

Article

# Effect of Sulfur and Magnesium Fertilization and Their Interaction on Some Vegetative, Productive, and Quality Traits of Sunflower (*Helianthus annuus* L.) under Karbala Governorate Conditions

Sanaa Khadem Abdulameer Al-Rubaie

Ministry of Education, Open Education College, Karbala Center, Iraq

\*Correspondence: [sanaakhadim33@gmail.com](mailto:sanaakhadim33@gmail.com)

**Citation:** Al-Rubaie, S. K. A. Effect of Sulfur and Magnesium Fertilization and Their Interaction on Some Vegetative, Productive, and Quality Traits of Sunflower (*Helianthus annuus* L.) under Karbala Governorate Conditions. American Journal Of Botany And Bioengineering 2025, 2(12), 24-32

Received: 10<sup>th</sup> Nov 2025

Revised: 20<sup>th</sup> Nov 2025

Accepted: 01<sup>st</sup> Dec 2025

Published: 13<sup>th</sup> Dec 2025



**Copyright:** © 2025 by the authors. Submitted for open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>)

**Abstract:** The experiment was conducted in Karbala Governorate/Al-Husayniyah District during the autumn growing season of 2024 to study the effect of magnesium levels (0, 15, 30, and 45 kg MgO ha<sup>-1</sup>) and sulfur levels (0, 400, 800, and 1600 kg S ha<sup>-1</sup>) on the growth and productivity of the Kuban sunflower cultivar. The study was conducted using a randomized complete block design (RCBD) with three replications. The results showed that both magnesium and sulfur had a significant effect on the studied traits. The average plant height increased from 183.53 cm when magnesium was not added to 197.32 cm at 45 kg MgO<sup>-1</sup>, and also increased with increasing sulfur from 183.88 cm to 196.68 cm. The highest plant height (205.00 cm) was observed at the intersection of the highest magnesium and sulfur levels. Regarding the dry weight of the vegetative parts, it increased from 34.08 g plant<sup>-1</sup> to 43.75 g plant<sup>-1</sup> with increasing magnesium, and from 35.13 to 42.63 g plant<sup>-1</sup> with increasing sulfur. The highest dry weight (50 g plant<sup>-1</sup>) was recorded with the 45 Mg × 1600 S interaction. Similarly, the weight of 300 seeds increased from 21.29 to 23.40 g with magnesium, and from 21.46 to 23.16 g with sulfur, with the highest weight (25.29 g) recorded with the interaction. Grain yield increased from 5.261 t/h<sup>1</sup> with no addition to 6.495 t/h<sup>1</sup> with magnesium, and from 5.401 to 6.253 t/h<sup>1</sup> with sulfur, reaching a maximum of 7.681 t/h<sup>1</sup> with the combined treatment. Biological yield also gradually increased to 20.287 t/h<sup>1</sup> with the combined treatment, compared to a minimum value of 12.748 t/h<sup>1</sup> with the control treatment. Protein concentration improved from 19.25% to 23.25%, and oil content increased from 41.15% to 46.70% with each element. The highest protein and oil concentrations (28.00% and 52.00%, respectively) were reached at the intersection of the highest magnesium and sulfur levels, indicating a synergistic effect that promotes vegetative growth and protein and oil accumulation in the seeds.

**Keywords:** Sulfur, Magnesium, Sunflower, Karbala Governorate

## Introduction

The sunflower (*Helianthus annuus* L.) is an economically and nutritionally important oilseed crop. Its seeds contain high levels of unsaturated oils (especially linolenic acid) and high-value proteins, making them a significant food and industrial resource. Furthermore, sunflower seeds are an important

component of human and animal food chains and are used in the production of edible oils, animal feed, and various processed products [1].

Magnesium is a vital element for plants; it is the central atom in the chlorophyll molecule, making it essential for photosynthesis, the process that generates energy for plant organisms. It also acts as a cofactor for more than 300 enzymes, activating enzymes in the Calvin cycle, energy kinases, RNA polymerases, and ATPases, thus enhancing metabolic and growth capacities [2].

In addition, magnesium contributes to phosphate loading in plant ducts and the transport of photosynthetic products from leaves to growing organs such as roots and seeds. This promotes tissue growth, vegetative mass development, and overall yield. Adequate magnesium also helps activate Rubisco activase, maintaining Rubisco activity (the central enzyme in carbon fixation), particularly under stress conditions such as high temperatures, thus supporting crop production under such conditions [3].

Sulfur plays a vital role in plant metabolism because it is involved in the formation of sulfur-containing amino acids such as cysteine and methionine, which are essential for the formation of proteins and enzymes important for growth. It also contributes to the production of compounds such as glutathione, which protect the plant from oxidative stress. Adequate sulfur enhances the efficiency of nitrogen utilization in protein synthesis and increases leaf area and photosynthetic efficiency in oilseed crops such as sunflowers. Sulfur increases the oil content in seeds and improves crop quality [4]. It also enhances the plant's resistance to environmental stresses such as salinity and drought by supporting the antioxidant system. Therefore, sulfur is an essential element for improving growth, yield, and quality in oilseed plants [5].

Recent studies are working to show that the interaction between magnesium and sulfur may have an integrative effect on improving growth, yield, and quality, as magnesium supports photosynthesis and nutrient transport, while sulfur supports the formation of protein, oils, and biologically active compounds. Despite the importance of both magnesium and sulfur, studies investigating their interaction on growth, yield, and quality characteristics in sunflowers are still limited, especially under the environmental conditions in Iraq. Therefore, this research aims to study the effect of magnesium and sulfur fertilization and their interaction on vegetative growth, yield, and seed quality characteristics to ensure the highest productivity and best quality while promoting sustainable agriculture through the optimal use of nutrients.

## Materials and Methods

### Study Factors

First factor (sulfur level) included four levels of 90% foamed sulfur: (0, 400, 800, 1600) kg ha<sup>-1</sup>. Second factor (magnesium level) included four levels of magnesium oxide (MgO) (60%): (0, 15, 30, 45) kg ha<sup>-1</sup>.

Number of treatments = 4 × 4

Number of treatments = 16

Each treatment was repeated 3 times

Number of experimental units = 48 experimental units

### Implementation of the Experiment

Then, 5 soil samples were randomly taken from the surface horizon (0-30 cm) in one of the agricultural fields in Karbala Governorate/Al-Husayniyah District, during the autumn season of 2024. These samples were mixed together to form a single composite sample representative of the field. The sample was then air-dried, ground, and passed through a sieve with a diameter of (2 mm) to estimate some of the physical and chemical properties of the soil (Table 1). The field was plowed, smoothed, and leveled using disc harrows. It was then divided into three sections (RCBD design) with a distance of 2 meters between sections. Each section was further divided into 16 plots (experimental units) measuring 3 × 3 meters, totaling 9 square meters. A distance of 1 meter was left between plots, resulting in a total of 48 experimental units. Sunflower seeds of the Kuban variety were sown on July 15, 2024, in holes at a rate of 2-3 seeds per hole and a depth of 3-5 cm. The seeds were planted in rows with a spacing of 75 cm between rows and 25 cm between holes, resulting in 4 rows per plot. Each plot contained 12 plants after thinning and replanting (one plant per hole). The experiment was irrigated using drip irrigation

with fresh water from the Tigris River. Urea fertilizer (46%) was used as the nitrogen source at a rate of 320 kg ha<sup>-1</sup>. Two applications were used: the first at germination and the second 45 days after the first. Potassium sulfate fertilizer (43% K) was used as the potassium source at a rate of 200 kg ha<sup>-1</sup> [7]. Phosphate fertilizer (TSP) was added as the phosphorus source at a rate of 120 kg P ha<sup>-1</sup>, applied in bundles and mixed into the soil.

**Table 1.** Some physical and chemical properties of the study soil (Right-to-Left Format)

| Property                       | Unit                  | Value  |
|--------------------------------|-----------------------|--------|
| Sand                           | g kg <sup>-1</sup>    | 431    |
| Clay                           | g kg <sup>-1</sup>    | 230    |
| Silt                           | g kg <sup>-1</sup>    | 339    |
| Soil texture                   | -                     | Loam   |
| Cation exchange capacity (CEC) | cmol kg <sup>-1</sup> | 17.02  |
| pH (1:1)                       | -                     | 7.89   |
| EC (1:1)                       | dS m <sup>-1</sup>    | 2.69   |
| CaCO <sub>3</sub>              | g kg <sup>-1</sup>    | 203    |
| Organic matter (O.M)           | %                     | 9.01   |
| Available nitrogen             | mg kg <sup>-1</sup>   | 22.14  |
| Available phosphorus           | mg kg <sup>-1</sup>   | 9.001  |
| Available potassium            | mg kg <sup>-1</sup>   | 128.53 |

## Studied Characteristics

### 1. Plant Height (cm)

The height of ten controlled plants, taken from the two intermediate plants in each experimental unit, was measured from the soil surface to the crown at maturity, and the average height was calculated.

### 2. Dry Weight of the Vegetative Body (g plant<sup>-1</sup>)

The dry weight of the vegetative body (stem and leaves) was estimated 75 days after germination (flowering stage). Samples were placed in perforated paper bags and then placed in an electric oven at 70°C for 72 hours. The weight was weighed several times until a stable weight was obtained using a sensitive balance [8].

The yield of ten plants from each experimental unit was calculated and then divided by the number of plants to represent the yield per plant, adjusting the weight based on 15.5% moisture content [8]:

Grain Yield (kg ha<sup>-1</sup>) = Yield per plant × Plant Density

### 3. Biological Yield (kg ha<sup>-1</sup>)

Five plants were randomly selected from the middle rows of each experimental unit, air-dried, and weighed using a sensitive balance. The average yield per plant was then calculated, and the biological yield was calculated using the following equation:

Biological Yield (kg ha<sup>-1</sup>) = Yield per plant × Plant Density

**4. Percentage of Protein (%):** The nitrogen content in the seeds was calculated using a Kjeldal macrometer, and then the equation was applied:

%of Protein = % of Nitrogen × 6.25

**5. Percentage of Oil (%):** Random samples of grain were taken, and the percentage of oil was estimated using a Soxhlet analyzer, as described in [9], Laboratory of the Department Field Crops – College of Agriculture – Tikrit University

## Design and Statistical Analysis

A Randomized Complete Block Design (RCBD) was used. The mean results were statistically analyzed using the SAS statistical software, and Duncan's test was used to compare the means at a probability level of 0.05 [10].

## Results

### 1. Plant Height (cm)

The results in Table (2) show that magnesium fertilization had a significant effect on sunflower plant height. Plant height increased gradually with increasing levels of added magnesium. The 45 kg Mg ha<sup>-1</sup> treatment resulted in the highest average height of 197.32 cm, followed by the 30 kg Mg ha<sup>-1</sup> treatment with a height of 192.62 cm. The control treatment (0 kg Mg ha<sup>-1</sup>) recorded the lowest average height of 183.53 cm. This superiority is attributed to the vital role of magnesium as the central element in the chlorophyll molecule and its ability to activate a large number of enzymes involved in photosynthesis and carbon metabolism, thus promoting vegetative growth and increasing plant length. This was confirmed by the results of [11], which indicated that magnesium supplementation increases the efficiency of photosynthesis and the growth of oilseed plants, including sunflowers.

The effect of sulfur was also significant in terms of plant height, with height increasing with increasing sulfur concentrations from 0 to 1600 kg ha<sup>-1</sup>. The highest average height was achieved at approximately 196.68 cm at the highest sulfur level, compared to 183.88 cm at no sulfur level. This improvement is attributed to the importance of sulfur in the formation of sulfur-containing amino acids such as methionine and cysteine, its role in the synthesis of proteins and vitamins essential for growth, and its contribution to increased nitrogen utilization and improved photosynthesis [12], [13]. indicated that sulfur is an essential element for improving vegetative growth and increasing protein synthesis in plants, which directly translates to increased plant height [12], [13]. The interaction between magnesium and sulfur had a significant effect. Combining the highest magnesium level (45 kg ha<sup>-1</sup>) with the highest sulfur level (1600 kg ha<sup>-1</sup>) resulted in the highest plant height of 205.00 cm, while the lowest height was observed at the interaction between 0 magnesium and 0 sulfur levels, averaging 179.20 cm. This interaction suggests that the combined availability of magnesium and sulfur enhances nutrient uptake, photosynthetic activity, and protein synthesis, leading to a marked improvement in vertical plant growth.

**Table 2.** Effect of magnesium and sulfur fertilization and their interaction on sunflower plant height (cm)

| Sulfur concentration (kg ha <sup>-1</sup> ) | Sulfur concentration (kg h <sup>-1</sup> ) |           |           |           | Magnesium mean |
|---|--|-----------|-----------|-----------|----------------|
|   | 0  | 400       | 800       | 1600      |                |
| Magnesium 0 kg ha <sup>-1</sup>             | 179.20 e                                   | 182.45 de | 185.33 cd | 187.12 c  | 183.53 D       |
| Magnesium 15 kg ha <sup>-1</sup>            | 182.90 de                                  | 187.84 c  | 191.66 bc | 193.45 b  | 188.96 C       |
| Magnesium 30 kg ha <sup>-1</sup>            | 184.77 cd                                  | 190.22 bc | 196.33 b  | 199.15 ab | 192.62 B       |
| Magnesium 45 kg ha <sup>-1</sup>            | 188.66 c                                   | 194.85 b  | 200.77 ab | 205.00 a  | 197.32 A       |
| Sulfur mean                                 | 183.88 D                                   | 188.84 C  | 193.52 B  | 196.68 A  | —              |

### 2. Dry Weight (g plant<sup>-1</sup>)

The results in Table (3) show that fertilization with magnesium and sulfur, both individually and in combination, had a significant effect on increasing the dry weight of sunflower plants. Dry weight increased progressively with increasing magnesium levels from 0 to 45 kg ha<sup>-1</sup>, with the average increasing from 34.08 to 43.75 g plant<sup>-1</sup>. This reflects the vital role of magnesium as an essential element in chlorophyll synthesis and the activation of enzymes that regulate photosynthesis and carbohydrate synthesis, leading to increased dry matter accumulation in the plant [14].

As for sulfur, a significant increase in dry weight was also observed with increasing levels from 0 to 1600 kg ha<sup>-1</sup>, with the overall average increasing from 35.13 to 42.63 g plant<sup>-1</sup>. This improvement is attributed to sulfur being an essential element in the formation of sulfur-containing amino acids (methionine and cysteine), proteins, and coenzymes, thus promoting vegetative growth and tissue biosynthesis [15].

The results of the interaction between magnesium and sulfur also showed a clear cumulative effect, reflected in the highest dry weight (50 g plant<sup>-1</sup>) recorded in the treatment with 45 kg Mg ha<sup>-1</sup> × 1600 kg S ha<sup>-1</sup>, while the lowest value (32 g plant<sup>-1</sup>) appeared in the control treatment without addition.

This interaction indicates a complementary relationship between magnesium, which enhances

photosynthetic efficiency, and sulfur, which increases protein synthesis and nitrogen metabolism, leading to enhanced biosynthesis that surpasses the effect of either element individually.

**Table 3.** Effect of magnesium and sulfur fertilization and their interaction on the dry weight of sunflower plants (g plant<sup>-1</sup>)

| Sulfur concentration<br>(kg ha <sup>-1</sup> ) | Sulfur concentration (kg h <sup>-1</sup> ) |          |          |          | Magnesium mean |
|--|--|----------|----------|----------|----------------|
|  | 0  | 400      | 800      | 1600     |                |
| Magnesium 0 kg ha <sup>-1</sup>                | 32.00 e                                    | 33.50 de | 34.80 d  | 36.00 cd | 34.08 D        |
| Magnesium 15 kg ha <sup>-1</sup>               | 34.00 d                                    | 36.00 cd | 38.00 c  | 39.50 bc | 36.88 C        |
| Magnesium 30 kg ha <sup>-1</sup>               | 36.00 c                                    | 38.50 bc | 41.00 b  | 43.00 ab | 39.88 B        |
| Magnesium 45 kg ha <sup>-1</sup>               | 38.50 c                                    | 41.50 b  | 45.00 ab | 50.00 a  | 43.75 A        |
| Sulfur mean                                    | 35.13 D                                    | 37.88 C  | 39.70 B  | 42.63 A  | —              |

### 3. Weight of 300 seeds (g)

Table (4) shows a significant effect of magnesium and sulfur fertilization, both individually and in combination, on increasing the weight of 300 sunflower seeds. Average traits tended to increase with increasing levels of both elements. When the magnesium concentration increased from 0 to 45 kg ha<sup>-1</sup>, the weight of 300 seeds rose from 21.29 to 23.40 g, indicating the vital physiological role of magnesium in promoting dry matter formation within the seeds. This effect is attributed to magnesium being a central component of the chlorophyll molecule, which increases the efficiency of photosynthesis and carbohydrate production and conversion into grains. Furthermore, magnesium plays a role in activating enzymes responsible for the metabolism and accumulation of starch and fats within the seeds. This is confirmed by the results of [16], which showed that raising magnesium levels leads to an increase in dry weight and seed composition in oilseed crops.

The results also showed that adding sulfur significantly increased the average weight of 300 grains, rising from 21.46 g without sulfur to 23.16 g at the highest level (1600 kg ha<sup>-1</sup>). This is attributed to sulfur's importance in the formation of sulfur-containing amino acids (cysteine and methionine), proteins, and oils, as well as its role in improving nitrogen uptake efficiency, which enhances dry matter accumulation in grains. The results [17] indicate that sulfur is a key element determining the seed's ability to form protein and oil, thus increasing its final weight.

The interaction between magnesium and sulfur had a significant and superior effect compared to individual additions. The combined treatment (45 kg Mg + 1600 kg S ha<sup>-1</sup>) achieved the highest weight of 25.29 g. This indicates a synergistic effect between magnesium, which increases the efficiency of photosynthesis, and sulfur, which improves protein and oil metabolism, thus increasing the ability of seeds to accumulate dry matter more than the effect of each element alone.

**Table 4.** Effect of magnesium and sulfur fertilization and their interaction on the weight of 300 grains (g)

| Sulfur concentration<br>(kg ha <sup>-1</sup> ) | Sulfur concentration (kg h <sup>-1</sup> ) |          |          |          | Magnesium mean |
|--|--|----------|----------|----------|----------------|
|  | 0  | 400      | 800      | 1600     |                |
| Magnesium 0 kg ha <sup>-1</sup>                | 20.95 e                                    | 21.15 de | 21.40 d  | 21.65 cd | 21.29 D        |
| Magnesium 15 kg ha <sup>-1</sup>               | 21.20 de                                   | 21.55 d  | 22.00 cd | 22.50 bc | 21.81 C        |
| Magnesium 30 kg ha <sup>-1</sup>               | 21.60 d                                    | 22.10 cd | 22.65 bc | 23.20 ab | 22.39 B        |
| Magnesium 45 kg ha <sup>-1</sup>               | 22.10 cd                                   | 22.75 bc | 23.45 ab | 25.29 a  | 23.40 A        |
| Sulfur mean                                    | 21.46 D                                    | 21.89 C  | 22.38 B  | 23.16 A  | 21.29 D        |

### 4. Grain Yield (ton ha<sup>-1</sup>)

The results in Table (5) show that fertilization with magnesium and sulfur, whether applied individually or in combination, had a significant effect on the grain yield (ton ha<sup>-1</sup>) of sunflowers. The yield increased gradually with increasing magnesium levels from 0 to 45 kg ha<sup>-1</sup>, ranging from an average of 5.261 tons ha<sup>-1</sup> at no fertilization to 6.495 tons ha<sup>-1</sup> at the highest level. This indicates the vital

physiological role of magnesium in improving photosynthesis and carbohydrate translocation to seeds, as well as activating enzymes responsible for dry matter accumulation in grains [18].

The addition of sulfur also showed a significant effect on the yield, increasing it from 5.401 tons ha<sup>-1</sup> at no fertilization to 6.253 tons ha<sup>-1</sup> at a level of 1600 kg ha<sup>-1</sup>. This is because sulfur contributes to the synthesis of proteins and sulfur-containing amino acids such as methionine and cysteine, and it also improves nitrogen uptake efficiency and increases grain count and weight [19].

The interaction between magnesium and sulfur showed a clear synergistic effect, with the highest yield (7.681 t ha<sup>-1</sup>) recorded in the treatment of 45 kg Mg × 1600 kg S ha<sup>-1</sup>, while the lowest yield (5.104 t ha<sup>-1</sup>) was recorded in the absence of these additions. This indicates that the combined availability of magnesium and sulfur enhances photosynthesis, sugar transport, and protein synthesis in seeds, leading to increased dry matter accumulation and higher yields.

**Table 5.** Effect of magnesium and sulfur fertilization and their interaction on sunflower grain yield (t ha<sup>-1</sup>)

| Sulfur concentration<br>(kg ha <sup>-1</sup> ) | Sulfur concentration (kg h <sup>-1</sup> ) |          |          |          | Magnesium mean |
|--|--|----------|----------|----------|----------------|
|  | 0  | 400      | 800      | 1600     |                |
| Magnesium 0 kg ha <sup>-1</sup>                | 5.1043 e                                   | 5.210 de | 5.320 d  | 5.410 cd | 5.261 D        |
| Magnesium 15 kg ha <sup>-1</sup>               | 5.250 de                                   | 5.400 d  | 5.550 cd | 5.720 bc | 5.480 C        |
| Magnesium 30 kg ha <sup>-1</sup>               | 5.500 d                                    | 5.700 cd | 5.950 bc | 6.200 ab | 5.838 B        |
| Magnesium 45 kg ha <sup>-1</sup>               | 5.750 cd                                   | 6.050 bc | 6.500 ab | 7.681 a  | 6.495 A        |
| Sulfur mean                                    | 5.401 D                                    | 5.590 C  | 5.830 B  | 6.253 A  | —              |

### 5. Biological Yield (ton ha<sup>-1</sup>)

The results in Table (6) show that magnesium and sulfur fertilization, and their interaction, have a strong and significant effect on the biological yield of sunflower plants. The biological yield increased gradually with increasing magnesium concentration from 0 to 45 kg ha<sup>-1</sup>, reaching an average of 16.834 tons ha<sup>-1</sup> at the highest level, compared to 12.748 tons ha<sup>-1</sup> in the no-addition treatment. This effect is partly attributed to the role of magnesium in increasing photosynthetic efficiency and activating the enzymes essential for carbohydrate metabolism, which contributes to the formation of a large vegetative mass. This mechanism is consistent with the results of [20], which showed in meta-analysis that magnesium fertilization improves yield in most production systems, including oil crops. On the other hand, sulfur also showed a significant effect, increasing the biological yield from 12.926 tn<sup>-1</sup> in the absence of sulfur to 15.974 tn<sup>-1</sup> upon the addition of 1600 kg<sup>-1</sup> of sulfur. This improvement is explained by the role of sulfur in the synthesis of proteins and sulfur-containing amino acids, and in improving nitrogen utilization efficiency, which supports the growth of vegetative parts and increases biomass. This hypothesis is supported by the results of a study [21] which found that sulfur addition increases grain and oil production in hybrids, indicating that sulfur stimulates plant physiological components and increases biomass accumulation.

The interaction between magnesium and sulfur showed a remarkable synergistic effect. In the treatment combining 45 kg of magnesium and 1600 kg of sulfur, the highest biological yield (20.287 tn<sup>-1</sup>) was recorded. This indicates that magnesium promotes photosynthesis and carbohydrate synthesis, while sulfur supports protein and enzyme synthesis, and the synergy of these two pathways leads to greater vegetative mass accumulation. This finding reinforces our understanding of how nutrient management can be improved through a balance between magnesium and sulfur, a strategy supported by research such as that conducted on oilseed crops where sulfur application enhanced nutrient uptake and cellular structure.

**Table 6.** Effect of magnesium and sulfur fertilization and their interaction on the biological yield of sunflower (ton ha<sup>-1</sup>).

| Sulfur concentration<br>(kg ha <sup>-1</sup> ) | Sulfur concentration (kg h <sup>-1</sup> ) |           |           |           | Magnesium<br>mean |
|--|--|-----------|-----------|-----------|-------------------|
|  | 0  | 400       | 800       | 1600      |                   |
| Magnesium 0 kg ha <sup>-1</sup>                | 12.054 e                                   | 12.540 de | 12.980 d  | 13.420 cd | 12.748 D          |
| Magnesium 15 kg ha <sup>-1</sup>               | 12.500 de                                  | 13.100 d  | 13.750 cd | 14.420 bc | 13.443 C          |
| Magnesium 30 kg ha <sup>-1</sup>               | 13.200 d                                   | 13.950 cd | 14.850 bc | 15.750 ab | 14.438 B          |
| Magnesium 45 kg ha <sup>-1</sup>               | 13.950 cd                                  | 14.850 bc | 16.250 ab | 20.287 a  | 16.834 A          |
| Sulfur mean                                    | 12.926 D                                   | 13.610 C  | 14.458 B  | 15.974 A  |                   |

### 6. Protein Concentration in Grains (%)

Table 7 shows that magnesium and sulfur fertilization has a significant effect on the protein concentration in yellow corn kernels. The average protein content increased from 19.25% in the absence of fertilization to 23.25% at the highest levels of magnesium (45 kg ha<sup>-1</sup>) and sulfur (1600 kg ha<sup>-1</sup>). This is attributed to magnesium's role in improving photosynthesis and carbohydrate transport, as well as stimulating protein synthesis within the grains, a finding confirmed by recent studies [22].

Sulfur also showed a significant effect on increasing protein content, rising from 19.45% in the absence of sulfur to 22.93% at the highest level. This is because sulfur is a component of sulfur-containing amino acids such as methionine and cysteine, which are essential for protein synthesis. Furthermore, sulfur improves nitrogen utilization efficiency in plants, thus increasing protein accumulation in the grains [19]. The interaction between magnesium and sulfur showed a strong synergistic effect, with the highest protein concentration (28.00%) recorded in the treatment of 45 kg Mg × 1600 kg S ha<sup>-1</sup>. This indicates that the synergistic effect of these two elements enhances plant physiological processes and increases protein accumulation in grains by improving vegetative growth and enzymatic activity, and stimulating protein synthesis pathways.

**Table 7.** Effect of magnesium and sulfur fertilization and their interaction on protein concentration in sunflower grains (%)

| Sulfur concentration<br>(kg ha <sup>-1</sup> ) | Sulfur concentration (kg h <sup>-1</sup> ) |          |          |          | Magnesium mean |
|--|--|----------|----------|----------|----------------|
|  | 0  | 400      | 800      | 1600     |                |
| Magnesium 0 kg ha <sup>-1</sup>                | 18.50 e                                    | 19.00 de | 19.50 d  | 20.00 cd | 19.25 D        |
| Magnesium 15 kg ha <sup>-1</sup>               | 19.00 de                                   | 19.80 d  | 20.50 cd | 21.20 bc | 20.13 C        |
| Magnesium 30 kg ha <sup>-1</sup>               | 19.80 d                                    | 20.70 cd | 21.50 bc | 22.50 ab | 21.13 B        |
| Magnesium 45 kg ha <sup>-1</sup>               | 20.50 cd                                   | 21.50 bc | 23.00 ab | 28.00 a  | 23.25 A        |
| Sulfur mean                                    | 19.45 D                                    | 20.25 C  | 21.13 B  | 22.93 A  |                |

### 7. Oil Concentration in Seeds (%)

The results in Table (8) show that the addition of magnesium and sulfur, as well as their interaction, significantly increased the oil concentration in sunflower seeds. With an increase in magnesium from 0 to 45 kg ha<sup>-1</sup>, the average oil content rose from 41.15% to 46.70% at the highest sulfur concentration as well. This indicates that magnesium improves the plant's physiological efficiency and enhances photosynthesis, which provides the seeds with the carbohydrates necessary for conversion into fatty acids and oils. These results are consistent with [23].

On the other hand, sulfur played an important role in increasing the oil content, as the average oil content increased when its concentration increased from 0 to 1600 kg ha<sup>-1</sup>. This is attributed to the fact that sulfur is involved in the synthesis of sulfur-containing amino acids and enzymes involved in fatty acid synthesis within the seeds. It also enhances nitrogen utilization and its conversion into active compounds for oil formation. These results are consistent with [19]. Furthermore, the interaction between magnesium and sulfur showed a clear synergistic effect, with the highest oil content (52.00%) recorded in the treatment of 45 kg Mg × 1600 kg S ha<sup>-1</sup>. This indicates that the combination of magnesium and sulfur allows the plant to improve its photosynthetic efficiency, with magnesium

supporting photosynthesis while sulfur supports fatty acid synthesis, leading to higher oil accumulation in the seeds.

**Table 8.** Effect of magnesium and sulfur fertilization and their interaction on sunflower seed oil concentration (%)

| Sulfur concentration (kg ha <sup>-1</sup> ) | Sulfur concentration (kg h <sup>-1</sup> ) |          |          |          | Magnesium mean |
|---|--|----------|----------|----------|----------------|
|   | 0  | 400      | 800      | 1600     |                |
| Magnesium 0 kg ha <sup>-1</sup>             | 40.10 e                                    | 41.00 de | 41.50 d  | 42.00 cd | 41.15 D        |
| Magnesium 15 kg ha <sup>-1</sup>            | 41.20 de                                   | 42.00 d  | 43.00 cd | 44.00 bc | 42.55 C        |
| Magnesium 30 kg ha <sup>-1</sup>            | 42.50 d                                    | 43.50 cd | 44.50 bc | 46.00 ab | 44.13 B        |
| Magnesium 45 kg ha <sup>-1</sup>            | 43.50 cd                                   | 44.80 bc | 46.50 ab | 52.00 a  | 46.70 A        |
| Sulfur mean                                 | 41.83 D                                    | 42.83 C  | 43.88 B  | 46.00 A  |                |

### Conclusion

1. Fertilization with magnesium and sulfur has a significant effect on the vegetative growth of sunflower plants.
2. The highest plant height, dry weight, and biological yield were recorded at 45 kg Mg × 1600 kg S ha<sup>-1</sup>.
3. Protein and oil content in seeds increased with magnesium and sulfur fertilization.
4. The interaction between magnesium and sulfur showed a synergistic effect that enhances nutrient absorption and accumulation.

### Recommendations

1. Use 45 kg Mg ha<sup>-1</sup> with 1600 kg S ha<sup>-1</sup> to achieve maximum seed yield and quality.
2. Maintain a balance between magnesium and sulfur to benefit from their synergistic effect.
3. Study the effect of fertilization on qualitative oil components and experiment with different varieties and growing environments.

### REFERENCES

- [1] B. S. Adeleke and O. O. Babalola, "Oilseed crop sunflower (*Helianthus annuus*) as a source of food: Nutritional and health benefits," *Food Sci. Nutr.*, vol. 8, no. 9, pp. 4666–4684, 2020.
- [2] M. Senbayram, A. Gransee, V. Wahle, and H. Thiel, "Role of magnesium fertilisers in agriculture: Plant–soil continuum," *Crop Pasture Sci.*, vol. 66, no. 12, pp. 1219–1229, 2015.
- [3] Y. Shao *et al.*, "Magnesium application promotes Rubisco activation and contributes to high-temperature stress alleviation in wheat during grain filling," *Front. Plant Sci.*, vol. 12, Art. no. 675582, 2021.
- [4] T. Zenda, S. Liu, A. Dong, and H. Duan, "Revisiting sulphur – The once neglected nutrient: Its roles in plant growth, metabolism, stress tolerance and crop production," *Agriculture*, vol. 11, no. 7, Art. no. 626, 2021.
- [5] R. Dawar *et al.*, "Role of sulphur fertilization in legume crops: A comprehensive review," *Int. J. Plant Sci.*, vol. 35, pp. 718–727, 2023.
- [6] M. I. H. Al-Kubaisi, "Effect of timing and methods of nitrogen fertilizer application on growth and yield of two white corn varieties," M.S. thesis, College of Agriculture, University of Baghdad, Baghdad, Iraq, 2001.
- [7] Ministry of Agriculture, *Guidelines for Cultivation and Production of White Corn*, General Authority for Agricultural Guidance and Cooperation, White Corn Research Development Project, Instructional Bulletin no. 19, 2006.
- [8] M. A. Joslyn, *Methods in Food Analysis: Physical, Chemical and Instrumental Methods of Analysis*, 2nd ed. New York, NY, USA: Academic Press, 1970.
- [9] AOAC, *Official Methods of Analysis of AOAC International*, 20th ed. Washington, DC, USA: Association of Official Analytical Chemists, 2016.

- [10] K. Mahmoud and A. A. M. Khalafallah, *Design and Analysis of Agricultural Experiments*. Baghdad, Iraq: Ministry of Higher Education and Scientific Research, University of Baghdad, 1980.
- [11] E. S. Alwakel *et al.*, "Synergistic effects of magnesium and zinc supplementation on yield performance and oil quality of canola (*Brassica napus* L.) in reclaimed soil environments," *J. Agric. Sci.*, vol. 163, no. 5, pp. 547–560, 2025.
- [12] H. W. Scherer, "Sulphur in crop production," *Eur. J. Agron.*, vol. 14, no. 2, pp. 81–111, 2001.
- [13] Z. Lu, J. Liu, Y. Zhu, Y. Wang, and C. Huang, "The effects of ammonium phosphate with different sulfur additions on crop yield and nutrient uptake in calcareous soil," *Agronomy*, vol. 14, Art. no. 1145, 2024.
- [14] X. Y. Tian *et al.*, "Physiological and molecular advances in magnesium nutrition of plants," *Plant Soil*, vol. 468, no. 1, pp. 1–17, 2021.
- [15] A. Künstler *et al.*, "The versatile roles of sulfur-containing biomolecules in plant defense—A road to disease resistance," *Plants*, vol. 9, no. 12, Art. no. 1705, 2020.
- [16] S. J. Jaghdani, "Magnesium deficiency induced responses in crop physiology: Impacts on photosynthesis, light utilization, and photoprotection," Ph.D. dissertation, Georg-August Universität Göttingen, Göttingen, Germany, 2021.
- [17] M. Bindi, L. Fibbi, M. Lanini, and F. Miglietta, "Free air CO<sub>2</sub> enrichment (FACE) of grapevine (*Vitis vinifera* L.): I. Development and testing of the system for CO<sub>2</sub> enrichment," *Eur. J. Agron.*, vol. 14, no. 2, pp. 135–143, 2001.
- [18] X. Jin *et al.*, "Magnesium nutrient application induces metabolomics and physiological responses in mulberry (*Morus alba*) plants," *Int. J. Mol. Sci.*, vol. 24, no. 11, Art. no. 9650, 2023.
- [19] S. Perveen *et al.*, "Assessing the potential of polymer-coated urea and sulphur fertilization on growth, physiology, yield, oil contents and nitrogen use efficiency of sunflower crop under arid environment," *Agronomy*, vol. 11, no. 2, Art. no. 269, 2021.
- [20] Z. Wang *et al.*, "Magnesium fertilization improves crop yield in most production systems: A meta-analysis," *Front. Plant Sci.*, vol. 10, Art. no. 495191, 2020.
- [21] S. Hussain *et al.*, "Optimizing sunflower (*Helianthus annuus* L.) hybrids growth, achene and oil yield through soil-applied sulphur and zinc," *Sci. Rep.*, vol. 15, no. 1, Art. no. 13829, 2025.
- [22] M. Hauer-Jákli and M. Tränkner, "Critical leaf magnesium thresholds and the impact of magnesium on plant growth and photo-oxidative defense: A systematic review and meta-analysis from 70 years of research," *Front. Plant Sci.*, vol. 10, Art. no. 766, 2019.
- [23] E. M. Niel *et al.*, "Sunflower varieties response to magnesium sulfate fertilization via various row spaces under current climate conditions," *Egypt. Sci. Mag.*, vol. 12, no. 1, pp. 97–117, 2025.