AJBS
Asian Journal of
Biological Sciences

OPEN ACCESS

Effect of Sulfur Levels and Application Timing on Microelement Concentration and Soil Interaction during the Growth Stages of *Zea mays* L.

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ABSTRACT

Background and Objective: Soil pH and micronutrient availability play a crucial role in the productivity of maize (*Zea mays* L.). However, limited information exists on how different levels and application times of agricultural sulfur influence the soil interaction degree and micronutrient concentrations during maize growth. This study aimed to evaluate the effect of sulfur application levels and timings on soil interaction (pH) and the concentration of iron, manganese, zinc, and copper at various growth stages of maize. **Materials and Methods:** A field experiment was conducted during the summer seasons of 2021-2022 at the College of Agriculture, University of Wasit. The experiment involved two sulfur application times 30 days before planting and 15 days after the first application with four sulfur levels (500, 1000, 1500, and 2000 kg/ha) in addition to a control. Soil pH and micronutrient concentrations in maize tissues were measured at germination, flowering, and harvesting stages. Data were statistically analyzed using Genstat and an electronic calculator based on ANOVA, with treatment means compared using the modified LSD test at a 0.05 significance level. **Results:** Sulfur application at 2000 kg/ha, added 30 days before planting, resulted in the lowest soil interaction (pH) values 6.43, 6.83, and 6.93 during germination, flowering, and harvesting, respectively, compared with the control (7.65, 7.68, and 7.77). The same treatment recorded the highest concentrations of iron (56.77 mg/kg/plant), manganese (46.80 mg/kg/plant), zinc (21.33 mg/kg/plant), and copper during the flowering stage, significantly exceeding the control values (33.47, 22.33, and 11.77 mg/kg/plant, respectively). **Conclusion:** The study demonstrated that applying 2000 kg/ha of agricultural sulfur 30 days before planting effectively reduced soil pH and enhanced the availability of essential micronutrients, thereby improving maize growth. These findings highlight the importance of optimizing sulfur management for better nutrient uptake and soil health in maize cultivation.

KEYWORDS

Sulfur levels, addition times, microelements, soil interaction degree, *Zea mays*

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INTRODUCTION

The *Zea mays* is one of the strategic crops in the world as a result of its high nutritional value and the increasing demand for it for food, industry, and biofuel purposes. It is considered economically important as its seeds contain carbohydrates, oils, and proteins. It was found that 1 kg of them liberates

ISSN: 1996-3351 (Print)
https://doi.org/10.3923/ajbs.2026.01.11

Received: 08 Sep. 2025
Accepted: 10 Jan. 2026
Published: 31 Mar. 2025

3460 calories and 93 g of protein, and that yellow corn occupies the second place in the world after wheat in terms of the cultivated area, which may reach about 166 million hectares. However, it occupies the first place in terms of production out of the total global production of grains, which amounted to 963 million tons. The cultivation of this plant is still low in Iraq. The production rate of yellow corn is about 340 thousand tons, and the area used for agriculture is 130 thousand hectares[1].

The sulfur constitutes 0.1% of the Earth's crust and in the soil; it is present in many forms, including free or combined forms with the basic elements Ca, Mg, Na, and K in the soils of arid and semi-arid regions. The sources of sulfur in the soil it is mineral sulfur, which includes pyrite and volcanic sources, and it may also be extracted from gas and oil. Mined sulfur is freely available in Iraq in the Al-Mishraq Region[2]. Also, pure sulfur S 100% can be used. As well as sulfur purification residues such as pure sulfur, agricultural sulfur 90%, and foamy sulfur 75% S, which is a by-product of sulfur manufacture, to increase the readiness of sulfur, phosphorus, and other nutrients from their compounds deposited in the soil, by reducing the degree of soil interaction through the formation of sulfuric acid H_2SO_4. This biological oxidation takes place by reviving the aerial soil, the genus Thiobacillus, including the type *Thiobacillus thiooxidans*, in order to compensate for the lack of sulfur in the plant and soil by reducing the use of phosphorus fertilizers. It is necessary to increase crop productivity and also plant resistance to fungal diseases[3].

The oxidation rate of sulfur may be affected by the date and amount of sulfur added, as well as the size of the sulfur particles. It was found that the rate of oxidation of sulfur added at a rate of 4 tons/ha may occur quickly and as a result, give effects that are reflected in the soil properties after two weeks of addition. However, the speed of oxidation and its effect on soil properties decreased by increasing the rate of addition at levels (8-12 µg/ha) and even after 8 months of the addition process. The Iraqi soil is considered one of the soils of the arid and semi-arid regions, as this may have a high content of calcium carbonate $CaCO_3$ and the degree of its interaction is high and tends to be alkaline. This leads to a decrease in the availability of nutrients, especially micronutrients. It is necessary to know the most important methods that will increase the availability and liberation of these elements, and thus increase the productivity and growth of the crop, which is important in increasing the physiological processes of the plant. Among these methods is the addition of agricultural sulfur, which participates in many reactions that may occur in the soil[4]. The degree of interaction in such soils tends to be alkaline, and this negatively affects most of the availability of nutrients needed for plant growth in the soil. This will be reflected in the agricultural yield and its components[5,6].

The production of sulfur in large quantities in Iraq, which may reach more than one million tons annually, therefore, adding it to calcareous soils will lead to an increase in the availability of nutrients in the soil, which will lead to an increase in the growth and production of crops, including the yellow corn crop. Therefore, the study aimed to study the effect of four different levels of agricultural sulfur with different application dates on the degree of soil interaction and the growth and yield. Also, study the effect of agricultural sulfur and the date of its addition on the liberation of microelements and the response of the crop.

MATERIALS AND METHODS

Experiment site: A field experiment was applied cultivating (*Zea mays* L.) in the fields of the College of Agriculture, Wasit University, Iraq, during the fall season 2021-2022 in sandy loam soil. The crop was planted on 7/8/2022.

Experiment factors: The experiment involved two factors, the first factor included four levels of agricultural sulfur: 0, 500, 1000, 1500, 2000 kg/ha, and these levels were coded (S1, S2, S3, and S4). The second factor included two dates for the addition, which is (adding agricultural sulfur a month before planting in July 1/7/2022, and adding agricultural sulfur 15 days after planting in 21/8/2022 and their symbols is (T1 and T2).

Preparing the experimental ground: An area of 260 m^2 was determined for the field, with dimensions of 30x12 m^2. The experimental land was plowed with a plow, and then plowed, and then the necessary leveling operations were carried out. The field was divided into three sectors, after which the process of plowing, leveling, and adjusting the land was done again, of the bushes, and three main drivers were opened along the field, including sub-slabs for each slab. The field was divided into 27 experimental units, and the field was divided into three large sectors. Each sector was divided into experimental units with dimensions 2×3 m^2 and a total area of 6 m^2. A distance between the treatments was within the sector or one repeater, as a precautionary measure to prevent the movement of water from one treatment to another.

Collect the soil samples: Soil samples were taken from the planting stage to the harvesting stage, including before planting from most of the experimental units, after dividing the field, and at various points to ensure representativeness of the field. They were used to estimate some chemical, physical, and fertility soil characteristics of the field Table 1. Samples were taken in the germination stage on 4/9/2022 and the flowering stage on 10/4/2022. Soil and plant samples were collected from each experimental unit in the germination and flowering stage to estimate Fe, Mn, Cu, and Zn, as well as the degree of soil interaction and electrical conductivity for these stages were also measured. Post-harvest samples were taken as well. Plant and soil samples were collected from each experimental unit at the end of the season to estimate Fe, Mn, Cu, and Zn in the plant after planting.

Planting of seeds: Seeds of *Zea mays* L. (Ministry of Agriculture, General Authority for Agricultural Research, Department of *Zea mays*) were planted in the autumn season on 8/7/2022 with 2-3 seeds in each round. Then, after germination, it was reduced to one plant. The distance between one line and another was 75 cm, and between one plant and another 25 cm, and by three meadows for each experimental unit, so that the number of plants was 36 plants per experimental unit, and sulfur was added by making an incision in the soil with a depth of 10 cm near the planting lines. The field was regularly irrigated after adding sulfur until the planting date was reached.

Irrigation method: Water was added to each experimental unit in a fixed quantity and according to the moisture content throughout the period of plant growth, to the stage of physiological maturity. The water was delivered to the field from a groundwater tank lined as a source of irrigation. Irrigation was done by

Table 1: Some physical and chemical characteristics of the study soil

Characterize	Value	Units
pH	7.8	-----
EC	2.61	dSm
Organic element	8.01	g/k
Ca^{+2}	6.41	mmole/L
Mg^{+2}	4.01	mmole/L
K^{+}	1.03	mmole/L
Na^{+}	4.69	mmole/L
Cl^{-1}	7.89	mmole/L
$SO_4^{=}$	8.53	mmole/L
$CO_3^{=}$	Nil	mg/kg
HCO_3^{-}	0.84	mmole/L
Ready nitrogen	36.32	mg/kg
Ready phosphorous	13.5	
Ready potassium	76.5	
Iron	0.65	mg/kg
Manganese	0.46	
Zinc	0.24	
Copper	0.14	
Soil texture	sand silt clay 12 475 513	Sandy loam
Density	1.18	mg/m
True density	2.58	

a flexible plastic pipe attached to a pump that works on kerosene to supply the field with water. During the irrigation process, amounts of water were added according to the moisture content at 50% depletion to all experimental units when planting, where each experimental unit was irrigated alone, and the drainage was fixed inside the experimental unit before starting each irrigation, as the number of irrigations from the beginning of cultivation to the irrigation of weaning reached 18 irrigations.

The method and time of adding chemical fertilizers: Urea fertilizer was used CO_2 (NH2) 46% N at a rate of 150 kg N/ha as a source of nitrogen, and concentrated superphosphate fertilizer 20% p Ca (H2Po4) (2.H2O) at a rate of (150 kg P/ha) as a source of phosphorus and potassium sulfate 50% (K2 SO4) at a rate of 60 kg/ha.

The first batch: It includes the addition of all phosphate fertilizers at planting and for all experimental units, 1/2 of the nitrogen fertilizer and 1/2 of the potassium fertilizer for experimental units, two weeks after germination. The second batch: Adding the remaining nitrogen and potassium fertilizer on 10/6/2022 to the experimental units.

Chemical and physical analyses of the soil

Physical analyses: Volumetric analysis of soil particles: The size distribution of soil particles was estimated using the Hydrometer method[7].

Density: It was estimated using the core sample method[8].

Chemical analyses

Degree of soil reaction: It was estimated in the soil extracted by dilution method 1:1 using a PH meter[9].

Electrical conductivity (EC): It was estimated in the extracted soil by the 1:1 dilution method and by using the EC meter.

The exchange capacity of positive ions (CEC): It was estimated by saturation with sodium acetate solution (1M) and extraction with ammonium acetate[7].

Calcium carbonate ($CaCO_3$): Where the percentage of calcium carbonate minerals was estimated using acid (1N) (HCl) and pulverizing the remaining acid by means of (1N)) (NaOH)[8].

Carbonate and bicarbonate ions: It was estimated by leaching with sulfuric acid 0.01N (H_2SO_4)[8].

Sulfate: The extraction of the ready sulfate ion was estimated using calcium phosphate (CaH_2PO_4), and then the concentration of sulfate in the extracts was measured by the turbidity method, using barium chloride $BaCl_2$. $2H_2O$ using a spectrophotometer at a wavelength of 420 nm.

Organic matter: It was estimated by the wet digestion method, according to the Walkley and black method[8].

Nitrogen: It was extracted using a solution of potassium chloride (2N), and estimated using the microcalculator[7].

Phosphorous: Sodium bicarbonate solution was used at (PH 8.5), and the color was changed using a solution of ammonium molybdate and ascorbic acid as a reducing agent, and it was measured by a spectrophotometer at a wavelength of 882 mn[10].

Potassium: An ammonium acetate solution (1 M) was used and measured using a Flame photometer[8].

Iron, manganese, zinc, and copper: The concentration of these elements in the soil was estimated by adding 20 mL of a 0.005 M standard extraction solution (DTPA), which reacts to a pH = 7.5, and was added to 10 g of soil, and was shaken for two hours and filtered. Then these ions were estimated using an atomic absorption spectroscopy device, Spectrophotometer type (PG500).

Analyses studied in the experiment

Soil analysis: Soil samples were taken from each experimental unit before the addition of agricultural sulfur. The samples were taken from a depth of 0-30 cm, mixed homogeneously, air-dried, smoothed, and then passed through a sieve with a diameter of 2 mm. A composite (representative) sample was taken from each treatment, in order to perform the above-mentioned analyses of the soil of the study, where the degree of soil interaction pH and the electrical conductivity Ec were measured in the soil filter at a ratio of 1:1 using the Ec meter and Ph meter, respectively. According to the methods described in BK and Shrestha[10], the concentration of iron, manganese, zinc and copper ions was also measured in the samples taken by the extraction method[11] by adding 20 mL of DTPA extraction solution with a reaction degree (pH = 7.5) to 10 g of soil, and it was shaken for two hours and filtered. Then, the concentrations of these ions were estimated using an atomic absorption device, and the sampling process was repeated to perform the above analyses for the soil of the field in the flowering stage. As for the harvesting stage, the degree of soil interaction, electrical conductivity, and the concentration of micronutrients were measured for the samples taken.

Plant analysis: The plant samples were taken in the vegetative growth stage, and an analysis process was carried out for the required elements, iron, manganese, zinc and copper, in the plant samples, and the wet digestion method was followed. A group of plant samples was taken randomly from each experimental unit in the stages of germination, flowering, and harvesting, then they were washed with plain water and then with distilled water to remove suspended dust, then dried and mixed homogeneously, then ground and placed in paper bags marked with transaction numbers.

Digestion of plant samples: Representative samples of the plant were taken in the stages of germination, flowering and harvesting from the vegetative system (stalk, leaves) prepared for analysis with a weight of 0.2 g of the plant sample, and placed in a volumetric glass (Pyrex) flask. The 3 mL of concentrated sulfuric acid was added to it and left for the next day until the color became black. To it was added 1 mL of a mixture of concentrated acids at a ratio of 1:1 (98% concentrated sulfuric acid +96% H_2SO_4 concentrated perchloric acid ($HClO_4$) and then placed on a hot plate for heating to complete the digestion process until the color of the solution became clear (colorless). Filtered by filter paper inside a volumetric flask with a capacity of 50 cm and completed the volume to the mark with distilled water. The elements were estimated using an atomic absorption spectrophotometer in the laboratory of the Technical Institute-Shatrah.

Statistical analysis: After conducting a data collection process and classifying it, statistically analyzed using the electronic calculator and the Genstat program according to the method used in the analysis of variance. The modified Least Significant Difference (LSD) test was used to compare the rates of the transactions at a significant level of 0.05.

RESULTS AND DISCUSSION

Effect of agricultural sulfur levels and application dates on the concentration of some micronutrients: The results of the statistical analysis, 30 days after germination of seeds, showed that there was a significant effect of the levels of added sulfur and the dates of addition in the germination stage (after 30 days of germination), and that the highest rate of decrease in the degree of reaction was when adding 2000 kg/ha (T1S4) on the first date (Table 2). The highest rate of decrease in the degree of interaction was 6.83 compared to the control treatment, which amounted to 7.65, which differed

Table 2: The effect of sulfur levels and application times on the degree of soil interaction during the growth stages of plants

		Degree of soil interaction		
Treatment code	Treatment/Average	After germination	Flowering	Post-harvest
T0S0	0	7.65	7.68	7.77
T1S1	500 kg/ha+first time	7.13	6.95	7.36
T1S2	1000 kg/ha+first time	6.95	6.83	7.26
T1S3	1500 kg/ha+first time	6.89	6.65	7.11
T1S4	2000 kg/ha+first time	6.83	6.43	6.93
T2S1	500 kg/ha+second time	7.24	6.98	7.4
T2S2	1000 kg/ha+second time	6.98	6.86	7.28
T2S3	1500 kg/ha+second time	6.95	6.76	7.15
T2S4	2000 kg/ha+second time	6.88	6.53	6.97
LSD	0.05211	0.05388	0.08596	

T0-T2 represent the sulfur application timing: T0: No sulfur (control), T1: Sulfur applied one month before planting (1/7/2022), T2: Sulfur applied 15 days after planting (21/8/2022), S1-S4 indicate sulfur rates: S1: 500 kg/ha, S2: 1000 kg/ha, S3: 1500 kg/ha, S4: 2000 kg/ha and LSD represents the least significant difference at $p<0.05$.

significantly from other treatments T1S3, T1S2, T1S1, T2S1, T2S2, T2S3, T2S4, which reached 6.88, 6.95, 6.98, 7.24, 7.13, 6.95, and 6.89, respectively. The results of the field experiment showed that there is a relationship between the level of addition of agricultural sulfur and the degree of interaction. The higher the level of addition of sulfur, the lower the degree of interaction.

The results have showed that there was a significant effect of the levels of added sulfur in reducing the degree of soil interaction during the flowering stage, as increasing the level of adding agricultural sulfur to the soil led to a decrease in the degree of soil interaction, as the sulfur treatment of 2000 (kg S/ha) for the first date achieved a significant superiority and gave the highest rate of decrease in the degree of soil interaction in the flowering stage (Table 2). It reached 6.43 compared to the control treatment, which gave the highest rate of 7.68, and the level of addition (2000 kg/ha) was significantly superior to the treatments for the two dates T1S3, T1S2, T1S1, T2S1, T2S2, T2S3, T2S4, which in turn was superior to the control treatment.

This effect is due to the microorganism responsible for that, Thiobacillus, which carried out the process of oxidation of sulfur and liberation of hydrogen ions, which led to a decrease in the degree of interaction and an increase in the readiness of the micronutrients Fe, Mn, Zn, and Cu in the soil. These results agree with Enujeke[12], that there is a significant effect on the decrease in the degree of soil reaction by increasing the amount of added sulfur.

The results also found that the harvest period after 120 days of planting, that the highest rate of decline was reached in the treatment of 2000 kg S/ha for the first date, which amounted to 6.93 compared to the control treatment, which was 7.77, and also differed significantly from the treatments T1S3, T1S2, T1S1, T2S1, T2S2, T2S3, T2S4, reaching 7.15, 7.28, 7. 4, 7.36, 7.26, 7.11 and 6.97 respectively. The effect resulting from sulfur was caused as a result of the oxidation processes accompanying this addition, which led to an increase in the formation of hydrogen ions and sulfuric acid, which worked to reduce the degree of soil interaction. These results agreed with Kandil[13], who indicated the significant effect as a result of adding sulfur, with increasing the levels of additions that improve the properties of soils with a high degree of reactivity and their trend towards a decrease over time after the addition process.

Concentration of iron in the plant (mg kg/plant): The results of the statistical analysis in Table 3 showed that there was a significant effect of the levels of added sulfur and the dates of its addition on the readiness of iron in the plant in the germination stage (30 days after germination). The rate was lower, reaching 33.36 mg kg/plant. This level was also significantly higher than the rest of the levels for

Table 3: The effect of sulfur levels and application times on iron availability during the growth stages of plants

		Rate of Fe concentration in the plant is mg kg/plant		
Treatment code	Treatment/Average	After germination	Fowering	Post-harvest
T0S0	0	33.36	33.47	33.5
T1S1	500 kg.ha^{-1}+first time	47.9	51.48	36.47
T1S2	1000 kg.ha^{-1}+first time	48.07	53.77	37.97
T1S3	1500 kg.ha^{-1}+first time	49.31	54.53	41.26
T1S4	2000 kg.ha^{-1}+first time	53.43	56.77	43.5
T2S1	500 kg.ha^{-1}+second time	47.09	50.7	35.03
T2S2	1000 kg.ha^{-1}+second time	47.04	52.38	36.43
T2S3	1500 kg.ha^{-1}+second time	48.74	53.83	39.33
T2S4	2000 kg.ha^{-1}+second time	52.2	55.17	41.43
LSD	0.05211	3.689	1.858	

T0-T2 represent the sulfur application timing: T0: No sulfur (control), T1: Sulfur applied one month before planting (1/7/2022), T2: Sulfur applied 15 days after planting (21/8/2022), S1-S4 indicate sulfur rates: S1: 500 kg/ha, S2: 1000 kg/ha, S3: 1500 kg/ha, S4: 2000 kg/ha and LSD represents the least significant difference at $p<0.05$

the two dates. The reason for this is due to the low degree of soil interaction, which is considered one of the factors helping to increase the readiness of nutrients in the soil, including iron, and this is consistent with Kaur and Sadana[14], Khaliq *et al.*[15]. As the degree of soil interaction is affected by the sulfur levels and the increase in the time period

The results showed that there is a significant effect of the levels of addition and the dates of addition on the readiness of iron at the flowering stage, the level of addition (2000 kg/ha) for the first appointment was significantly higher and gave the highest rate for this trait amounted to 56.77 mg kg/plant compared to the control treatment that gave the lowest rate reaching 33.47 mg kg/plant and this level was also superior Significantly increased on the rest of the levels and for the two dates T1S3, T1S2, T1S1, T2S1, T2S2, T2S3, T2S4, where the concentrations were 55.17, 53.83, 52.38, 50.7, 54.53, 53.77, 51.48 mg/plant, respectively.

The levels and dates of addition affected the readiness of the iron element in the flowering stage, as the level of addition (2000 kg/ha) for both dates gave the highest rates for this characteristic, reaching 56.77,55.17 mg kg/plant compared to the control treatment, which amounted to 33.47 mg kg/plant. The results showed that there was a significant effect of the levels of addition and the dates of addition on the readiness of iron at the harvest stage, where the level of addition (2000 kg/ha) for the first date was significantly higher and gave the highest rate for this trait amounted to 43.5 mg kg/Plant, compared to the control treatment, which gave the lowest rate, amounting to 33.5 mg kg/Plant. It did not differ significantly from the treatment. T1S3 and also treatment T2S4 for the second appointment did not differ significantly from treatment T2S3, and significant differences appeared between all treatments T1S3, T1S2, T1S1, T2S1, T2S2, T1S4, T2S4 (Table 3).

Manganese concentration in the plant (mg kg/plant): The results of the statistical analysis showed that there was a significant effect of the levels of added sulfur and the dates of its application on the readiness of manganese in the plant in the germination stage (30 days after germination). The lowest rate was 22.64 mg kg/plant, and did not differ significantly with the treatments, T2S3, T2S4, T1S3, which averaged 27.13, 27.83, 27.67 mg kg/plant, and significant differences appeared with the collection of levels, T1S2, T1S1, T2S1, T2S2, and the reason for this is due to the significant effect of agricultural sulfur and its addition in sufficient quantities To improve the chemical properties of the soil, including reducing the degree of interaction resulting from the biological oxidation of microorganisms, which led to the formation of sulfuric acid and then increasing the readiness of the micronutrients in it, such as manganese, and this is consistent with what was found by Khan *et al.*[16] and Dwyer *et al.*[17].

Table 4: Effect of sulfur levels and application times on manganese readiness during the growth stages of plant

		Rate of Mg concentration in the plant is mg kg/plant		
Treatment code	Treatment/Average	After germination	Flowering	Post-harvest
T0S0	0	22.64	22.33	20.47
T1S1	500 kg/ha+first time	25.31	41.67	21.57
T1S2	1000 kg/ha+first time	26.62	42.6	22.67
T1S3	1500 kg/ha+first time	27.67	45.29	23.6
T1S4	2000 kg/ha+first time	28.47	46.8	26.93
T2S1	500 kg/ha+second time	24.2	40.93	20.93
T2S2	1000 kg/ha+second time	26.47	41.07	22.47
T2S3	1500 kg/ha+second time	27.13	42.53	23.2
T2S4	2000 kg/ha+second time	27.83	46.03	23.73
LSD	0.05211	2.264	4.431	

T0-T2 represent the sulfur application timing: T0: No sulfur (control), T1: Sulfur applied one month before planting (1/7/2022), T2: Sulfur applied 15 days after planting (21/8/2022), S1-S4 indicate sulfur rates: S1: 500 kg/ha, S2: 1000 kg/ha, S3: 1500 kg/ha, S4: 2000 kg/ha and LSD represents the least significant difference at $p<0.05$

The results showed that there was a significant effect of the levels of addition and dates of addition on manganese readiness at the flowering stage, the level of addition exceeded 2000 (kg/ha) for the first date and gave the highest rate for this trait amounted to 46.8 mg kg/plant compared to the comparison treatment that gave the lowest rate as it amounted to 22.33 mg kg/plant and did not differ significantly from the treatments T1S3, T2S4, which amounted to 45.29, 46.03 mg kg/plant, and showed significant differences with the rest of the levels and for the two dates, T1S2, T1S1, T2S1, T2S2, T2S3, where the concentrations were 42.53, 41.07, 40.93, 42.6, 41.67 mg kg/plant on respectively. The reason for this is that the addition of sulfur at this level affected the degree of soil interaction through the formation of sulfuric acid, resulting from the oxidation of sulfur and a cycle in increasing the readiness of micronutrients by decreasing the rate of chemical equilibrium and sedimentation for them and reducing some of them, including the element manganese, and making it absorbable by plants. Increase its readiness and absorption by the plant (Table 4).

The levels and dates of addition affected the readiness of the element manganese in the flowering stage. The addition level of 2000 (kg/ha) for both dates gave the highest rates for this characteristic, reaching 46.03, 46.8 mg kg/plant, compared to the comparison treatment, which amounted to 22.33 mg kg/plant The results showed that there was a significant effect of the levels of addition and the dates of addition on the readiness of manganese at the harvest stage, where the level of addition of 2000 (kg/ha) for the first date was significantly higher and gave the highest rate for this trait amounting to 26.93 mg kg/plant compared to the control treatment that gave the lowest rate, reaching 20.47 mg kg/plant. This level was also superior on the rest of the levels and for the dates T1S3, T1S2, T1S1, T2S1, T2S2, T1S4, T2S4 (Table 4).

Copper concentrate in the plant (Cu mg kg/plant): The results of the statistical analysis showed that there was a significant effect of the levels of added sulfur and the dates of addition on the readiness of copper in the plant in the germination stage (30 days after germination). It was significant differences appeared with the rest of the levels: T1S3, T1S2, T1S1, T2S1, T2S2, T2S3, T2S4. This is consistent with Chu *et al.*[18] and Martinez and Ramos[19].

The results indicated that there was a significant effect of the levels of addition and the dates of addition on the readiness of copper at the flowering stage. The level of addition (2000 kg/ha) for the first date was significantly higher and gave the highest rate for this trait, amounting to 6.84 mg kg/plant, compared to the control treatment. It has been given the lowest rate, amounting to 3.66 mg kg/plant, where there are significant differences. With the rest of the levels and for the two dates T1S3, T1S2, T1S1, T2S1, T2S2, T2S3, T2S4, where the concentrations were 6.67, 6.44, 6.16, 5.86, 6.48, 6.26, 5.99 mg kg/plant, respectively. The reason for this is that the addition of sulfur at this level affected the degree of L reaction Soil through the formation of sulfuric acid, resulting from sulfur oxidation, and a cycle in increasing the readiness of micronutrients by decreasing the degree of soil interaction and making the copper element absorbable by plants (Table 5).

Table 5: Effect of sulfur levels and application times on copper readiness during the growth stages of plant

		Rate of Cu concentration in the plant is mg kg/plant		
Treatment code	Treatment/Average	After germination	Flowering	Post- harvest
T0S0	0	3.84	3.66	3.8
T1S1	500 kg/ha+first time	5.36	5.99	4.23
T1S2	1000 kg/ha+first time	5.49	6.26	4.67
T1S3	1500 kg/ha+first time	5.93	6.48	4.75
T1S4	2000 kg/ha+first time	6.43	6.84	5.27
T2S1	500 kg/ha+second time	5.13	5.86	4.07
T2S2	1000 kg/ha+second time	5.4	6.16	4.37
T2S3	1500 kg/ha+second time	5.84	6.44	4.66
T2S4	2000 kg/ha+second time	6.03	6.67	4.8
LSD	0.05211	0.4860	0.2933	

T0-T2 represent the sulfur application timing: T0: No sulfur (control), T1: Sulfur applied one month before planting (1/7/2022), T2: sulfur applied 15 days after planting (21/8/2022), S1-S4 indicate sulfur rates: S1: 500 kg/ha, S2 = 1000 kg/ha, S3 = 1500 kg/ha, S4: 2000 kg/ha and LSD represents the least significant difference at $p<0.05$

The levels and dates of addition affected the readiness of the copper element in the flowering stage. The addition level of 2000 (kg/ha) for both dates gave the highest rates for this trait that reaching 6.84, 6.67 mg kg/plant, compared to the control treatment, which amounted to 3.66 mg kg/plant. The results showed that there was a significant effect of the levels of addition and the dates of addition on the readiness of copper at the harvest stage, where the level of addition 2000 (kg/ha) for the first date was significantly higher and gave the highest rate for this trait amounted to 5.27 mg kg/plant, compared to the control treatment that gave the lowest rate, reaching 3.8 mg kg/plant, and this level was significantly superior to the rest. Levels and dates T1S3, T1S2, T1S1 , T2S1, T2S2, T2S3, T2S4 (Table 5).

Concentration of zinc in the plant (Cu mg Kg/plant): The results of the statistical analysis showed that there was a significant effect of the levels of added sulfur and the dates of application on the readiness of zinc in the plant in the germination stage (30 days after germination). The rate decreased, reaching 12.83 mg kg/plant, and did not differ significantly with the treatment T2S4, as it reached 16.06 mg kg/plant, and significant differences appeared with the rest of the levels T1S3, T1S2, T1S1, T2S1, T2S2, T2S3, T2S4 with Tabak *et al.*[20], Nazar *et al.*[21] and Oluwatosin and Ajani[22] found, the sulfur added to the soil at the level of 2000 (kg/ha) had a significant effect in increasing the concentration and readiness of the zinc element.

The results indicated that there was a significant effect of the levels of addition and dates of addition on the readiness of zinc at the flowering stage. The level of addition of 2000 (kg/ha) for the first date was significantly higher and gave the highest rate for this trait, amounting to 21.33 mg kg/plant, compared to the comparison treatment, which gave the lowest rate, amounting to 11.77 mg kg/plant. It did not show any differences. Significant with the treatments T1S3, T1S2, T2S3, T2S4, which amounted to 17.07, 20.9, 18.33, 17.5 mg kg/plant, where significant differences appeared with the rest of the levels and for the two dates, T1S1, T2S1, T2S2, where the concentrations were 16.73, 15.63, 16.47 mg kg/plant, respectively. The reason for this was as a result of the increase in the levels of added sulfur, which led to a decrease in the degree of interaction of the soil, which led to an increase in the availability of micronutrients, including zinc, and thus its absorption by plants, and this is consistent with Singh *et al.*[23]; Tisdale *et al.*[24]; Valentinuza and Tollenaar[25] and Wn *et al.*[26] that the added sulfur in an amount of 2000 (kg/ha) led to an increase in the zinc content of plants.

The levels and dates of addition affected the readiness of the element zinc in the flowering stage. The addition level of 2000 (kg/ha) for both dates gave the highest rates that reaching 21.33, 18.33 mg kg/plant, compared to the control treatment, which amounted 11.77 mg kg/plant. The results showed that there was no significant effect of the levels of addition and the dates of addition on the readiness of

Table 6: The effect of sulfur levels and application times on zinc availability during the growth stages of plants

		Rate of Zn concentration in the plant is mg kg/plant		
Treatment code	Treatment/Average	After germination	flowering	Post- harvest
T0S0	0	12.83	11.77	10.82
T1S1	500 kg/ha+first time	14.99	16.47	10.13
T1S2	1000 kg/ha+first time	15.33	17.07	10.29
T1S3	1500 kg/ha+first time	15.7	20.9	10.56
T1S4	2000 kg/ha+first time	16.63	21.33	11.44
T2S1	500 kg/ha+second time	14.72	15.63	9.86
T2S2	1000 kg/ha+second time	15.17	16.73	10.16
T2S3	1500 kg/ha+second time	15.57	17.5	10.27
T2S4	2000 kg/ha+second time	16.06	18.33	10.68
LSD	0.05211	0.8328	5.320	

T0-T2 represent the sulfur application timing: T0: No sulfur (control), T1: Sulfur applied one month before planting (1/7/2022), T2: Sulfur applied 15 days after planting (21/8/2022), S1-S4 indicate sulfur rates: S1: 500 kg/ha, S2: 1000 kg/ha, S3: 1500 kg/ha, S4: 2000 kg/ha and LSD represents the least significant difference at $p<0.05$

zinc at the harvest stage, where the level of addition 2000 (kg/ha) for the first date was significantly higher and gave the highest rate for this trait amounting to 11.44 mg kg/plant, compared to the comparison treatment that gave the lowest rate, reaching 10.82 mg kg/plant. This level also showed Significant superiority over the T2S1 treatment, which amounted to 9.86 mg kg/plant, and did not show significant differences with the rest of the treatments, T1S3, T1S2, T1S1, T2S2, T2S3, T2S4 (Table 6).

CONCLUSION

The study concludes that the use of agricultural sulfur at the level of 2000 (kg/ha) 30 days before planting reduces the degree of soil reaction during germination, flowering, and harvesting, and thus increases the readiness of manganese, iron, copper and zinc in the flowering and harvesting stage, which is reflected in the increase in the plant content of micronutrients. Adding agricultural sulfur in general improves crop growth and increases grain yield.

SIGNIFICANCE STATEMENT

This study discovered the significant role of agricultural sulfur levels and application timings in reducing soil pH and improving micronutrient availability in maize, which can be beneficial for enhancing nutrient uptake, soil health, and overall crop productivity. The findings provide valuable insights into how sulfur influences soil plant interactions, especially during critical growth stages. Moreover, this study will help researchers uncover the critical areas of sulfur micronutrient dynamics that many researchers were not able to explore. Thus, a new theory on optimized sulfur management for sustainable maize production may be arrived at.

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