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Enhancing growth, yield, and oil quality of two sunflower cultivars through integrated bio-fertilizers and mineral fertilization levels

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Abstract

Two experiments were conducted at the research farm Faculty of Agriculture, Al-Azhar University, Assiut, Egypt, during two consecutive summer seasons (2021 and 2022). The experiments aimed to study the maximization of production and quality of two sunflower cultivars (Sakha 53 and Giza 102) using some biofertilizers *Azotobacter chrococcum*, *Bacillus megaterium*, *Bacillus circulons* and control without biofertilization, along with different levels of mineral fertilizers (50, 75, and 100% of the recommended dose of NPK). A split-split plot design was used: three replications, with cultivars allocated in the main plots, while mineral fertilizers allocated in the sub plots, and biofertilizers were distributed in the sub-sub plots, in three replicates. The results showed that Giza 102 plants outperformed Sakha 53 in plant height at harvest, head diameter, 100-seed weight, seed yield (kg/feddan) (feddan = 4200 m² = 0.420 hectares = 1.037 acres), and seed oil content in both seasons. Plant height at harvest, head diameter, head seed number, 100-seed weight, and seed yield (kg/feddan) also increased with a 100% increase in NPK. The highest values were achieved with the 100% addition of mineral fertilizer. However, seed oil content was better with the 75% addition of mineral fertilizer. Increases in plant height at harvest, head diameter, head seed number, 100-seed weight, seed yield (kg/feddan), and seed oil content were also found with the use of biofertilizers, especially *Bacillus circulons*, in both seasons.

Keywords: Sunflower, mineral fertilizers, biofertilizers.

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1. Introduction

Sunflower (*Helianthus annuus* L.) is one of the most important oil seed crops, contributing significantly to global vegetable oil production. It is widely cultivated due to its adaptability to various climatic conditions and its high oil and protein content (Skoric *et al*., 2008). However, optimizing fertilization strategies is essential to enhance sunflower yield and quality while maintaining soil health and reducing environmental pollution (Tahat *et al*., 2020). Nowadays, the high prices of chemical fertilizers, inconsistency in soil nutrition and the risk to human health have led to the increased use of manure for soil fertility. Manure can improve soil fertility, increase its water holding capacity, reduce soil erosion, improve the amount of oxygen, and promote beneficial organisms and productivity (Hamza and Abdel Hady, 2010). Biofertilizers are microbial pollen grains that may contain fungal or algal species. They are mixed with seeds before planting to provide the plant with nutrients by activating them in the soil or root layer. Their use has yielded tangible and clear results in terms of reducing the rate of mineral fertilizer application, in addition to indirectly increasing crop yields due to changes in soil conditions and plant physiology. Biofertilizers reduce environmental pollution by reducing the consumption of environmentally harmful chemical fertilizers (Hussein, 2021). Biofertilization is a sustainable agricultural approach that utilizes beneficial microorganisms such as nitrogen-fixing bacteria and phosphorus-solubilizing fungi to improve nutrient availability and plant growth (Vessey, 2003). Studies have shown that biofertilizers can enhance crop productivity while minimizing reliance on synthetic fertilizers, thus contributing to environmentally friendly farming (Bashan *et al*., 2014). In contrast, mineral fertilization provides essential nutrients in readily available forms, ensuring optimal plant development and yield (Singh and Ryan, 2015). Ahmed *et al*. (2015) observed that the use of biofertilization had a significant effect on plant height, head diameter, 1000-seed weight, seed yield, and oil content compared to the control treatment (without biofertilization). The integration of bio and mineral fertilization has been proposed as an effective strategy to maximize nutrient use efficiency and improve crop performance (Mahanty *et al*., 2016). This research aims to evaluate the combined effects of bio and mineral fertilization on the growth and productivity of two sunflower cultivars. It will assess key parameters such as nutrient uptake, seed quality, and oil content while considering the environmental and economic sustainability of different fertilization approaches. The findings will contribute to the development of optimized fertilization strategies for sunflower cultivation, ensuring both high yields and sustainable agricultural practices.

2. Materials and methods

A field experiment was conducted at the

farm of the Faculty of Agriculture, Al-Azhar University, Assiut Branch, Egypt during the two summer agricultural seasons of 2021 and 2022 AD, to studying the effect of using some bio-fertilizers (*Azotobacter chrococcum, Bacillus megaterium* and *Bacillus circulons*) and different levels of mineral fertilization (50, 75 and 100% of the recommended dose from N.B.K. and its impact on yield and quality of sunflower cultivars (Sakha-53 and Giza-102) under the conditions of Assiut governorate. Seeds were sown in holes spaced 20 cm apart along the row,and the seeds were thinned to one plant /hill before the first irrigation. The sub-plot area was 10.5 m² (3 × 3.5 m), equivalent to 1/400 of feddan (feddan = 4200 m² = 0.420 hectares = 1.037 acres) in both seasons, no diseases or pests were recorded.

2.1 Soil analysis

The chemical and physical properties of the investigated site were determined according to Page *et al*. (1982) and Klute (1986) and they are shown in Table (1).

Table (1): The Mechanical and chemical analysis of soil field experiment.

Characteristics Physical analysis	Seasons		Characteristics Chemical analysis	Seasons	
	2021	2022		2021	2022
Sand	26.42	25.00	Organic matter (%)	1.09	0.93
Silt	35.23	34.33	Available N (ppm)	77.00	70.05
Clay	38.35	40.67	Available P (ppm)	120.67	118.30
Soil texture	Clay loam		Available K (ppm)	105.40	95.53
			PH (sp. m^{-1})	7.82	7.91
			E.C. (ds. m^{-1})	1.05	1.15
			Total $CaCO_3$ (%)	2.43	2.63

2.2 Studied factors

2.2.1 Mineral fertilization

Three levels (50 ,75 and 100%) were applied for each of the following:

- Nitrogen fertilization (ammonium nitrate 33.5%).
- Phosphorus fertilization (single superphosphate 15.5%).
- Potassium fertilization (potassium sulfate 48%).

2.2.2 Bio-fertilization

- Bio-N (*Azotobacter chrococcum* L.).
- Bio-P (*Bacillus megaterium* L.).
- Bio-K (*Bacillus circulons* L.).
- Control without bio-fertilization.

The bacteria used in the study obtained from Biofertilizer Production Unit, Central Laboratory, Agricultural Research Center, Giza, Egypt.

2.3 Experimental design

The experiment was carried out in randomized complete block design (RCBD) using a split-split plot design with three replicates to study the effect of different cultivars, mineral fertilization levels, and bio-fertilization treatments on (sunflower growth and yield). The main plots were allocated cultivars, mineral fertilization: 50, 75 and 100% of the recommended dose allocated sub-sub plots were treated with four bio-fertilization treatments. Each treatment combination was replicated three times.

2.4 Studied characters

At harvest, ten plants from three inner rows of every treatment in three replications were chosen to determine the following data:

- Plant height (cm).
- Head diameter (cm).
- Number of seeds/head.
- 100-seeds weight (g).
- Seed yield (kg/feddan).
- Oil content (%) was determined according to A.O.A.C. by using Soxhelt (1984).

2.5 Statistical analysis

The collected data were analyzed using the ANOVA technique (Snedecor and Cochoran, 1972). The mean comparison was made through computer-based statistical analysis by computer package Statistics 10 program for the Windows Version (Statistics, 2013). The analysis of variance and level of significance along with the least significant difference (LSD) Test were done following (Gomez and Gomez,1984).

3. Results and discussions

3.1 Effect of mineral and bio-fertilizer application plant height of sunflower cultivars during 2021 and 2022 seasons

Data in Table (2), show that the Giza 102 cultivar significantly surpassed Sakha 53 in plant height at harvest during both seasons. This superiority may be attributed to genetic differences between the cultivars; these findings are in agreement with Lakshman *et al*. (2021) and Skoric *et al.* (2008), who reported that genetic background significantly affects plant morphological traits, particularly height under diverse environmental and nutrient conditions. Regarding increase in NPK levels from 50 to 100% led to clear improvements in plant height in both seasons. Positive response is likely due to the critical roles of nitrogen in protein and enzyme formation, phosphorus in cell division and energy transfer, potassium in regulating water uptake and enzyme activity. Similar conclusions were reported by El-Ganaini (2009) and Zubillaga *et al.* (2002), who found that full mineral fertilization improved sunflower height by enhancing nutrient uptake and physiological efficiency. Applying biofertilizers especially *Azotobacter chrococcum* (Bio-N), *Bacillus megaterium* (Bio-P), and *Bacillus circulans* (Bio-K) significant increases in plant height compared to the untreated control. These results can be attributed to improved nutrient solubilization and availability, production of plant growth regulators like auxins and gibberellins. These findings agree with Shehata and El-Khawas (2003) and Yousefpoor *et al*. (2014), demonstrated that using microbial inoculants improved sunflower height due to enhanced nitrogen fixation and auxin production. Regarding interaction C × F (Cultivar × NPK): Significant in 2021 only, indicating variation in cultivar response to mineral levels depending on season. C × Bio (Cultivar × Biofertilizer): Significant in both seasons, indicating that sunflower cultivars vary in responsiveness to microbial inoculants. F × Bio (NPK × Bio): Not significant in 2021 but significant in 2022. C × F × Bio (Three-way interaction): Not significant in either season. These findings agree with Abou-Khadra *et al*. (2002) and Saleh *et al*. (2004), who noted that cultivar response to integrated nutrient management depends on environmental factors and cultivar genotype.

Table (2): Effect of mineral fertilization and biofertilizer on plant height (cm) of two sunflower at harvest during 2021 and 2022 seasons.

Cultivars (C)	NPK Levels (F)	Plant height (cm) at harvest									
		Biofertilizer (Bio) kg/feddan									
		2021					2022				
		Control	N	P	K	Mean	Control	N	P	K	Mean
Sakha 53	50%	174.89	180.11	183.22	185.77	181.00	174.44	177.55	179.89	184.11	179.00
	75%	178.00	184.55	187.66	189.23	184.86	177.33	181.22	185.00	187.44	182.75
	100%	179.89	186.55	189.12	191.23	186.69	180.11	185.89	187.55	189.89	185.86
	Mean	177.59	183.74	186.67	188.74	184.18	177.29	181.55	184.14	187.15	182.53
Giza 102	50%	182.88	185.55	189.66	192.66	187.69	177.55	180.88	182.66	185.33	181.61
	75%	185.66	188.66	191.00	195.55	190.22	179.55	184.89	187.00	188.88	185.08
	100%	187.55	190.66	193.44	198.00	192.41	182.44	188.22	190.22	192.33	188.30
	Mean	185.37	188.29	191.37	195.40	190.11	179.85	184.66	186.63	188.85	185.00
Mean of NPK levels	50%	178.88	182.83	186.44	189.22	184.34	176.00	179.22	181.28	184.72	180.30
	75%	181.83	186.61	189.33	192.39	187.54	178.44	183.05	186.00	188.16	183.91
	100%	183.72	188.61	191.28	194.61	189.55	181.27	187.05	188.89	191.11	187.08
	Mean	181.48	186.01	189.02	192.07	187.14	178.57	183.11	185.39	188.00	183.76
L.S.D 0.05											
Cultivars (C)		2.0112					0.5079				
NPK Levels (F)		0.3868					0.6754				
Biofertilizer (Bio)		0.3459					0.3547				
C × F		0.547					N. S				
C × Bio		0.489					0.501				
F × Bio		N. S					0.614				
C × F × Bio		0.847					N. S				

N is bio-N (*Azotobacter chrococcum* L.), P is bio-P (*Bacillus megaterium* L.), K is bio-K (*Bacillus circulons* L.) and N.S is non-significant.

3.2 Effect of mineral and biofertilizer application on head diameter of sunflower plants at harvest during 2021 and 2022 seasons

Data in Table (3) show that the Giza 102 cultivar recorded slightly higher head diameter values than Sakha 53 at harvest in both seasons, though the differences were not statistically significant. These results are similar to those obtained by Kandil *et al.* (2017), Hassanein *et al.* (2017) and Hafez *et al*. (2021), demonstrated that sunflower genotypes differ in their capacity to modify head structure and oil traits under various agronomic inputs.

Table (3): Effect of mineral fertilization and biofertilizer on head diameter of two sunflower cultivars at harvest during 2021 and 2022 seasons.

Cultivars (C)	NPK Levels (F)	Head diameter									
		Biofertilizer (Bio) kg/feddan									
		2021					2022				
		Control	N	P	K	Mean	Control	N	P	K	Mean
Sakha 53	50%	18.997	20.720	21.943	22.107	20.942	17.663	19.110	19.330	19.660	18.941
	75%	19.943	21.440	22.330	22.940	21.663	18.440	19.440	19.887	20.330	19.524
	100%	20.773	21.497	23.330	23.773	22.343	18.997	20.330	20.887	21.553	20.442
	Mean	19.904	21.219	22.534	22.940	21.649	18.367	19.627	20.034	20.514	19.636
Giza 102	50%	18.350	20.553	22.607	23.000	21.128	17.887	18.663	19.220	19.550	18.830
	75%	19.330	21.830	23.163	23.273	21.899	18.330	19.660	20.330	20.660	19.745
	100%	20.773	22.607	23.607	23.830	22.704	18.660	20.440	21.107	21.997	20.551
	Mean	19.484	21.663	23.126	23.368	21.910	18.292	19.588	20.219	20.736	19.709
Mean of NPK levels	50%	18.673	20.637	22.275	22.553	21.035	17.775	18.887	19.275	19.605	18.885
	75%	19.637	21.635	22.747	23.107	21.781	18.385	19.550	20.108	20.495	19.635
	100%	20.773	22.052	23.468	23.802	22.524	18.828	20.385	20.997	21.775	20.496
	Mean	19.694	21.441	22.830	23.154	21.779	18.329	19.607	20.127	20.625	19.672
L.S.D 0.05											
Cultivars (C)		2.0112					N.S.				
NPK Levels (F)		0.3868					0.2528				
Biofertilizer (Bio)		0.3459					0.2213				
C × F		0.547					N.S.				
C × Bio		0.489					0.313				
F × Bio		N. S					0.383				
C × F × Bio		0.847					0.542				

N is bio-N (*Azotobacter chrococcum* L.), P is bio-P (*Bacillus megaterium* L.), K is bio-K (*Bacillus circulons* L.) and N.S is non-significant.

Increasing NPK levels from 50 to 100% led to a significant and consistent enhancement in head diameter in both growing seasons. This improvement is attributed to the synergistic role of nitrogen in vegetative growth, phosphorus in energy metabolism and flowering, and potassium in assimilate translocation and water regulation. These results are similar to those obtained by Babar *et al*. (2024), Zamanian and Yazdandoost (2021) and Keshta *et al.* (2008), found that higher N and P inputs improved both nitrogen uptake and head development in sunflower. Application of biofertilizers especially *Bacillus megaterium* and *Bacillus circulans* significantly increased head diameter compared to the untreated control. The observed enhancement is linked to the ability of beneficial microbes to increase nutrient solubility, improve root development, and produce plant hormones that support flowering and reproductive growth. These results are similar to those obtained by Hassanein *et al*. (2017), Hafez *et al.* (2021) and Khandekar *et al*. (2018), reported significant increases in sunflower head diameter and biomass when plants were treated with *Azotobacter* and *Bacillus* strains. Also, these results are the opposite of what was obtained by Abd El-Rahman *et al*. (2016) and Zamanian and Yazdandoost (2021). Regarding interaction C × F: Not significant in both seasons. C × Bio: Significant in both seasons. F × Bio:

Significant in both seasons. C × F × Bio: Also significant, emphasizing the importance of tailored combinations of cultivar, mineral, and bio fertilizer management for maximizing head development. These interaction results align with findings by Badawy *et al.* (2010). who highlighted cultivar-specific responses to integrated nutrient management practices.

3.3 Effect of mineral and biofertilizer application on number of seeds per head of two sunflower cultivars during 2021 and 2022 seasons

Data in Table (4) revealed that Giza 102 significantly outperformed Sakha 53 in the number of seeds per head during both seasons. This superiority can be attributed to the genetic potential of Giza 102 in producing larger and more fertile floral head, enhancing seed set and pollination efficiency. These results are similar to those obtained by Lakshman *et al*. (2021), Al-Doori and Delymi (2014) and Abou-Khadra *et al.* (2002), reported significant genotypic variation among sunflower cultivars in seed yield components under integrated fertilization. Increasing NPK levels from 50 to 100% resulted in a significant and consistent increase in seed number per head in both cultivars and seasons. This improvement is linked to the vital role of nitrogen in promoting vegetative vigor and flower formation, phosphorus in enhancing flowering and fruit set, and potassium in improving pollen viability and fertilization success. These results are similar to those obtained by Jonnagorla (2021), Zamanian and Yazdandoost (2021) and Saleem and Malik (2004), confirmed that integrated nutrient management, especially involving N and P, significantly increased seed production per head. Application of biofertilizers (*Azotobacter chroococcum* – Bio-N, *Bacillus megaterium* – Bio-P, *Bacillus circulans* – Bio-K) significantly enhanced seed number per head compared to the untreated control. The highest values were obtained under 100% NPK combined with both Bio-P and Bio-K, particularly in Giza 102, The improvement may be attributed to better nutrient uptake, stimulation of plant hormones (e.g., auxins). These results are similar to those obtained by Baliah and Priya (2017), Yousefpoor and Youdi (2014), and Jonagold *et al*. (2021) observed that biofertilizer application improved fruit set and productivity due to enhanced nutrient availability and hormonal balance. Also, these results are the opposite of what was obtained by Zamanian and Yazdandoost (2021) and Ahmad and Nasrollah zadeh (2018). Regarding interaction C × F (Cultivar × Mineral Fertilizer): Significant during both seasons. C × Bio (Cultivar × Biofertilizer): Also significant, suggesting that each cultivar responded differently to microbial inoculants. F × Bio (Mineral × Biofertilizer): Showed significant synergistic interaction. C × F × Bio (Triple Interaction): Highly significant, confirming that optimal results depend on the right combination of cultivar, NPK level, and biofertilizer. These results are similar to those obtained by Amara and Dahdoh (1997), emphasized the importance of evaluating triple interaction effects for improving seed productivity in sandy soils.

Table (4): Effect of mineral fertilization and biofertilizer on number of seeds/head of two sunflower cultivars at harvest during 2021 and 2022 seasons.

Cultivars (C)	NPK Levels (F)	Number of seeds/head									
		Biofertilizer (Bio) kg/feddan									
		2021					2022				
		Control	N	P	K	Mean	Control	N	P	K	Mean
Sakha 53	50%	857.3	980.2	1042.6	1052.9	983.2	858.6	986.9	1046.1	1109.4	1000.2
	75%	883.0	995.3	1107.9	1114.2	1025.1	886.2	1015.2	1113.8	1124.6	1035.0
	100%	978.0	1016.6	1125.0	1149.9	1067.4	893.3	1037.5	1125.3	1182.7	1059.7
	Mean	906.1	997.4	1091.8	1105.7	1025.2	879.4	1013.2	1095.1	1138.9	1031.6
Giza 102	50%	928.0	1042.8	1133.5	1137.8	1060.5	814.3	965.1	1045.2	1065.8	972.6
	75%	965.0	1069.4	1143.1	1151.3	1082.2	925.9	1028.6	1147.6	1151.4	1063.4
	100%	1026.8	1115.1	1188.6	1274.5	1151.2	950.3	1135.0	1181.6	1195.0	1115.5
	Mean	973.	1075.8	1155.1	1187.9	1098.0	896.8	1042.9	1124.8	1137.4	1050.5
Mean of NPK levels	50%	892.7	1011.5	1088.1	1095.3	1021.9	836.5	976.0	1045.7	1087.6	986.4
	75%	924.0	1032.4	1125.5	1132.8	1053.7	906.1	1021.9	1130.7	1138.0	1049.2
	100%	1002.4	1065.8	1156.8	1212.2	1109.3	921.8	1086.3	1153.5	1188.9	1087.6
	Mean	939.7	1036.6	1123.4	1146.8	1061.6	888.1	1028.1	1109.9	1138.2	1041.1
L.S.D 0.05											
Cultivars (C)		4.9590					3.0278				
NPK Levels (F)		2.2964					1.9297				
Biofertilizer (Bio)		2.1988					1.8497				
C × F		3.261					2.662				
C × Bio		3.170					2.529				
F × Bio		3.883					3.097				
C × F × Bio		5.491					4.380				

N is bio-N (*Azotobacter chrococcum* L.), P is bio-P (*Bacillus megaterium* L.), K is bio-K (*Bacillus circulons* L.) and N.S is non-significant.

3.4 Effect of mineral and biofertilizer application on 100-seed weight of two sunflower cultivars during 2021 and 2022 seasons

Data in Table (5) showed that the cultivar Giza 102 significantly surpassed Sakha 53 in 100-seed weight during both growing seasons. This superiority may be attributed to the genetic capacity of Giza 102 to allocate assimilates more efficiently into reproductive organs, leading to the development of heavier seeds. These results are similar to those obtained by Lakshman *et al.* (2021), Hafez *et al*. (2021) and Saleh *et al*. (2004). reported significant genotypic variation in sunflower hybrids for seed size and weight under fertilization regimes. Increasing NPK levels from 50 to 100% led to a progressive and significant increase in 100-seed weight in both seasons. This improvement is likely due to the role of nitrogen in enhancing photosynthetic capacity, phosphorus in energy transfer and seed development, and potassium in carbohydrate translocation and seed filling. These results are similar to those obtained by Ahmad and Nasrollahzadeh (2018), Osman and Awed (2010) and Handayati and Sihombing (2019), confirmed that adequate and balanced mineral nutrition, especially N and P, significantly enhanced seed weight in sunflower. Application of biofertilizers containing nitrogen-fixing, phosphate-solubilizing, and potassium-mobilizing bacteria significantly increased 100-seed weight compared to the untreated control. The highest values were obtained under 100% NPK combined with biofertilizers, particularly with the combination of Bio-P and Bio-K in Giza 102, these enhancements may be attributed to improved nutrient uptake, better root proliferation, and the microbial stimulation of plant growth regulators such as auxins and cytokinins. These results are similar to those obtained by Pramanik and Bera (2013), Hafez *et al*. (2021) and Keshta *et al*. (2008), demonstrated that biofertilizer application positively affected seed quality and size due to improved nutrient availability. The interaction effects among the studied factors were mostly significant. regarding interaction C × F (Cultivar × Mineral Fertilizer): Not significant in 2021, but significant in 2022. C × Bio and F × Bio: showed significant interactions in both seasons. C × F × Bio: Significant in 2021 only, which reflects the importance of integrated nutrient management tailored to both cultivar and environmental conditions. Application of biofertilizers containing nitrogen-fixing, phosphate-solubilizing, and potassium-mobilizing bacteria significantly increased 100-seed weight compared to the untreated control. The highest values were obtained under 100% NPK combined with biofertilizers, particularly with the combination of Bio-P and Bio-K in Giza 102. These results are similar to those obtained by Hafez *et al*. (2021) and Keshta *et al*. (2008). demonstrated that biofertilizer application positively affected seed quality and size due to improved nutrient availability. Baliah and Priya (2017) also highlighted the role of bio-inoculants in improving seed traits in oilseed crops.

Table (5): Effect of mineral fertilization and biofertilizer on 100-seeds weight (g) of two sunflower cultivars at harvest during 2021 and 2022 seasons.

Cultivars (C)	NPK Levels (F)	100-seeds weight (g)									
		Biofertilizer (Bio) kg/feddan									
		2021					2022				
		Control	N	P	K	Mean	Control	N	P	K	Mean
Sakha 53	50%	7.1700	7.5033	7.7700	7.7900	7.5583	6.4867	6.8833	6.9800	7.1800	6.8825
	75%	7.2867	7.9533	8.0833	8.4667	7.9475	6.6300	7.4267	7.5700	7.7600	7.3467
	100%	7.4733	8.5000	8.5833	8.3467	8.2258	6.7633	7.9333	8.0100	8.5933	7.8250
	Mean	7.3100	7.9856	8.1456	8.2011	7.9106	6.6267	7.4144	7.5200	7.8444	7.3514
Giza 102	50%	7.0833	7.9100	8.0233	8.1700	7.7967	6.4967	7.2867	7.3533	7.5433	7.1700
	75%	7.3000	8.4133	8.5300	8.7100	8.2383	6.6700	7.5033	7.8667	8.3500	7.5975
	100%	7.5800	8.8367	8.9800	9.3100	8.6767	6.9467	8.6267	9.1233	9.4200	8.5292
	Mean	7.3211	8.3867	8.5111	8.7300	8.2372	6.7044	7.8056	8.1144	8.4378	7.7656
Mean of NPK levels	50%	7.1267	7.7067	7.8967	7.9800	7.6775	6.4917	7.0850	7.1667	7.3617	7.0263
	75%	7.2933	8.1833	8.3067	8.5883	8.0929	6.6500	7.4650	7.7183	8.0550	7.4721
	100%	7.5267	8.6683	8.7817	8.8283	8.4512	6.8550	8.2800	8.5667	9.0067	8.1771
	Mean	7.3156	8.1861	8.3283	8.4656	8.0739	6.6656	7.6100	7.8172	8.1411	7.5585
L.S.D 0.05											
Cultivars (C)		0.1465					9.486				
NPK Levels (F)		0.1644					0.0221				
Biofertilizer (Bio)		0.1286					0.0201				
C × F		N. S					0.031				
C × Bio		0.181					0.028				
F × Bio		0.222					0.034				
C × F × Bio		0.315					N. S				

N is bio-N (*Azotobacter chrococcum* L.), P is bio-P (*Bacillus megaterium* L.), K is bio-K (*Bacillus circulons* L.) and N.S is non-significant.

3.5 Effect of mineral and biofertilizer application on seed yield of two sunflower cultivars during 2021 and 2022 seasons

Data in Table (6) show that Giza 102 significantly outperformed Sakha 53 in seed yield (kg/feddan) during both growing seasons. This advantage may be attributed to Giza 102's greater sink strength, higher seed set per head, and better nutrient utilization efficiency. These results are similar to those obtained by Lakshman *et al*. (2021), Nasim *et al*. (2012), and Ali *et al*. (2020), highlighted genotypic differences in seed yield under integrated fertilization in sunflower. Seed yields significantly increased with the rising NPK levels from 50 to 100% in both seasons. In 2021, yield raise from 1211.8 kg/feddan at 50% NPK to 1454.9 kg/feddan at 100%. Similarly, in 2022, yield increased from 1226.4 kg/feddan to 1468.4 kg/feddan at 100% NPK. This trend emphasizes the vital role of nitrogen, phosphorus, and potassium in enhancing photosynthetic efficiency, reproductive success, and assimilate translocation towards developing seeds. These results are similar to those obtained by Gawali and Unni (2018), Ahmed *et al*. (2010) and Zamanian and Yazdandoost (2021), reported that integrated NPK application significantly enhanced sunflower seed yield under field conditions.

Table (6): Effect of mineral fertilization and biofertilizer on seed yield(kg/feddan) of two sunflower cultivars at harvest during 2021 and 2022 seasons.

Cultivars (C)	NPK Levels (F)	Seed yield (kg/feddan)									
		Biofertilizer (Bio) kg/feddan									
		2021						2022			
		Control	N	P	K	Mean	Control	N	P	K	Mean
Sakha 53	50%	888.5	1041.6	1275.4	1361.8	1141.8	903.1	1086.7	1335.3	1378.5	1175.9
	75%	982.2	1195.2	1583.8	1602.1	1340.8	1005.3	1382.0	1474.5	1502.1	1341.0
	100%	995.9	1388.3	1663.6	1715.1	1440.7	1107.8	1325.3	1565.1	1692.1	1422.6
	Mean	955.5	1208.4	1507.6	1559.6	1307.8	1005.4	1264.6	1458.3	1524.2	1313.1
Giza 102	50%	929.1	1298.5	1433.0	1466.5	1281.8	1004.8	1294.4	1384.2	1423.9	1276.8
	75%	983.6	1342.0	1516.8	1572.4	1353.7	1042.5	1335.3	1450.0	1503.3	1332.8
	100%	1025.3	1404.8	1706.0	1740.00	1469.0	1177.4	1405.6	1705.4	1768.5	1514.2
	Mean	979.3	1348.4	1551.9	1593.0	1368.2	1074.9	1345.1	1513.2	1565.2	1374.6
Mean of NPK levels	50%	908.8	1170.1	1354.2	1414.2	1211.8	954.0	1190.5	1359.8	1401.2	1226.4
	75%	982.9	1268.6	1550.3	1587.2	1347.3	1023.9	1358.6	1462.2	1502.7	1336.9
	100%	1010.6	1396.5	1684.8	1727.5	1454.9	1142.6	1365.4	1635.3	1730.3	1468.4
	Mean	967.4	1278.4	1529.8	1576.3	1337.9	1040.2	1304.9	1485.8	1544.7	1343.9
L.S.D 0.05											
Cultivars (C)		20.801						0.6898			
NPK Levels (F)		6.9553						1.6230			
Biofertilizer (Bio)		8.2969						3.0711			
C × F		9.828						2.295			
C × Bio		11.747						4.342			
F × Bio		14.387						5.319			
C × F × Bio		20.347						7.522			

N is bio-N (*Azotobacter chrococcum* L.), P is bio-P (*Bacillus megaterium* L.), K is bio-K (*Bacillus circulons* L.) and N.S is non-significant.

Application of biofertilizers (*Azotobacter chrococcum* Bio-N, *Bacillus megaterium* Bio-P, *Bacillus circulans* Bio-K) significantly improved seed yield compared to the control. The highest yields were obtained from the combination of 100% NPK + Bio-P + Bio-K. These results may be due to enhanced nutrient solubilization, increased auxin production, and improved root development, leading to greater nutrient uptake and seed filling. These results are similar to those obtained by Alzamel *et al*. (2022), Hafez *et al*. (2021) and Ghabour *et al*. (2019), confirmed the effectiveness of microbial inoculants in increasing crop productivity by improving nutrient availability and hormonal activity. Regarding interaction (C × F, C × Bio, F × Bio, and C × F × Bio) showed statistically significant effects during both seasons. These results are similar to those obtained by Fawzy *et al*. (2016).

3.6 Effect of mineral and biofertilizer application on oil content of two sunflower cultivars during 2021 and 2022 seasons

The data in Table (7) indicated no significant differences between the two sunflower cultivars (Sakha 53 and Giza 102) in oil content during both seasons, as the cultivar effect was statistically non-significant. This suggests that both cultivars possess similar genetic capacity for oil accumulation under the given environmental and management conditions. These results are similar to those obtained by Lakshman *et al*. (2021), Ali *et al*. (2020) and Kandil *et al*. (2017), reported that oil content in sunflower is predominantly influenced by environmental and nutritional factors, with limited variation attributed to cultivar genetics. Also, these results are the opposite of what was obtained by Salama *et al*. (2012) and Al-Douri (2011). Increasing the NPK fertilizer levels significantly enhanced oil content in both growing seasons. In 2021, the mean oil content increased from 43.24% (50% NPK) to 43.70% (75% NPK), then slightly decreased to 43.19% (100% NPK). Similarly, in 2022, oil content values were 43.15%, 43.74%, and 43.32% at 50%, 75%, and 100% NPK levels, respectively. The slight decline at the highest fertilization level may be associated with excessive vegetative growth induced by high nitrogen, possibly reducing oil deposition in seeds. These results are similar to those obtained by Gawali and Unni (2018), Babar *et al*. (2024) and Alzamel *et al*. (2022). Also, these results are the opposite of what was obtained by Hassanein *et al*. (2017) and Badawy *et al*. (2010), observed that moderate NPK fertilization enhanced oil yield, while excessive nitrogen reduced oil concentration due to altered assimilate partitioning. Application of biofertilizers significantly improved oil percentage compared to untreated controls. The highest oil values were recorded under combinations of *Bacillus megaterium* (Bio-P) and *Bacillus circulans* (Bio-K) with mineral fertilizers, particularly at 75% NPK level. The improvement is likely due to enhanced nutrient uptake, especially phosphorus and potassium, which are crucial in fatty acid synthesis and oil accumulation. These results are similar to those obtained by Ahmed and El-Araby (2012) and Abd El-Rahman *et al*. (2016), confirmed that biofertilizers improve oil content by enhancing nutrient availability and promoting metabolic activity, reported that phosphate-solubilizing and potassium-mobilizing bacteria positively affect oil seed crop productivity.

Table (7): Effect of mineral fertilization and biofertilizer on oil content (%) of two sunflower cultivars at harvest during 2021 and 2022 seasons.

Cultivars (C)	NPK Levels (F)	Oil content (%)									
		Biofertilizer (Bio) kg/feddan									
		2021					2022				
		Control	N	P	K	Mean	Control	N	P	K	Mean
Sakha 53	50%	41.183	42.530	44.447	44.393	43.138	41.527	42.430	44.520	44.113	43.148
	75%	41.500	43.550	45.577	44.387	43.753	41.490	43.570	45.273	45.297	43.908
	100%	40.363	43.607	44.813	43.593	43.094	40.383	43.430	44.933	43.760	43.127
	Mean	41.016	43.229	44.946	44.124	43.329	41.133	43.143	44.909	44.390	43.394
Giza 102	50%	40.210	43.190	45.573	44.387	43.340	40.157	43.640	45.353	43.420	43.142
	75%	41.560	43.547	45.230	44.287	43.656	41.373	43.473	45.193	44.250	43.572
	100%	39.460	43.670	44.33	45.720	43.295	40.273	43.933	44.343	45.530	43.520
	Mean	40.410	43.469	45.044	44.798	43.430	40.601	43.682	44.963	44.400	43.412
Mean of NPK levels	50%	40.697	42.860	45.010	44.390	43.239	40.842	43.035	44.937	43.767	43.145
	75%	41.530	43.548	45.403	44.337	43.705	41.432	43.522	45.233	44.773	43.740
	100%	39.912	43.638	44.572	44.657	43.195	40.328	43.682	44.638	44.645	43.323
	Mean	40.713	43.349	44.995	44.461	43.379	40.867	43.413	44.936	44.395	43.403
L.S.D 0.05											
Cultivars (C)		N. S					N. S				
NPK Levels (F)		0.1642					0.1408				
Biofertilizer (Bio)		0.1573					0.1841				
C × F		N. S					0.199				
C × Bio		0.222					0.260				
F × Bio		0.272					0.318				
C × F × Bio		0.385					0.451				

N is bio-N (*Azotobacter chrococcum* L.), P is bio-P (*Bacillus megaterium* L.), K is bio-K (*Bacillus circulons* L.) and N.S is non-significant.

Regarding interaction C × F (Cultivar × Mineral Fertilizer): Non-significant in 2021, significant in 2022. C × Bio (Cultivar × Biofertilizer): Significant in both seasons. F × Bio (Mineral × Biofertilizer): Highly significant in both years. C × F × Bio (Triple Interaction): Statistically significant in 2022. These results are similar to those obtained by Amara and Dahdoh (1997).

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