Sunflower Varieties Response to Magnesium Sulfate Fertilization via Various Row Spaces under Current Climate Conditions

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ABSTRACT

Field experiments were conducted during the growing summer seasons of 2023 and 2024 in Etay El-Baroud Agricultural Research Station, ARC, El-Behera governorate, Egypt using a split-split plot design to investigate the response of the three sunflower varieties cultivated in two-row Spaces (60 and 70 cm) to four rates of magnesium and sulfur as ($MgSO_4 6H_2O$) as fertilization treatments under the present interrupted climate conditions. *For the plant growth,* the results showed that Giza 120 variety demonstrated superiority in growth traits like plant height, head diameter, and 100-seed weight, often reaching peak performance with the highest fertilization and wider rows. *For the yield,* also, Giza 120 variety consistently produced the highest seed yield per plant and overall sunflower seed yield, achieving a peak of 1.82 Mg fed^{-1} under the narrow rows and highest fertilizer rate (65 kg fed^{-1}). In contrast, the Giza 102 variety showed the most significant increase in stem diameter and achieved the highest oil yield (706.57 kg fed^{-1}) and oil content (40.44%) under the narrowest rows and highest fertilization. The Sakha 53 variety, exhibited the highest harvest index, highlighting its superior efficiency in converting biomass to yield. *For quality parameters,* Giza 120 produced the average highest oil yield with relative increase 10.76, 11.72% and average protein yield about 11.96, 10 % compared with Shaka 95 and Giza 102, respectively. *Nutrient uptake,* in both seeds and total biomass consistently enhanced N, P, and K uptake by increasing fertilization, in addition Giza 120 and Sakha 53 generally outperformed Giza 102 in nutrient accumulation, although some varietal and spacing-specific differences were noted. *Soil fertility,* the results cleared that integrated management of row spacing, cultivar selection, and magnesium sulfate ($MgSO_4$) fertilization significantly enhances soil fertility. The results showed that there were significant interactions among row spacing, variety, and fertilizer rate emphasized the importance of integrated crop management for optimizing sunflower productivity and quality. These findings provide critical insights for refining fertilization and agronomy practices to maximize sunflower yield and oil production in semi-arid environments such as Egypt.

Keywords: **Sunflower Varieties, row Space, Magnesium sulfate fertilizer, oil content.**

INTRODUCTION

Globally, sunflower (*Helianthus annuus* L.) is a major oil crop (Al-Myali *et al*, 2020). Sunflower seeds are an excellent source of oil (40–50%) and protein (26%) (Petraru *et al*, 2021). It is regarded as one of the finest vegetable oils in the world (Esmaeilian *et al*, 2012) and has applications in both medicine and food preparation (Al-Myali *et al*, 2020). Additionally, its low cholesterol content makes it an essential component of the human diet (Sumon *et al*, 2020).

The production process requires selecting the right Cultivar, a factor often overlooked, though it can significantly increase returns with only a slight additional cost (Kumar and Nagesh, 2019). For successful farming practices and optimal crop-nutrient management, it is crucial to consider the fundamental principles of mineral plant nutrition, including the physical, chemical, and biological processes in plants and soils (Senbayram *et al*, 2015).

Magnesium and sulfur are both considered macronutrients for plants. Magnesium is an indispensable component for plant growth and development and plays a significant role in plant defense mechanisms during abiotic stress situations (Cakmak and Kirkby, 2008; Cakmak and Yazici, 2010; Gransee and Führs, 2013; Huber and Jones, 2013).

The primary function of magnesium in plants is its role as the central atom in the chlorophyll molecule within the light-absorbing complex of chloroplasts. It also plays a vital role in carbon dioxide fixation during photosynthesis (Cakmak and Kirkby, 2008; Cakmak and Yazici, 2010; Gerendás and Führs, 2013). Magnesium's high phloem mobility allows it to be easily transported to the plant's actively growing areas, where it is essential for chlorophyll formation, enzyme activation for protein biosynthesis, and the export of photosynthates to support both vegetative and generative growth.

Visual signs of magnesium deficiency typically appear first in older leaves (Cakmak and Kirkby, 2008; Gransee and Führs, 2013). Such deficiencies can negatively impact biomass formation and reduce plant resilience to environmental stresses by impairing

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various biochemical and physiological processes. The application of magnesium-containing fertilizers can improve crop yield and contribute to better human and animal nutrition and health (Malakouti, 1999).

Sulfur fertilizer is commonly applied to oilseed crops, similar to phosphorus (Patel *et al*, 2019). It is essential for the synthesis of proteins, oils, and vitamins, and it also supports flowering and improves the quality of oilseeds. Additionally, sulfur-containing compounds are critical for oil production in oilseed crops; approximately 16 kg of sulfur is required for 91% dry matter and improved yield (McGrath and Zhao, 1996; Scherer, 2001).

Sulfur contributes to amino acid synthesis, enhanced cell division, and photosynthetic activity, leading to improved growth and yield characteristics such as increased plant height, head diameter, and stem girth (Intodia and Tomar, 1997; Raja *et al*, 2007). It also plays a role in the transformation of carbohydrates into oil and is necessary for the creation of the fatty acid-containing enzyme thiokinase (Sreemannarayana *et al*, 1998). Increased sulfur application positively impacts grain yield (Čeh *et al*, 2008). When sulfur is applied, plants grow more quickly compared to when it is not applied (Hussain and Thomas, 2010). Sulfur supports photosynthesis as it is a component of succinyl CoA, which is involved in chlorophyll synthesis, thereby enhancing photosynthesis and stimulating vegetative growth.

Optimal plant spacing is critical for optimal production and quality; plant population is an important agronomic strategy (Beg *et al*, 2007). In general, wider row spacing produces taller plants, larger heads, and heavier seeds. However, excessive spacing might result in poorer plant density and overall output. Narrower row spacing can enhance plant density and yields, but it may also result in smaller plants and heads due to resource competition (Hidayat *et al*, 2017).

The impacts of climate change are not merely theoretical; they are real and have a direct bearing on agricultural output. Droughts, floods, and heat waves are examples of extreme weather occurrences that negatively impact soil health, interfere with planting plans, and reduce agricultural yields. In many parts of the world, climate change is predicted to have an impact on yields and complicate efforts to boost them. Higher temperatures will exacerbate drought stress and accelerate crop development, while also raising crop yield variability and the likelihood of yield failures (**Lobell *et al*, 2011**).

Although Earth's climate has fluctuated throughout time, the current warming is occurring at a rate that hasn't been observed in 10,000 years. It takes a great quantity of additional heat energy to raise Earth's average annual surface temperature even a little bit because of the enormous size and heat capacity of the world's seas. The worldwide average surface temperature has increased by about 2 degrees Fahrenheit (1 C^{o}) since the pre-industrial era (1850-1900 in **NOAA**'s data), which may not seem like much, but it represents a considerable increase in the amount of heat that has collected (**NOAA, 2024**).

Egypt suffers from a very large shortage in the production of oil crops, as it is sufficient to produce only 5% of the oil needs, and the rest of the needs are imported in foreign currency, which causes a large burden on the state budget. The seeds and oil yield of sunflowers is influenced by factors such as cultivar selection, soil nutrient levels, water sufficiency and climate conditions. Therefore, the expansion of sunflower cultivation as one of the oil crops that can be grown in Egypt during different cultivation periods; information is needed about the best varieties, planting Spaces, and the importance of magnesium and sulfur as fertilizer elements that are not included in fertilization programs.

This investigation aimed to study the performance of certain sunflower varieties under different rates of magnesium sulfate ($MgSO_4$) fertilizer and row spacing to enhance sunflower productivity, quality and, in addition, soil fertility under the present interrupted climate conditions.

MATERIALS AND METHODS

Soil Sampling and Analysis:

Field experiments were conducted in Etay El-Baroud Agricultural Research Station, ARC, El-Behera Governorate located on (30º 89' E, 30º 65' N), during the two successive growing summer seasons of 2023 and 2024 to investigate the performance of three sunflower varieties (Var) (*Shaka 53, Giza 102, Giza 120*) cultivated in two rows Spaces (*RowS*) (60, 70 cm) using four magnesium sulfate ($MgSO_4 6H_2O$) (Mg/S) soil application rates (control, 25, 35, and 65 kg fed^{-1} as $MgSO_4$ equal to 0, 4.42, 6.20, 11.50 kg MgO fed^{-1}) contains 0, 3.5, 4.93 and 9.15 kg S fed^{-1}: (hectare = 2.40 fed).

The experiment followed a split-split plot statistical design distributed by a completely randomized blocks design (RCBD). The Row Spaces (*RowS*) treatments were assigned to the main plots, whereas sunflower varieties (*Var*) were assigned to the subplots, and $MgSO_4$ fertilization rates (*FerR*) were assigned to the sub-sub plots. Using four replicates, each plot consisted of five ridges 4 m length and 0.6 or 0.7 m *RowS* and 20 cm Space between plants.

Whether data.

Table 1. Weather data of Egypt-El-Behera-Etay El Barod-Monthly-2023-2024

	2023				2024			
Months	**T_{min}**	**T_{max}**	**TP**	**SD**	**T_{min}**	**T_{max}**	**TP**	**SD**
May	17.28	32.86	0.5	13.74	17.85	33.27	0.2	13.73
June	21.01	36.38	2.9	14.12	22.43	39.84	2.1	14.12
July	23.37	39.78	0	13.91	24.04	38.9	0.7	13.92
Average	20.55	36.34	3.4	13.92	21.44	37.34	3	13.92
T_{min}	Minimum Air Temperature (°C)			TP	Total Precipitation (mm)			
T_{max}	Maximum Air Temperature (°C)			SD	Sunshine Duration (Hours)			

*Egyptian Ministry of Agriculture & Land Reclamation. ARC. Central Lab for Agricultural Climate.

Cultural practices:

Sunflower seeds were sown on May 15, 2023, and 2024, using hand drills. Superphosphate (15.5% P_2O_5) was applied at a rate of 100 kg fertilizer fed^{-1} during land preparation. Nitrogen fertilizer was applied as (urea 46% N) at a rate of 30 kg N fed^{-1}, applied into two equal splits: half was added 21 days after sowing, and the second half before the subsequent irrigation. Magnesium sulfate ($MgSO_4.6H_2O$) fertilizer was applied as a soil amendment once, before the first irrigation after germination, at four rates. Potassium was used at a rate of 25 kg fed^{-1} K_2O and 9 kg S as 50 kg potassium sulfate fertilizer at the second irrigation. Throughout the two growing seasons, we followed standard agricultural practices for sunflower cultivation according to FCRI recommendations.

Soil Sampling and Analysis:

Surface soil samples were collected before planting for primary physical and chemical analysis and after harvesting for fertility parameters. Particle size distribution of sand, silt, and clay was determined using the hydrometer method (FAO, 1970). Electrical conductivity (EC) was measured in soil past using a conductivity meter, whereas on 1:2.5 soil–water suspension pH was determined with a pH meter (Jackson, 1973). The Kjeldahl method was used to determine mineral nitrogen (NH_4 + NO_3) determined according to Jackson (1973). Soil-available phosphorus (Av. P) was extracted using 0.5 N $NaHCO_3$ as described by Olsen *et al.* (1954), and its concentration was determined using the ascorbic acid method (Olsen and Watanabe, 1965). The amount of exchangeable potassium (Ex. K) was extracted using NH_4-acetate solution and measured with a flame photometer (Black *et al.*, 1965; Cottenie *et al.*, 1982). Organic matter (OM) content was determined using the Walkley-Black method (Black *et al*, 1965), and total Calcium carbonate ($CaCO_3$) was measured using a calcimeter method (Allison and Moodie, 1965). The main physical, chemical and nutritional properties of the experimental soil for the two growing seasons are presented in Table2.

Table 2 . Some physical, chemical and nutritional properties of soil before planting

Growing season	**Physical properties**				**Nutritional properties**				**Chemical properties**	
	Sand	Silt	Clay	Texture	OM	Min- N	Av. P	Ex. K	pH**	EC*
	%				%	mg Kg^{-1}				dSm^{-1}
2023	20.30	25.01	54.60	Clay	2.12	85.00	20.54	360.00	8.18	2.10
2024	17.08	22.92	60.00	Clay	2.37	87.50	18.60	346.04	8.11	1.20
	Total $CaCO_3$	Cation*				Anion*				
		Na^+	K^+	Ca^{++}	Mg^{++}	Cl^-	CO_3^{--}	HCO_3^-		SO_4^{--}
	%	meq L^{-1}								
2023	5.81	4.10	2.90	3.00	1.50	4.50	-	3.50		3.50
2024	5.78	2.50	1.00	1.50	1.00	2.50	-	1.50		1.00

* Soil paste ** Soil: water (1: 2.5)

Plant Vegetative Measures, Analysis, Yield and Yield Components:

Ten plants were randomly selected from each sub-sub plot at harvesting to determine vegetative growth such as Plant heights (PH), head diameter (HD), stem diameter (SD) were measured. Yield and yield components included seed yield (SY), straw yield (SY) and biological yield (BY) were determined for plants harvested from the middle two lines for each experimental plot. The harvest index (HI) was calculated as the ratio of seed yield to biological yield. The preparation of plant samples followed the method described by Chapman and Pratt (1961) to evaluate the yield quality of sunflower verities and nutrient uptake under different treatments. Total nitrogen was determined using the method outlined by Bremner and Mulvaney (1982), Protein content (%) was subsequently calculated by multiplying TN % by 5.75. Oil content (%) was determined by Soxhlet apparatus using hexane as a solvent according to AOAC (1990). Whereas oil and protein yield (kg fed^{-1}) were considered by multiplying the Oil content %, Protein content %, respectively, by seed yield (SY) (kg fed^{-1}). Total phosphorus was determined using the colorimetric method described by Jackson (1973), while total potassium was measured using a flame photometer (**Page *et al.*,** 1982). Additionally, NPK uptake for seed and biological yield, as well as total NPK uptake, were calculated.

Statistical analysis:

The obtained data were statistically analyzed according to the method described by **Snedecor and** Cochrom (1980). Following the least significant difference test (LSD), we analyzed the combination for the two growing seasons and achieving an average data (L.S.D) of 5%.

RESULTS AND DISCUSSION

Vegetative characters

Plant height, Head and Stem diameter (cm)

The growth traits of Sunflower plant (Table 3) clearly demonstrate the positive effects of increasing rates of magnesium sulfate ($MgSO_4$) fertilizer (*FerR*), variety selection (*Var*), and row spacing (*RowS*) on plant height (PH), head diameter (HD), and stem diameter (SD). Although row spacing had a significant impact on plant height, the results were statistically insignificant.

Table 3. Plant height, Head and Stem diameter (cm) as affected by different RowS, sunflower Var. and Mg/S FerR and their interaction

		PH	*HD*	*SD*			*PH*	*HD*	*SD*
60		161.92	17.15	2.90	*Shaka 53*		165.09	17.66	2.66
					Giza 102		159.64	16.75	3.14
70		167.05	17.75	2.90	*Giza 120*		168.73	17.94	2.90
RowD LSD 0.05		*26.44*	*1.89*	*ns*	*Var LSD 0.05*		*4.53*	*0.78*	*0.14*
RowS1	*Shaka 53*	162.93	16.72	2.75	*0*		128.31	9.19	2.33
RowS1	*Giza 102*	155.94	16.73	2.68					
RowS1	*Giza 120*	166.90	18.00	3.28	*25*		160.13	17.21	2.74
RowS2	*Shaka 53*	167.25	18.61	2.57	*35*		177.12	20.73	3.40
RowS2	*Giza 102*	163.34	16.77	3.60	*65*		192.38	22.66	3.12
RowS2	*Giza 120*	170.56	17.89	2.53					
LSD 0.05		*4.41*	*0.76*	*0.14*	*FerR LSD 0.05*		*4.51*	*1.21*	*0.54*
RowS1	0	131.02	9.54	2.36	*Shaka 53*	*0*	127.88	8.79	2.12
					Shaka 53	*25*	160.85	18.34	2.48
RowS1	25	155.68	16.25	2.56	*Shaka 53*	*35*	179.2	20.78	3.06
RowS1	35	173.44	20.22	3.4	*Shaka 53*	*65*	192.43	22.75	2.98
RowS1	65	187.56	22.58	3.28	*Giza 102*	*0*	125.91	8.85	2.59
					Giza 102	*25*	158.06	16.59	3.02
RowS2	0	125.61	8.85	2.31	*Giza 102*	*35*	171.37	20.12	3.56
					Giza 102	*65*	183.22	21.43	3.38
RowS2	25	164.58	18.18	2.92	*Giza 120*	*0*	131.16	9.93	2.3
RowS2	35	180.80	21.25	3.30	*Giza 120*	*25*	161.47	16.71	2.72
RowS2	65	197.20	22.75	2.97	*Giza 120*	*35*	180.79	21.31	3.58
					Giza 120	*65*	201.50	23.81	3.01
*RowD*FerR*		*6.46*	*2.01*	*ns*	*Var*FerR LSD 0.05*		*4.97*	*ns*	*ns*
*RowS*Var*FerR*		*9.94*	*ns*	*ns*					

Plant height increased progressively with higher *FerR* rates, with Giza 120 *Var*. reaching the tallest heights of 201.50 cm at the maximum application *FerR* of 65 Mg/S fed^{-1}. Shaka 53 and Giza 102 varieties were slightly shorter but also benefited from the increased fertilizer. This indicates natural genetic diversity among varieties in their response to vertical growth.

In terms of head diameter, Giza 120 recorded the largest size at 17.95 cm, followed closely by Shaka 53 at 17.65 cm, while Giza 102 had the smallest head diameter at 16.75 cm. The similar trend was observed for HD, where it increased with higher *FerR*. Giza 120 and Shaka 53 produced larger heads, especially under $RowS_2$, where Shaka 53 reached its peak head size of 23.12 cm (area 419.6 cm^2).

Stem diameter also showed a positive correlation with fertilizer application rates, particularly in Giza 102, which achieved the maximum stem thickness at the highest *FerR* (65 kg fed^{-1}). Giza 120 *Var* produced the widest stems at 60 cm *RowS*, although this was not the case at 70 cm spacing. Overall, narrower $RowS_1$ slightly favored stem thickness, while PH and HD showed minor benefits or were comparable at $RowS_2$.

These results emphasize that the application of Mg/S, the choice of variety, and planting density all play crucial roles in optimizing sunflower growth parameters. The data suggest that wider *RowS* reduces competition for light and nutrients, allowing plants to grow taller.

The interaction among *RowS*, *Var*, and *FerR* significantly influenced plant height (Fig. 1). However, the complex interactions among these factors also significantly impacted both head and stem diameter. The combined effects of these factors varied considerably with different treatment combinations. The Giza 120 *Var* consistently produced the tallest plants, and its strongest response to fertilizer was observed at the 70 cm spacing, indicating its superior nutrient use efficiency under wider spacing.

Stem diameter responses were more specific to each variety under particular fertilizer and spacing combinations. The statistical analysis showed that *SD* was influenced by *Var*, *RowS*, *FerR*, and their interactions. Giza 102 demonstrated the most significant increase in stem thickness in response to higher fertilizer levels, regardless of spacing. Conversely, Giza 120 showed a relatively lower response at wider spacing. These findings suggest that the most effective management practices for promoting stem thickness—specifically the use of wider spacing ($RowS_2$) and higher fertilizer rates (35–65 kg $MgSO_4$)—are particularly beneficial for the Giza 102 variety. Conversely, Shaka 53 developed a poor stem structure under all treatments, suggesting its unsuitability for optimizing stem growth. These findings emphasize the requirement for genotype-specific agronomic management to optimize stem development and potentially biomass yield.

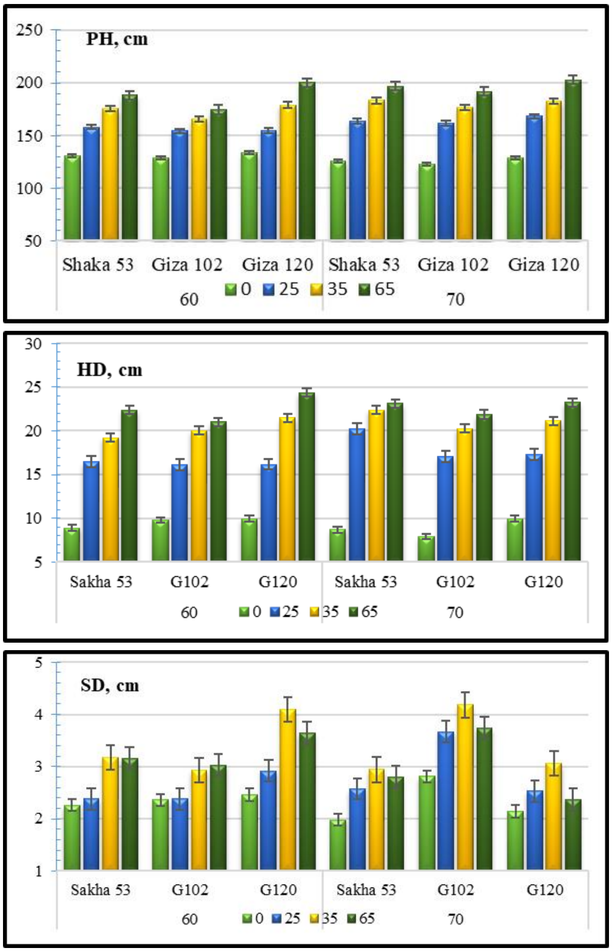

Fig. 1. Plant height, Head and Stem diameter (cm) as affected by the interaction among RowS, Sunflower Var and Mg/S FerR., respectively

These interactions suggest that single management factor is not sufficient implementation to obtain optimal sunflower growth. Instead, it is essential to integrate considerations of variety characteristics, planting density, and precise fertilizer application to effectively maximize plant vigor and yield components. This finding aligns with the results of Ibrahim et al. (2024).

Many factors play an important role in determining plant height. These factors include environmental conditions such as light, water, and temperature, along with internal influences like genetics and plant growth hormones. Plant height (PH) is a key characteristic of the ideal plant type, impacting biomass production, yield, resistance to lodging, and suitability for mechanized harvesting. However, because many of the complex processes governing plant growth and development are still not fully understood, breeding alone has yet to produce the most optimal plants. PH is affected by genotype, hormonal regulation within the plant, environmental factors, and interactions with neighboring plants (Miao et al., 2024).

Yield and Yield Components

100- Seed wt. (g)

Results in Table 4 indicate that *RowS*, *Var* and Mg/S *FerR* and have a significant impact on 100-seed weight. Giza 120 consistently yields the highest 100-seed weight (7.42 g). The application of fertilizer demonstrates a significant main effect: increasing *FerR* from 0 to 65 kg per fed consistently boosts the 100-seed weight.

The combination treatment, $RowS_1$, weight of 100-seed for Giza 120 rises from 5.17 g at zero fertilizer to 9.38 g at 65 kg fed^{-1}. Meanwhile, in $RowS_2$, it increases from 5.33 g to 9.97 g (Fig. 2). Similarly, Shaka 53 and Giza 102 varieties also exhibited notable increases with fertilizer application; however, Giza 120 was superior in 100-seed weight across all levels of *FerR*. The combination between $RowS_2$ × G120 × 65 Mg/S yields the highest 100-seed weight (9.97 g) confirming it as the optimal combination for this parameter.

Table 4. Some Yield parameters as affected by different RowS, Var and Mg/S FerR and their interaction

Treatments		100-Seed wt.	Seed Y pl^{-1}	Seed Y	HI
		g		Mg fed^{-1}	%
RowS	$RowS_1$	6.98	49.99	1.43	30.23
	$RowS_2$	7.42	52.29	1.31	30.60
L.S.D 0.05		0.200	2.14	0.041	ns
Var.	Sakha 53	7.16	50.98	1.35	30.74
	Giza 102	7.03	47.06	1.30	30.54
	Giza 120	7.42	55.37	1.45	29.98
L.S.D 0.05		0.15	1.40	0.039	ns
FerR	0	4.93	29.11	0.89	31.95
	25	6.38	42.03	1.27	31.36
	35	8.01	58.24	1.58	30.85
	65	9.48	75.18	1.72	27.52
L.S.D 0.05		0.14	1.35	0.034	1.21
$RowS_1$	Sakha 53	6.94	49.86	1.37	30.52
	Giza 102	6.78	45.89	1.39	30.93
	Giza 120	7.21	54.22	1.52	29.25
$RowS_2$	Sakha 53	7.37	52.11	1.34	30.96
	Giza 102	7.28	48.25	1.20	30.16
	Giza 120	7.62	56.53	1.38	30.7
Rows* Var		ns	ns	0.043	1.18
$RowS_1$	0	4.97	28.85	1.00	33.5
	25	6.00	40.18	1.36	31.58
	35	7.69	56.66	1.60	29.31
	65	9.24	74.25	1.74	26.55
$RowS_2$	0	4.89	29.37	0.79	30.39
	25	6.75	43.88	1.18	31.13
	35	8.33	59.81	1.56	32.39
	65	9.72	76.11	1.70	28.50
L.S.D 0.05		0.15	ns	0.048	1.71
Sakha 53	0	4.88	28.66	0.89	31.9
	25	6.40	42.77	1.30	32.36
	35	7.94	58.33	1.53	30.86
	65	9.41	74.16	1.70	27.82
Giza 102	0	4.66	26.88	0.84	33.63
	25	6.21	37.77	1.15	30.64
	35	7.89	51.38	1.55	30.75
	65	9.36	72.22	1.65	27.16
Giza 120	0	5.25	31.77	0.96	30.31
	25	6.53	45.55	1.36	31.06
	35	8.21	65.00	1.65	30.95
	65	9.68	79.16	1.81	27.59
L.S.D 0.05		ns	2.35	0.059	ns
RowS*Var*FerS		0.26	ns	0.084	ns

These findings suggest that cultivar-dependent adjustments in fertilizer application and row spacing can effectively optimize sunflower seed yield through enhanced seed weight (Ayenew et al. 2024). Moreover, higher applications of Mg/S fertilizer significantly promote larger seed size, and the selection of the right variety further amplifies this effect, with Giza 120 exhibiting the greatest gains in seed weight. This highlights the importance of appropriate magnesium sulfate fertilization in conjunction with selecting high-performing sunflower varieties to maximize seed quality and yield potential. These findings are in agreement with those of Kandil *et al* (2017), who found that 1000-achene weight (g) and achene yield (kg ha^{-1}) differed significantly between sunflower varieties.

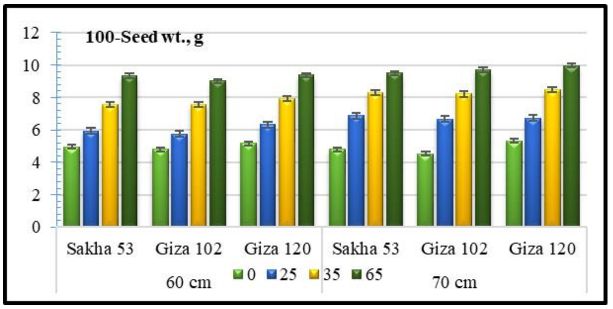

Fig. 2. 100-Seed wt., (g) as affected by the interaction among different RowS, Var and Mg/S FerR

Seed Yield plant^{-1}, g

Data presented in Table 4, and Fig. 3 indicate that seed yield per plant is significantly influenced by *RowS*, *Var*, and *FerR* independently, but not by their interactions. The narrower *RowS*$_1$ generally resulted in slightly lower yields compared to *RowS*$_2$, although the differences were minimal. Among the varieties, Giza 120 produced the highest seed yield per plant (55.37 g), and at $RowS_2$ with *FerR* with 65 kg fed^{-1}, it achieved an impressive yield of 79.44 g. This was followed by Shaka 53 and Giza 102.

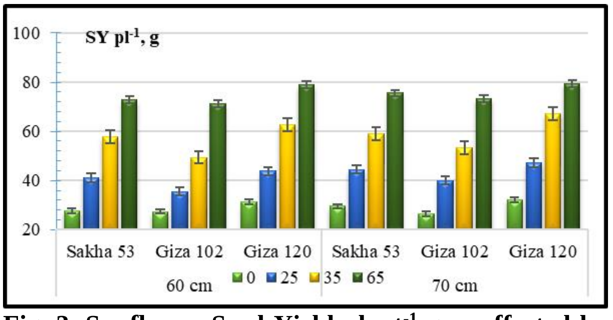

Fig. 3. Sunflower Seed Yield plant^{-1} g as affected by the interaction among different RowS, Var and Mg/S FerR

Seed yields consistently increased with higher fertilizer rates across all varieties and row spacings, with the highest yields observed at the greatest *FerR*. Overall, these results emphasize the importance of applying suitable Mg/S fertilizer levels and selecting high-yielding varieties like Giza 120, noting that while row spacing has a lesser, though still noticeable, impact on seed yield per plant in sunflower cultivation.

Seed Yield, Mg fed^{-1}

Sunflower seed yield (Mg fed^{-1}) results Table 4 and Fig. 4 indicated that *RowS*, *Var*, and *FerR* application contributed significantly to yield. Among the two *RowS*, the narrower spacing generally led to slightly higher yields compared to the wider spacing. Yield showed a positive response to fertilizer application, with increases from 0 to 65 kg fed^{-1}, resulting in a relative increase 92.30 %. Interaction effects revealed that Giza 120 consistently showing the highest seed yield at all fertilizer levels, reaching up to 1.82 Mg fed^{-1} at 65 kg *FerR* under *RowS*$_1$. Sakha 53 and Giza 102 exhibited somewhat lower yields but followed the same increasing trend with fertilizer.

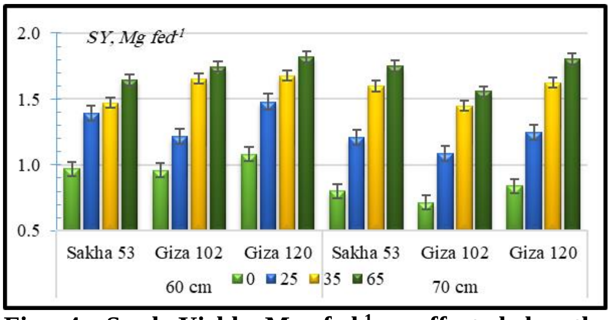

Fig. 4. Seed Yield, Mg fed^{-1}as affected by the interaction among different RowS, Var and Mg/S FerR

Interaction effects indicated that the Giza 120 variety consistently produced the highest seed yield at all fertilizer levels, reaching up to 1.82 Mg per fed at 65 kg of FerR under the narrow row spacing ($RowS_1$). The varieties Sakha 53 and Giza 102 exhibited somewhat lower yields but followed a similar increasing trend in response to fertilizer application.

The three-way interaction among row spacing, variety, and fertilizer confirms that the combined management of these factors is crucial for optimizing sunflower seed yield. The highest yield of 1.82 Mg per fed resulted from the interaction of Giza 120 at RowS1 with the highest fertilizer application, leading to a relative increase of 68.29%.

Overall, the findings emphasize that optimizing the Mg/S fertilizer application rate, selecting high-yield varieties like Giza 120, and managing planting density effectively can significantly enhance sunflower seed production. These results are consistent with the findings of Kandil et al. (2017).

The significant response of Giza 120 *Var*. to fertilization suggests its superior nutrient use efficiency, making it a promising candidate for enhancing sunflower yields (Maklad. 2023).

Harvest Index, %

The results presented in Table 4 and Fig. 5 indicate that both *RowS*$_1$ and *RowS*$_2$ had similar mean harvest index (HI) levels, with *RowS*$_1$ showing a slight increase. This suggests that narrower spacing may enhance the efficiency of assimilate partitioning. Among the studied varieties, Giza 102 exhibited the highest HI, followed by Sakha 53, while Giza 120 consistently had the lowest HI. This highlights the superiority of Giza 102 in effectively converting biomass into yield.

As fertilizer levels exceeded 25 kg per fed, HI declined progressively, demonstrating that moderate or no fertilizer promotes enhanced partitioning, whereas excessive fertilizer favors vegetative growth over reproductive development. The interaction between *RowS* and *Var* interaction further confirmed Giza 102's reliability in performance across both spacings, while Giza120 remained consistently low. The interaction between *RowS*$_1$ × Fertilizer interaction revealed that HI decreased with increasing fertilizer application. Giza102 maintained high HI at fertilizer levels between 0 and 25 kg fed^{-1}. Similar trends were observed when examining the interaction of *RowS*$_2$ × *FerR*.

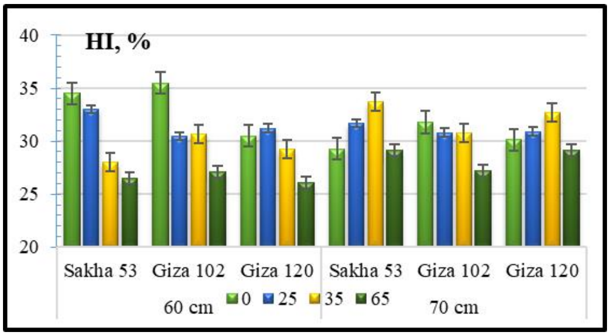

Fig. 5. Harvest index, % as affected by the interaction among different RowS, Var and Mg/S FerR

The interaction between variety and fertilizer indicated that Giza102 achieved a high HI at low fertilizer, while all varieties experienced reduced performance at a fertilizer level of 65 kg fed^{-1}. In three-way interactions, Giza 102 performed best under *RowS*$_1$ with 0–25 kg fed^{-1}, whereas Giza120 recorded the lowest HI across all cases. Under *RowS*$_2$ with 65 kg fed^{-1} of fertilizer, there was a significant reduction in HI across all varieties.

Giza 102, grown under *RowS*$_1$ with low fertilizer application, provides the best conditions for maximizing HI. However, Giza120 consistently performed below the optimum, highlighting the need for optimizing the interaction between genotype and management practices in sunflower cultivation (Ibrahim, 2023). These findings align with El-Dissoky *et al* (2017), who found that higher $MgSO_4$ levels increased maize grain yields. The improvement in achene yield may be attributed to the ability of magnesium sulfate fertilizer capacity to enhance magnesium availability for plant growth at adequate levels or to its positive effect on soil microorganisms (Fajemilehin *et al.*, 2008).

Additionally, Abd EL-Satar et al. (2017) found that significant differences in yield and related parameters among sunflower cultivars. Sakha 53 exhibited the highest HI and the heaviest weights for 100 seeds, seeds per plant, and per feddan, while Giza 102 recorded the lowest values for these traits. The discrepancies in these characteristics could be due to variations in the genetic composition of the sunflower cultivars. Similar results have been reported by Ibrahim (2012), Ali et al. (2014), and Nasim et al. (2017).

A deficiency in sulfur fertilizer can reduce crop yields by decreasing both the number of seeds per plant and the weight of each individual seed (Hocking et al., 1987). Nasreen and Huq (2002) found that sunflower seed yields increased with the application of sulfur fertilizer, but only up to a certain limit. Aslam et al. (2018) noted that maize yield was significantly affected by various yield characteristics, including cob weight without sheath, the number of grains per cob, biological yield, 1000-grain weight, grain yield, and harvest index, particularly with increasing levels of $MgSO_4$ fertilizer.

These results highlight the essential role of magnesium in plant growth. Magnesium acts as a cofactor for enzymes that play a crucial role in phosphorylation processes. Furthermore, it serves as a connector between the pyrophosphate structures of ATP or ADP, DNA, RNA, and enzyme molecules. Additionally, magnesium is necessary for the synthesis of amino acids and fats (Mengel and Kirkby, 2001).

Quality traits:

A combination of seed composition, oil properties, and processing appropriateness determines sunflower quality.

Seed and Biological nutrient uptake, kg fed^{-1}

Data provided tin Table (7) and Fig (2,3) comprehensively details the effects of *RowS*, *Var* and Mg/S *FerR* (0, 25, 35, 65 kg fed^{-1}) on both seed and biological yield nutrient uptake. Sunflower N uptake is influenced by numerous factors, including nutrient management, fertilizer application, and environmental conditions. Also, P uptake is a critical aspect of its nutrient management, influencing growth, yield, and oil quality. Likewise, K is essential for sunflower growth, influencing water regulation, enzyme activation, disease resistance, and oil quality.

Table 7. Seed and Biological N, P and K uptake, kg fed^{-1} as affected by different RowS, Cul and Mg/S FerR and their interaction

		Seed NPK uptake			Biological NPK uptake		
		N uptake	**P uptake**	**K uptake**	**N uptake**	**P uptake**	**K uptake**
60		0.429	0.029	0.111	0.830	0.248	1.121
70		0.387	0.024	0.093	0.700	0.220	1.159
LSD 0.05 RowS		*0.017*	*ns*	*0.006*	*0.038*	*ns*	*0.029*
Shaka 53		0.390	0.034	0.106	0.790	0.216	1.170
Giza 102		0.397	0.021	0.096	0.740	0.210	1.090
Giza 120		0.437	0.023	0.104	0.766	0.276	1.160
LSD 0.05 Var		*0.018*	*0.004*	*0.005*	*ns*	*0.029*	*ns*
0		0.233	0.016	0.060	0.387	0.109	0.409
25		0.390	0.025	0.093	0.648	0.207	0.871
35		0.489	0.033	0.123	0.917	0.281	1.408
65		0.521	0.031	0.133	1.110	0.340	1.872
LSD 0.05 FerR		*0.018*	*0.005*	*0.012*	*0.076*	*0.022*	*0.122*
RowS1	*Sakha 53*	0.406	0.036	0.114	0.854	0.225	1.087
	Giza 102	0.432	0.020	0.103	0.801	0.213	1.078
	Giza 120	0.450	0.029	0.116	0.835	0.307	1.199
RowS2	*Shaka 53*	0.375	0.032	0.098	0.726	0.207	1.252
	Giza 102	0.363	0.023	0.090	0.678	0.208	1.131
	Giza 120	0.424	0.017	0.092	0.697	0.246	1.093
LSD 0.05		*0.022*	*0.006*	*0.015*	*0.093*	*0.027*	*0.149*
RowS1	0	0.266	0.018	0.070	0.411	0.110	0.284
	25	0.438	0.030	0.106	0.720	0.223	0.753
	35	0.494	0.037	0.134	0.934	0.294	1.495
	65	0.519	0.029	0.134	1.254	0.366	1.954
RowS2	0	0.201	0.013	0.050	0.362	0.107	0.533
	25	0.342	0.021	0.080	0.575	0.190	0.990
	35	0.483	0.029	0.112	0.899	0.268	1.322
	65	0.523	0.033	0.132	0.965	0.315	1.790
*RowD*FerR*		*0.025*	*0.007*	*0.017*	*0.107*	*0.031*	*0.172*
Shaka 53	0	0.221	0.023	0.065	0.377	0.072	0.385
	25	0.385	0.034	0.103	0.660	0.197	0.983
	35	0.487	0.042	0.124	0.996	0.266	1.323
	65	0.469	0.037	0.133	1.126	0.329	1.988
Giza 102	0	0.219	0.011	0.055	0.348	0.082	0.374
	25	0.345	0.020	0.079	0.607	0.161	0.799
	35	0.476	0.028	0.125	0.889	0.274	1.349
	65	0.549	0.027	0.126	1.114	0.322	1.838
Giza 120	0	0.260	0.013	0.060	0.435	0.172	0.467
	25	0.440	0.022	0.097	0.675	0.261	1.553
	35	0.503	0.028	0.120	0.864	0.302	1.790
	65	0.545	0.029	0.140	1.090	0.370	0.832
*LSD 0.05 Var*FerR*		*0.031*	*0.009*	*0.021*	*0.131*	*0.038*	*0.211*
*RowD*Var*FerR*		*0.044*	*0.012*	*0.029*	*0.185*	*0.054*	*0.299*

Seed N, P and K uptake increases noticeably with higher *FerR*, reaching its peak at 65 kg fed^{-1} across all *Var* and *RowS*, except for P, K at narrow *RowS* the peak was at 35 kg fed^{-1}. Giza 120 showed the highest seed N uptake, 54.53 kg fed^{-1} at 65 kg fertilizer rate, and in both 60 cm and 70 cm *RowS* (51.92, 52.31 kg fed^{-1}), respectively. Phosphorus uptake in seeds generally increased with fertilizer rates, though in some cases, such as Shaka 53 at 60 cm spacing, it declined slightly at the highest fertilizer level. Potassium seed uptake peaks was 14.01 kg fed^{-1} in Giza 120 at 65 kg fed^{-1} *FerR*. The narrower 60 cm row spacing tended to favor higher N and K uptake in seeds compared to the 70 cm spacing. Varietal differences were also evident, as Giza 120 and Shaka 53 generally outperformed Giza 102 in seed nutrient accumulation. Generally, the results pointed that the need to selecting high-performing varieties, optimizing $MgSO_4$ fertilizer application and row spacing to maximize nutrient content in sunflower seeds and potentially improve crop productivity.

Biological nutrient uptake, which reflects the total plant biomass including seeds and vegetative parts, the data indicate significant increases in N, P and K uptake with rising *FerR* across all varieties and both row spacings. Nitrogen uptake by the whole plant biological yield nearly tripled from the lowest treatment to the highest 65 kg fed^{-1} *FerR*, with Shaka 53 at 60 cm spacing reaching over 125 kg fed^{-1}. Phosphorus uptake also showed strong increases with fertilizer, particularly in Giza 120 under the 60 cm row spacing where it peaked at 37.02 kg fed^{-1}. Potassium uptake demonstrated the most pronounced response, increasing to as high as nearly 199 kg fed^{-1} in Shaka 53 at 60 cm spacing and 65 kg fed^{-1} fertilizer rate, reflecting high biomass accumulation and nutrient absorption capacity. Interestingly, while narrower row spacing generally enhanced nitrogen and phosphorus uptake, the wider spacing sometimes recorded higher potassium uptake in biological yield, suggesting differing nutrient partitioning or uptake dynamics. These findings collectively support that careful adjustment of cultivation practices tailored to specific varieties can maximize both seed and total plant nutrient use efficiency.

Significant interaction effects among RowS, Var and FerR emphasize that integrated management decisions are critical for optimizing nutrient uptake and overall biomass production in sunflower cultivation. Nitrogen uptake, N plays a dual role in sunflower oil production, enhancements seed yield (more oil yield) and influences oil synthesis (fatty acid metabolism). However, the relationship is non-linear—excess N can reduce oil% % while increasing protein.

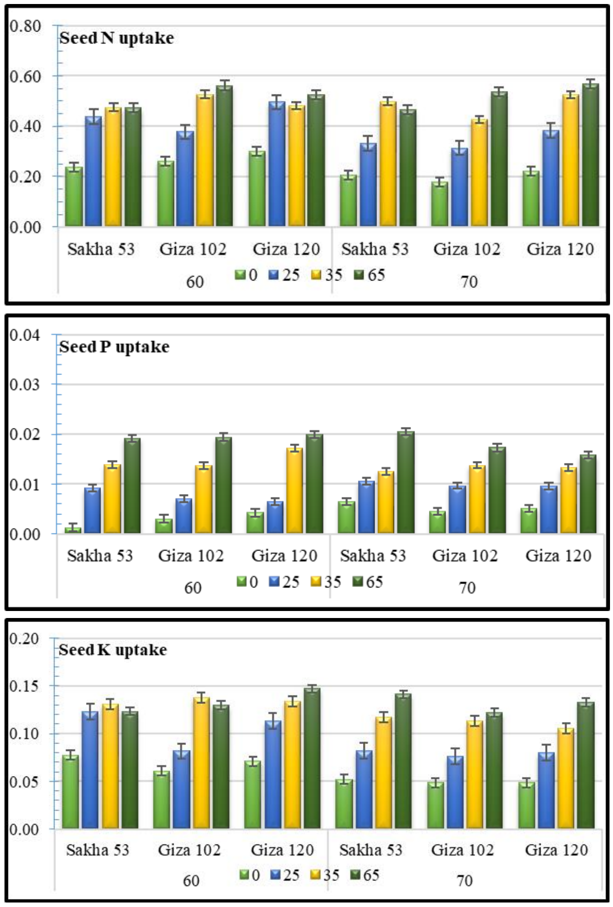

Fig. 2. Seed N, P and K uptake as affected by the interaction among RowS, Var and Mg/S FerR

There is a clear positive response to increasing *FerR* for all varieties and row spacings. Giza 102 shows a marked increase in seed N uptake from 26.16 kg fed^{-1} at zero *FerR* to 56.22 kg fed^{-1} at 65 kg fed^{-1} under $RowS_1$. Similarly, at $RowS_2$, Giza 120 increases from 22.02 to 56.76 kg fed^{-1}, indicating that higher *FerR* consistently improves seed N content regardless of spacing or variety. ***Phosphorus uptake*** displays more variable trends; it tends to increase with fertilizer rates but sometimes declines at the highest rates, notably in Shaka 53 at 60 cm (dropping back to 2.62 kg fed^{-1} at 65 kg fed^{-1}), while $RowS_2$, P uptake steadily rises with fertilizer for the same variety, reaching 4.81 kg fed^{-1}. ***Potassium uptake*** in seeds also generally rises with *FerR*, but the magnitude and pattern of response vary by variety and spacing. Giza 120 achieves the highest seed K uptake of 14.72 kg fed^{-1} at 65 kg fed^{-1} fertilizer rate under 60 cm spacing, while Shaka 53 reaches 14.15 kg fed^{-1} at wider *RowS* with the same *FerR*. Overall, these interactions highlight that optimizing *FerR*, selecting suitable varieties, and adjusting row spacing are all critical to maximizing nutrient uptake in sunflower seeds, with fertilizer application playing a dominant role in enhancing N and K uptake.

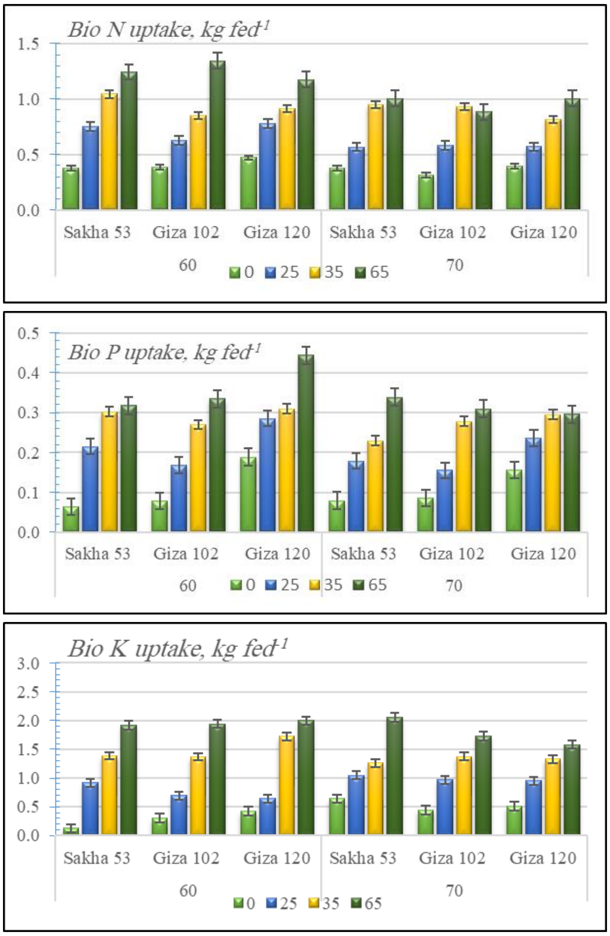

Fig. 3. Biological N, P and K uptake as affected by the interaction among RowS, Var. and Mg/S FerR

Sunflower biological yield nutrient uptake data reveal that N, P and K absorption by the whole plant significantly increase with higher $MgSO_4$ *FerR* across all varieties and *RowS*. Narrower *RowS* generally enhances nitrogen and phosphorus uptake, with Shaka 53 and Giza 102 showing peak N uptake above 120 kg fed^{-1} at 65 kg fertilizer, while phosphorus uptake peaks notably in Giza 120 at around 44 kg fed^{-1}. Potassium uptake demonstrates the most substantial increases, reaching nearly 200 kg fed^{-1} in Giza 120 at $RowS_1$ and 65 kg *FerR*, highlighting the high nutrient demand and biomass accumulation capacity of sunflower plants. At the wider 70 cm spacing, potassium uptake remains elevated in some varieties but nitrogen and phosphorus uptake tends to be lower. These findings emphasize the importance of integrated management of fertilizer application, variety selection, and row spacing to optimize nutrient use efficiency and maximize biomass production in sunflower cultivation.

Overall, the data underscores the importance of integrated crop management practices—optimizing row spacing, selecting appropriate varieties, and applying adequate fertilizer rates—to maximize nutrient uptake efficiency and improve crop productivity. The results align with known factors affecting potassium availability and uptake, such as soil moisture, root system efficiency, and fertilizer management, which collectively influence crop potassium nutrition and yield potential

Studies show that increasing fertilizer rates of N, P and K generally enhances their uptake by crops, thereby improving biomass production and yield. Molecular mechanisms involving specific ion transporters and their regulation by protein phosphorylation further modulate nutrient uptake capacity under varying environmental and nutritional conditions. Overall, improving biological NPK uptake through integrated management of fertilization, crop selection, and planting configuration is essential for sustainable crop production and nutrient use efficiency (Chen *et al*, 2008)

Oil percentage

Sunflower oil content (%) is a critical quality parameter influenced by genetics, environment, and agronomic practices. Oil content (%) is influenced by the interaction of *RowS*, *Var* and Mg/S *FerR*, though the effects of *RowS* or *Var* were insignificant, however Giza 120 has the highest oil content (33.57%). Oil percentage shows increase as *FerR* rose by relative increase (35.56 %) compared to control (0 Fertilizer). The interaction between Giza 102 and the highest *FerR* showed the highest oil percentage (39.05%), followed by Giza 120 and Shaka 53. *RowS* effects were minor but tended to favor 70 cm spacing, which slightly improved oil content for Shaka 53 and Giza 102. The interaction effects were significant, indicating that while *RowS* is the primary driver of oil percentage, fine-tuning cultivar and spacing combinations can further optimize oil content. *These results highlight* the importance of $MgSO_4$ fertilization in enhancing seed oil concentration, with cultivar-specific responses modulated by planting density.

Interactions among RowS, Var and FerR significant meaningfully influence sunflower oil concentration. Giza 102 exhibited fairly stable oil content around 30-31%, while Shaka 53 and Giza 120 showed more fluctuation depending on row spacing and fertilizer. The interaction among Giza 102 at the highest FerR under the narrow RowS has the highest oil concentration (40.44 %), while the control has the lowest mean value (27.64%). This means that the response of oil content to fertilizer application depends on both the variety planted and the row spacing used. Therefore, optimizing oil content in sunflower requires an integrated approach considering all three parameters simultaneously, rather than managing each factor independently.

Table 8. Seed Oil, % as affected by different RowS, Var and Mg/S FerR and their interaction

		0	*25*	*35*	*65*	*RowS*
*$RowS_1$*FerR*		25.93	30.43	33.77	37.53	31.91
*$RowS_2$*FerR*		29.54	32.74	34.63	37.65	33.64
FerR		27.73	31.58	34.2	37.59	*Var*
*Var*FerR*	*Sakha 53*	27.29	30.99	33.17	36.94	32.10
	Giza 102	26.21	30.75	34.65	39.05	32.66
	Giza 120	29.70	33.02	34.78	36.78	33.57
$RowS_1$	*Sakha 53*	30.19	*Giza 102*	33.91	*Giza 120*	31.64
$RowS_2$		34.00		33.71		33.21
L.S.D 0.05	*RowS*	*ns*	*Var*	*ns*	*FerR*	*0.62*
RowS Var*		*ns*		*Var* FerR*		*1.08*
RowS FerR*		*0.88*		*RowS*Var* FerR*		*1.53*

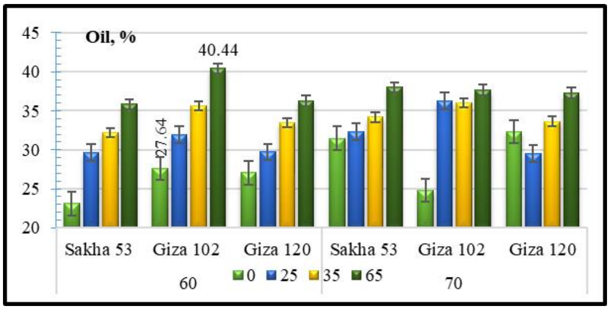

Fig. 4. Oil content %, as affected by the interaction among different RowS, Var and Mg/S FerR

Oil Yield, Kg fed^{-1}

Data in Table 9 reveal the effects of *RowS*, sunflower *Var,* and Mg/S *FerR* on oil yield (kg fed^{-1}), including their interactions. Although *RowS* alone is not statistically significant for oil yield, the variety effect is significant, with Giza 120 generally producing the highest oil yield (492.24 kg fed^{-1}). Oil yield increases consistently with higher *FerR* across all varieties and both *RowS*. Giza 102 at *$RowS_1$* shows an increase from 265.19 kg fed^{-1} at zero fertilizer to 706.57 kg fed^{-1} at 65 kg fed^{-1}, while Shaka 53 at *$RowS_2$* increases from 252.55 to 665.27 kg fed^{-1} over the same fertilization range. Giza 120 performs strongly as well, with peak values around 666.00 kg fed^{-1} at 60 cm and 671.46 kg fed^{-1} at *$RowS_2$* under the highest fertilizer treatment.

Importantly, all interaction terms— *RowS* by *Var*, *Var* by *FerR*, *RowS* by *FerR*, and the three-way interaction among *RowS*, *Var* and *FerR* —are statistically significant, indicating that the response of oil yield to fertilizer application depends on specific combinations of variety and planting density. Under 60 cm spacing, Shaka 53 has greater gains with fertilizer increase compared to its performance at 70 cm spacing, and Giza 102 shows more variability between spacings. The interaction among trible tested treatment reviled that the highest oil yield (706.57 kg fed^{-1}) obtained by Giza 102 under the narrow *RowS* with the highest *FerR*. These significant interaction effects underscore the necessity of integrating fertilizer management with selecting suitable variety and optimized row spacing to maximize sunflower oil yield. Generally, the data support that tailored agronomic practices considering these factors synergistically will produce the best oil yield outcomes.

Table 9. Oil Yield, kg fed^{-1} as affected by different RowS, Var and Mg/S FerR and their interaction

		0	*25*	*35*	*65*	*RowS*
*$RowS_1$*FerR*		261.11	413.47	541.67	652.65	467.23
*$RowS_2$*FerR*		234.20	388.69	539.85	641.08	450.95
FerR		247.66	401.08	540.76	646.86	*Var*
*Var*FerR*	*Sakha 53*	239.01	401.25	509.43	628.06	444.44
	Giza 102	221.59	355.40	538.88	646.54	440.60
	Giza 120	282.37	446.60	573.98	666.00	492.24
$RowS_1$	*Sakha 53*	425.43	*Giza 102*	487.48	*Giza 120*	488.77
$RowS_2$		463.45		393.72		495.79
LSD 0.05	*RowS*	ns	*Var*	22.72	*FerR*	15.05
*RowS*Var*		18.44	*Var*FerR*		26.08	
*RowS*FerR*		21.29	*RowS*Var*FerR*		36.88	

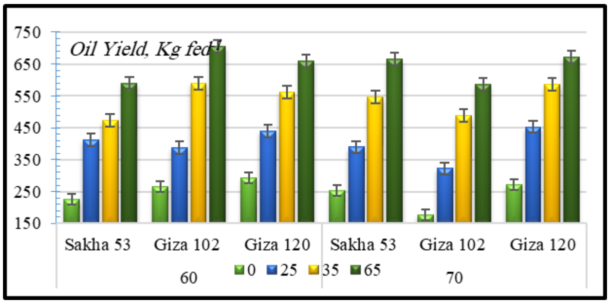

Fig. 5. Oil Yield, Kg fed^{-1} as affected by the interaction among different RowS, Var and Mg/S FerR

Seed Protein percentage

Seed protein %, as affected by *RowS*, sunflower *Var*, and *FerR*, are presented in Table (11). The data show that seed quality characteristics for sunflower varieties differed significantly due to treatment application and their interaction. Narrow *RowS$_1$* significantly increases protein content, with a relative increase by 44.00%. Sakha 95 has the lowest protein content. Protein content peaked at 35 kg fed^{-1} *FerR* (17.79%) overall but declined slightly at 65 kg fed^{-1} (17.45%). Narrower *RowS$_1$* generally enhanced protein levels for Shaka 53 and Giza 120, while Giza 102 uniquely thrived at 70 cm with high *FerR*, except for Giza 102, which increased by 6.5% at the highest *FerR*. Giza 102 achieved the highest protein content (19.78% at 70 cm *RowS* and 65 *FerR*), outperforming Shaka 53 (highest value 18.58% at 60 cm and 35 *FerR*) and Giza 120 (peak 19.32% at 60 cm and 25 *FerR*). The three-way interaction revealed cultivar-specific optima, with Giza 102's exceptional performance at wider spacing contrasting with other varieties' preferences for narrower rows. These findings highlight the importance of aligning cultivar selection with spatial and nutrient management strategies to maximize seed protein quality.

Protein Yield, Kg fed^{-1}

Protein yield (kg fed^{-1}) is maximized through collaborative interactions among *RowS*, *Var* and $MgSO_4$ fertilization. Giza 120 achieved the highest yield (326.37 kg fed^{-1} at 70 cm *RowS* and 65 kg fed^{-1} *FerR*), outperforming Shaka 53 (286.27 kg fed^{-1} at 70 cm and 35 *FerR*) and Giza 102 (323.25 kg fed^{-1} at 60 cm and 65 *FerR*). While 60 cm row spacing generally enhanced yields for Giza 102 and Shaka 53 (+14% for Giza 102 vs. 70 cm), Giza 120 uniquely thrived at 70 cm under high *FerR*, suggesting cultivar-specific spatial optimization. Fertilizer responses varied: protein yield increased consistently with *FerR* for Giza *Var* (peaking at 65 kg fed^{-1}), whereas Shaka 53 plateaued at 35 kg fed^{-1}.

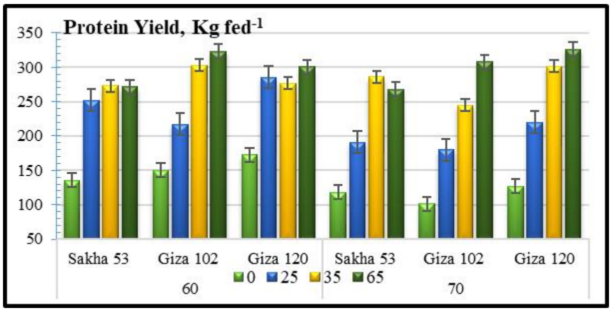

Fig. 6. Protein Yield, Kg fed^{-1} as affected by the interaction among different RowS, Var and $MgSO_4$ FerR

Table 10. Seed Protein, % as affected by different RowS, Var and Mg/S FerR and their interaction

		0	***25***	***35***	***65***	***RowS*Var***	***RowS***
60	*Sakha 53*	14.12	18.11	18.58	16.50	16.83	
	Giza 102	15.60	17.87	18.27	18.52	17.57	
	Giza 120	15.95	19.32	16.50	16.50	17.07	
*RowS$_1$*FerR*		15.22	18.43	17.79	17.17		17.15
70	*Sakha 53*	14.76	15.81	17.91	15.30	15.95	
	Giza 102	14.09	16.62	16.92	19.78	16.85	
	Giza 120	15.05	17.64	18.57	18.11	17.34	
*RowS$_2$*FerR*		14.63	16.69	17.80	17.73		16.71
FerR		14.93	17.56	17.79	17.45	*Var*	
*Var*FerR*	*Sakha 53*	14.44	16.96	18.25	15.90	16.39	
	Giza 102	14.85	17.25	17.60	19.15	17.21	
	Giza 120	15.50	18.48	17.54	17.31	17.21	
LSD 0.05	*RowS*	0.18	*Var*	0.54	*FerR*		0.74
	*RowS*Var*			0.90		*Var*FerR*	1.28
	*RowS*FerR*			1.04		*RowS*Var*FerR*	1.81

Table 11. Protein Yield, Kg fed^{-1} as affected by different RowS, Var and Mg/S FerR and their interaction

		0	25	35	65	RowS
*$RowS_1$*FerR*		152.99	251.6	284.25	298.56	246.85
*$RowS_2$*FerR*		115.49	196.94	277.62	300.76	222.70
FerR		134.24	224.27	280.94	299.66	*Var*
*Var*FerR*	*Sakha 53*	127.12	221.34	279.76	269.72	224.49
	Giza 102	125.92	198.58	273.79	315.70	228.50
	Giza 120	149.68	252.89	289.27	313.56	251.35
RowS1	*Shaka 53*	233.18	*Giza 102*	248.40	*Giza 120*	258.97
RowS2		215.78		208.59		243.72
LSD 0.05	*RowS*	9.94	*Var*	10.09	*FerR*	10.31
*RowS*Var*		12.62		*Var*FerR*		17.85
*RowS*FerR*		14.57		*RowS*Var*FerR*		25.24

The three-way interaction revealed that Giza 120 at 70 cm and 65 *FerR* delivered a 22% yield advantage over their 60 cm performance, defying the broader trend favoring narrower rows. These results emphasize the need for integrated management, balancing cultivar physiology, spatial arrangements, and nutrient thresholds to optimize protein production.

In assumption, seed protein content and protein yield in sunflower were significantly influenced by the interactive effects of row spacing, cultivar selection, and magnesium sulfate fertilization rates.

Magnesium is an essential nutrient for a wide array of fundamental physiological and biochemical processes in plants. It largely involves chlorophyll synthesis, production, transportation, and utilization of photo-assimilates enzyme activation, and protein synthesis. Using magnesium fertilizer in the soil and on leaves significantly increase the nitrogen content in the shoots and grains of rice (Zubing *et al*, 2024).

Magnesium sulfate applications in the soil or via spray did not significantly alter yield, N %, or removal. Magnesium fertilizer improved the quality and productivity of rapeseed crops (Geng *et al*, 2021) as well as soybean and pomelo crops (Grzebisz, 2013; Zhang *et al*, 2022; Lu *et al*, 2022). Magnesium insufficiency impacts photosynthesis and glucose partitioning. Magnesium is vital for plant growth and plays a role in various physiological processes. A lack of magnesium can impact photosynthesis and carbohydrate partitioning, causing decreased crop growth and yield (Zubing *et al*, 2024).

The relationship between cultivar and environment has a significant impact on both production and quality (Aboelkassem, 2021). Hocking *et al* (1987) stated that sulfur fertilizer has no effect on oil concentration in seeds.

This review supports the assumption that the interactive effects of row spacing, cultivar selection, and magnesium sulfate fertilization rates significantly influence seed protein content and protein yield in sunflower, with parallel evidence from maize seed quality studies highlighting the importance of integrated crop management for optimizing seed composition and yield.

Impact of climate change on Productivity

Data illustrated in Fig (9) and the experimental data demonstrate that sunflower seed yields achieved under optimized agronomic practices, including cultivar selection, row spacing, and magnesium sulfate fertilization, substantially exceed the government-reported mean production of 1.1 Mg fed^{-1}.

Figure (8) illustrates a clear relationship between sunflower seed productivity and the combined effects of temperature, which has undergone substantial change in air temperature and as a result, the mean yield of El-Behaira Governate. Across all treatments, seed yields ranged from approximately 1.0 to over 2.0 Mg fed^{-1}, with the highest yields observed at 65 kg $MgSO_4$ fed^{-1}, nearly doubling the government average in some cases. Even the lowest-yielding experimental treatments matched or slightly surpassed the government mean, while typical yields were 27–54% higher, and the best-performing combinations reached up to 82% above the national benchmark.

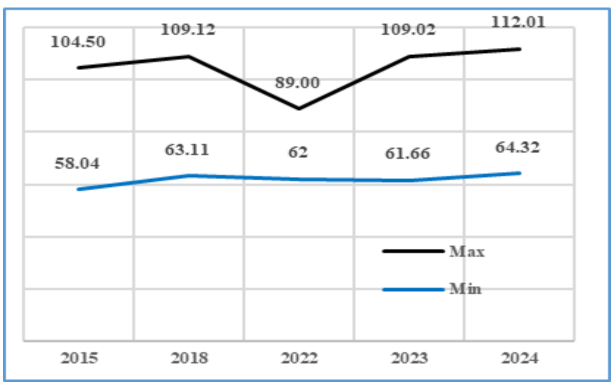

Fig. 7. Summation of max – min temp

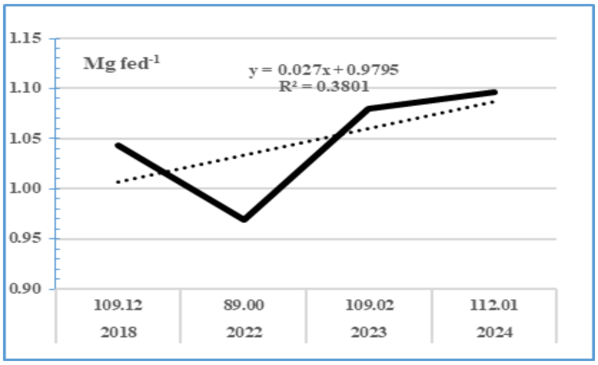

Fig. 8. Sunflower productivity in ElBahira (Mg fed^{-1})

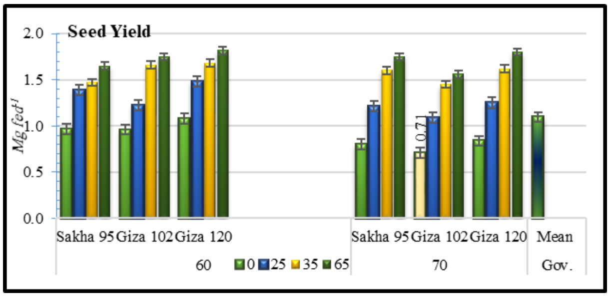

Fig. 9. SY (Mg fed^{-1}) as affected by different treatment compared with the Government productivity mean

This significant yield advantage underscores the potential for improved management practices such as narrower row spacing and higher fertilizer rates to elevate sunflower productivity well beyond current national averages.

These findings pointed the importance of adopting integrated, evidence-based agronomic strategies to maximize crop output and close the gap between actual farm yields and the attainable potential demonstrated in research trials. The integrating optimal temperature regimes with targeted fertilizer management and cultivar selection can significantly enhance sunflower yields beyond standard government benchmarks.

Soil fertility

Soil Organic Matter (g kg^{-1})

The data in Table 12 and Fig. 10 showed that SOM ranged from 0.96% to 2.10%, with notable interactions between agricultural practices. Wider *RowS*$_2$ generally resulted in lower SOM compared to *RowS*$_1$, with a relative decrease percentage of 25.56%. SOM percentage increased with higher $MgSO_4$ *FerR*, particularly under 60 cm *RowS*, where Giza 120 achieved the highest SOM (2.10%) at 65 kg fed^{-1} $MgSO_4$. varieties responded differentially: Giza 120 consistently showed superior SOM accumulation across fertilizer rates (1.14–1.99%), while Shaka 53 exhibited more moderate increases (1.14–1.61%). Significant interactions revealed that optimal SOM enhancement occurred when combining narrower *RowS*$_1$, O_4 rates ≥35 kg fed^{-1}, and high-performing varieties like Giza 120.

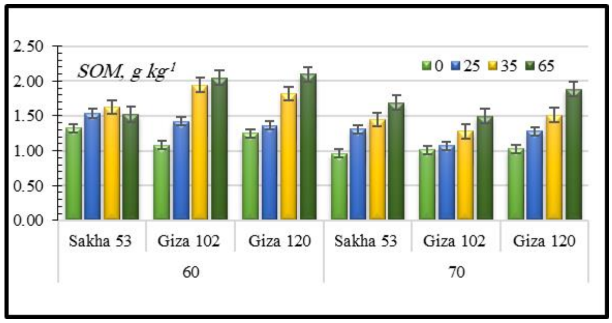

Fig. 10. Soil Organic Matter (g kg^{-1}) as affected by the interaction among different RowS, Var and Mg/S FerR

Soil Mineral N, mg kg^{-1}

Soil mineral N content (Table 12 and Fig. 11) was influenced by the interaction of *RowS*, *Var* and magnesium sulfate *FerR*, although the effects of *RowS* or *Var* were insignificant. Increasing $MgSO_4$ rates consistently elevated the soil Min. N mean values, with the highest *FerR* (65 kg fed^{-1}) produced the greatest mineral N concentrations across all treatments, reached up to 198.67 mg kg^{-1} in Giza 120 at 60 cm spacing. Average soil mineral N was similar between the two rows spacing, with 60 cm and 70 cm showed comparable values (133.53 mg kg^{-1} and 134.14 mg kg^{-1}, respectively). Cultivar differences were also slight, though Giza 102 tended to have slightly higher mineral N levels overall. The significant interactions, particularly the three-way interaction, indicated that combined management of row spacing, cultivar selection, and fertilizer application can affect soil nitrogen dynamics. These results underscore the importance of integrated nutrient management to maintain adequate soil mineral N for optimal sunflower growth and productivity.

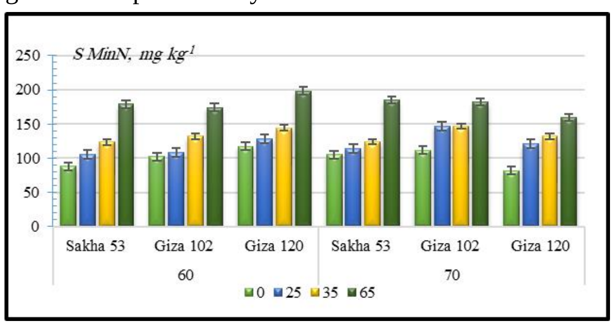

Fig. 11. Mineral N (mg kg^{-1}) as affected by the interaction among different RowS, Var and $MgSO_4$ FerR

Table 12: Soil Organic Matter, g Kg^{-1}, Mineral N, Available P and Exchangeable K, mg Kg^{-1} as affected by the interaction among different RowS, Cul and Mg/S

Treatments		SOM	Min. N	Av-P	Exch. K
		g Kg^{-1}		mg kg^{-1}	
	60	1.59	133.53	14.71	229.57
	70	1.33	134.14	15.13	249.09
RowS LSD 0.05		*0.22*	*ns*	*ns*	17.57
	Sakha 53	1.43	127.92	14.80	254.25
	Giza 102	1.42	138.08	15.22	227.89
	Giza 120	1.53	135.50	14.74	235.85
Var LSD 0.05		*0.12*	*ns*	*1.53*	*15.83*
	0	1.11	101.11	7.55	205.20
	25	1.33	120.56	14.55	227.39
	35	1.61	133.89	17.09	249.12
	65	1.79	179.78	20.48	275.61
FerR LSD 0.05		*0.18*	*23.07*	*2.04*	*16.94*
RowS$_1$	*Sakha 53*	1.50	123.92	15.26	244.97
	Giza 102	1.62	129.17	13.60	219.22
	Giza 120	1.63	147.50	15.27	224.52
RowS$_2$	*Sakha 53*	1.35	131.92	14.34	263.54
	Giza 102	1.21	147.00	16.83	236.57
	Giza 120	1.43	123.50	14.21	247.18
LSD 0.05		*0.22*	*32.63*	*2.50*	*21.51*
RowS$_1$	0	1.22	102.67	7.57	206.27
	25	1.44	114.00	15.47	215.34
	35	1.80	133.44	16.21	237.53
	65	1.89	184.00	19.58	259.13
RowS$_2$	0	1.00	99.56	7.52	204.14
	25	1.22	127.11	13.63	239.45
	35	1.41	134.33	17.97	260.70
	65	1.69	175.56	21.39	292.09
*RowS*FerR*		*0.25*	*39.96*	*2.89*	*24.84*
Shaka 53	*0*	1.14	96.50	8.92	219.48
	25	1.42	109.33	14.77	244.82
	35	1.54	123.83	17.15	265.92
	65	1.61	182.00	18.36	286.78
Giza 102	*0*	1.05	107.00	7.10	185.51
	25	1.25	127.50	14.90	205.13
	35	1.61	139.50	17.58	238.13
	65	1.77	178.33	21.29	282.81
Giza 120	*0*	1.14	99.83	6.62	210.61
	25	1.32	124.83	13.98	232.23
	35	1.67	138.33	16.56	243.31
	65	1.99	179.00	21.81	257.24
*Var*FerR LSD 0.05*		*0.31*	*28.26*	*3.53*	*30.43*
*RowS*Var*FerR*		*0.43*	*56.51*	*5.00*	*43.03*

These findings underscore the importance of integrated management of spatial arrangement, cultivar selection, and magnesium supplementation for soil health improvement. Application of $MgSO_4$ *FerR* to the soil showed notable improvements in soil fertility parameters, particularly the enhancement of OM and the availability of macronutrients. These results are consistent with established findings in the literature and can be attributed to the multifaceted roles of magnesium (Mg^{2+}) and sulfur (S) in soil-plant-microbe interactions. Fertilizers affect soil microbial processes and functions. Magnesium fertilizer application affects soil microbial biomass, activity, and bacterial community composition (Yang *et al*, 2021).

Soil Available P, mg kg^{-1}

Soil available P was significantly influenced by the interactions among *RowS*, *Var* and magnesium sulfate *FerR*. Increasing $MgSO_4$ application consistently elevated soil available P, with the highest fertilizer rate (65 kg fed^{-1}) resulting in the greatest P concentrations across all varieties and row spacing, reaching up to 23.27 mg kg^{-1} in Giza 102 at 70 cm spacing. Although differences between the two-row spacing (60 cm and 70 cm) were relatively small, 70 cm spacing tended to show slightly higher soil available P on average (15.13 mg kg^{-1}) compared to 60 cm (14.71 mg kg^{-1}). Among varieties, Giza 102 generally maintained higher soil P levels across fertilizer treatments, followed by Shaka 53 and Giza 120. The significant three-way interaction indicated that the combined effect of row spacing, cultivar, and fertilizer rate plays a crucial role in modulating soil P availability, which is essential for optimizing nutrient uptake and crop productivity. These findings emphasize the importance of integrated nutrient and spatial management strategies to maintain and enhance soil fertility in sunflower cultivation.

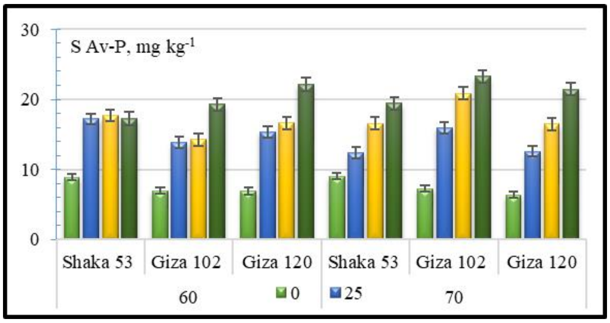

Fig. 12. Soil Av-P, mg kg^{-1} as affected by the interaction among different RowS, Var and $MgSO_4$ FertR

Soil Exchangeable K, mg kg^{-1}

The data presented in Table (12) and Fig. (13) showed that the increasing $MgSO_4$ application enhanced soil exchangeable K, with the highest fertilizer rate (65 kg fed^{-1}) producing the greatest K concentrations across all varieties and *RowS*, reaching up to 309.95 kg fed^{-1} in Giza 102 at 70 cm spacing. The significant interactions, including the three-way interaction, highlight the complex influence of spatial arrangement, genotype, and fertilization on soil potassium availability. These findings emphasize the importance of integrated management practices to optimize soil nutrient status and support sustainable sunflower production.

The above data revealed that soil health and fertility in sunflower cultivation are strongly enhanced by integrated management of *RowS*, *Var* selection, and $MgSO_4$ fertilization. Increasing $MgSO_4$ rates consistently improved soil nutrient availability, with the highest fertilizer rates elevating soil P, mineral N, and exchangeable K to levels conducive to optimal plant growth. Notably, SOM content also increased with higher $MgSO_4$ application, particularly in the 60 cm *RowS* and in *Var* like Giza 120, reaching up to 1.99%, which is indicative of improved nutrient retention capacity. While row spacing effects varied among nutrients—with 70 cm spacing slightly affect soil P and K overall, narrower spacing supported higher mineral N and organic matter levels. Verities differences further influenced nutrient dynamics, reflecting genetic variation in nutrient uptake and soil interaction. These findings underscore the importance of balanced fertilization combined with appropriate spatial and genetic management to sustain and enhance soil fertility, thereby supporting long-term productivity and soil health in sunflower cropping systems

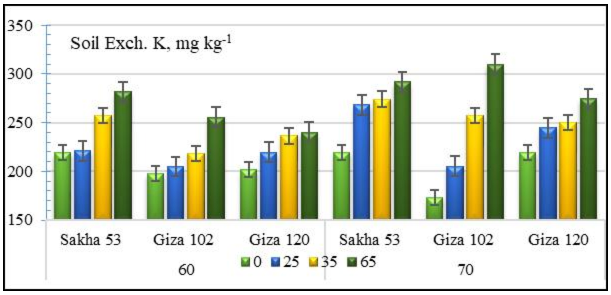

Fig. 13. Soil Exch K, mg kg^{-1} as affected by the interaction among different RowS, Var and Mg/S FerR

Regular magnesium sulfate application can effectively restore magnesium and sulfur in the soil, loosening the soil structure and creating a favorable growing environment for plants. Magnesium plays a critical role in driving processes that enhance organic matter accumulation and nutrient dynamics in soils. According to Yang *et al* (2023), adequate Mg^{2+} levels promote photosynthesis and plant biomass production, leading to increased deposition of organic residues in the soil.

A highly significant positive quadratic association between the percentages of soluble and exchangeable magnesium (SMgP, EMgP) was found, especially when the concentration of magnesium in the soil solution was less than 20%. Additionally, when the SMgP value was higher than 20%, this association showed that EMgP was slightly lower than SMgP (Abou El-Soud, *et al*, 2016).

The improvement in nutrient availability, particularly for nitrogen, phosphorus, and potassium, can be partly attributed to the sulfur component of magnesium sulfate. Sulfur oxidation produces sulfate ions (SO_4^{2-}), which lower soil pH and increase the solubility of nutrients like phosphorus and zinc, as reported by Jaggi *et al* (2005). This mechanism is particularly significant in clay soils, where high cation exchange capacity can limit nutrient mobility. The enhanced solubilization and uptake of nutrients observed in the present study are consistent with findings by Abdallah *et al* (2013), who demonstrated that sulfur amendments improve nutrient availability and plant uptake in calcareous soils under saline irrigation conditions. Additionally, magnesium's role in supporting beneficial microbial activity further explains the observed improvements in soil fertility.

CONCLUSIONS

Indeed, it is well established that the actual availability of Mg over a growing season heavily depends on (i) various environmental factors (e.g., rainfall and timing), (ii) site-specific conditions (e.g., soil type, availability of other nutrients), and (iii) the crop species, making precise prediction almost impossible. The development of recommendations for Mg nutrition is most promising when crop species are considered in greater detail.

Therefore, it is concluded that magnesium sulfate ($MgSO_4$) fertilization significantly enhanced sunflower growth, nutrient uptake, seed yield, and oil yield, with the best results observed at the highest applied rate (65 kg fed^{-1}). Giza 120 exhibited superior performance in growth parameters, seed, and oil yield, confirming its suitability under the tested conditions. Also, revealed that seed oil content percentage tended to decline with increasing fertilizer rates, but total oil yield increased substantially due to higher biomass and seed production.

Narrower row spacing (60 cm) favored nitrogen and phosphorus uptake and biomass accumulation, while wider spacing (70 cm) supported taller plants and in some cases greater potassium uptake. Significant interactions among row spacing, variety, and fertilizer rate highlight the necessity for integrated crop management practices to optimize sunflower productivity and oil quality.

Regarding climate change impacts, the study was conducted under current interrupted climate conditions, which often present challenges such as drought and high temperature stress. Similar research indicates that magnesium plays a key role in improving sunflower tolerance to drought by enhancing physiological and biochemical traits, including antioxidant enzyme activity and photosynthetic pigment content, thereby mitigating yield losses under stress. Incorporating Mg fertilization into sunflower crop management thus not only boosts productivity but also strengthens resilience to climate variability, making it a vital strategy for sustainable sunflower production in semi-arid and drought-prone regions like Egypt.

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الملخص العربي

تأثير مسافات الزراعة وإضافة سماد كبريتات المغنيسيوم على بعض أصناف عباد الشمس تحت الظروف المناخية السائدة

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تم إجراء تجارب حقلية خلال موسمي الصيف لعامي ٢٠٢٣ و٢٠٢٤ في محطة بحوث إيتاي البارود ، مركز البحوث الزراعية بمحافظة البحيرة – مصر، باستخدام تصميم القطع المنشقة لمرتين لدراسة استجابة ثلاثة أصناف مختلفة من عباد الشمس وأربع معدلات من التسميد بكبريتات المغنيسيوم ($MgSO_4 \cdot 6H_2O$) تحت تأثير مسافات الزراعة بين الصفوف (٦٠ و ٧٠ سم) تحت الظروف المناخية السائدة . وقد أوضحت النتائج بالنسبة لنمو النبات ، أظهر صنف جيزه ١٢٠ تفوقًا في خصائص النمو مثل ارتفاع النبات وقطر الرأس ووزن ١٠٠ بذرة ، حيث وصل إلى أفضل أداء عند أعلى معدلات التسميد تحت المسافات الأوسع بين الصفوف . أما بالنسبة للمحصول فقد أعطي صنف جيزة ١٢٠ أعلى محصول بذور عباد الشمس لكل نبات وأعلى إنتاج لمحصول البذور ، مسجلاً ذروة بلغت ١.٨٢ طن للفدان تحت مسافة الصفوف الأضيق وأعلى معدل تسميد (٦٥ كجم للفدان). وفي المقابل أظهر صنف جيزة ١٠٢ زيادة ملحوظة في قطر الساق وحقق أعلى إنتاج للزيت (٧٠٦.٥٧ كجم للفدان) وأعلى محتوى زيت (٤٠.٤٤٪) في ظروف تباعد الصفوف الأضيّق وأعلى معدل تسميد. أما صنف سخا ٥٣ فقد أظهر أعلى معامل حصاد مما يدل على كفاءته العالية في تحويل الكتلة الحيوية إلى محصول.

فيما يتعلق بجودة المحصول، أنتج صنف جيزة ١٢٠ أعلى متوسط لإنتاج الزيت مع زيادة نسبية بلغت ١٠.٧٦٪ و١١.٧٢٪ ، ومتوسط إنتاج بروتين حوالي ١١.٩٦٪ و١٠٪ مقارنةً بصنفي سخا ٥٣ وجيزه ١٠٢ على التوالي. أما امتصاص المغذيات فزاد امتصاص النيتروجين والفوسفور والبوتاسيوم في كل من البذور والكتلة الحيوية الكلية مع زيادة معدلات التسميد، كما تفوق صنفا جيزة ١٢٠ وسخا ٥٣ عمومًا على جيزة ١٠٢ في تراكم المغذيات، مع وجود فروقات محددة حسب الأصناف وتباعد الصفوف.

فيما يخص خصوبة التربة ، أوضحت النتائج أن الإدارة المتكاملة لتباعد الصفوف واختيار الأصناف وتسميد كبريتات المغنيسيوم ($MgSO_4$) تعزز بشكل كبير خصوبة التربة. وأظهرت النتائج وجود تفاعلات هامة بين تباعد الصفوف والصنف ومعدل التسميد ، مما يؤكد أهمية الإدارة المتكاملة للمحاصيل لتحسين إنتاجية وجودة عباد الشمس .

ولذا تُوفر هذه النتائج رؤى مهمة لتحسين استراتيجيات التسميد والزراعة لزيادة إنتاجية محصول عباد الشمس والزيت في البيئات شبه الجافة مثل مصر.