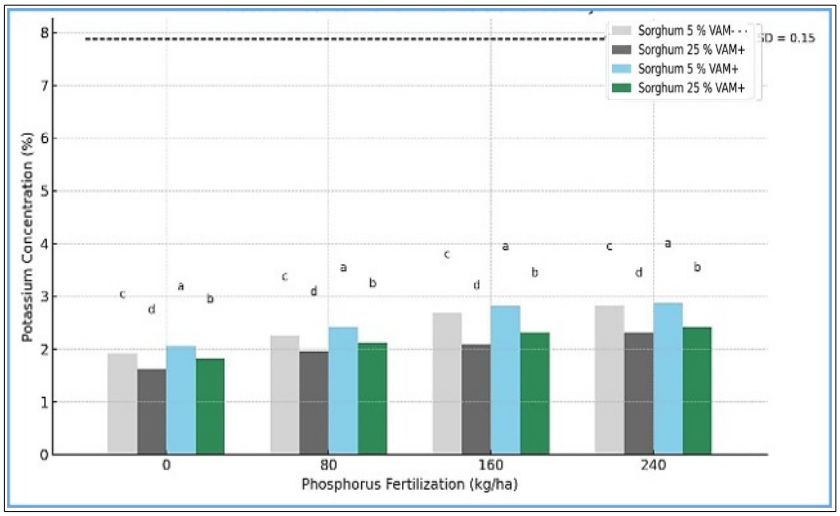


Fig. 9. The impact of inoculation with mycorrhizal fungi, phosphate fertilisation, gypsum percentage and their interaction on the K concentration (%) in the vegetative part after 30 days.

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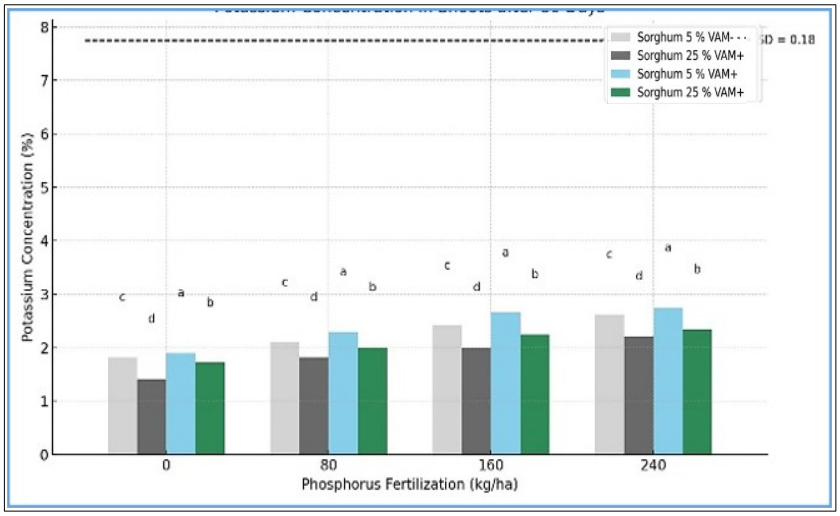


Fig. 10. The effect of inoculation with mycorrhizal fungi, phosphate fertilisation, gypsum percentage and the interaction between them on the K concentration (%) in the vegetative part after 80 days.

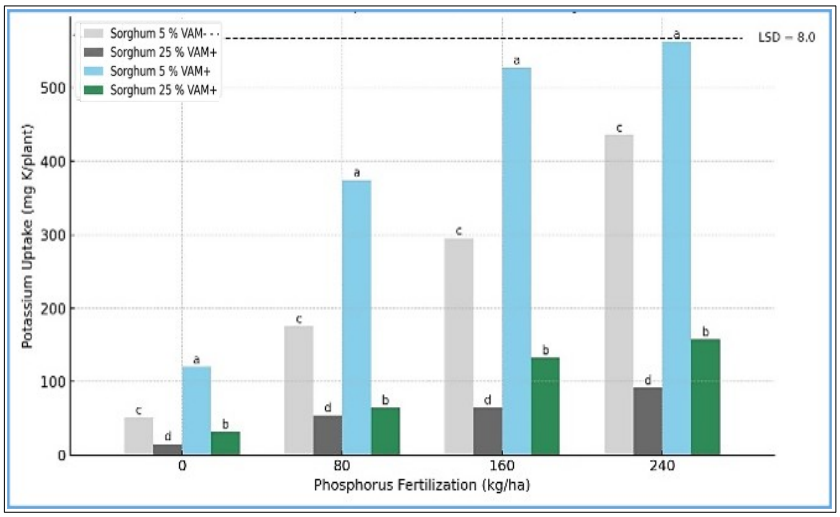


Fig. 11. The effect of inoculation with mycorrhizal fungi, phosphate fertilisation, gypsum percentage and the interaction between them on the amount of K absorbed in the vegetative part of *Sorghum bicolor* (mg K. plant^{-1}) after 30 days.

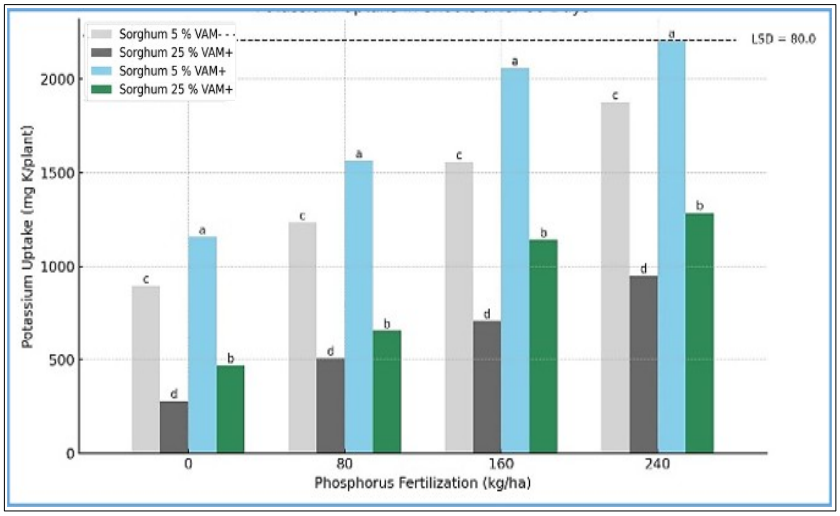


Fig. 12. The effect of inoculation with mycorrhizal fungi, phosphate fertilisation, gypsum percentage and the interaction between them on the amount of K absorbed in the vegetative part of *Sorghum bicolor* (mg K. plant^{-1}) after 80 days.

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Potassium uptake was increased substantially by P in both vegetative growth periods, particularly during the second period which could be attributed to greater dry matter accumulation. More phosphorus facilitated the growth of root biomass and depth, which was beneficial for nutrient and water absorption capacity (19). The treatment of soils with increasing levels of gypsum (5 % to 25 %) on K uptake also showed similar response; higher concentrations decreased considerably over those exhibiting lower concentrations, especially in deficient soils. This is possibly because high Ca^{+2} and SO_4^{-2} concentrations in soil led to lower K availability in the rhizosphere (29).

The VAM inoculation enhanced K uptake, particularly when combined with phosphorus fertilisation at 240 kg P ha^{-1}, suggesting a joint effect that improves nutrient transfer in the low fertility soil (22). The highest K uptake was observed when VAM inoculation and low level of gypsum (5 %) were combined, which might be associated with better soil conditions and the interaction between root and microbe. The highest uptake of K was found for the triple treatment (VAM + 240 kg P ha^{-1} + 5 % gypsum), thus validating the mutual benefit of combined chemical and biological soil amendments.

Effect of arbuscular mycorrhizal fungi, phosphorus fertilisation and gypsum on iron and zinc uptake in sorghum

Inoculation with AMF significantly enhanced Fe and Zn concentrations in sorghum shoots at 80 days after sowing, with increases of 28.37 % and 19.5 %, respectively (Fig. 13 and 14). This enhancement is due to the large AMF hyphal network which further expands the root surface area and enhances the absorption of low-mobile micronutrients including Fe and Zn especially in soils with restricted availability (18, 30). The AMF are important for the transfer of nutrients by diffusion and increasing plant nutrient uptake. These effects were more pronounced when AMF and supplemental P with gypsum were combined, indicating that the two had synergistic impacts on enhanced micronutrient acquisition in stress soil.

Phosphorus fertilisation had significant effects on Fe and Zn contents in sorghum leaves. Application of 80 kg P ha^{-1} improved Fe and Zn uptake than control (Fig. 15 and 16) and higher rates (160 and 240 kg P ha^{-1}) decreased their concentrations in the sorghum plant-especially Fe-probably by dilution of the nutrients or precipitation as insoluble phosphates [such as Fe3(PO4)2 under alkaline soil conditions. High levels of gypsum (25 %) also led to a significant reduction in Fe and Zn contents attributed to Ca-induced antagonism, which restricts the availability and uptake of micronutrients by competition and precipitation effect (24). Inoculation with AM fungi significantly increased absorption of Fe and Zn. The best treatment combinations were AM colonisation with 80 kg P ha^{-1} for Fe and 160 kg P ha^{-1} for Zn. Moreover, the highest concentrations of micronutrients were recorded under the combined AM inoculation and 5 % gypsum treatment, showing that both inoculation and application of 5 % gypsum had synergistic effects on nutrient availability and/or uptake (23).

Available phosphorus in the soil after planting

Inoculation with AMF resulted in a consistent decrease in soil available P across both soil types and plant growth stages (Fig. 17 and 18), likely due to enhanced P uptake by sorghum roots through mycorrhizal symbiosis (18). On the other hand, those available P levels increased with phosphorus fertilisation, except for the 240 kg ha^{-1} treatment. But the increase was mitigated to some extent by AMF inoculation and higher gypsum amount (25 %), which might have facilitated P fixing processes via adsorption and precipitation reactions (25). A general decrease in available P was seen in the later stages of growth ascribed to enhanced plant uptake and transformation to forms with lower solubility (31).

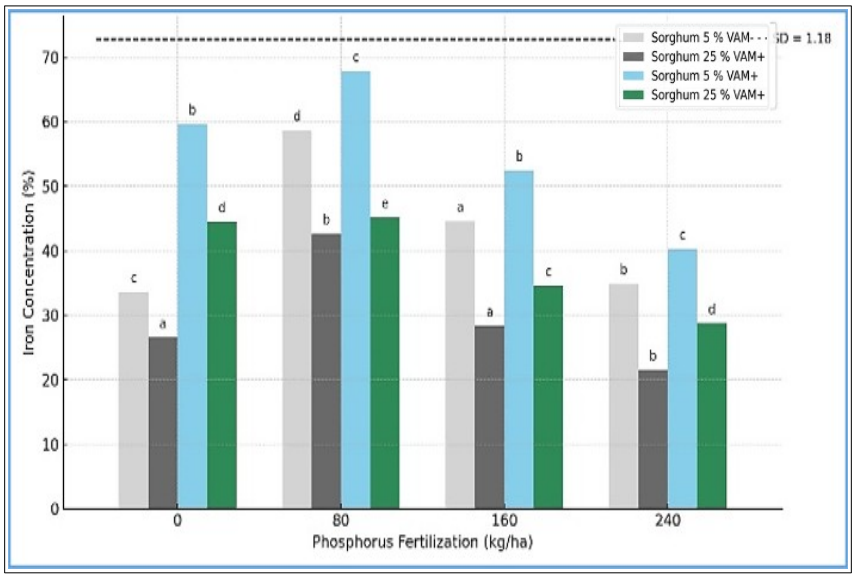


Fig. 13. The effect of mycorrhizal fungi, phosphate fertilisation, gypsum percentage and their interaction on the concentration of iron in the plant (%) after 80 days.

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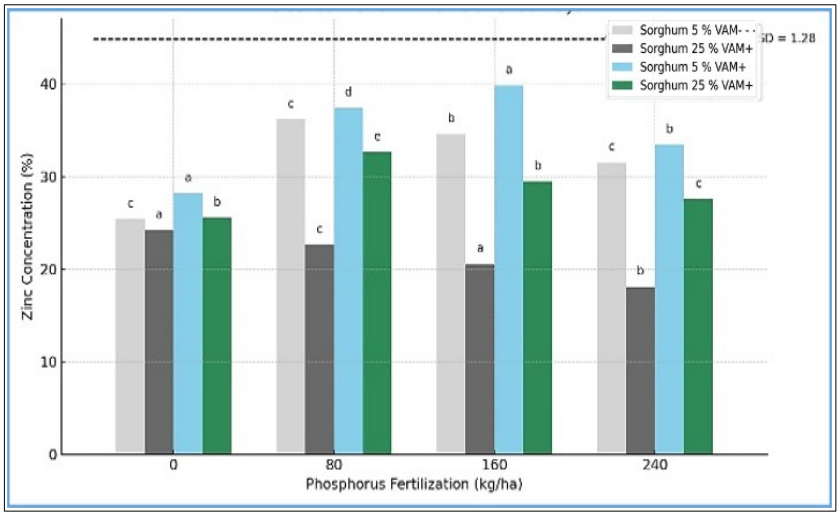


Fig. 14. The effect of mycorrhizal fungi, phosphate fertilisation, gypsum percentage and their interaction on the concentration of zinc in the plant (%) after 80 days.

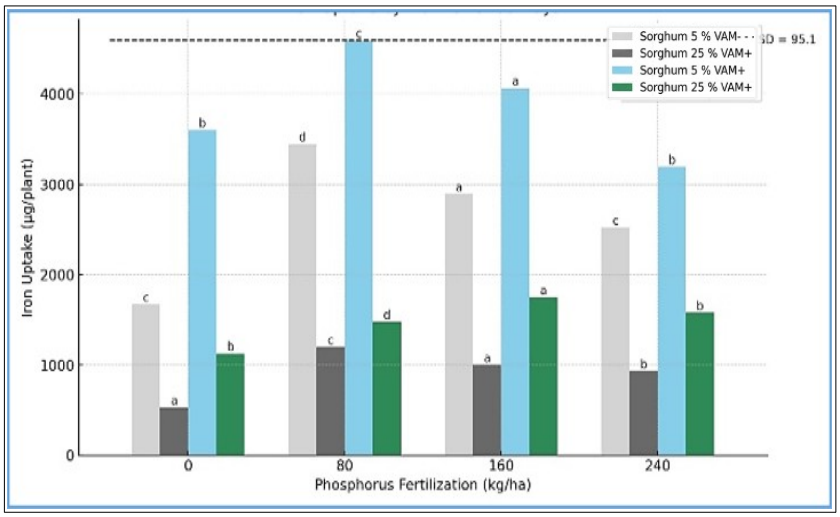


Fig. 15. The effect of mycorrhizal fungi, phosphate fertilisation, gypsum percentage and their interaction on the amount of iron absorbed by the plant (µg plant^{-1}) after 80 days.

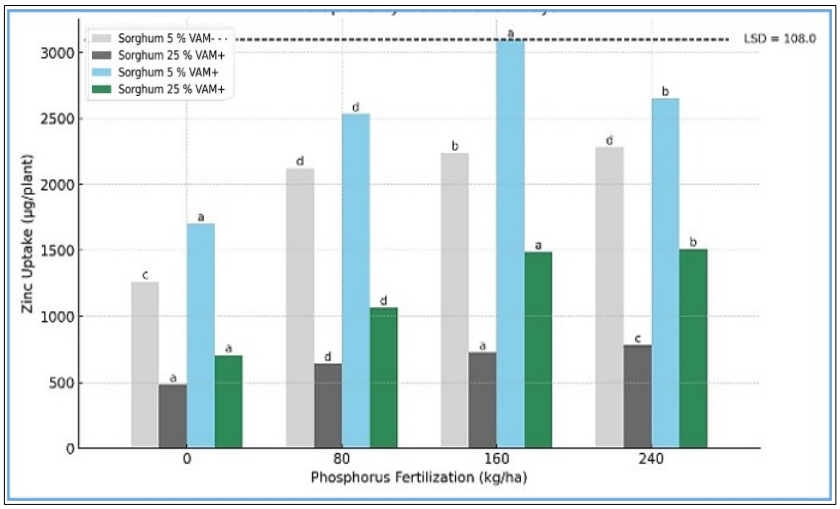


Fig. 16. The effect of mycorrhizal fungi, phosphate fertilisation, gypsum percentage and their interaction on the amount of zinc absorbed by the plant (µg plant^{-1}) after 80 days.

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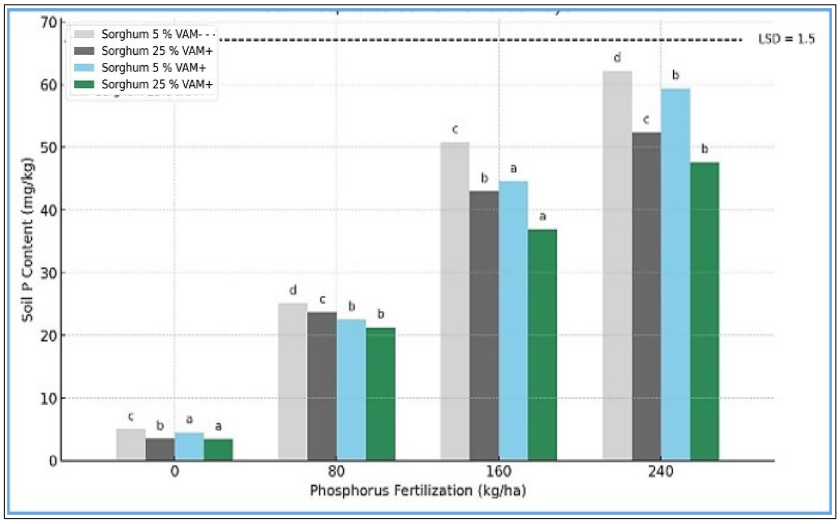


Fig. 17. Influence of mycorrhizal inoculation, phosphate fertilisation, soil type and their interaction as related to the soil phosphorus content (mg P kg^{-1}) 30 days.

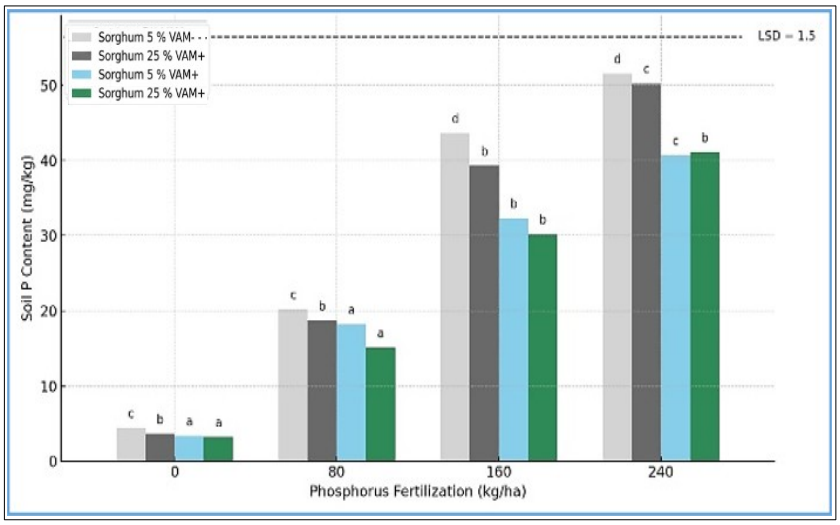


Fig. 18. Impact of inoculation with mycorrhizal fungi, phosphate application, soil and the interaction between these factors on the content of soil P (mg P/kg soil) 80 days.

Effects of AMF inoculation x gypsum levels. The interaction between AMF inoculation and gypsum levels showed that the most available P was found in non-inoculated soil with low gypsum rate (5 %). This indicates that AMF stimulate P uptake, particularly in low-gypsum soils with higher microbial compatibility. A strong triple interaction between P fertilisation (240 kg P ha^{-1}), AMF inoculation and percentage of gypsum showed the available P content was decreased in inoculated conditions, especially for soils with low gypsum. In contrast, increased gypsum supply restrained the AMF potential due to lower microbial viability and gypsum-induced chemical limitations.

The reduction in soil available P in mycorrhizal treatments may be attributed to increased P uptake through the extraradical hyphal network of AMF. These results are consistent with those of recent studies reporting that AMF mediated nutrient acquisition is enhanced under stress and low-nutrient soil conditions (18, 26).

Conclusion

This research confirmed that both phosphate fertilisation and controlled gypsum application with arbuscular mycorrhizal fungi (AMF) inoculation can simultaneously increase nutrient acquisition and plant growth of Sorghum bicolor in a in a gypsiferous soil. The AMF colonisation increased uptake of macro- and micronutrients through enhanced root colonisation, moderate phosphate application (approximately 240 kg P ha^{-1}) was able to enhance nutrient mobilisation as well as nutrient availability. High gypsum level (25 %) inhibited the uptake of nutrients because of ionic toxicity and precipitation. optimal results were achieved in the case of AMF inoculation together with phosphate fertilisation and 5 % gypsum, indicating a high degree of synergy between biological and chemical amendments. In conclusion, the integrated strategy provides an efficient and sustainable way for improving soil fertility, nutrient utilisation efficiency and crop productivity in arid and semi-arid areas.

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Authors' contributions

AMA conducted the fieldwork and sample collection. RQK and SNM performed the laboratory work, including sample analysis, soil biology, mycology, culturing and analysis of biological media. MJF wrote the soil fertility section and interpreted the results, while HMY wrote the microbiology section and interpreted its results. HMA performed the statistical analysis, revised the manuscript, supervised the study and handled the correspondence. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest

Authors do not have any conflict of interests to declare.

Ethical issues

None

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