Effect of Magnesium and Boron Soil Fertilization and Their Interaction on Growth and Yield of Sunflower (*Helianthus annuus* L.) Grown in Gypsum Soil

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Abstract

A field experiment was conducted in gypsum soil at the College of Agriculture, Tikrit University, located at the geographical coordinates (34°41′03.9″N, 43°39′02.0″E), during the 2024 growing season. The aim was to determine the effect of soil fertilization with magnesium (magnesium oxide) at four levels (0, 7, 14, and 21 kg ha^{-1}) and boron (boric acid) at four levels (0, 5, 10, and 15 kg ha^{-1}), and the interaction between them, on some growth and yield characteristics of sunflower crops. The experiment was conducted using a randomized complete block design (RCBD) with a two-person operation and three replications, with a total of (48) experimental units. The results of the experiment showed a significant effect of both magnesium and boron fertilization, and their interaction, on most growth and yield characteristics of sunflower plants. The values of the studied characteristics tended to increase gradually with increasing application levels. The interaction treatment of 21 kg Mg ha^{-1} + 15 kg B ha^{-1} achieved the highest values for most characteristics, while the control treatment of 0 kg Mg ha^{-1} + 0 kg B ha^{-1} recorded the lowest values. The dry weight of the first cutting ranged between 26.1 and 49.9 g $plant^{-1}$, with average maximum and minimum values of 49.9 and 26.1 g $plant^{-1}$, respectively. The dry weight of the second cutting ranged between 65.3 and 117.6 g $plant^{-1}$. The absolute growth rate ranged from 1.302 to 2.113 g $plant^{-1}day^{-1}$, while the grain yield ranged from 2.812 to 4.912 Mg ha^{-1}, and the biological yield ranged from 9.52 to 15.86 Mg ha^{-1}.

The results also showed a clear improvement in soil fertility after harvest as a result of integrated fertilization. The available magnesium concentration in the soil ranged from 8.318 to 20.911 mg kg^{-1}, while the available boron concentration ranged from 0.27 to 0.88 mg kg^{-1}. Overall, the highest average values for the studied traits were observed with the treatment of 21 kg Mg ha^{-1} + 15 kg B ha^{-1}, while the no-fertilization treatment recorded the lowest average values.

Keywords: Magnesium, Boron, Soil fertilization, Gypsum soil, Sunflower.

Introduction:

Sunflower (*Helianthus annuus* L.) is one of the world's most important oilseed crops with a high oil content of about 40-50% which varies depending on variety and environmental conditions and therefore its economic and nutritional importance. In addition, its oil has high content of unsaturated fatty acids, especially oleic and linoleic acids, which were found to be good vegetable oils for human nutrition and food. In addition, sunflower seeds contain a large amount of proteins, vitamins, antioxidants, especially vitamin E which improves the nutritional and health value of the seeds.[1]

The sunflower is very tolerant of a broad variety of environmental conditions. It can be grown in temperate and semi-arid regions, and has good water and nutrient use efficiency relative to many other oilseed crops and is an appropriate choice for water-limited environments and for climate change. Moreover, the production of new varieties and

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hybrids through modern genetic breeding programs has added to the importance of achieving high yield varieties and hybrids that have high oil quality and increased tolerance to biotic and abiotic stresses, thereby improving food security and demand for vegetable oil in the world.[2]

In many dry and semi-dry areas, including the majority of the gypsum soils in Iraq, the cultivation of sunflower is widespread. These soils contain a large amount of gypsum (hydrated calcium sulfate) that will influence the physical and chemical properties of the soil. Soils with a high gypsum content have poor structure and water holding capacity and nutrient availability. It also causes the accumulation of hard gypsum horizons which may limit root penetration and uptake of water and nutrients and thus reduce plant growth and productivity, particularly under high levels of gypsum in the root zone. But with proper agricultural practices such as better fertilization, the productivity of these soils can be improved and agricultural use efficiency can be increased.[3]

Magnesium (Mg) is a secondary macronutrient needed for plant growth. It is at the heart of the chlorophyll molecule and activates more than 300 enzymes in the process of photosynthesis, carbohydrate transport, energy production and protein synthesis. Magnesium deficiency results in impaired photosynthetic efficiency and less production of dry matter and yield, especially in soils lacking in magnesium availability, or high levels of calcium and other competing elements. In calcareous and gypsum soils, the problem of magnesium deficiency is often caused by competition between calcium and magnesium for exchange and absorption sites. This can be beneficial for achieving better photosynthetic efficiency and higher yields and growth in many oilseed and field crops [4] and fertilization with magnesium would be an effective strategy.

Boron is a micronutrient essential by sunflower in relatively high amounts as compared to many other field crops. It is involved in cell wall formation, cell wall stability, carbohydrate transport and regulation of growth of meristematic tissue. Moreover, it is essential for reproductive activities by enhancing the viability of pollen, germination of pollen grains and elongation of pollen tubes, resulting in better fertilization rate and seed production. Boron effect is more pronounced in soils with low organic matter content or in calcareous and gypsum soils where plant availability of B is limited [5]. There is evidence that balanced applications of boron to sunflower enhance seed-set, thousand-seed weight and oil production. But

when levels are above the optimum, symptoms of toxicity and a decrease in productivity can occur.

Since magnesium and boron are relatively scarce in gypsum soils, and they both have complementary activity in the physiology and reproduction of sunflower crops, the research into the effects of soil fertilization of these elements and their interaction is of great scientific and practical importance in developing fertilizing programmes that are appropriate for this type of soil. Therefore, this study aims to determine the effects of magnesium and boron soil fertilization, and their interaction, on certain growth and yield characteristics of sunflowers grown in gypsum soil.

Materials and Methods

Study Factors

Factor 1 (Magnesium Fertilization): Magnesium was added in the form of magnesium oxide (MgO) (60.30%) at four levels: 0, 7, 14, and 21 kg ha^{-1}.

Factor 2 (Boron Fertilization): Boron was added in the form of boric acid (H_3BO_3) (17%) at four levels: 0, 5, 10, and 15 kg ha^{-1}.

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Experiment Implementation

The field experiment was conducted at the experimental station of the Department of Soil Science and Water Resources, College of Agriculture, Tikrit University at geographical coordinates of (34°41′03.9″N, 43°39′02.0″E). Upper soil samples (0–30 cm) were randomly taken from five locations. Samples were collected and thoroughly mixed to get a composite sample from the experimental field. The composite soil sample was then air dried, ground and passed through a 2 mm sieve, and selected physical and chemical properties of the soil determined as shown in Table 1.

Table (1) Selected Physical and Chemical Properties of the Experimental

Property	Unit	Value	Analytical Method
Sand	g kg^{-1}	523	Determined by the hydrometer method [8].
Clay	g kg^{-1}	167	
Silt	g kg^{-1}	310	
Soil Texture	—	Clay Loam	Classified according to the particle-size distribution determined by the hydrometer method [8].
Cation Exchange Capacity (CEC)	cmolc kg^{-1}	17.23	Determined using 1 M ammonium acetate solution [8].
Soil Reaction (pH, 1:1 soil:water suspension)	—	7.68	Measured using a digital pH meter [9].
Electrical Conductivity (EC, 1:1 soil:water extract)	dS m^{-1}	2.39	Measured using an electrical conductivity meter (EC meter) [9].
Gypsum ($CaSO_4$)	g kg^{-1}	71.23	Determined according to the dilution method described by [8].
Calcium Carbonate ($CaCO_3$)	g kg^{-1}	212.11	Determined by the gravimetric method [9].
Organic Matter (O.M.)	g kg^{-1}	9.51	Determined by the wet digestion method [8].
Available Nitrogen (N)	mg kg^{-1}	20.91	Determined according to the Micro-Kjeldahl method [8].
Available Phosphorus (P)	mg kg^{-1}	6.09	Extracted using 0.5 M sodium bicarbonate ($NaHCO_3$) solution at pH 8.5 according to Olsen's method [10].
Available Potassium (K)	mg kg^{-1}	166.33	Extracted with ammonium acetate solution according to the method described in [8] and determined using a flame photometer.
Available Magnesium (Mg)	mg kg^{-1}	14.60	Extracted with 1 M ammonium acetate solution at pH 7.0 and determined using an Atomic Absorption Spectrophotometer (AAS).
Available Boron (B)	mg kg^{-1}	0.472	Available boron was extracted using the hot-water extraction method, and its concentration was determined by Atomic Absorption Spectrophotometry according to the method described in [11].

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The experimental field was prepared for planting by disc harrow plowing, harrowing and leveling. Afterwards, the field was subdivided into three replications in a randomized complete block design (RCBD). Two replications were each made with 16 experimental plots, each 3 × 3 m² with a 1-m spacing between plots. Therefore, there were total 48 experimental units in the experiment. On July 15, 2024, sunflower seeds of the Kuban cultivar were sown at a rate of 2-3 seeds per hill and at a planting depth of 3-5 cm. Distance between rows was kept 75 cm and between hills within the row, 25 cm. There were 4 rows per experimental unit. Seedlings were thinned after emergence to plant 1 per hill.

Application of magnesium as magnesium oxide and boron as boric acid was done simultaneously before sowing by side dressing method. The urea fertilizer with 46% N was added 300 kg ha^{-1} and split applied. The first application was at emergence and the second 45 days after the first application. The localized placement method was used to apply Triple superphosphate (TSP) fertilizer at 120 kg P ha^{-1}. This fertilization method provided a fairly even supply of the other nutrients for all treatments, allowing the effects of the two nutrients tested to be singled out.

Two rates of potassium (K) (43% of the form potassium sulfate fertilizer) were used. The first application was done when planting and second 45 days after planting with a dose of 200 kg K ha^{-1} [7] each. Irrigation was done on plants during the experimental period as per their water needs. Manual weed control was carried out as needed.

Characteristics Studied

1. Dry Weight of the First and Second Cuttings (g $plant^{-1}$)

Dry matter content of the whole vegetative growth of the cutting including leaf and stem was calculated for all the cuttings. The first sampling was done 30 days after germination and second sampling was done 60 days after germination. The dried collected plant materials were placed in perforated paper bags and dried in an electric oven for 72 hours at 70°C. The samples were then weighed at regular intervals until a constant weight was obtained with a precision balance [12].

2. Absolute Growth Rate (A.G.R.) (g $plant^{-1}$ day^{-1})

The absolute growth rate of the sunflower was calculated using equation [13], as follows:

A.G.R. (Absolute Growth Rate) (g $plant^{-1}$ day^{-1}) = (W2 - W1) ÷ (T2 - T1)

W1 and W2 represent the dry weight of the vegetative part at the first and second cuttings, respectively, and T1 and T2 represent the time of the first and second cuttings, respectively, measured in days.

3. Grain Yield (Mg ha^{-1})

The grain yield of ten plants was determined for each experimental unit. The total yield from these plants was divided by the number of plants to obtain yield per plant and the weight of yield recorded adjusted to 15.5% moisture [12]. The individual plant grain yield was then divided by the plant population density to provide grain yield per hectare:

4. Biological yield (Mg ha^{-1})

Five plants were randomly taken from the middle rows of each experimental unit. After air drying, the plants were weighed to a precision using a precision balance. The

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mean plant production was then determined and the biological yield estimated using the following equation:

Biological yield (Mg ha^{-1}) = Yield per plant × Plant density

5. Postharvest magnesium and boron concentrations (mg kg^{-1})

Random soil samples were taken from each experimental unit after harvest from a depth of (0-30) cm, air-dried, ground, and passed through a sieve with a diameter of (2) mm. The available magnesium in the ammonium acetate extract (1 nM) was determined using an atomic absorption spectrometer, according to the methods described in [9].

The available boron was estimated using hot water and an extraction ratio of (1 soil:2 solution), and the boron concentration was estimated using an atomic spectrometer according to the method [11].

Statistical design and analysis

A randomized complete block design (R.C.B.D) was used with a two-factor system, where magnesium fertilization was represented at four levels and boron fertilization at four levels and three replicates. The average results were analyzed statistically using the SAS statistical program, and the least significant difference (L.S.D) test was used to compare the averages at the probability level (0.05) [14].

Results and Discussion

1-1 Dry Weight of the First Cutting (g plant^{-1})

The results in Table (2) show that soil fertilization with magnesium led to a significant increase in the dry weight of the first cutting, as the average of this trait gradually increased with increasing levels of application. The treatment with 21 kg of magnesium ha^{-1} recorded the highest average of 43.5 g plant^{-1}, followed by the treatment with 14 Mg ha^{-1} with an average of 39.1 g plant^{-1}, and then the treatment with 7 kg ha^{-1} which yielded 33.9 g plant^{-1}. The average for the treatment without application was the lowest at 29.1 g plant^{-1}. This improvement is due to the important functions of magnesium in plants. Magnesium is the central atom of the molecule of chlorophyll, and plays a part in activating more than 300 enzymes associated with the process of photosynthesis, the fixing of carbon dioxide, ATP synthesis, and the transport of carbohydrates from leaves to the growing tissues. This will enhance the efficiency of photosynthesis and dry matter production. Additionally, magnesium availability in gypsum soils can reduce the effects of low available magnesium and high calcium, which can benefit the vegetative growth of plants. The results are in agreement to those of [16] who showed that optimum magnesium levels, led to an improvement in photosynthetic efficiency and dry matter production.

As for the fertilisation of boron, these results indicated that the dry matter of the vegetative parts increased significantly with boron application. The average weight of no-application treatment was 31.4 g plant^{-1}, 35.3 g plant^{-1} with 5 kg ha^{-1} of B and 38.4 g plant^{-1} with 10 kg ha^{-1} of B. The treatment of 15 kg ha^{-1} showed the highest average weight per plant of 40.6 g plant^{-1}. This is due to the important role of B in cell wall formation, cell wall stability, the integrity of plasma membranes, and the translocation of sugars and carbohydrates from the leaves to the growing organs. This promotes faster cell division and cell elongation, which promotes the growth of more biomass. Boron also plays a role in the efficiency of nutrient use and this directly affects the dry weight of the vegetative parts

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of the plants. The result agrees with the values reported by [15] which indicate that boron is physiologically important for plant growth and dry matter formation.

The effect of Magnesium x Boron on dry weight of vegetative parts was significant. The highest value was 49.9 g plant^{-1}, corresponding with the treatment where 21 kg of magnesium ha^{-1} and 15 kg of boron ha^{-1} were applied, the lowest value was 26.1 g plant^{-1} in the treatment that did not have magnesium and boron applied.

Table (2) Effect of fertilization with magnesium and boron and the interaction between them on the dry weight of the vegetative mass of the first cutting (g plant^{-1})

Magnesium Level (kg ha^{-1})	Boron Level (kg ha^{-1})				Mean Magnesium
	0	5	10	15	
0	26.1	28.4	30.2	31.5	29.1
7	29.8	33.1	35.6	37.2	33.9
14	33.5	37.9	41.3	43.8	39.1
21	36.2	41.6	46.4	49.9	43.5
Mean Boron	31.4	35.3	38.4	40.6	-

LSD (0.05)	Magnesium	Boron	Mg × B Interaction
	2.35	2.28	4.70

2-2 Dry Weight of the Green Body - Second Cutting (g plant^{-1})

The results in Table (3) indicate that soil fertilization with magnesium led to a significant The dry weight of the green body was increased at the second cutting. At the application rates of 7, 14 and 21 kg Mg ha^{-1}, this characteristic increased to 81.6, 92.7 and 103.8 g plant^{-1}, respectively, on average compared with the no-apply treatment. As the plant develops, the importance of magnesium in photosynthetic efficiency and in the activation of some enzymes involved in carbon fixation and in the transport of photosynthetic products results in an increased dry matter content as the plant grows.[17]

In the case of boron, results indicated that applying higher rate of B increased the dry weight of the vegetative parts with average 76.6, 84.9, 91.8, and 96.5 g plant^{-1} at 0, 5, 10, and 15 kg B ha^{-1}, respectively. This is thought to be due to the ability of boron to stimulate cell division and elongation and increase the movement of sugar from the foliage to the growing tissues, thereby enhancing dry matter production. This result agrees with that of [18] who showed that Boron supplied in the form of Boric Acid was found to be beneficial to vegetative growth and biomass production of sunflowers.

The interaction of Mg and B was also significant in this case, since the application of 21kg Mg e^{-1} and 15kg B e^{-1} produced the best vegetative body dry weight of 117.6 g plant^{-1} compared to not adding B and Mg which had the lowest dry weight of 65.3 g plant^{-1}.

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Table (3) Effect of fertilization with magnesium and boron and the interaction between them on the dry weight of the vegetative body of the second cutting (g plant^{-1})

Magnesium Level (kg ha^{-1})	Boron Level (kg ha^{-1})				Mean Magnesium
	0	5	10	15	
0	65.3	70.1	74.6	77.2	71.8
7	72.4	79.8	85.3	88.9	81.6
14	80.6	90.2	97.5	102.4	92.7
21	87.9	99.7	109.8	117.6	103.8
Mean Boron	76.5	84.9	91.8	96.5	-
LSD (0.05)	Magnesium 3.81		Boron 3.19		Mg × B Interaction 6.52

3-3 Absolute Growth Rate (g plant^{-1} day^{-1})

From the result in Table (4) it is observed that there is a significant improvement in the absolute growth rate of sunflower plants as a result of soil fertilization by magnesium. This trait showed gradual increase with increasing rates and the highest average value (1.895 g plant^{-1} day^{-1}) was observed in the 21 kg ha^{-1} rate as compared to the control (1.423 g plant^{-1} day^{-1}). This improvement is due to the fact that magnesium is part of the molecule of chlorophyll and is a basic factor in the activation of many enzymes involved in the fixation of carbon dioxide and in the process of photosynthesis. In addition, it is involved in an increase in dry matter accumulation and the absolute growth rate by participating in the formation of Mg-ATP complexes used for energy transfer within the cell, as well as loading sugars into the phloem and transporting them to the growing organs. Sufficient levels of magnesium also ensure the integrity of the chloroplasts and postpone senescence of leaves, thereby extending the efficiency of photosynthesis and the rate of vegetative growth. The findings tie in with those of [19] and.[20]

Besides, the absolute growth rate increased significantly with increasing the level of boron fertilization and increased from 1.473 to 1.804 g plant^{-1} day^{-1} when the level of boron fertilization was raised up to 15 kg ha^{-1}. This is attributed to boron's vital role in maintaining cell wall structure and plasma membrane stability, as well as its contribution to cell division and elongation, and the regulation of sugar and solute transport to growth areas. This, in turn, speeds up the development of new tissues and rate of dry matter production. Boron also plays a role in making the growth processes more efficient in terms of better utilization of other nutrients and better activity of meristematic tissue. The results agree with .[21]

The effect of magnesium with boron was highly significant for the absolute growth rate. The treatment with 21 kg Mg ha^{-1} and 15 kg B ha^{-1} had the highest growth rate of 2.113 g plant^{-1} day^{-1}, and the lowest growth rate was observed in the control treatment with 1.302 g plant^{-1} day^{-1}. This means that the two elements complement each other. Magnesium results in more efficient photosynthesis and carbohydrate synthesis, and boron aids in the movement of these materials to growing tissues and helps keep meristematic cell activities going,

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which increases the rate of dry matter increase and the absolute rate of growth. In addition, the combined treatment brings better nutrient balance which increases the efficiency of nutrient use and plant physiological activity, particularly when the nutrient availability in the soil is low, a phenomenon that is known as the superiority of the combined treatment over the nutrient addition via the two elements separately.

Table (4) Effect of fertilization with magnesium and boron and the interaction between them on the absolute growth rate (g plant^{-1} day^{-1})

Magnesium Level (kg ha^{-1})	Boron Level (kg ha^{-1})				Mean Magnesium
	0	5	10	15	
0	1.302	1.394	1.472	1.526	1.423
7	1.418	1.532	1.611	1.678	1.560
14	1.534	1.697	1.805	1.897	1.733
21	1.639	1.842	1.986	2.113	1.895
Mean Boron	1.473	1.616	1.718	1.804	-

LSD (0.05)	Magnesium	Boron	Mg × B Interaction
	0.056	0.051	1.102

4-4 Grain Yield (Mg ha^{-1})

As shown in Table (5), the application of magnesium fertilizer to the soil significantly improved the yield of sunflower grain. Increasing rates of application of magnesium resulted in a progressive increase in grain production. The maximum yield of 4382 Mg ha^{-1} was recorded with the application of 21 kg Mg ha^{-1}, followed by 3.940 Mg ha^{-1} at 14 kg Mg ha^{-1} and 3.475 Mg ha^{-1} at 7 kg Mg ha^{-1}. The control treatment (no magnesium 0 kg Mg ha^{-1}) recorded the lowest yield of 3.092 Mg ha^{-1}.

This increase in yield could be due to the importance of magnesium in plant physiology, particularly in the production of chlorophyll and activation of many enzymes related to photosynthetic processes. Magnesium is also essential in sucrose transport in the phloem, as well as the movement of the photosynthetic products from leaves to sink organs. Thus, sufficient magnesium supply can improve grain production through an increase in seed filling. The results are in agreement with those of [22] who found that magnesium application to magnesium deficient calcareous soils showed significant improvement in yield of sunflower..

The results also show that boron fertilization significantly increased grain yield. The average yield was 3.305 Mg ha^{-1} when boron was not added, then it rose to 3639 Mg ha^{-1} with the addition of 5 kg B ha^{-1}, and to 3.886 Mg ha^{-1} at a level of 10 kg B ha^{-1}. The 15 kg B ha^{-1} level recorded the highest average yield of 4.059 Mg ha^{-1}. This can be explained by the vital role of boron in improving flower formation, increasing pollen germination efficiency, lengthening the pollen tube, and completing the fertilization process. Furthermore, it contributes to sugar translocation and regulates carbohydrate metabolism within the plant, which positively impacts the number and weight of filled seeds and the grain yield.

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These results are consistent with those reported in [23].

The interaction between magnesium and boron showed a significant effect on grain yield, as the treatment of adding 21 kg Mg ha⁻ ¹ with 15 kg B ha⁻ ¹ recorded the highest yield of 4.912 Mg ha⁻ ¹, while the control treatment recorded the lowest yield of 2.812 Mg ha⁻ ¹.

Table (5). Effect of magnesium and boron fertilization and their interaction on sunflower grain yield (Mg ha⁻ ¹)

Magnesium Level (kg ha⁻ ¹)	Boron Level (kg ha⁻ ¹)				Mean Magnesium
	0	5	10	15	
0	2.812	3.045	3.212	3.298	3.092
7	3.124	3.421	3.618	3.735	3.475
14	3.487	3.856	4.127	4.289	3.940
21	3.796	4.234	4.587	4.912	4.382
Mean Boron	3.305	3.639	3.886	4.059	-
LSD (0.05)	Magnesium		Boron		Mg × B Interaction
	0.168		0.146		0.292

5.5 Biological Yield (Mg ha⁻ ¹)

The results in Table (6) show that soil fertilization with magnesium led to a significant increase in the biological yield of sunflower plants. The average yield increased gradually with increasing application levels. The highest average yield was recorded at 14.27 tons ha⁻ ¹ at 21 kg Mg ha⁻ ¹, followed by 14 kg Mg ha⁻ ¹ at 12.92 tons ha⁻ ¹, and then 7 kg Mg ha⁻ ¹ at 11.45 tons ha⁻ ¹. The yield of control treatment (0 kg Mg ha-1) was the lowest average of 10.30 tons ha-1.

This superiority is attributed to the fact that magnesium is a part of the molecule of chlorophyll and plays a significant role in the activation of many enzymes that are involved in photosynthesis and carbohydrate metabolism. Moreover, it is involved in the production of ATP and is a stimulator of sugar loading in the phloem, increasing the amount of dry matter produced and accumulated in the plant, which has a positive effect on biological yield. This result is consistent with the result reported by [24] that sufficient magnesium nutrition results in an improvement of photosynthetic efficiency and increased biomass in the crops.

Boron fertilization also resulted in a significant increase in biological yield. The 15 kg B ha⁻ ¹ level yielded the highest average of 13.26 Mg ha⁻ ¹, followed by the 10 kg B ha⁻ ¹ level with an average of 12.75 Mg ha⁻ ¹, and then the 5 kg B ha⁻ ¹ level with an average of 11.99 Mg ha⁻ ¹.The control treatment (0 kg B ha⁻ ¹) recorded the lowest average yield of 10.94 Mg ha⁻ ¹.

This is attributed to boron's contribution to cell wall formation and the maintenance of cell membrane integrity. It also plays a crucial role in sugar transport, cell division regulation, and meristematic tissue growth, thereby increasing the efficiency of photosynthesis utilization and promoting dry matter accumulation in the plant. [25] demonstrated that boron supplementation increased dry matter production and

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sunflower seed yield due to improved plant physiological activity.

The interaction between the two study factors showed a significant effect on biological yield. The treatment of 21 kg Mg ha^{-1} × 15 kg B ha^{-1} resulted in the highest yield of 15.86 tons ha^{-1}, while the control treatment of 0 kg Mg ha^{-1} × 0 kg B ha^{-1} recorded the lowest yield of 9.52 tons ha^{-1}.

Table (6) Effect of fertilization with magnesium and boron and the interaction between them on the biological yield of sunflower (Mg ha^{-1})

Magnesium Level (kg ha^{-1})	Boron Level (kg ha^{-1})				Mean Magnesium
	0	5	10	15	
0	9.520	10.140	10.630	10.910	10.300
7	10.380	11.270	11.890	12.240	11.450
14	11.460	12.680	13.520	14.020	12.920
21	12.390	13.870	14.950	15.860	14.270
Mean Boron	10.940	11.990	12.750	13.260	

LSD (0.05)	Magnesium	Boron	Mg × B Interaction
	0.410	0.340	0.690

6.6 Post-Harvest Soil Magnesium Concentration (mg kg^{-1})

The results in Table (7) indicate that magnesium fertilization significantly increased the post-harvest soil magnesium concentration. The average concentration increased gradually with increasing application levels, with the highest average magnesium recorded at 20.010 mg kg^{-1}, compared to the control treatment which recorded the lowest average at 8.910 mg kg^{-1}. This is attributed to the fact that the added magnesium was not fully utilized by the plant, resulting in some remaining in an exchangeable form within the cation exchange complex in the soil. Furthermore, the increased magnesium concentration in the soil solution enhanced the chances of the exchange sites retaining this element, which was reflected in the higher post-harvest magnesium concentration. This result aligns with the findings of Wang et al. (2020), who demonstrated that increasing magnesium fertilization rates leads to higher levels of available magnesium in the soil, with the extent of the increase varying depending on soil properties and cation exchange capacity.

As far as available boron concentration is concerned, the result indicated that there was a significant effect on available magnesium concentration in the soil. The average is slowly rising from 13.563 mg kg-^{1} without the application of boron to 15.109 mg kg-^{1} at the highest level of boron application. This is due to the ability of boron to promote better root system development and more efficient plant physiological processes, which subsequently led to better root environment and thus less magnesium leaching from the root zone. In addition, better nutrient balance could lead to greater soil cation exchangeable magnesium. Indirect effects on microbial activity and nutrient dynamics may also be influenced by boron, and affect the availability of magnesium after the growing season. There was also a significant interaction effect between magnesium and boron level, which was observed in the

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results. The highest post harvest level of magnesium was recorded at the highest rate of magnesium and boron (12.0 mg kg^{-1}), and the lowest level of magnesium was recorded under the control treatment at 8.318 mg kg^{-1}. Table (7) Effect of Magnesium and Boron Fertilization and Their Interaction on Post-Harvest Soil Available Magnesium Concentration (mg kg^{-1})

Table (7) Effect of magnesium and boron fertilization and the interaction between them in Post-harvest Soil Magnesium Concentration (mg kg^{-1})

Magnesium Level (kg ha^{-1})	Boron Level (kg ha^{-1})				Mean Magnesium
	0	5	10	15	
0	8.318	8.741	9.093	9.487	8.910
7	11.582	12.137	12.624	13.081	12.356
14	15.214	15.873	16.295	16.958	16.085
21	19.137	19.712	20.281	20.911	20.010
Mean Boron	13.563	14.116	14.573	15.109	
LSD (0.05)	Magnesium		Boron		Mg × B Interaction
	0.624		0.517		1.035

7-7 Post-Harvest Soil Available Boron Concentration (mg kg^{-1})

As shown in Table (8), the post-harvest soil available boron concentration was significantly affected by the boron fertilization. The average values of the concentration increased with increasing amounts of boron applied: from 0.293 mg kg^{-1} without boron application to 0.448, 0.615 and 0.800 mg kg^{-1} at 5, 10 and 15 kg ha^{-1}, respectively. This increasing trend has arisen because part of the boron applied has been left in the soil once the plant has absorbed all of its requirements. Bulk amounts not taken up by the plant stay in the soil solution or are weakly complexed to soil particles, augmenting the amount of boron available after the crop harvest. As regards the effect of magnesium levels, it was found that the available amount of boron in the soil significantly increased. The average concentration was 0.493 mg kg^{-1} when magnesium was not added, then it rose to 0.518, 0.553, and 0.593 mg kg^{-1} at levels of 7, 14, and 21 kg ha^{-1}, respectively. This rise in this can be attributed to the fact that Magnesium addition had a positive effect on soil fertility and nutrient balance which eventually enhanced the root environment and nutrient dynamics, allowing a higher proportion of Boron to remain available after harvest. In addition, under specific conditions, plant nutrition modifications can lead to a decrease in boron depletion, which can result in a higher soil residual concentration. This result is in line with the result obtained by [26] who said that nutrient balance directly influences with the micronutrient dynamics of the soil and that balanced fertilization management helps to increase nutrient-use efficiency and nutrient availability.

The interaction between magnesium and boron levels significantly affected the post-harvest boron concentration in the soil. The treatment that included the addition of 21 kg magnesium ha^{-1} and 15 kg boron ha^{-1} recorded the highest concentration of 0.88 mg kg^{-1}, while the treatment that did not add either element recorded the lowest concentration of 0.27 mg kg^{-1}.

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Table (8) Effect of fertilization with magnesium and boron and the interaction between them in Post-Harvest Soil Available Boron Concentration (mg kg⁻ ¹)

Magnesium Level (kg ha⁻ ¹)	Boron Level (kg ha⁻ ¹)				Mean Magnesium
	0	5	10	15	
0	0.27	0.41	0.56	0.73	0.493
7	0.28	0.43	0.59	0.77	0.518
14	0.30	0.46	0.63	0.82	0.553
21	0.32	0.49	0.68	0.88	0.593
Mean Boron	0.293	0.448	0.615	0.800	
LSD (0.05)	Magnesium		Boron		Mg × B Interaction
	0.032		0.040		0.059

Conclusions and Recommendations

Conclusions

• The results showed that soil fertilization with magnesium significantly and progressively affected all studied growth and yield characteristics, with the best performance achieved at the (21) kg ha⁻ ¹ level.

• Soil fertilization with boron resulted in a significant improvement in growth characteristics and yield, with optimal performance achieved at a level of 15 kg ha⁻ ¹ of boric acid. This was associated with improved fertilization efficiency and grain filling.

• The interaction between magnesium and boron fertilization levels showed a clear and significant advantage when 21 kg magnesium ha⁻ ¹ was added with 15 kg boron ha⁻ ¹. This treatment achieved the highest values in all growth and yield characteristics.

Recommendations

• It is recommended to conduct this experiment in the field at multiple locations and across different growing seasons to verify the results.

• Follow-up studies to assess the response to elevated levels of magnesium and boron, and assess the toxicity threshold and where necessary, reduce the risk of toxicity, especially for boron.

• Investigate the effect of magnesium and boron fertilization on qualitative characteristics such as oil and protein content in sunflower seeds.

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