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Effect of Plant Density and Mycorrhizal Fungi on Sorghum Productivity Under Toshka Conditions, Egypt

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Abstract: Toshka, in the south of Egypt's Western Desert near the Sudanese border, is characterised by extreme summer heat (maximum air temperature above 50 °C), virtually no rainfall and sandy soils, while livestock producers in the region face a shortage of green forage and high feed costs because the area lies about 1,300 km from Cairo. A two-season field experiment (summer 2025 and 2026) was conducted at the Toshka Experimental Station of the Desert Research Center to evaluate the effects of three in-row plant spacings (20, 25 and 30 cm) and five rates of arbuscular mycorrhizal fungi (AMF) inoculum applied as seed coating (0, 500, 1000, 1500 and 2000 g) on the growth, forage yield and profitability of sweet sorghum (*Sorghum bicolor* (L.) Moench). The 15 treatment combinations were arranged in a split-plot design in randomized complete blocks with three replications. Inoculation with 1500 g AMF gave the highest values of all studied traits, increasing fresh forage yield by about 45% over uninoculated plants, whereas raising the rate to 2000 g reduced it by about 8%. The 25 cm spacing exceeded the 20 cm spacing by about 25% in fresh forage yield. The combination of 1500 g AMF with 25 cm spacing produced the maximum fresh forage yield (25.67 and 30.04 t fed^{-1} in the first and second seasons, respectively) and the highest net return (13,660 and 19,115 LE fed^{-1}), although it did not differ significantly from 1500 g AMF with 30 cm spacing in fresh or dry forage yield. Coating sweet sorghum seed with 1500 g AMF and sowing at 25 cm between hills is therefore recommended for forage production under Toshka conditions.

Key words: *Sorghum bicolor*; sweet sorghum; arbuscular mycorrhizal fungi; plant spacing; forage yield; net return; Toshka

1. Introduction

Sorghum (*Sorghum bicolor* (L.) Moench) is a multipurpose crop grown for grain, green forage, silage, syrup and bioenergy, and ranks fifth among the world's cereals after maize, wheat, rice and barley. Its grain contains approximately 10–12% protein, 70% carbohydrates and 3% fat **(Balai *et al.*, 2024)**. In the 2024/25 season, sorghum occupied about 40.8 million ha worldwide, with a production of 61.8 million t and an average yield of 1.52 t ha^{-1} **(USDA, 2024)**. In Egypt, where the crop is known

locally as *dhorra rafi'a*, sorghum was grown on an average of about 151 thousand ha (≈360 thousand fed) during 2000–2019, with a mean annual production of about 822 thousand t, and Fayoum is the leading governorate in both area and production **(Elasraag, 2023)**. Although the consumption of sorghum grain as a staple food has declined with changing diets and incomes, its use as feed and fodder for livestock continues to increase because of its high yield potential, wide adaptability and good nutritive value **(Balai *et al.*, 2024)**. Sweet sorghum is particularly attractive as a forage crop for hot, dry regions because it produces a large biomass of juicy, sugar-rich stalks and tolerates heat and water shortage better than maize.

The Toshka region, a major agricultural development zone in the southern Western Desert of Egypt, has an extremely arid climate with practically no rainfall, summer air temperatures that exceed 50 °C and sandy soils of low organic matter and fertility. Livestock producers in the region suffer from a shortage of green forage and from the high cost of feed transported from the Nile Valley, about 1,300 km away. Identifying heat-tolerant forage crops and management practices that raise their productivity with limited inputs is therefore a priority for sustainable animal production in this area.

Plant density is one of the most important agronomic factors determining forage yield. It governs the intensity of competition among plants for light, water and nutrients: excessive density produces thin stalks, small panicles and greater lodging, whereas low density leaves resources unused and reduces yield per unit area. In sweet sorghum, dry matter yield increased with plant population from 8 to 16 plants m^{-2} **(Martin and Kelleher, 1984)**, whereas under the high solar radiation of desert environments biomass yield was relatively tolerant of wider in-row spacing **(Ottman and Ray, 2018)**. Because the optimum density depends on the genotype, soil and climate, it must be determined for each environment **(Abd El-Aziz and El Shahed, 2021)**.

Sorghum is a nutrient-exhaustive crop that requires large amounts of nutrients for optimal production **(Balai *et al.*, 2024)**. However, the high cost of chemical fertilizers and their adverse effects on soil health have encouraged integrated nutrient management, in which mineral fertilizers are combined with organic manures and biofertilizers to sustain productivity and soil quality **(Das *et al.*, 2015)**. The combined use of biofertilizers, organic manure and mineral fertilizers increases system productivity and maintains the nutrient balance of the soil **(Gawai and Pawar, 2007; Bargaz *et al.*, 2018)**, while organic matter improves soil structure, porosity and water intake **(Weil and Magdoff, 2004)** – properties that are especially limiting in sandy desert soils.

Arbuscular mycorrhizal fungi (AMF) form symbiotic associations with the roots of most crop plants. Their extraradical hyphae extend beyond the nutrient-depletion zone around the roots and increase the uptake of phosphorus, micronutrients and water, and AMF-colonised plants show greater tolerance of drought, heat and salinity **(Smith and Read, 2008; Begum *et al.*, 2019)**. In sorghum, AMF inoculation has increased grain yield and nutrient content **(Watts-Williams *et al.*, 2022)** and, under field conditions, biomass, panicle length and grain yield **(Díaz Franco *et al.*, 2013; Tia *et al.*, 2026)**. The benefit obtained, however, depends on the inoculum rate, the host plant and soil conditions, particularly the level of available phosphorus **(Smith and Smith, 2011; Balzergue *et al.*, 2013)**. Information on the optimum AMF rate for sweet sorghum, and on its interaction with plant density under the harsh conditions of Toshka, is scarce.

The present study therefore aimed to (i) evaluate the effects of three in-row plant spacings, five rates of AMF inoculum and their interaction on the growth, yield components and forage yield of sweet sorghum, and (ii) assess the economic return of these practices under Toshka conditions.

2. Materials and Methods

Experimental site and growing seasons

Field experiments were conducted during the 2025 and 2026 summer seasons at the Toshka Experimental Station of the Desert Research Center, located in the Toshka development zone in the southern Western Desert, Aswan Governorate, Egypt (22°28′10.4″ N, 31°32′27.5″ E; 201 m above sea level). Sowing took place on 1 May 2025 and 3 May 2026.

Climate, soil and irrigation water

No rainfall was recorded during either growing season. The monthly maximum air temperature ranged from 38 to 53 °C in 2025 and from 39 to 54 °C in 2026, peaking in July, while relative humidity did not exceed 28% (Fig. 1). The soil of the experimental site is a moderately saline, calcareous sandy loam (Table 1). Irrigation water was obtained from groundwater well and applied by drip irrigation; its chemical analysis is presented in Table 1.

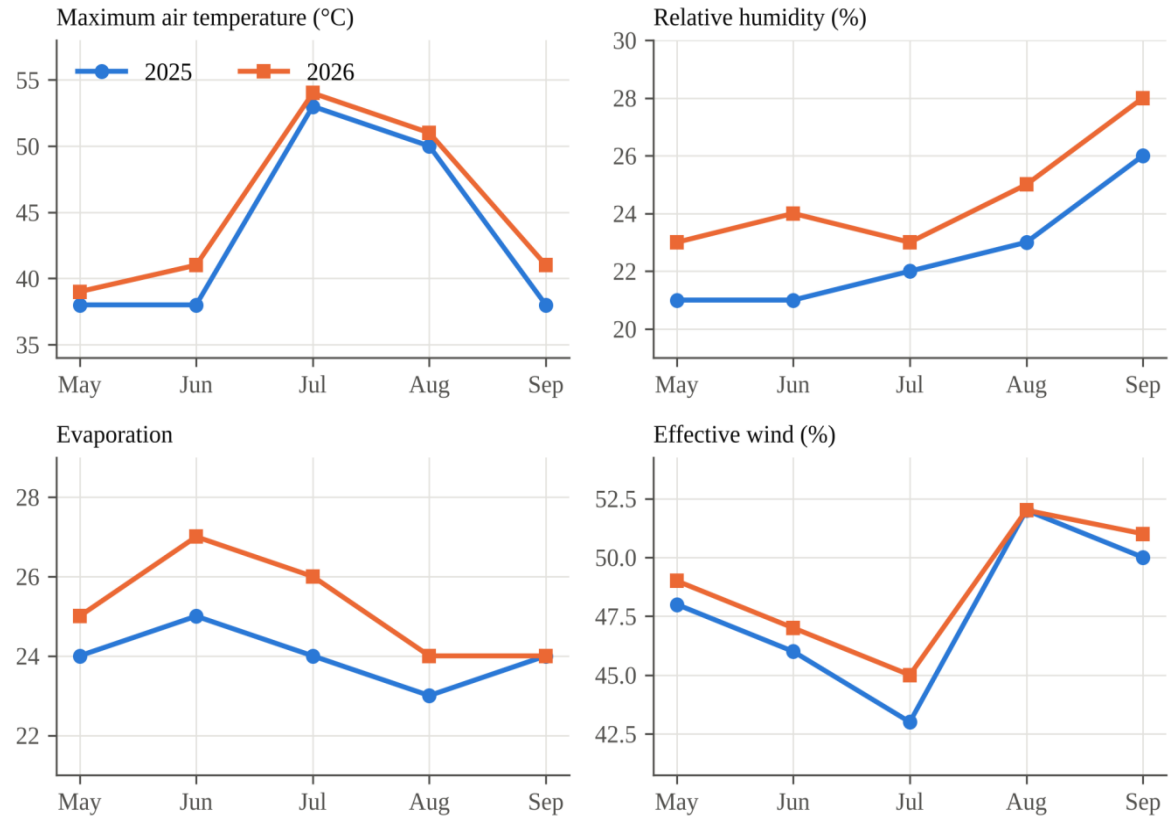


Fig. (1). Monthly meteorological data at the Toshka Experimental Station during the 2025 and 2026 growing seasons (May–September)

Treatments and experimental design

The experiment comprised 15 treatment combinations of three in-row plant spacings (20, 25 and 30 cm between hills) and five rates of AMF inoculum (0, 500, 1000, 1500 and 2000 g/fed^{-1} applied as a seed coating immediately before sowing. The treatments were arranged in a split-plot design in randomized complete blocks with three replications; plant spacings were assigned to the main plots and AMF rates to the sub-plots. The sub-plot area was 42 m² (7 rows, length 12 m long and distance 50 cm apart). Seeds of sweet sorghum cultivar Dorado were obtained from Agricultural Research Center. The AMF inoculum was obtained fromDesert Research Center .

Fertilization and crop management

Organic manure compost was incorporated at 20 t fed^{-1} during soil preparation, together with calcium superphosphate (15.5% P_2O_5) at 30 kg P_2O_5 fed^{-1} (≈194 kg fed^{-1}). Potassium sulphate (48% K_2O) at 50 kg K_2O fed^{-1} (≈104 kg fed^{-1}) and ammonium sulphate (20.6% N) at 60 kg N fed^{-1} (≈291 kg fed^{-1}) were broadcast before sowing. A further 100 kg N fed^{-1} was applied as ammonium nitrate (33.5% N; ≈300 kg fed^{-1}) in three equal doses before irrigation at 30, 60 and 80 days after sowing (DAS), giving a total of 160 kg N fed^{-1}. Plants were thinned to four per hill at 30 DAS and to one plant per hill at 40 DAS. All other cultural practices were carried out as recommended for sweet sorghum in the region.

Table (1). Physical and chemical properties of the experimental soil (0–30 cm depth, before sowing) and chemical analysis of the irrigation water (means of the two seasons)

Soil property	Value	Irrigation water property	Value
Particle size distribution (%)		pH	7.98
Sand	75.08	EC (dS m^{-1})	3.42
Silt	16.56	SAR	3.65
Clay	8.36	***Soluble cations (meq L^{-1})***	
Texture class	Sandy loam	Na^+	7.61
pH	7.86	K^+	3.39
EC (dS m^{-1})	4.97	Ca^{2+}	4.94
$CaCO_3$ (%)	9.63	Mg^{2+}	3.76
CEC (cmol(+) kg^{-1})	9.37	***Soluble anions (meq L^{-1})***	
Soluble cations (meq L^{-1})		CO_3^{2-}	–
Na^+	22.61	HCO_3^-	7.45
K^+	1.98	Cl^-	4.68
Ca^{2+}	14.34	SO_4^{2-}	7.57
Mg^{2+}	10.17		
Soluble anions (meq L^{-1})			
CO_3^{2-}	–		
HCO_3^-	4.94		
Cl^-	19.87		
SO_4^{2-}	25.29		

EC: electrical conductivity; CEC: cation exchange capacity; SAR: sodium adsorption ratio.

Data recorded

At harvest (120 DAS), ten guarded plants were randomly taken from the inner rows of each sub-plot to determine plant height (cm), fresh leaf weight, fresh stalk weight and dry leaf weight (g $plant^{-1}$), panicle length (cm) and panicle weight (g $plant^{-1}$). Dry weights were determined after oven-drying at 70 °C to constant weight. Panicle weight, fresh forage yield and dry forage yield per unit area were and expressed in kg fed^{-1} (1 feddan = 4,200 m^2 = 0.42 ha).

Economic evaluation

Production costs included land rent, irrigation, labour, seed, fertilizers, AMF inoculum, pesticides, fuel and machinery for sowing, pest control and harvesting. Total production costs were 18,430 LE fed^{-1} and the farm-gate price of fresh forage was 1,250 LE t^{-1}. Returns were calculated as follows:

$$\text{Gross return (LE fed}^{-1}\text{)} = \text{fresh forage yield (t fed}^{-1}\text{)} \times \text{price (LE t}^{-1}\text{)}$$

$$\text{Net return (LE fed}^{-1}\text{)} = \text{gross return} - \text{total production costs}$$

Statistical analysis

Data of each season were subjected to analysis of variance for a split-plot design (Gomez and Gomez, 1984) using SPSS version 20.0. Treatment means were compared using the least significant difference (LSD) test at the 5% level of probability; means within a column followed by the same letter(s) are not significantly different.

3. Results and Discussion

Effect of AMF inoculation rate

The rate of AMF inoculum significantly affected all growth and yield traits in both seasons (Tables 2 and 3). All traits increased progressively with increasing inoculum rate up to 1500 g, which gave the highest values, and then declined at 2000 g. Compared with uninoculated plants, inoculation with 1500 g AMF increased plant height by 47.9 and 48.2%, fresh stalk weight by 57.1 and 56.7%, dry leaf weight by 38.7 and 35.1% and panicle length by 25.0% in the first and second seasons, respectively (Table 2). Fresh leaf weight increased by 15.0 and 15.7%, but the 1500 g rate did not differ significantly from the 1000 and 2000 g rates for this trait.

Similarly, 1500 g AMF increased panicle weight by 58.2 and 56.9% per plant and by 54.8% per feddan, and increased fresh and dry forage yields by about 45–46% in both seasons (Table 3). Fresh forage yield rose from 16.20 to 23.49 t fed^{-1} in 2025 and from 18.96 to 27.48 t fed^{-1} in 2026. Increasing the rate from 1500 to 2000 g reduced fresh forage yield by 8.1%, while the 500 and 1000 g rates did not differ significantly in fresh or dry forage yield. Consequently, the highest net return (10,926 and 15,916 LE fed^{-1}) was obtained with 1500 g AMF, compared with only 1,822 and 5,265 LE fed^{-1} for uninoculated plants.

The positive response to AMF can be attributed to the extensive extraradical hyphal network, which explores a larger soil volume than roots alone and enhances the uptake of phosphorus, micronutrients and water, and to the improved tolerance of inoculated plants to heat, drought and salinity stress **(Smith and Read, 2008; Begum *et al.*, 2019)**. These benefits are particularly relevant to the saline sandy soil and extreme summer heat of Toshka. Comparable gains have been reported for sorghum: seed inoculation with *Glomus intraradices* increased grain yield by about 524 kg ha^{-1} and the benefit–cost ratio by about 17% across 21 commercial fields in Mexico **(Díaz Franco *et al.*, 2013)**, and field inoculation with indigenous AMF increased biomass, panicle length and grain yield on Sudanese vertisols **(Tia *et al.*, 2026)**. The decline at the highest rate indicates that inoculum beyond 1500 g gave no additional benefit; a greater carbon cost to the host plant is one possible explanation, but root colonization was not measured in this study and this needs confirmation. The relatively generous mineral P and N supply may also have limited the magnitude of the mycorrhizal response, because high phosphorus availability suppresses the establishment of the symbiosis **(Smith and Smith, 2011; Balzergue *et al.*, 2013)**. Similar trends in response to biofertilization and organic amendments under the sandy soils of Egypt were reported by **El-Metwally *et al.* (2010)**, **Abd El-Aziz (2023)** and **Habib and Abd El-Aziz (2026)**.

Effect of plant spacing

In-row plant spacing significantly affected all traits in both seasons (Tables 4 and 5). The 25 cm spacing gave the highest values, followed by 30 cm, whereas 20 cm gave the lowest. Compared with 20 cm, the 25 cm spacing increased plant height by 15.7 and 15.3%, fresh leaf weight by 35.8 and 35.5%, fresh stalk weight by 20.7 and 20.8%, dry leaf weight by 40.6 and 40.5% and panicle length by 30.4 and 29.6% in 2025 and 2026, respectively (Table 4). Likewise, panicle weight per plant increased by 36.7 and 37.1% and fresh and dry forage yields by about 25% (Table 5). Panicle weight did not differ significantly between the 25 and 30 cm spacings, but the 25 cm spacing produced 4.3% more fresh forage than 30 cm. The highest net returns (8,370 and 12,925 LE fed^{-1}) were therefore obtained at 25 cm.

Close spacing (20 cm) intensifies competition among neighbouring plants for water, nutrients and light; under the limited water- and nutrient-holding capacity of sandy soil and high evaporative demand, this produced smaller plants with lighter stalks, leaves and panicles. Wider spacing (30 cm) allowed vigorous individual plants but fewer plants per unit area. The 25 cm spacing appears to provide the best balance between individual plant performance and plant population. These results agree with reports that sweet sorghum biomass responds to plant population **(Martin and Kelleher, 1984)** and that, in irrigated desert environments, stalk weight per plant increases with wider in-row spacing while biomass per unit area is maintained over a range of spacings **(Ottman and Ray, 2018)**. Similar responses to plant density were reported for maize under the newly reclaimed soils of South Sinai **(Abd El-Aziz and El Shahed, 2021)**. Fig. 2 summarises the relative gains obtained from the best AMF rate and the best spacing.

Table (2). Effect of AMF inoculation rate on growth traits of sweet sorghum in the 2025 and 2026 seasons

AMF rate	Plant height (cm)	Fresh leaf weight (g plant^{-1})	Fresh stalk weight (g plant^{-1})	Dry leaf weight (g plant^{-1})	Panicle length (cm)
2025 season					
Uninoculated	119 E	60 B	266 D	31 D	24 D
500 g/fed	125 D	62 B	298 C	34 C	25 C
1000 g/fed	137 C	63 AB	302 C	41 B	27 B
1500 g/fed	176 A	69 A	418 A	43 A	30 A
2000 g/fed	167 B	65 AB	388 B	42 B	27 B
LSD at 0.05	1.20	3.66	3.94	0.45	0.22
2026 season					
Uninoculated	139 E	70 B	312 D	37 D	28 D
500 g/fed	147 D	72 B	349 C	40 C	29 C
1000 g/fed	161 C	74 AB	353 C	48 B	31 B
1500 g/fed	206 A	81 A	489 A	50 A	35 A
2000 g/fed	196 B	76 AB	454 B	49 B	32 B
LSD at 0.05	1.41	4.28	4.61	0.53	0.25

Means within a column in each season followed by the same letter(s) are not significantly different at $P \leq 0.05$.

Table (3). Effect of AMF inoculation rate on panicle weight, forage yield and economic return of sweet sorghum in the 2025 and 2026 seasons.

AMF rate	Panicle weight (g plant^{-1})	Panicle weight (kg fed^{-1})	Fresh forage yield (kg fed^{-1})	Dry forage yield (kg fed^{-1})	Gross return (LE fed^{-1})	Net return (LE fed^{-1})
2025 season						
Uninoculated	55 E	2,303 E	16,202 D	397 D	20,252 D	1,822 D
500 g/fed	69 D	2,867 D	18,544 C	456 C	23,180 C	4,750 C
1000 g/fed	78 C	3,173 C	18,732 C	458 C	23,415 C	4,985 C
1500 g/fed	87 A	3,566 A	23,485 A	580 A	29,356 A	10,926 A
2000 g/fed	85 B	3,438 B	21,572 B	520 B	26,965 B	8,535 B
LSD at 0.05	0.93	39.4	207	4.24	259	259
2026 season						
Uninoculated	65 E	2,695 E	18,956 D	464 D	23,695 D	5,265 D
500 g/fed	81 D	3,355 D	21,696 C	534 C	27,120 C	8,690 C
1000 g/fed	91 C	3,712 C	21,916 C	536 C	27,395 C	8,965 C
1500 g/fed	102 A	4,173 A	27,477 A	679 A	34,346 A	15,916 A
2000 g/fed	99 B	4,022 B	25,239 B	609 B	31,548 B	13,118 B
LSD at 0.05	1.09	46.0	242	4.96	303	303

Means within a column in each season followed by the same letter(s) are not significantly different at $P \leq 0.05$. Gross return = fresh forage yield × 1,250 LE t^{-1}; net return = gross return − 18,430 LE fed^{-1} (total production costs).

Table (4). Effect of in-row plant spacing on growth traits of sweet sorghum in the 2025 and 2026 seasons

Spacing (cm)	Plant height (cm)	Fresh leaf weight (g plant^{-1})	Fresh stalk weight (g plant^{-1})	Dry leaf weight (g plant^{-1})	Panicle length (cm)
2025 season					
20 cm	134 C	53 C	300 C	32 C	23 C
25 cm	155 A	72 A	362 A	45 A	30 A
30 cm	146 B	66 B	341 B	38 B	27 B
LSD at 0.05	0.93	2.83	3.05	0.35	0.17
2026 season					
20 cm	157 C	62 C	351 C	37 C	27 C
25 cm	181 A	84 A	424 A	52 A	35 A
30 cm	171 B	77 B	399 B	45 B	32 B
LSD at 0.05	1.09	3.32	3.57	0.41	0.20

Means within a column in each season followed by the same letter(s) are not significantly different at $P \leq 0.05$.

Table (5). Effect of in-row plant spacing on panicle weight, forage yield and economic return of sweet sorghum in the 2025 and 2026 seasons

Spacing (cm)	Panicle weight (g plant^{-1})	Panicle weight (kg fed^{-1})	Fresh forage yield (kg fed^{-1})	Dry forage yield (kg fed^{-1})	Gross return (LE fed^{-1})	Net return (LE fed^{-1})
2025 season						
20 cm	60 B	2,481 B	17,157 C	421 C	21,446 C	3,016 C
25 cm	82 A	3,386 A	21,440 A	525 A	26,800 A	8,370 A
30 cm	82 A	3,341 A	20,524 B	501 B	25,655 B	7,225 B
LSD at 0.05	0.72	30.5	160	3.28	200	200
2026 season						
20 cm	70 B	2,903 B	20,073 C	493 C	25,091 C	6,661 C
25 cm	96 A	3,962 A	25,084 A	614 A	31,355 A	12,925 A
30 cm	96 A	3,909 A	24,013 B	586 B	30,016 B	11,586 B
LSD at 0.05	0.84	35.7	188	3.84	234	234

Means within a column in each season followed by the same letter(s) are not significantly different at $P \leq 0.05$. Gross and net returns as defined in Table 3.

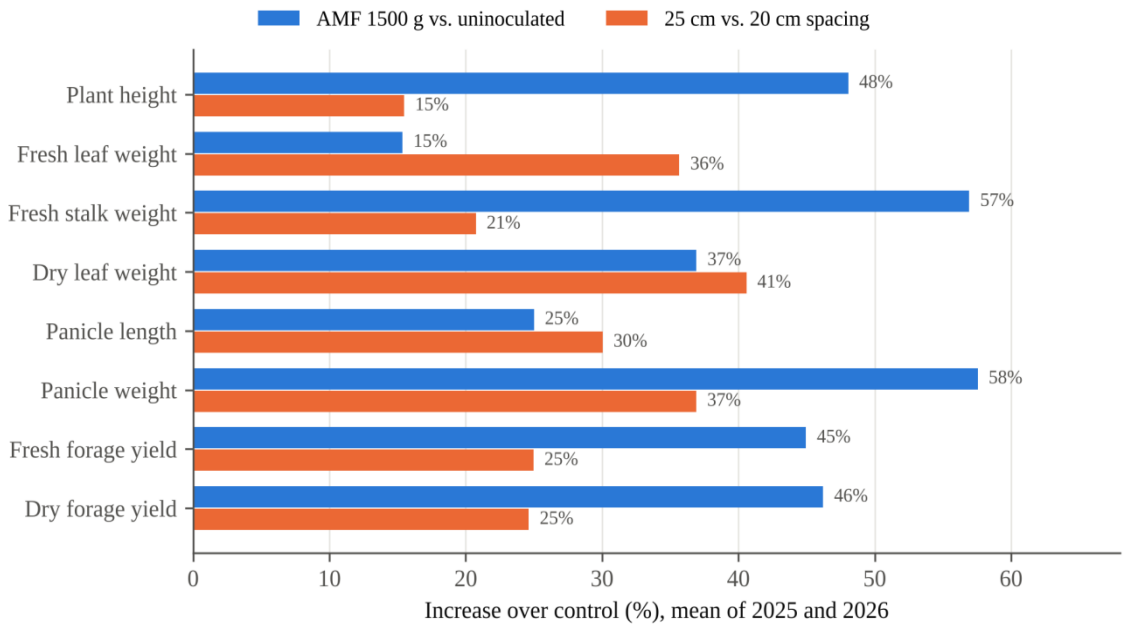


Fig. (2). Relative increase (%) in growth and yield traits of sweet sorghum resulting from inoculation with 1500 g AMF (compared with uninoculated plants) and from 25 cm spacing (compared with 20 cm), mean of the 2025 and 2026 seasons

Effect of the interaction between AMF rate and plant spacing

The interaction between AMF rate and plant spacing was significant for all traits in both seasons (Tables 6 and 7; Fig. 3). Plant height ranged from 112 cm (uninoculated, 20 cm) to 182 cm (1500 g AMF, 25 cm) in 2025, and from 131 to 213 cm for the same combinations in 2026. Fresh leaf weight ranged from 48 to 80 g plant^{-1} in 2025 and from 56 to 93 g plant^{-1} in 2026, and dry leaf weight from 28.3 to 53.0 g plant^{-1} and from 33 to 62 g plant^{-1}, respectively. At 1500 g AMF, plant height, fresh leaf weight and dry leaf weight did not differ significantly among the three spacings, whereas fresh stalk weight was highest at 25 and 30 cm (467 and 463 g plant^{-1} in 2025; 547 and 542 g plant^{-1} in 2026) and panicle length was highest at 25 cm only (34 and 40 cm).

The combination of 1500 g AMF and 25 cm spacing produced the heaviest panicles (103 and 121 g plant^{-1}; 4,217 and 4,934 kg fed^{-1} in 2025 and 2026, respectively), significantly exceeding all other combinations (Table 7). It also gave the highest fresh forage yield (25,672 and 30,036 kg fed^{-1}), dry forage yield (627 and 733 kg fed^{-1}) and gross return (32,090 and 37,545 LE fed^{-1}); for these three traits, however, it was statistically at par with 1500 g AMF at 30 cm. Compared with uninoculated plants at 20 cm, this combination increased fresh forage yield by 66.8% in both seasons. As shown in Fig. 2, the response of fresh forage yield to the AMF rate followed the same pattern at all three spacings, peaking at 1500 g. Net return (Fig. 4) ranged from only 807 LE fed^{-1} (uninoculated, 20 cm) to 13,660 LE fed^{-1} (1500 g AMF, 25 cm) in 2025, and from 4,077 to 19,115 LE fed^{-1} in 2026. These results agree with **Abd El-Aziz and Anter, 2023; Anter *et al.*, 2024; Mehanna *et al.*, 2024; Habib and Abd El-Aziz, 2026)**.

The superiority of this combination suggests that the two factors acted in a complementary way: AMF improved the capacity of each plant to acquire water and nutrients, while the 25 cm spacing limited competition among plants without sacrificing plant population. This agrees with the yield and profitability gains reported for AMF-inoculated sorghum under contrasting field environments **(Díaz Franco *et al.*, 2013; Watts-Williams *et al.*, 2022; Tia *et al.*, 2026)**, and with the combined effects of organic or biological amendments and agronomic management reported under the newly reclaimed sandy soils of Egypt **(Abd El-Aziz *et al.*, 2017, 2018; Abd El-Aziz and Attia, 2022).**

Table (6). Effect of the interaction between AMF inoculation rate and in-row plant spacing on growth traits of sweet sorghum in the 2025 and 2026 seasons

AMF rate	Spacing (cm)	Plant height (cm)	Fresh leaf weight (g plant^{-1})	Fresh stalk weight (g plant^{-1})	Dry leaf weight (g plant^{-1})	Panicle length (cm)
2025 season						
Uninoculated	20 cm	112 H	48 E	245 J	28.3 H	22 I
	25 cm	116 G	54 DE	262 HI	30.7 FG	23 H
	30 cm	116 GH	49 E	249 IJ	29.7 GH	22 HI
500 g/fed	20 cm	123 F	55 DE	268 H	31.3 EF	23 H
	25 cm	130 E	58 CDE	298 G	34.7 D	24 G
	30 cm	128 E	58 CDE	292 G	32.3 E	24 G
1000 g/fed	20 cm	131 E	58 CDE	298 G	34.7 D	25 F
	25 cm	153 C	66 BCD	341 E	36.7 C	28 E
	30 cm	137 D	60 CDE	324 F	35.7 CD	26 F
1500 g/fed	20 cm	179 A	77 AB	410 B	52.3 A	30 C
	25 cm	182 A	80 A	467 A	53.0 A	34 A
	30 cm	181 A	79 A	463 A	53.0 A	31 B
2000 g/fed	20 cm	153 C	66 BCD	348 E	43.0 B	29 DE
	25 cm	168 B	76 AB	385 C	43.3 B	29 D
	30 cm	167 B	70 ABC	369 D	43.0 B	29 D
LSD at 0.05		2.08	6.34	6.83	0.78	0.38
2026 season						
Uninoculated	20 cm	131 H	56 E	286 J	33 H	26 I
	25 cm	136 G	63 DE	307 HI	35 FG	27 H
	30 cm	135 GH	57 E	292 IJ	34 GH	26 HI
500 g/fed	20 cm	143 F	65 DE	313 H	36 EF	27 H
	25 cm	152 E	68 CDE	348 G	40 D	28 G
	30 cm	149 E	68 CDE	342 G	37 E	28 G
1000 g/fed	20 cm	153 E	69 CDE	349 G	40 D	30 F
	25 cm	179 C	77 BCD	399 E	42 C	33 E
	30 cm	160 D	71 CDE	379 F	41 DE	30 F
1500 g/fed	20 cm	210 A	90 AB	479 B	61 A	35 C
	25 cm	213 A	93 A	547 A	62 A	40 A
	30 cm	212 A	92 A	542 A	62 A	37 B
2000 g/fed	20 cm	179 C	78 BCD	407 E	50 B	33 DE
	25 cm	197 B	89 AB	450 C	51 B	34 D
	30 cm	196 B	82 ABC	432 D	50 B	34 D
LSD at 0.05		2.44	7.42	7.99	0.91	0.44

Means within a column in each season followed by the same letter(s) are not significantly different at $P \leq 0.05$.

Table (7). Effect of the interaction between AMF inoculation rate and in-row plant spacing on panicle weight, forage yield and economic return of sweet sorghum in the 2025 and 2026 seasons

AMF rate	Spacing (cm)	Panicle weight (g plant^{-1})	Panicle weight (kg fed^{-1})	Fresh forage yield (kg fed^{-1})	Dry forage yield (kg fed^{-1})	Gross return (LE fed^{-1})	Net return (LE fed^{-1})
2025 season							
Uninoculated	20 cm	35 K	1,519 K	15,390 G	375 I	19,237 G	807 G
	25 cm	50 I	2,161 I	15,774 G	386 I	19,717 G	1,287 G
	30 cm	43 J	1,783 J	15,749 G	385 I	19,686 G	1,256 G
500 g/fed	20 cm	72 H	2,937 H	15,867 G	387 I	19,833 G	1,403 G
	25 cm	73 H	2,981 H	18,637 E	456 G	23,296 E	4,866 E
	30 cm	73 H	2,964 H	17,350 F	428 H	21,687 F	3,257 F
1000 g/fed	20 cm	78 G	3,183 G	19,270 DE	471 F	24,087 DE	5,657 DE
	25 cm	81 EFG	3,299 EFG	19,640 D	488 E	24,550 D	6,120 D
	30 cm	80 FG	3,258 FG	19,603 D	480 EF	24,503 D	6,073 D
1500 g/fed	20 cm	89 C	3,656 C	23,632 B	576 B	29,540 B	11,110 B
	25 cm	103 A	4,217 A	25,672 A	627 A	32,090 A	13,660 A
	30 cm	95 B	3,868 B	25,514 A	626 A	31,892 A	13,462 A
2000 g/fed	20 cm	82 EF	3,323 EF	20,783 C	509 D	25,978 C	7,548 C
	25 cm	86 CD	3,465 D	21,481 C	526 C	26,851 C	8,421 C
	30 cm	83 DE	3,428 DE	21,248 C	514 CD	26,560 C	8,130 C
LSD at 0.05		1.61	68.2	359	7.34	448	448
2026 season							
Uninoculated	20 cm	40 K	1,777 K	18,006 G	439 I	22,507 G	4,077 G
	25 cm	59 I	2,529 I	18,455 G	452 I	23,068 G	4,638 G
	30 cm	50 J	2,087 J	18,426 G	451 I	23,032 G	4,602 G
500 g/fed	20 cm	84 H	3,436 H	18,564 G	453 I	23,205 G	4,775 G
	25 cm	85 H	3,488 H	21,805 E	533 G	27,256 E	8,826 E
	30 cm	85 H	3,468 H	20,299 F	501 H	25,373 F	6,943 F
1000 g/fed	20 cm	91 G	3,725 G	22,545 DE	551 F	28,181 DE	9,751 DE
	25 cm	94 EFG	3,860 EFG	22,978 D	571 E	28,722 D	10,292 D
	30 cm	93 FG	3,812 FG	22,935 D	561 EF	28,668 D	10,238 D
1500 g/fed	20 cm	104 C	4,277 C	27,649 B	674 B	34,561 B	16,131 B
	25 cm	121 A	4,934 A	30,036 A	733 A	37,545 A	19,115 A
	30 cm	111 B	4,525 B	29,851 A	732 A	37,313 A	18,883 A
2000 g/fed	20 cm	95 G	3,854 G	24,108 DE	590 F	30,134 DE	8,755 DE
	25 cm	99 EFG	4,019 EFG	24,917 D	610 E	31,147 D	9,768 D
	30 cm	96 FG	3,976 FG	24,647 D	596 EF	30,809 D	9,430 D
LSD at 0.05		1.86	79.1	416	8.51	519	519

Means within a column in each season followed by the same letter(s) are not significantly different at $P \leq 0.05$. Gross and net returns as defined in Table 3.

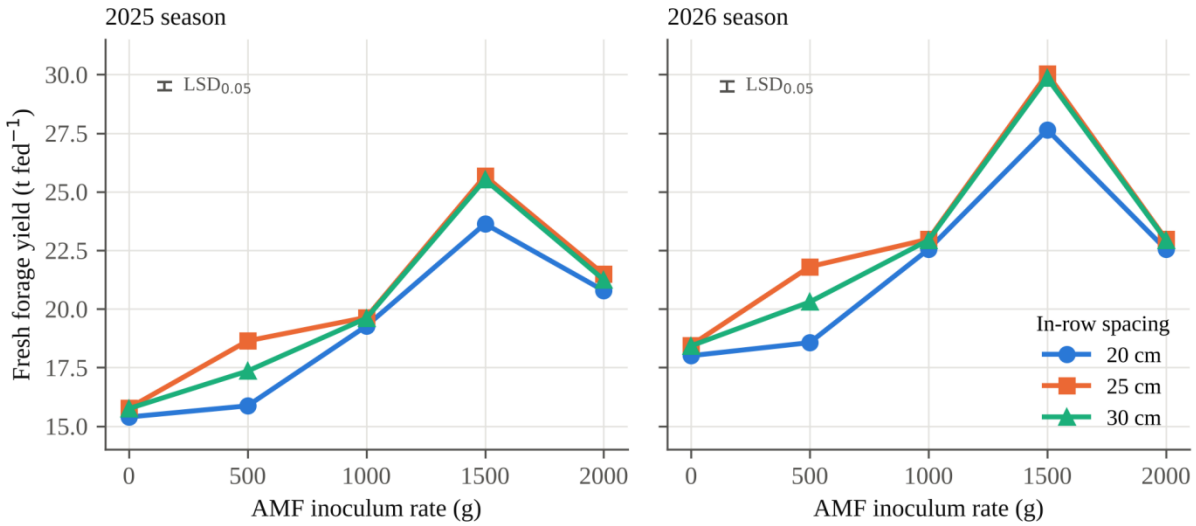


Fig. (3). Response of fresh forage yield of sweet sorghum to AMF inoculation rate at three in-row plant spacings in the 2025 and 2026 seasons. The vertical bar is the LSD at 0.05 for the interaction

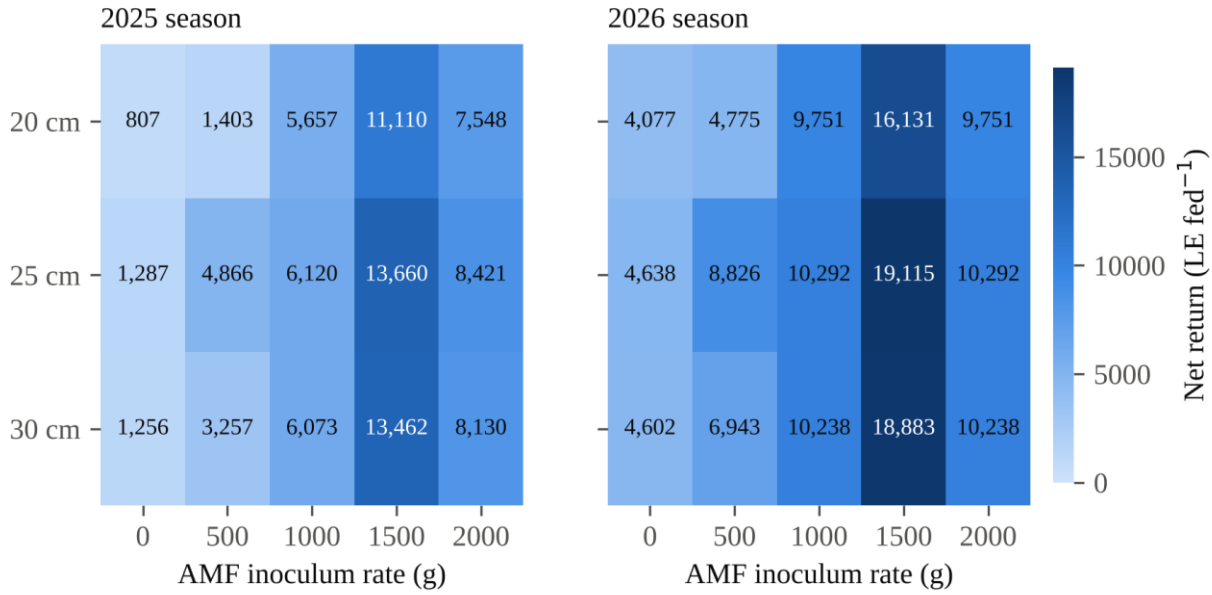


Fig. (4). Net return (LE fed^{-1}) of sweet sorghum as affected by the combinations of AMF inoculation rate and in-row plant spacing in the 2025 and 2026 seasons (gross return minus total production costs of 18,430 LE fed^{-1})

4. Conclusion

Toshka is one of the most arid regions in the world: no rainfall was recorded during the study, summer maximum temperatures exceeded 50 °C, and crops depend entirely on irrigation with saline groundwater. Under these conditions, coating sweet sorghum seed with 1500 g AMF inoculum and sowing at 25 cm between hills produced the highest growth, panicle weight, fresh and dry forage yields and net return in both seasons. The 1500 g rate with 30 cm spacing gave statistically similar forage yields, whereas increasing the inoculum to 2000 g reduced yield and profitability. This practice is therefore recommended for green forage production in Toshka and similar desert environments. Further studies should quantify root colonization, nutrient uptake, forage quality and water productivity, and should test lower mineral phosphorus rates in combination with AMF inoculation.

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