J. of Soil Sciences and Agricultural Engineering, Mansoura Univ., Vol. 15 (6): 135 - 141, 2024

Journal of Soil Sciences and Agricultural Engineering

Journal homepage & Available online at: www.jssae.journals.ekb.eg

Synergistic Effects of Elemental Sulfur Soil Addition and Beneficial Elements Spraying on Onions

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ABSTRACT

Onion cultivation faces challenges related to nutrient management, impacting growth, yield and quality. Therefore, this study aimed to evaluate the synergistic effects of elemental sulfur and beneficial elements on onion quantitative and qualitative parameters. The experimental design included treatments with three sulfur rates as the main factor (control, 150 and 200 kg fed^{-1}) and five beneficial elements as the sub-main factor (without as control, calcium at rate of 500 g Ca-EDTA fed^{-1}, zinc at rate of 500 g Zn-EDTA fed^{-1}, copper at rate of 500 g Cu-EDTA fed^{-1}and manganese at rate of 500 g Mn-EDTA fed^{-1}). Results showed that the highest sulfur rate (200 kg fed^{-1}) combined with manganese (500 g fed^{-1}) yielded the best outcomes. This combination significantly enhanced nutrient availability, photosynthetic efficiency, and overall plant health, leading to superior growth parameters and higher concentrations of photosynthetic pigments and essential chemical constituents in the onion bulbs. Furthermore, the application of sulfur and microelements (copper and zinc in particular) also exhibited substantial improvements in yield and bulb quality. The study concluded that the integrated use of elemental sulfur and microelements is crucial for optimizing onion production. These findings underscore the importance of balanced nutrient management in achieving robust growth and high-quality onion produce, offering a practical solution to the nutrient management challenges in onion cultivation.

***Keywords**:* Sulfur, Copper, Zinc, Manganese, Calcium.

INTRODUCTION

Onion (*Allium cepa* L.) is a crucial crop worldwide, valued not only for its culinary uses but also for its nutritional and medicinal properties (ElGhamry *et al.* 2024). The demand for high-quality onions necessitates effective agricultural practices that optimize growth and yield (Olsovska *et al.* 2024). One such practice is the application of elemental sulfur and microelements, which play a vital role in plant nutrition and soil health (Amare, 2020).

Elemental sulfur is known to enhance soil acidity, thereby increasing the availability of essential nutrients (Przygocka-Cyna *et al.* 2020). This is particularly important for onions, which require specific soil conditions for optimal growth (Sałata *et al.* 2021). Additionally, microelements such as manganese (Mn), copper (Cu), calcium (Ca) and zinc (Zn) are critical for various physiological processes, including enzyme activation, photosynthesis, and protein synthesis (ElGhamry *et al.* 2024; El-Sherbeny *et al.* 2024; Tsewang *et al.* 2024).

Despite the known benefits of these elements, there is limited research on their combined effects on onion growth and yield. The synergistic effects of micronutrients with elemental sulfur are profound. When used in tandem, elemental sulfur not only improves the solubility of micronutrients but also enhances their uptake and utilization efficiency by plants. This synergistic relationship boosts plant metabolism, promotes robust growth, and increases resistance to various stresses. For instance, sulfur's role in the synthesis of vital amino acids and proteins complements the action of micronutrients in enzymatic functions and cellular metabolism, leading to a more holistic improvement in plant health and productivity. Such combined applications are crucial for sustainable agricultural practices, ensuring adequate nutrition and optimal crop performance even in soils with inherent nutrient limitations (Barczak *et al.* 2019).

This study aims to fill this gap by investigating the impact of different rates of elemental sulfur and various microelement treatments on onion cultivation. Specifically, the study examines how these treatments influence growth parameters, photosynthetic pigments, yield and chemical constituents of onions. By analyzing the synergistic effects of these treatments, the research seeks to provide insights into optimizing nutrient management for enhanced onion production. The findings of this study are expected to contribute to more effective agricultural practices, leading to improved yield and quality of onion bulbs. This research underscores the importance of balanced nutrient management in agriculture, highlighting how strategic use of elemental sulfur and microelements can drive significant improvements in crop outcomes.

MATERIALS AND METHODS

The field experiment was implemented, using a split-plot experimental design, in a private farm located at Met-Antar village (coordinates 31°4'54"N - 31°24'4"E), Talkha district, El-Dakahlia governorate, Egypt during seasons of 2022/23 and 2023/24. The experimental design included treatments with three sulfur rates as the main factor (control, 150 kg fed^{-1} and 200 kg fed^{-1}) and five beneficial elements as

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DOI: 10.21608/jssae.2024.295230.1231

the sub-main factor (without as control, calcium at rate of 500 g Ca-EDTA fed^{-1}, zinc at rate of 500 g Zn-EDTA fed^{-1}, copper at rate of 500 g Cu-EDTA fed^{-1}and manganese at rate of 500 g Mn-EDTA fed^{-1}), each replicated three times. The studied beneficial elements were in chelated form, including Mn-EDTA (9%Mn), Zn-EDTA (9%Zn), Cu-EDTA (9%Cu) and Ca-EDTA (9%Ca). Each subplot measured 9.0 m^2 (3.0 m x 3.0 m). Seedlings (Cv. Giza Red, 60 days old) were transplanted on November 14th in both investigated seasons. Mineral fertilization, irrigation, weeding and pest control were done depending on the guidelines followed in the region for onion production based on the recommendations of the Egyptian Ministry of Agriculture and Soil Reclamation (MASR). The elemental sulfur was added immediately before transplanting with the studied rates, while the external application of the studied microelements was executed four times at 15-day intervals, starting one month after transplanting. The harvest was done after 160 days from transplanting during both studied seasons.

Also, before transplanting, a composite soil sample (at a depth of 0-30 cm) was analyzed using standard methods as described by Tandon (2005) and the initial soil properties are illustrated in Table1. At 90 days post-transplanting, many traits were measured such as plant height and fresh & dry weights. Additionally, chlorophyll and carotene values were determined as described by Hentschel *et al.* (2002). Leaf nutrient concentrations (NPK) were estimated at 90 days post-transplanting using the Kjeldahl method, spectrophotometer and flame photometer, respectively as described by Tandon (2005). At 160 days post-transplanting, bulb yield parameters were assessed like average bulb fresh weight, bulb & neck diameter as well as total and marketable bulb yield. Various bulb quality characteristics were determined according to AOAC (2000), including vitamin C, total dissolved solids, total sugar , dry matter, fiber, anthocyanin pigment, pyruvic acid, carbohydrates and protein (%).

Table 1. Attributes of initial soil

Properties	**Values**
Physical properties	
Sand,%	24
Silt	28
Clay	48
Textural class	Clay
Chemical properties	
EC dSm^{-1}	4.00
pH	8.0
Copper, mgKg^{-1}	0.25
Manganese, mgKg^{-1}	0.90
Zinc, mgKg^{-1}	0.80
Calcium, g 100g^{-1}	1.80
Nitrogen, mgKg^{-1}	38.0
Phosphorus, mgKg^{-1}	7.46
Potassium, mgKg^{-1}	222

Data were statistically analyzed as described by Gomez and Gomez (1984). Means were compared using the least significant difference (LSD) test at a 5% significance level.

RESULTS AND DISCUSSION

Onion traits after 90 days from transplanting

Growth parameters and photosynthetic pigments

Data presented in Table 2 indicates that both elemental sulfur and microelements significantly influenced the growth parameters and photosynthetic pigments of onions after 90 days of transplanting across the 2022/23 and 2023/24 seasons.

Table 2. Impact of applying elemental sulfur and spraying microelements on onion growth parameters and photosynthetic pigments 90 days after transplanting during seasons of 2022/23 and 2023/24

Treatments		**Growth parameters**						**Photosynthetic pigments**			
		Plant height, cm		**Fresh weight, g plant^{-1}**		**Dry weight, g plant^{-1}**		**Chlorophyll, SPAD reading**		**Carotene, mg g^{-1}**	
		1st season	**2nd season**	**1st season**	**2nd season**	**1st season**	**2nd season**	**1st season**	**2nd season**	**1st season**	**2nd season**
Main factor: Elemental sulfur rates											
S_1: 0.0 kg fed^{-1} (control)		66.25c	68.53c	68.44c	70.89c	7.96c	8.20c	42.09c	42.70c	0.290c	0.301c
S_2: 150 kg fed^{-1}		70.72b	72.85b	71.74b	73.36b	8.47b	8.68b	43.12b	43.71b	0.321b	0.327b
S_3: 200 kg fed^{-1}		77.23a	79.16a	75.68a	77.18a	9.03a	9.26a	44.23a	44.90a	0.374a	0.390a
LSD at 5%		0.72	0.42	0.70	0.31	0.06	0.05	0.31	0.33	0.003	0.003
Sub main factor: Micro elements											
F_1: Without (control)		68.46e	70.45e	70.49d	72.13c	8.26c	8.54d	42.71c	43.29c	0.312e	0.321d
F_2: Ca (500g fed^{-1})		69.70d	71.78d	71.21cd	72.85c	8.36c	8.66c	42.88bc	43.50bc	0.319d	0.332c
F_3: Zn (500g fed^{-1})		71.78c	74.12c	71.93bc	74.21b	8.50b	8.68c	43.20abc	43.84ab	0.331c	0.344b
F_4: Cu (500g fed^{-1})		72.92b	74.80b	72.70ab	74.51ab	8.61ab	8.80b	43.41ab	44.03ab	0.337b	0.347b
F_5: Mn (500g fed^{-1})		74.13a	76.40a	73.42a	75.34a	8.71a	8.89a	43.54a	44.19a	0.343a	0.352a
LSD at 5%		0.64	0.68	0.83	0.90	0.11	0.09	0.57	0.54	0.005	0.004
Interaction											
S_1	F_1	63.55	65.58	67.28	69.40	7.70	8.05	41.70	42.27	0.283	0.297
	F_2	64.90	66.92	68.02	70.14	7.84	8.18	41.85	42.44	0.286	0.301
	F_3	66.91	68.91	68.18	70.88	7.96	8.11	42.10	42.70	0.290	0.304
	F_4	67.61	70.25	68.95	71.55	8.10	8.26	42.37	43.05	0.294	0.299
	F_5	68.28	70.96	69.74	72.46	8.21	8.39	42.44	43.02	0.296	0.302
S_2	F_1	68.53	71.10	70.36	71.76	8.27	8.60	42.69	43.20	0.304	0.310
	F_2	69.80	72.59	71.06	72.43	8.37	8.55	42.91	43.56	0.313	0.318
	F_3	71.06	72.46	71.66	74.26	8.47	8.66	43.17	43.71	0.322	0.328
	F_4	71.47	72.86	72.44	73.80	8.56	8.78	43.32	43.89	0.330	0.337
	F_5	72.73	75.23	73.17	74.55	8.67	8.82	43.52	44.18	0.339	0.344
S_3	F_1	73.29	74.66	73.84	75.23	8.79	8.98	43.74	44.38	0.350	0.355
	F_2	74.40	75.83	74.54	75.97	8.86	9.24	43.88	44.49	0.359	0.377
	F_3	77.37	81.00	75.94	77.50	9.07	9.27	44.33	45.10	0.380	0.400
	F_4	79.68	81.29	76.70	78.18	9.16	9.34	44.53	45.16	0.386	0.405
	F_5	81.39	83.00	77.36	79.00	9.25	9.45	44.66	45.38	0.395	0.411
LSD at 5%		1.13	1.21	1.48	1.60	0.20	0.16	1.02	0.96	0.008	0.008

Means within a row followed by a different letter (s) are statistically different at a 0.05 level

Individual effect of elemental sulfur

Application of elemental sulfur significantly increased plant height. The highest sulfur rate (200 kg fed^{-1}) resulted in the greatest plant height, reaching 77.23 cm and 79.16 cm in the first and second seasons, respectively. This increase is attributed to sulfur's role in decreasing soil pH and enhancing nutrient availability (Hamaiel *et al.* 2020), which supports better vegetative growth. Similarly, fresh and dry weights of the plants increased with higher sulfur rates. The fresh weight for the highest sulfur rate was 75.68 g $plant^{-1}$ and 77.18 g $plant^{-1}$ in the respective seasons. Sulfur helps in amino acid synthesis, improving plant vigor and biomass. Chlorophyll content, measured as SPAD readings, and carotene levels were significantly higher with increased sulfur application. The highest chlorophyll content recorded was 44.23 and 44.90, and carotene levels were 0.374 mg g^{-1} and 0.390 mg g^{-1} in the first and second seasons, respectively. Sulfur is crucial for chlorophyll formation and photosynthesis efficiency.

Individual effect of microelements

Among the microelements, Mn (500 g fed^{-1}) led to the highest plant height (74.13 cm and 76.40 cm for the first and second seasons). Manganese plays a vital role in photosynthesis and enzyme activation, which likely contributed to this increase. The fresh and dry weights were also highest with Mn treatment, recording 73.42 g $plant^{-1}$ and 75.34 g $plant^{-1}$, respectively. This can be linked to manganese's role in nitrogen assimilation and protein synthesis. **Also,** the application of Mn resulted in the highest chlorophyll and carotene contents. Chlorophyll readings were 43.54 and 44.19, while carotene levels were 0.343 mg g^{-1} and 0.352 mg g^{-1} in the first and second seasons. Manganese's involvement in the photosynthetic electron transport system enhances these pigments' levels. The Cu treatment came in the second order in terms of the values of growth parameters and photosynthetic pigments, and this may be due to the vital role of copper in enzyme activation and lignin synthesis. Copper is essential for various physiological processes, including photosynthesis and respiration. It acts as a cofactor for enzymes involved in the electron transport chain, facilitating the transfer of electrons and enhancing energy production. Additionally, copper plays a crucial role in lignin synthesis, which strengthens plant cell walls and improves structural integrity, leading to enhance plant growth and development (Gupta, 1997).

Zinc treatment came in the third order, and this may be due to the vital role of zinc in protein synthesis and growth hormone production. Zinc is a key component of several enzymes and proteins, including those involved in DNA and RNA synthesis, which are fundamental for cell division and growth. Zinc also influences the synthesis of auxins, which are plant hormones that regulate growth and development (Hafeez *et al.* 2013). This role in hormone production helps to promote better root and shoot growth, contributing to overall improved plant vigor (Hamaiel *et al.* 2021; Reddy and Kumari, 2022).

The Ca treatment was superior to the control treatment, which came in the last order, and this may be due to the vital role of calcium in cell wall stability and signal transduction. Calcium is a critical element in the formation and stabilization of cell walls, providing structural support and rigidity. It also functions as a secondary messenger in signal transduction pathways, aiding in the plant's response to various environmental stimuli and stress factors. These functions of calcium enhance the plant's ability to maintain cellular integrity and adapt to changing conditions, thereby promoting better growth and development compared to the untreated control (Abd-Elhamied and Abd El-Hady, 2018; Saito and Uozumi, 2020).

Interaction effects

The interaction between elemental sulfur and microelements showed significant enhancements in all measured parameters. The combination of 200 kg fed^{-1} sulfur with Mn (500 g fed^{-1}) yielded the highest values across all growth parameters and photosynthetic pigments, indicating a synergistic effect. For example, this combination resulted in a plant height of 81.39 cm and 83.00 cm, and chlorophyll content of 44.66 and 45.38 in the first and second seasons, respectively.

Chemical constituents

Table 3 provides the data on the chemical composition of onions, showing significant effects of sulfur and microelements on nitrogen (N), phosphorus (P), and potassium (K) content.

Table 3. Impact of applying elemental sulfur and spraying microelements on onion chemical content 90 days after transplanting during seasons of 2022/23 and 2023/24

Treatments		N %		P %		K %	
		1st season	2nd season	1st season	2nd season	1st season	2nd season
Main factor: Elemental sulfur rates							
S_1: 0.0 kg fed^{-1} (control)		2.71c	2.82c	0.259c	0.269c	2.33c	2.42c
S_2: 150 kg fed^{-1}		3.14b	3.21b	0.299b	0.304b	2.70b	2.76b
S_3: 200 kg fed^{-1}		3.65a	3.72a	0.343a	0.360a	3.04a	3.10a
LSD at 5%		0.03	0.05	0.002	0.002	0.06	0.07
Sub main factor: Micro elements							
F_1: Without (control)		3.00e	3.09e	0.284e	0.292e	2.54e	2.61e
F_2: Ca (500g fed^{-1})		3.05d	3.15d	0.291d	0.302d	2.60d	2.67d
F_3: Zn (500g fed^{-1})		3.16c	3.25c	0.301c	0.314c	2.71c	2.79c
F_4: Cu (500g fed^{-1})		3.26b	3.34b	0.310b	0.319b	2.78b	2.84b
F_5: Mn (500g fed^{-1})		3.36a	3.43a	0.316a	0.328a	2.83a	2.89a
LSD at 5%		0.04	0.05	0.004	0.004	0.03	0.03
Interaction							
S_1	F_1	2.60	2.73	0.246	0.259	2.20	2.31
	F_2	2.62	2.75	0.250	0.263	2.23	2.34
	F_3	2.66	2.79	0.259	0.271	2.34	2.45
	F_4	2.79	2.89	0.267	0.272	2.41	2.49
	F_5	2.90	2.96	0.274	0.279	2.49	2.54
S_2	F_1	2.97	3.03	0.281	0.287	2.54	2.58
	F_2	3.05	3.11	0.290	0.295	2.63	2.69
	F_3	3.14	3.22	0.300	0.306	2.72	2.79
	F_4	3.23	3.28	0.308	0.314	2.78	2.83
	F_5	3.34	3.41	0.316	0.321	2.84	2.90
S_3	F_1	3.43	3.50	0.325	0.330	2.89	2.95
	F_2	3.50	3.58	0.332	0.349	2.93	3.00
	F_3	3.69	3.75	0.346	0.364	3.08	3.14
	F_4	3.77	3.85	0.355	0.373	3.15	3.20
	F_5	3.85	3.92	0.358	0.385	3.17	3.23
LSD at 5%		0.07	0.08	0.007	0.008	0.05	0.06

Means within a row followed by a different letter (s) are statistically different at a 0.05 level

Individual effect of elemental sulfur

Nitrogen content increased with higher sulfur rates, with the highest rate (200 kg fed^{-1}) achieving 3.65% and

3.72% N in the respective seasons. Sulfur enhances nitrogen metabolism and protein synthesis, contributing to higher N content. Similar trends were observed for phosphorus and potassium. The highest sulfur rate resulted in the highest P and K content, with values of 0.343% and 0.360% P, and 3.04% and 3.10% K, respectively. Sulfur improves root development and nutrient uptake efficiency, which is reflected in these results.

Individual effect of microelements

Among microelements, Mn again led to the highest N content (3.36% and 3.43%). This is consistent with manganese's role in nitrogen metabolism. Mn treatment also resulted in the highest P (0.316% and 0.328%) and K (2.83% and 2.89%) contents. Manganese enhances the utilization of phosphorus and potassium in plants. The Cu treatment ranked second in terms of NPK content in the leaves, followed by the Zn treatment, the Ca treatment, and finally, the control treatment. Copper's vital role includes enzyme activation and lignin synthesis. It serves as a cofactor for enzymes in the electron transport chain, enhancing energy production, and it is crucial for lignin synthesis, which strengthens plant cell walls, thus improving structural integrity and nutrient uptake. Zinc is essential for protein synthesis and growth hormone production. It is a key component of enzymes and proteins involved in DNA and RNA synthesis, which are fundamental for cell division and growth. Zinc also influences the synthesis of auxins, plant hormones that regulate growth, contributing to better root and shoot development. Calcium is crucial for cell wall stability and signal transduction. It stabilizes cell walls, providing structural support and rigidity, and functions as a secondary messenger in signal transduction pathways, helping plants respond to environmental stimuli and stress factors, thereby enhancing cellular integrity and growth. The control treatment, which did not receive additional elements, showed the lowest NPK content, indicating the significant positive impact of supplementing with Cu, Zn, and Ca on nutrient uptake and overall plant health.

Interaction effects

The interaction effects between sulfur and microelements were also significant for chemical constituents. The combination of 200 kg fed^{-1} sulfur and Mn (500 g fed^{-1}) resulted in the highest nutrient contents, showing a strong synergistic effect. For example, this combination yielded 3.85% and 3.92% N, 0.358% and 0.385% P, and 3.17% and 3.23% K in the first and second seasons, respectively. The finding are in agreement with those of Przygocka-Cyna *et al.* (2020); Sałata *et al.* (2021); ElGhamry *et al.* (2024); El-Sherbeny *et al.* (2024); Tsewang *et al.* (2024).

Onion traits after 160 days from transplanting (yield and quality)

Table 4 indicates the effect of applying elemental sulfur and spraying microelements on onion yield parameters 160 days after transplanting during seasons of 2022/23 and 2023/24, while Table 5 illustrates the impact of the studied treatments on onion bulb quality parameters.

Individual effect of elemental sulfur

The application of elemental sulfur had a significant impact on various parameters related with onion yield across two seasons (2022/23 and 2023/24). As seen in Table 4, increasing sulfur rates led to notable improvements in average bulb weight, bulb diameter, neck diameter, total bulb yield and marketable bulb yield. The highest sulfur rate (200 kg fed^{-1}) produced the best results, with the largest average bulb weight (106.95 g in the first season and 109.17 g in the second season) and the highest total bulb yield (40.73 tons ha^{-1} in the first season and 41.57 tons ha^{-1} in the second season). Additionally, as depicted in Table 6, the application of sulfur notably augmented the levels of vitamin C, total dissolved solids (TDS), total sugars, dry matter, fiber, anthocyanin, pyruvic acid, carbohydrates and protein content. These enhancements demonstrated a gradual rise corresponding to the increased sulfur rates.

This could be attributed to sulfur's role in protein synthesis and enzyme activation, which are crucial for growth and development. It is well known that sulfur is an essential macronutrient that plays a crucial role in plant growth and development. The addition of sulfur to the soil, particularly in the form of elemental sulfur, has several significant benefits for onion crop cultivation. Sulfur application might have improved the availability of other essential nutrients like nitrogen (N), phosphorus (P), and potassium (K) by influencing soil pH and nutrient solubility. This can lead to better nutrient uptake and utilization by onion plants. Elemental sulfur might have helped in reducing soil pH value by converting to sulfuric acid through microbial activity. This process lowers soil pH, making nutrients more available and accessible to onion plants. Sulfur is a critical component of amino acids like cysteine and methionine, which are building blocks for proteins and enzymes. It also plays a vital role in the formation of chlorophyll, enhancing the plant's ability to photosynthesize effectively. The addition of sulfur might have led to increased onion yield and improved quality of produce. Sulfur led to enhanced bulb size, weight, and overall yield. It also contributes to the pungency and flavor of onions, which are important quality attributes. Sulfur plays a role in the formation of glucosinolates and other secondary metabolites that help plants resist diseases and pests. Enhanced sulfur nutrition can improve a plant's natural defense mechanisms, reducing the incidence of diseases. Sulfur contributes to the formation of soil organic matter and improves soil structure. Better soil structure facilitates root growth, water infiltration, and air circulation, promoting healthier plant development.

Individual effect of microelements

Data presented in Tables 4 and 5 demonstrate that spraying microelements resulted in additional enhancements in both onion yield and quality parameters. Copper (Cu), Zinc (Zn), Manganese (Mn) and Calcium (Ca) treatments exhibited significant improvements across all measured traits related to bulb yield and quality compared to the control group. Among these, the Manganese treatment emerged as the most effective, while copper notably followed in second place, contributing significantly to the enhancement of bulb yield and quality. Zinc and Calcium treatments subsequently followed. The roles of each of these elements were previously mentioned (Shehata *et al.* 2019; Doklega and Abd El-Hady, 2023).

Interaction effects

Interaction effects showed that the combination of higher sulfur rates with microelements yielded superior results. Specifically, the combination of 200 kg fed^{-1} sulfur with manganese (Mn) resulted in the highest values of all studied onion yield and quality parameters. This suggests a synergistic effect of sulfur and microelements in enhancing onion quantitative and qualitative traits. The obtained results are in harmony with those of Przygocka-Cyna *et al.* (2020); Sałata *et al.* (2021); ElGhamry *et al.* (2024); El-Sherbeny *et al.* (2024); Tsewang *et al*. (2024).

Table 4. Impact of applying elemental sulfur and spraying microelements on onion yield parameters 160 days after transplanting during seasons of 2022/23 and 2023/24

Treatments		Average bulb (g, FW)		Bulb diameter (cm)		Neck diameter (cm)		Total bulb yield (ton ha^{-1})		Marketable bulb yield (ton ha^{-1})	
		1st season	2nd season	1st season	2nd season	1st season	2nd season	1st season	2nd season	1st season	2nd season
Main factor: Elemental sulfur rates											
S_1: 0.0 kg fed^{-1} (control)		85.19c	88.25c	4.22c	4.34c	0.90c	0.94c	32.44c	33.60c	31.27c	31.95c
S_2: 150 kg fed^{-1}		96.05b	98.22b	5.30b	5.43b	1.40b	1.43b	36.58b	37.40b	34.98b	36.11b
S_3: 200 kg fed^{-1}		106.95a	109.17a	6.49a	6.68a	2.14a	2.19a	40.73a	41.57a	38.69a	39.75a
LSD at 5%		0.20	0.10	0.08	0.11	0.05	0.04	0.08	0.04	0.77	0.31
Sub main factor: Micro elements											
F_1: Without (control)		91.97e	94.10e	4.87e	5.02e	1.27e	1.30e	35.02e	35.84e	33.51e	34.36e
F_2: Ca (500g fed^{-1})		95.06d	97.24d	5.10d	5.28d	1.38d	1.42d	36.20d	37.03d	34.25d	35.21d
F_3: Zn (500g fed^{-1})		96.47c	99.62c	5.39c	5.55c	1.46c	1.50c	36.74c	37.94c	35.01c	35.99c
F_4: Cu (500g fed^{-1})		97.97b	100.41b	5.57b	5.69b	1.60b	1.63b	37.31b	38.24b	35.69b	36.61b
F_5: Mn (500g fed^{-1})		98.86a	101.36a	5.75a	5.87a	1.70a	1.73a	37.65a	38.60a	36.45a	37.51a
LSD at 5%		0.40	0.40	0.08	0.06	0.04	0.04	0.15	0.15	0.27	0.44
Interaction											
S_1	F_1	81.78	84.40	3.82	3.99	0.77	0.81	31.14	32.14	29.87	30.17
	F_2	85.13	87.77	3.97	4.13	0.84	0.88	32.42	33.42	30.57	31.15
	F_3	85.38	88.70	4.25	4.34	0.88	0.92	32.51	33.78	31.29	32.00
	F_4	85.73	88.99	4.44	4.52	0.96	0.99	32.65	33.89	31.89	32.86
	F_5	87.93	91.36	4.63	4.73	1.07	1.09	33.48	34.79	32.71	33.58
S_2	F_1	93.16	95.02	4.83	5.01	1.14	1.16	35.47	36.18	33.49	34.50
	F_2	94.82	96.72	5.10	5.22	1.25	1.28	36.11	36.83	34.26	35.39
	F_3	95.29	98.63	5.30	5.41	1.33	1.36	36.29	37.56	34.97	36.13
	F_4	98.38	100.25	5.47	5.62	1.56	1.59	37.46	38.17	35.75	36.85
	F_5	98.63	100.50	5.78	5.88	1.71	1.74	37.56	38.27	36.43	37.69
S_3	F_1	100.97	102.89	5.95	6.07	1.90	1.94	38.45	39.18	37.17	38.41
	F_2	105.22	107.22	6.24	6.50	2.05	2.10	40.07	40.83	37.92	39.09
	F_3	108.76	111.54	6.61	6.89	2.18	2.22	41.42	42.47	38.77	39.86
	F_4	109.79	111.99	6.79	6.94	2.27	2.32	41.81	42.65	39.42	40.13
	F_5	110.02	112.22	6.84	6.99	2.32	2.36	41.90	42.73	40.20	41.25
LSD at 5%		0.70	0.70	0.13	0.11	0.07	0.08	0.27	0.27	0.47	0.77

Means within a row followed by a different letter (s) are statistically different at a 0.05 level

Table 5. Impact of applying elemental sulfur and spraying microelements on onion bulb quality parameters 160 days after transplanting during seasons of 2022/23 and 2023/24

Treatments		Vitamin C mg/100g		TDS %		Total sugar %		Dry matter %	
		1st season	2nd season	1st season	2nd season	1st season	2nd season	1st season	2nd season
Main factor: Elemental sulfur rates									
S_1: 0.0 kg fed^{-1} (control)		10.97c	11.42c	9.75c	10.10c	5.47c	5.58c	9.87c	10.04c
S_2: 150 kg fed^{-1}		12.20b	12.70b	10.81b	11.05b	5.79b	5.93b	11.13b	11.33b
S_3: 200 kg fed^{-1}		13.19a	13.74a	11.72a	11.97a	6.12a	6.26a	12.09a	12.29a
LSD at 5%		0.17	0.21	0.20	0.15	0.08	0.07	0.09	0.24
Sub main factor: Micro elements									
F_1: Without (control)		11.65e	12.14e	10.36e	10.60e	5.65c	5.77c	10.58e	10.76e
F_2: Ca (500g fed^{-1})		11.93d	12.43d	10.56d	10.80d	5.73b	5.86b	10.85d	11.05d
F_3: Zn (500g fed^{-1})		12.14c	12.63c	10.75c	11.11c	5.78b	5.92b	11.05c	11.24c
F_4: Cu (500g fed^{-1})		12.33b	12.84b	10.97b	11.24b	5.87a	6.01a	11.23b	11.41b
F_5: Mn (500g fed^{-1})		12.55a	13.07a	11.16a	11.43a	5.92a	6.06a	11.45a	11.63a
LSD at 5%		0.17	0.15	0.11	0.12	0.07	0.08	0.14	0.09
Interaction									
S_1	F_1	10.48	10.91	9.31	9.62	5.34	5.46	9.43	9.57
	F_2	10.72	11.17	9.51	9.80	5.42	5.53	9.67	9.85
	F_3	10.99	11.45	9.76	10.13	5.46	5.58	9.86	10.02
	F_4	11.17	11.63	9.96	10.33	5.53	5.64	10.06	10.21
	F_5	11.47	11.94	10.20	10.60	5.59	5.71	10.33	10.53
S_2	F_1	11.67	12.19	10.37	10.57	5.62	5.73	10.56	10.75
	F_2	12.07	12.60	10.60	10.81	5.70	5.86	10.98	11.17
	F_3	12.23	12.72	10.77	11.14	5.77	5.92	11.17	11.38
	F_4	12.42	12.93	11.07	11.28	5.89	6.06	11.37	11.57
	F_5	12.61	13.07	11.26	11.44	5.93	6.08	11.59	11.78
S_3	F_1	12.80	13.31	11.39	11.61	5.99	6.11	11.75	11.95
	F_2	13.00	13.51	11.57	11.80	6.06	6.21	11.91	12.12
	F_3	13.20	13.73	11.72	12.07	6.12	6.27	12.10	12.32
	F_4	13.40	13.96	11.88	12.11	6.20	6.34	12.26	12.46
	F_5	13.58	14.20	12.03	12.26	6.24	6.38	12.44	12.59
LSD at 5%		0.30	0.26	0.19	0.22	0.12	0.15	0.24	0.15

Means within a row followed by a different letter (s) are statistically different at a 0.05 level

Table 5. cont.

Treatments		Fiber, %		Anthocyanin, mg 100g^{-1}		Pyruvic acid, πmol g^{-1}		Carbohydrates, %		Protein, %	
		1stseason	2ndseason	1stseason	2nd season	1stseason	2nd season	1stseason	2ndseason	1stseason	2ndseason
Main factor: Elemental sulfur rates											
S_1: 0.0 kg fed^{-1} (control)		3.00c	3.09c	25.58c	26.50b	4.58c	4.77c	15.17c	15.63c	7.02c	7.30c
S_2: 150 kg fed^{-1}		3.64b	3.73b	26.35b	26.93b	5.54b	5.66b	16.08b	16.49b	7.67b	7.84b
S_3: 200 kg fed^{-1}		4.27a	4.40a	27.75a	28.31a	6.88a	6.94a	17.26a	17.65a	8.46a	8.56a
LSD at 5%		0.12	0.05	0.18	0.54	0.05	0.05	0.31	0.09	0.19	0.06
Sub main factor: Micro elements											
F_1: Without (control)		3.38e	3.50e	25.94c	26.55d	5.22d	5.38e	15.68c	16.22b	7.42d	7.65d
F_2: Ca (500g fed^{-1})		3.49d	3.61d	26.58b	27.18c	5.38c	5.55d	15.89b	16.36b	7.54c	7.78c
F_3: Zn (500g fed^{-1})		3.66c	3.76c	26.52b	27.37bc	5.68b	5.84c	16.39a	16.77a	7.84b	7.94b
F_4: Cu (500g fed^{-1})		3.78b	3.86b	26.80ab	27.46av	6.00a	6.02b	16.38a	16.73a	7.84b	8.04ab
F_5: Mn (500g fed^{-1})		3.89a	3.97a	26.95a	27.66a	6.04a	6.16a	16.52a	16.86a	7.94a	8.10a
LSD at 5%		0.10	0.05	0.34	0.26	0.07	0.07	0.19	0.20	0.07	0.10
Interaction											
	F_1	2.77	2.89	24.88	25.69	4.33	4.56	14.69	15.36	6.79	7.12
	F_2	2.87	2.99	26.25	27.09	4.39	4.61	14.76	15.40	6.85	7.19
S_1	F_3	3.00	3.06	25.38	26.35	4.56	4.78	15.73	16.04	7.01	7.35
	F_4	3.15	3.21	25.65	26.56	4.72	4.89	15.23	15.55	7.16	7.42
	F_5	3.24	3.31	25.76	26.80	4.89	4.99	15.46	15.80	7.28	7.42
	F_1	3.36	3.50	25.84	26.33	5.04	5.15	15.65	16.26	7.42	7.58
	F_2	3.46	3.53	26.10	26.58	5.25	5.37	15.85	16.18	7.54	7.72
S_2	F_3	3.70	3.78	26.32	27.24	5.55	5.68	16.09	16.45	7.68	7.86
	F_4	3.79	3.88	26.61	27.12	5.82	5.93	16.33	16.74	7.80	7.95
	F_5	3.90	3.97	26.87	27.37	6.04	6.16	16.48	16.81	7.91	8.08
	F_1	4.02	4.10	27.12	27.63	6.30	6.43	16.70	17.05	8.05	8.23
	F_2	4.13	4.32	27.38	27.88	6.50	6.65	17.06	17.48	8.23	8.42
S_3	F_3	4.27	4.46	27.87	28.53	6.93	7.07	17.34	17.83	8.83	8.61
	F_4	4.40	4.49	28.16	28.70	7.46	7.22	17.57	17.91	8.56	8.73
	F_5	4.54	4.64	28.22	28.80	7.19	7.33	17.61	17.97	8.64	8.80
LSD at 5%		0.18	0.09	0..60	0.45	0.12	0.12	0.33	0.34	0.13	0.17

Means within a row followed by a different letter (s) are statistically different at a 0.05 level

CONCLUSION

The application of elemental sulfur and microelements has been shown to significantly and synergistically enhance the growth parameters, photosynthetic pigments, chemical constituents, yield and bulb quality of onions. The most notable results were obtained with the highest sulfur rate (200 kg fed^{-1}) combined with manganese (500 g fed^{-1}), which led to improved nutrient availability, enhanced photosynthesis, and better overall plant health. This combination yielded the best outcomes, demonstrating the critical role of these elements in onion cultivation.

Generally, farmers should consider applying elemental sulfur at a rate of 200 kg fed^{-1} along with microelements, especially manganese at 500 g fed^{-1}, to achieve the best results in onion cultivation. Regular soil testing should be conducted to determine the specific nutrient needs of the soil. Customized nutrient management plans based on these tests can help optimize the effectiveness of sulfur and microelement applications. Adopting an integrated approach to nutrient management, combining the use of macro and micronutrients, can enhance plant health and productivity. This approach should be tailored to the specific requirements of the crop and the local soil conditions. Continued research is recommended to explore the long-term effects of these treatments and their interactions with other agricultural practices. Additionally, studies on different varieties of onions and in various climatic conditions would help generalize the findings.

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التأثيرات التآزرية للاضافه الارضيه للكبريت العنصري مع الرش بالعناصر المفيدة على البصل

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الملخص

تواجه زراعة البصل تحديات تتعلق بإدارة المغذيات، مما يؤثر على النمو والإنتاج والجودة. ولذلك، تهدف هذه الدراسة إلى تقييم التأثيرات التآزرية للكبريت العنصري مع الرش بالعناصر المفيدة على المدلولات الكمية والنوعية للبصل. تضمن التصميم التجريبي ثلاثة معدلات كبريت كعامل رئيسي [٠,٠ كجم فدان$^{-١}$ كمعاملة كنترول، و١٥٠ كجم فدان$^{-١}$، و٢٠٠ كجم فدان$^{-١}$] وخمسة عناصر مفيدة كعامل منشق [بدون (كنترول)، الكالسيوم بمعدل ٥٠٠ جم كالسيوم مخلبي فدان$^{-١}$، زنك بمعدل ٥٠٠ جم زنك مخلبي فدان$^{-١}$، نحاس بمعدل ٥٠٠ جم نحاس مخلبي فدان$^{-١}$ ومنجنيز بمعدل ٥٠٠ جم منجنيز مخلبي فدان$^{-١}$].أظهرت النتائج أن أعلى معدل كبريت (٢٠٠ كجم فدان$^{-١}$) مع المنجنيز (٥٠٠ جم ف فدان$^{-١}$) حقق أفضل النتائج. أدى هذا المزيج إلى تعزيز توافر العناصر الغذائية وكفاءة التمثيل الضوئي والصحة العامة للنبات بشكل كبير، مما أدى إلى معايير نمو فائقة وتركيزات أعلى من أصباغ التمثيل الضوئي والمكونات الكيميائية الأساسية في بصيلات البصل.علاوة على ذلك، ساهمت إضافة الكبريت والعناصر الصغري مثل النحاس والزنك أيضًا في تحسينات كبيرة في المحصول وجودة الأبصال. وخلصت الدراسة إلى أن الاستخدام المتكامل للكبريت والعناصر الصغري أمر بالغ الأهمية لتحسين إنتاج البصل. تؤكد هذه النتائج على أهمية الإدارة المتوازنة للمغذيات في تحقيق نمو قوي وإنتاج بصل عالي الجودة، مما يوفر حلاً عمليًا لتحديات إدارة المغذيات في زراعة البصل.