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Unveiling the Synergistic Role of Elemental Sulfur, Potassium Supplements and Methionine in Improving Yield and Quality of Onion

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IMPROVING qualitative and quantitative traits of the onion (*Allium cepa* L.) plant, a strategic crop, is essential to meet increasing agricultural demands and enhance crop quality. The current study, conducted over two successive growing seasons (2022/23 and 2023/24), aimed to investigate the synergistic effects of elemental sulfur, various potassium supplements and methionine amino acid on the growth, yield and quality of onion plants. The experiment was arranged in a split-split plot design, as the main factor was the application of elemental sulfur (applied at a rate of 360 kg ha^{-1} or non-application). The sub-main factor involved different forms of potassium supplements applied as foliar sprays at rate of 750 mg K_2O L^{-1} [Control (no potassium), potassium silicate (K_2SiO_3), potassium citrate ($K_3C_6H_5O_7$), potassium nitrate(KNO_3)], while the sub-sub main factor included methionine amino acid, either sprayed at 100 mg L^{-1} or not sprayed. The results show that the application of elemental sulfur significantly improved onion performance regarding growth, quantitative and qualitative traits (e.g., fresh and dry weights, leaf area, chlorophyll a & b contents, bulb weight and diameter, marketable yield, total dissolved solids, dry matter, vitamin C and anthocyanin pigment) across measured parameters. Potassium silicate emerged as the most effective potassium supplement, followed by potassium citrate then potassium nitrate, and lately the control. Additionally, methionine application enhanced both the growth, yield and quality traits of onions. The combined application of elemental sulfur, potassium silicate, and methionine produced the highest values for growth, yield and quality attributes. Finally, it can be concluded that the usage of elemental sulfur, potassium supplements, particularly potassium silicate, and methionine is so beneficial to enhance the performance of onions. This integrated approach not only maximizes crop yield but also improves the quality of onions, offering a sustainable pathway to augment onion production. Future research should explore the long-term effects of these treatments and their interactions with other agronomic practices to further optimize onion cultivation.

Keywords: Potassium silicate, Potassium citrate, Potassium nitrate, *Allium cepa* L.

1. Introduction

Onion (*Allium cepa* L.), one of the most widely cultivated and consumed vegetable crops worldwide, holds a significant place in both culinary and medicinal applications **(Sami *et al.* 2021).** Renowned for its pungent aroma and distinct flavor, onion is an indispensable ingredient in various cuisines across the globe. From a nutritional perspective, onions are low in calories yet rich in vitamins, minerals, and antioxidants **(Lee *et al.* 2023).** They are a good source of vitamin C, which is vital for immune function, skin health, and collagen synthesis. Onions also contain vitamin B6, folate, and a range of phytonutrients including quercetin and sulfur-containing compounds that have been associated with numerous health benefits, such as anti-inflammatory and anticancer properties **(Ndiaye *et al.* 2024).** Economically, onions represent a crucial agricultural product, contributing significantly to the income of farmers and playing a vital role in the agricultural economy **(Awad *et al.* 2024).** They are a staple crop in many regions due to their relatively low cost of production and high market demand **(Elmasry and Marey 2024).** In terms of chemical content, onions are notable for their high levels of organosulfur compounds, such as thiosulfate and sulfoxides, which not only contribute to their characteristic pungency but also have potent antibacterial and antifungal effects **(Ndiaye *et al.* 2024).**

Elemental sulfur, a crucial nutrient in agriculture, plays a significant role in enhancing crop performance through various mechanisms **(González-Morales *et al.* 2017; Hamaiel *et al.* 2020).** It has been increasingly recognized for its potential to improve soil fertility and optimize plant growth. Its application is known to influence soil pH levels, facilitating better nutrient uptake by plants and thereby enhancing their overall health and

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productivity **(Przygocka-Cyna *et al.* 2020; Sałata *et al.* 2021).**

Potassium (K) is an essential macronutrient that plays a crucial role in plant growth and development **(Abd El-Hady *et al.* 2021).** It is involved in various physiological processes including enzyme activation, protein synthesis, photosynthesis, and the regulation of osmotic pressure and stomatal opening **(Ali *et al.* 2021).** Foliar application of potassium is a highly effective method of supplying this nutrient to plants, allowing for rapid uptake and immediate effect, especially in conditions where soil application may not be as effective due to soil type or environmental factors **(Hekal and Moussa 2023).** Foliar feeding ensures that nutrients are directly available to the plants, which can be particularly beneficial during critical stages of growth or in correcting nutrient deficiencies **(El Shafei *et al.* 2023).**

Potassium silicate, with the chemical formula K_2SiO_3, is a soluble potassium salt that also provides silicon, an important secondary nutrient for plants **(Sarhan and Shehata, 2023).** Silicon is known to enhance plant resistance to biotic and abiotic stresses, including pests, diseases, and drought. The application of potassium silicate not only supplies essential potassium but also fortifies the plant's structural integrity and improves resistance to environmental stressors **(Sharma *et al*. 2022).** It has been shown to improve crop yield and quality by enhancing cell wall strength, increasing photosynthetic efficiency, and promoting better water use efficiency **(Metwally *et al.* 2024).**

Potassium citrate, denoted by the chemical formula $K_3C_6H_5O_7$, is a potassium salt of citric acid and is known for its excellent solubility and bioavailability **(Ali *et al.* 2021).** This compound provides a readily available source of potassium, which is essential for energy production and enzyme function in plants. Additionally, the citrate component acts as a chelating agent, facilitating the uptake of other essential nutrients **(Fawaz *et al.* 2024).** Potassium citrate is particularly effective in improving crop quality, enhancing flavor, and increasing resistance to physiological disorders. Its application can lead to better overall plant health and improved yield by optimizing nutrient uptake and utilization **(Metwally *et al.* 2024).**

Potassium nitrate, represented by the chemical formula KNO_3, is a common source of potassium and nitrogen, two critical nutrients for plant growth **(Alebidi *et al.* 2021).** This compound provides a balanced supply of potassium and nitrogen, promoting robust vegetative growth and enhancing fruit development. The nitrate form of nitrogen is readily absorbed by plants, contributing to efficient nutrient uptake and utilization. Potassium nitrate is particularly beneficial in supporting the synthesis of proteins, chlorophyll, and other vital compounds, thereby improving plant vigor and productivity **(Khudhair and Hamza, 2024).** It is widely used in foliar applications to correct potassium deficiencies and support optimal plant health.

Methionine, an essential amino acid with the chemical structure $C_5H_{11}NO_2S$, plays a vital role in plant metabolism and growth **(Faiyad *et al.* 2020).** As a precursor to important biomolecules such as proteins, polyamines, and ethylene, methionine is involved in various physiological processes including cell division, growth regulation, and stress response. In plants, methionine contributes to the synthesis of sulfur-containing compounds that are crucial for detoxification and defense mechanisms **(El-Bauome *et al.* 2022).** The application of methionine as a foliar spray provides a direct source of this amino acid, enhancing the plant's ability to synthesize proteins and other essential compounds, leading to improved growth, yield, and quality of crops **(El-Beltagi *et al.* 2023; Khater *et al.* 2024**).

The primary objective of this study was to investigate the synergistic effects of elemental sulfur, various potassium supplements, and methionine on the growth, yield, and quality of onion plants over two successive growing seasons. By integrating these treatments, the study aimed to enhance both the qualitative and quantitative traits of onions, thereby addressing the increasing agricultural demand for high-quality produce and contributing to the sustainability and profitability of onion cultivation.

2. Materials and Methods

This research was carried out on a private farm located at Met-Antar village, Talkha district, El-Dakahlia governorate, Egypt, at geographical coordinates 31°4'54"N - 31°24'4"E. The study spanned two consecutive growing seasons (2022/23 season and 2023/24 season). The experiment utilized a split-split plot design to evaluate the effects of elemental sulfur, various potassium supplements and methionine on onion growth, yield and quality. **Figure 1** illustrates the flowchart of the current research work. The main factor was the application of elemental sulfur (applied at a rate of 360 kg ha^{-1} or non-application). The sub-main factor involved different forms of potassium supplements applied as foliar sprays at a rate of 750 mg K_2O L^{-1} [Control (without potassium), potassium silicate (K_2SiO_3), potassium citrate ($K_3C_6H_5O_7$), potassium nitrate (KNO_3)], while the sub-sub main factor included methionine amino acid, either sprayed at 100 mg L^{-1} or not sprayed. The elemental sulfur was procured from the Egyptian commercial market (Shams Chemical Company) and incorporated into the soil at the start of the trial. All potassium supplements were also obtained from Shams Chemical Company.

Methionine was similarly sourced from the local market. Prior to transplanting, initial soil samples were collected from a depth of 0-25 cm to analyze physical and chemical characteristics. The analysis followed standard methods as per **Sparks et al. (2020) and Dane and Topp (2020).** The soil properties, including texture, pH, organic matter content, and nutrient levels, are detailed in Table 1. Onion seedlings of the cultivar "Giza Red," aged 60 days, were sourced from a private nursery. Transplanting was done on November 18th of each season. Seedlings were planted with a 10 cm spacing between plants under a drip irrigation system to ensure efficient water use and nutrient delivery. Each combined treatment with its replicates (replicated twice, resulting in three replicates) covered an area of 16 m² (4.0 m x 4.0 m), as it was divided into lines. The studied elemental sulfur was applied to the soil according to the designated treatments at the beginning of the trial. This was integrated into the soil to ensure uniform distribution and effective incorporation.

The base fertilization regime followed standard practices outlined by the Ministry of Agriculture and Soil Reclamation (MASR). It included urea (46% N), which is applied as the primary nitrogen source *via* fertigation system. Additionally, calcium superphosphate (15.5% P_2O_5) was applied before transplanting immediately to provide phosphorus (before installing the drip irrigation network). Potassium sulphate (48% K_2O_5), as the traditional practice, was used as a potassium source to meet onion needs, as it also was added *via* fertigation system.

Foliar applications of potassium treatments and methionine were conducted four times during the growing season using a hand sprayer. Each application used a solution volume of 900 L ha^{-1}. The first application was done one month after transplanting, with subsequent applications at two-week intervals to ensure consistent nutrient availability and absorption.

Harvesting was performed manually 160 days after transplanting, ensuring that the onions were mature and had reached optimal size for evaluation. Data collection focused on a range of growth parameters, yield and its components as well as quality traits as shown in Table 2. Data were statistically analyzed using the CoStat software package **(Version 6.303, CoHort, USA, 1998-2004),** following procedures similar to those described by **Gomez and Gomez (1984)** and using Duncan's Multiple Range Test.

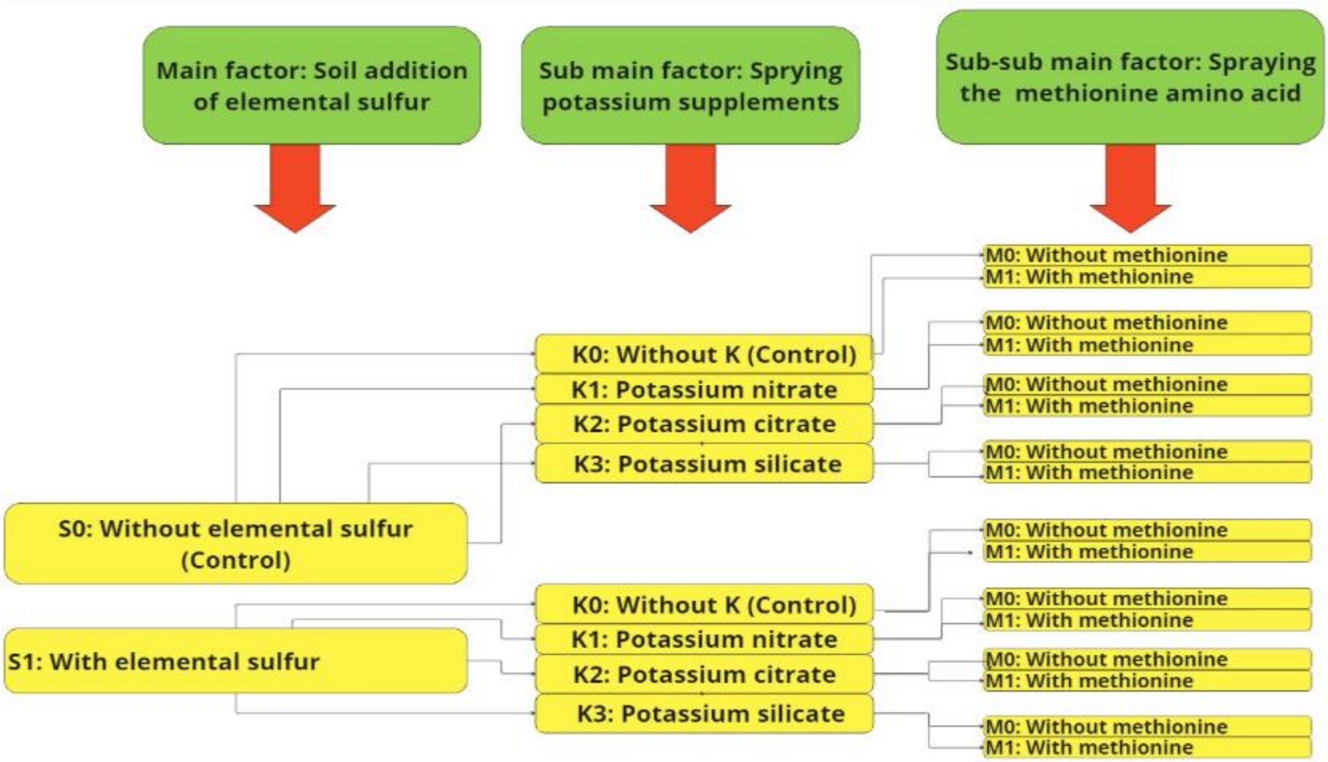

Fig. 1. Flowchart of the experiment.

Table 1. Fundamental initial soil characteristics.

Characteristics	Values
Clay, g 100g^{-1}	49
Sand, g 100g^{-1}	29
Silt, g 100g^{-1}	22
Texture class	Clay
Available nitrogen, mg kg^{-1} soil	32.2
Available phosphorus, mg kg^{-1} soil	9.30
Available potassium, mg kg^{-1} soil	209
Organic matter, g 100g^{-1}	1.34
Electric conductivity (EC), dSm^{-1}	2.59
Soil pH or soil reaction	8.00

Table 2. Measurements during the studied stages.

Parameters	Methods	References
After a period of 75 days from transplanting		
Plant height (cm), shoot fresh and dry weights (g plant^{-1})	Manually and visually	--------------
Leaf area (LA,cm^2 plant^{-1})	Mathematically (LA=Length × Width× Correction factor)	**[1]**
Chlorophyll a & b and carotene (mg g^{-1} FW)	Spectrophotometrically, using acetone	**[2]**
Plant samples digestion	Using a mixture of $HClO_4$ + H_2SO_4	**[3]**
Leaf chemical NPK (%DW)	Micro-Kjeldahl (for N), spectrophotometric(for P) and flame photometer (for K)	**[4]**
After a period of 160 days from transplanting		
Average bulb weight (g), bulb diameter (cm), neck diameter (cm), total bulb yield (metric ton ha^{-1}) and marketable bulb yield (metric ton ha^{-1})	Manually and visually	----------
Total carbohydrates percentage,%	Anthrone method	**[5]**
Protein percentage,%	Micro-kjeldahl	**[6]**
Total dissolved solids,%	Hand refractometer	**[6]**
Fiber	Sulfuric acid and sodium hydroxide	**[7]**
Total sugar ,%	Sulfuric acid and phenol	**[8]**
Dry mater,%	Using the oven	**[1]**
Vitamin C, mg 100g^{-1}(F.W)	Spectrophotometrically using potassium permanganates	**[6]**
Anthocyanin pigment, mg 100g^{-1}	Spectrophotometrically using HCl	**[9]**
Pyruvic acid, µmol g^{-1}	Spectrophotometrically using Trichloroacetic acid (TCA)	**[10]**

List of refs: [1] Garnier *et al.* (2001), **[2]** Wellburn (1994),[**3]** Peterburgski (1968)**,[4]** Walinga *et al.* (2013), **[5]** Hedge and Hofreiter (1962),**[6]** A.O.A.C (2000), **[7]** Sadasivam and Manickam (1996), **[8]** Dey (1990), **[9]** Schoefs (2004), **[10]**Anthon and Barrett (2003).

3. Results

3.1 Performance at 75 days

Table 3, 4 and 5 provide comprehensive data on how different treatments, including the application of elemental sulfur, various forms of potassium supplements and methionine amino acid, affected the growth traits (plant height, fresh and dry weights and leaf area, Table 3), photosynthetic pigments (Chl a, Chl b and carotene, Table 4) and leaf chemical constituents (N, P and K, Table 5) of onion plants during two consecutive seasons (2022/23 and 2023/24) at period of 75 days after transplanting. The data of these Tables show that the application of elemental sulfur (S_1) markedly improved all aforementioned growth parameters, photosynthetic pigments and leaf chemical constituents compared to the control (S_0). The trend was similar during both seasons. Among the potassium supplements, potassium silicate (K_3) resulted in the highest values for plant height, fresh weight, dry weight, leaf area, Chl a, Chl b, carotene, N, P and K across both seasons, followed by potassium citrate (K_2) then potassium nitrate (K_1) and lastly the control (K_0). Additionally, the spraying methionine (M_1) significantly enhanced all measured growth traits compared to the control (M_0). The pattern remained consistent across both seasons. Generally, it can be noticed that the most notable improvement in growth parameters, photosynthetic pigments and leaf chemical constituents was observed with the combination of elemental sulfur, potassium silicate, and methionine. The same trend was found for both studied seasons. The F-tests indicate significant differences at the 5% level for all measured parameters, reinforcing the reliability of the results. Generally, it can be observed that the combination of treatments consistently resulted in superior performance compared to individual treatments, highlighting the importance of integrated nutrient management in onion cultivation.

Table 3. Effect of elemental sulfur, diverse potassium supplements and methionine amino acid on the growth traits of onion plants at 75 days after transplanting during the studied seasons.

Treatments			Plant height, cm		Fresh weight, g plant^{-1}		Dry weight, g plant^{-1}		Leaf area, cm^2 plant^{-1}	
			1st season	2nd season	1st season	2nd season	1st season	2nd season	1st season	2nd season
Main factor: Soil addition of elemental sulfur										
S_0: Without elemental sulfur (Control)			72.57b	74.90b	66.57b	68.26b	9.53b	9.66b	215.36b	222.51b
S_1: With elemental sulfur			85.71a	87.79a	75.27a	77.33a	10.85a	11.01a	272.72a	278.35a
F-test			**	**	**	**	**	**	**	**
Sub main factor: Spraying potassium supplements										
K_0: Without K (Control)			76.77d	79.00d	69.43d	71.03d	9.84d	9.98d	225.16d	232.49d
K_1: Potassium nitrate			78.34c	80.67c	70.53c	72.22c	10.04c	10.19c	238.30c	245.70c
K_2: Potassium citrate			80.00b	82.26b	71.35b	73.55b	10.31b	10.46b	251.14b	256.23b
K_3: Potassium silicate			81.45a	83.45a	72.37a	74.39a	10.57a	10.72a	261.56a	267.30a
F-test			**	**	**	**	**	**	**	**
Sub-sub main factor: Spraying the methionine amino acid										
M_0: Without methionine (Control)			78.75b	81.17a	70.63b	72.42b	10.12b	10.27b	240.82b	247.21b
M_1: With methionine			79.53a	81.53a	71.21a	73.17a	10.26a	10.40a	247.26a	253.65a
F-test			**	*	**	**	**	**	**	**
Interaction										
S_0	**K_0**	**M_0**	69.29	71.76	64.93	66.24	9.11	9.28	192.23	201.67
		M_1	70.24	72.44	65.33	67.23	9.24	9.35	198.37	208.34
	K_1	**M_0**	71.05	73.82	65.60	67.67	9.27	9.40	205.61	215.59
		M_1	71.25	73.91	66.34	67.66	9.44	9.58	211.75	219.30
	K_2	**M_0**	72.59	75.49	66.54	67.94	9.57	9.70	219.28	223.68
		M_1	74.35	75.76	67.23	69.94	9.75	9.87	224.63	229.65
	K_3	**M_0**	75.55	77.09	67.97	69.35	9.89	10.01	232.40	237.22
		M_1	76.22	78.93	68.65	70.07	9.97	10.10	238.63	244.62
S_1	**K_0**	**M_0**	82.87	85.49	73.39	75.22	10.41	10.55	251.33	256.36
		M_1	84.69	86.31	74.09	75.42	10.58	10.73	258.72	263.60
	K_1	**M_0**	85.42	87.62	74.73	76.21	10.66	10.83	264.21	270.01
		M_1	85.62	87.34	75.46	77.31	10.78	10.93	271.64	277.89
	K_2	**M_0**	86.35	89.34	75.64	77.76	10.92	11.10	276.77	282.30
		M_1	86.69	88.46	75.98	78.56	11.01	11.18	283.89	289.29
	K_3	**M_0**	86.90	88.72	76.22	78.97	11.13	11.32	284.74	290.87
		M_1	87.15	89.08	76.65	79.16	11.28	11.45	290.48	296.47
F-test			**	**	**	**	**	**	**	**

Means within a column followed by a different letter (s) are statistically different at 5%.

Table 4. Effect of elemental sulfur, diverse potassium supplements and methionine amino acid on the photosynthetic pigments of onion plants at 75 days after transplanting during the studied seasons.

Treatments			Chlorophyll a (mg g^{-1} FW)		Chlorophyll b		Carotene	
			1st season	2nd season	1st season	2nd season	1st season	2nd season
Main factor: Soil addition of elemental sulfur								
S_0: Without elemental sulfur (Control)			0.874b	0.892b	0.509b	0.521b	0.295b	0.308b
S_1: With elemental sulfur			0.984a	1.018a	0.543a	0.566a	0.351a	0.365a
F-test			**	**	**	**	**	**
Sub main factor: Spraying potassium supplements								
K_0: Without K (Control)			0.889d	0.908d	0.514c	0.526d	0.301d	0.313d
K_1: Potassium nitrate			0.918c	0.944c	0.523b	0.536c	0.315c	0.328c
K_2: Potassium citrate			0.945b	0.977b	0.533a	0.549b	0.331b	0.346b
K_3: Potassium silicate			0.962a	0.992a	0.534a	0.564a	0.345a	0.360c
F-test			**	**	**	**	**	**
Sub-sub main factor: Spraying the methionine amino acid								
M_0: Without methionine (Control)			0.923b	0.948b	0.526a	0.540b	0.320b	0.333b
M_1: With methionine			0.934a	0.963a	0.526a	0.547a	0.326a	0.340a
F-test			**	**	*	**	**	**
Interaction								
S_0	**K_0**	**M_0**	0.820	0.846	0.493	0.494	0.278	0.288
		M_1	0.843	0.860	0.501	0.501	0.282	0.293
	K_1	**M_0**	0.860	0.884	0.506	0.512	0.288	0.302
		M_1	0.871	0.886	0.511	0.513	0.291	0.303
	K_2	**M_0**	0.882	0.899	0.518	0.517	0.301	0.315
		M_1	0.890	0.909	0.522	0.538	0.304	0.317
	K_3	**M_0**	0.905	0.920	0.526	0.543	0.308	0.320
		M_1	0.918	0.934	0.493	0.552	0.312	0.326
S_1	**K_0**	**M_0**	0.937	0.959	0.530	0.551	0.320	0.333
		M_1	0.954	0.969	0.532	0.556	0.324	0.337
	K_1	**M_0**	0.966	0.980	0.536	0.559	0.335	0.348
		M_1	0.977	1.027	0.538	0.561	0.346	0.361
	K_2	**M_0**	1.003	1.043	0.543	0.567	0.356	0.370
		M_1	1.005	1.055	0.549	0.572	0.365	0.382
	K_3	**M_0**	1.011	1.052	0.555	0.576	0.375	0.391
		M_1	1.015	1.061	0.562	0.584	0.387	0.402
F-test			**	**	**	**	**	**

Means within a column followed by a different letter (s) are statistically different at 5%.

Table 5. Effect of elemental sulfur, diverse potassium supplements and methionine amino acid on the leaf chemical constituents of onion plants at 75 days after transplanting during the studied seasons.

Treatments			Nitrogen (%)		Phosphorus (%)		Potassium (%)	
			1st season	2nd season	1st season	2nd season	1st season	2nd season
Main factor: Soil addition of elemental sulfur								
S_0: Without elemental sulfur (Control)			2.81b	2.91b	0.305b	0.314b	2.29b	2.35b
S_1: With elemental sulfur			3.54a	3.61a	0.379a	0.387a	3.01a	3.07a
F-test			**	**	**	**	**	**
Sub main factor: Spraying potassium supplements								
K_0: Without K (Control)			2.92d	3.02d	0.317d	0.326d	2.48d	2.54d
K_1: Potassium nitrate			3.05c	3.15c	0.335c	0.345c	2.57c	2.64c
K_2: Potassium citrate			3.29b	3.36b	0.351b	0.359b	2.68b	2.74b
K_3: Potassium silicate			3.44a	3.51a	0.364a	0.372a	2.86a	2.93a
F-test			**	**	**	**	**	**
Sub-sub main factor: Spraying the methionine amino acid								
M_0: Without methionine (Control)			3.14b	3.22b	0.337b	0.346b	2.62b	2.68b
M_1: With methionine			3.21a	3.29a	0.346a	0.355a	2.68a	2.74a
F-test			**	**	**	**	**	**
Interaction								
S_0	**K_0**	**M_0**	2.54	2.66	0.268	0.278	2.11	2.15
		M_1	2.56	2.69	0.278	0.292	2.15	2.22
	K_1	**M_0**	2.60	2.73	0.287	0.301	2.19	2.25
		M_1	2.71	2.81	0.301	0.312	2.22	2.28
	K_2	**M_0**	2.90	2.96	0.311	0.318	2.25	2.32
		M_1	2.98	3.04	0.323	0.330	2.36	2.41
	K_3	**M_0**	3.07	3.14	0.332	0.339	2.50	2.57
		M_1	3.13	3.21	0.339	0.347	2.57	2.63
S_1	**K_0**	**M_0**	3.25	3.31	0.357	0.364	2.81	2.86
		M_1	3.33	3.40	0.365	0.372	2.87	2.93
	K_1	**M_0**	3.41	3.48	0.372	0.380	2.92	2.98
		M_1	3.48	3.56	0.380	0.389	2.96	3.03
	K_2	**M_0**	3.60	3.67	0.384	0.392	3.02	3.08
		M_1	3.68	3.75	0.387	0.395	3.11	3.17
	K_3	**M_0**	3.76	3.84	0.390	0.398	3.17	3.24
		M_1	3.79	3.87	0.395	0.403	3.20	3.27
F-test			**	**	**	**	**	**

Means within a column followed by a different letter (s) are statistically different at 5%

3.2 Performance at 160 days (Quantitative and qualitative yield)

Table 6 illustrates the impact of elemental sulfur, diverse potassium supplements and methionine amino acid on quantitative parameters such as average bulb weight, bulb and neck diameters, total bulb yield and marketable bulb yield (**Figure 2)** at the harvest stage during both investigated seasons. Additionally, Table 7 illustrates the impact of studied treatments on qualitative parameters, including carbohydrates, protein, TDS, fiber, total sugar, dry matter, vitamin C, anthocyanin and pyruvic acid after harvest during both seasons. The results presented in these Tables demonstrate that the application of elemental sulfur significantly enhanced all measured quantitative and qualitative traits of onions after harvest compared to those grown without sulfur. Potassium silicate proved to be the most effective potassium supplement, followed by potassium citrate and then potassium nitrate, with the control showing the least improvement. Additionally, the application of methionine improved both the quantitative and qualitative traits of onions compared to the control. The combined use of elemental sulfur, potassium silicate, and methionine resulted in the highest values for all measured parameters, reflecting superior quantitative and qualitative traits of onions post-harvest.

Table 6. Effect of elemental sulfur, diverse potassium supplements and methionine amino acid on the yield and component of onion plants at 160 days after transplanting (harvest stage) during the studied seasons.

Treatments			Average bulb weight (g)		Bulb diameter (cm)		Neck diameter (cm)		Total bulb yield (metric ton ha^{-1})		Marketable bulb yield (metric 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: Soil addition of elemental sulfur												
S_0: Without sulfur			85.12b	86.73b	4.79b	4.85b	1.29b	1.33b	32.41b	33.03b	32.31b	32.99b
S_1: With sulfur			102.03a	104.02a	6.81a	6.90a	2.39a	2.44a	38.85a	39.61a	37.80a	38.53a
F-test			**	**	**	**	**	**	**	**	**	**
Sub main factor: Spraying potassium supplements												
K_0: Without K			89.12d	90.75d	5.23d	5.30d	1.48d	1.53d	33.94d	34.56d	32.98d	33.68d
K_1: Potassium nitrate			91.52c	93.39c	5.60c	5.69c	1.71c	1.75c	34.85c	35.56c	34.37c	35.12c
K_2: Potassium citrate			94.78b	96.66b	5.94b	6.01b	1.98b	2.02b	36.09b	36.81b	35.77b	36.47b
K_3: Potassium silicate			98.87a	100.72a	6.43a	6.51a	2.21a	2.25a	37.65a	38.35a	37.11a	37.78a
F-test			**	**	**	**	**	**	**	**	**	**
Sub-sub main factor: Spraying the methionine amino acid												
M_0: Without methionine			92.73b	94.53b	5.70b	5.78b	1.78b	1.82b	35.31b	36.00b	34.71b	35.45b
M_1: With methionine			94.42a	96.23a	5.90a	5.97a	1.91a	1.95a	35.96a	36.64a	35.40a	36.08a
F-test			**	**	**	**	**	**	**	**	**	**
Interaction												
S_0	**K_0**	**M_0**	82.15	83.82	4.20	4.25	1.13	1.19	31.28	31.92	29.84	30.54
		M_1	82.38	83.77	4.32	4.38	1.08	1.14	31.37	31.90	30.52	31.29
	K_1	**M_0**	82.83	84.42	4.53	4.58	1.20	1.26	31.55	32.15	31.30	32.03
		M_1	83.09	84.82	4.62	4.67	1.27	1.31	31.64	32.30	31.89	32.71
	K_2	**M_0**	84.14	85.45	4.80	4.86	1.31	1.34	32.04	32.54	32.73	33.37
		M_1	86.81	88.50	5.05	5.10	1.38	1.41	33.06	33.70	33.43	33.99
	K_3	**M_0**	88.81	90.50	5.25	5.31	1.44	1.46	33.82	34.46	34.02	34.74
		M_1	90.73	92.58	5.55	5.62	1.53	1.56	34.55	35.25	34.76	35.27
S_1	**K_0**	**M_0**	94.88	96.57	6.07	6.14	1.73	1.77	36.13	36.78	35.38	36.08
		M_1	97.09	98.83	6.32	6.42	1.96	2.00	36.97	37.63	36.16	36.79
	K_1	**M_0**	99.02	100.96	6.56	6.69	2.06	2.11	37.71	38.45	36.75	37.54
		M_1	101.13	103.36	6.68	6.80	2.29	2.34	38.51	39.36	37.51	38.19
	K_2	**M_0**	103.02	105.39	6.79	6.87	2.50	2.56	39.23	40.13	38.16	38.98
		M_1	105.16	107.28	7.10	7.20	2.72	2.77	40.05	40.85	38.77	39.54
	K_3	**M_0**	106.96	109.09	7.40	7.50	2.84	2.89	40.73	41.54	39.51	40.28
		M_1	109.00	110.72	7.51	7.59	3.04	3.11	41.51	42.16	40.14	40.84
F-test			**	**	**	**	**	**	**	**	**	**

Means within a column followed by a different letter (s) are statistically different at 5%

Table 7. Effect of elemental sulfur, diverse potassium supplements and methionine amino acid on bulb quality traits plants at 160 days after transplanting (harvest stage) during the studied seasons.

Treatments	Carbohydrates		Protein		TDS		Fiber		Total sugar	
	(%)									
	1st season	2nd season	1st season	2nd season	1st season	2nd season	1st season	2nd season	1st season	2nd season
Main factor: Soil addition of elemental sulfur										
S_0: Without sulfur	15.75b	16.15b	7.41b	7.52b	9.84b	10.08b	2.90b	2.99b	5.61b	5.75
S_1: With sulfur	18.14a	18.51a	8.51a	8.63a	11.79a	12.12a	3.95a	4.04a	6.20a	6.36
F-test	**	**	**	**	**	**	**	**	**	**
Sub main factor: Spraying potassium supplements										
K_0: Without K	16.34d	16.72d	7.71d	7.81d	10.33d	10.56d	3.07d	3.15d	5.73d	5.86d
K_1: Potassium nitrate	16.65c	17.05c	7.85c	7.97c	10.59c	10.83c	3.27c	3.36c	5.82c	5.95c
K_2: Potassium citrate	17.09b	17.48b	8.02b	8.14b	10.93b	11.27b	3.57b	3.67b	5.96b	6.14b
K_3: Potassium silicate	17.69a	18.08a	8.26a	8.38a	11.42a	11.76a	3.80a	3.89a	6.10a	6.28a
F-test	**	**	**	**	**	**	**	**	**	**
Sub-sub main factor: Spraying the methionine amino acid										
M_0: Without methionine	16.85b	17.23b	7.91b	8.03b	10.74b	11.01b	3.37b	3.47b	5.87b	6.01b
M_1: With methionine	17.04a	17.44a	8.01a	8.13a	10.90a	11.20a	3.48a	3.56a	5.94a	6.10a
F-test	**	**	**	**	**	**	**	**	**	**
Interaction										
S_0 K_0 M_0	15.10	15.40	7.19	7.31	9.32	9.45	2.48	2.56	5.42	5.51
S_0 K_0 M_1	15.21	15.72	7.23	7.31	9.41	9.68	2.56	2.64	5.46	5.62
S_0 K_1 M_0	15.35	15.76	7.26	7.36	9.55	9.75	2.67	2.77	5.48	5.62
S_0 K_1 M_1	15.46	15.84	7.34	7.45	9.57	9.78	2.75	2.86	5.57	5.68
S_0 K_2 M_0	15.73	16.26	7.38	7.49	9.76	9.99	3.03	3.15	5.60	5.72
S_0 K_2 M_1	15.95	16.26	7.48	7.59	10.03	10.42	3.13	3.19	5.73	5.96
S_0 K_3 M_0	16.45	16.81	7.61	7.71	10.45	10.69	3.25	3.31	5.78	5.90
S_0 K_3 M_1	16.74	17.15	7.82	7.94	10.67	10.91	3.32	3.45	5.87	5.99
S_1 K_0 M_0	17.44	17.77	8.15	8.26	11.22	11.51	3.57	3.68	6.00	6.15
S_1 K_0 M_1	17.62	17.98	8.25	8.37	11.39	11.60	3.66	3.73	6.06	6.17
S_1 K_1 M_0	17.82	18.19	8.36	8.49	11.54	11.78	3.77	3.86	6.09	6.21
S_1 K_1 M_1	17.99	18.42	8.45	8.56	11.71	11.99	3.89	3.96	6.15	6.29
S_1 K_2 M_0	18.23	18.58	8.54	8.69	11.88	12.22	3.99	4.13	6.22	6.38
S_1 K_2 M_1	18.44	18.80	8.67	8.80	12.04	12.44	4.12	4.20	6.28	6.49
S_1 K_3 M_0	18.66	19.05	8.74	8.88	12.21	12.66	4.24	4.32	6.37	6.59
S_1 K_3 M_1	18.89	19.31	8.87	9.00	12.37	12.77	4.38	4.46	6.40	6.62
F-test	**	**	**	**	**	**	**	**	**	**

Means within a column followed by a different letter (s) are statistically different at 5%

Table 7. Cont.

Treatments			Dry matter, %		Vitamin C, mg $100g^{-1}$		Anthocyanin, mg $100g^{-1}$		Pyruvic acid, πmol g^{-1}	
			1st season	2nd season	1st season	2nd season	1st season	2nd season	1st season	2nd season
Main factor: Soil addition of elemental sulfur										
S_0: Without elemental sulfur (Control)			9.88b	10.21b	10.15b	10.26b	25.43b	26.09b	5.33b	5.46b
S_1: With elemental sulfur			12.27a	12.53a	12.35a	12.52a	28.12a	28.68a	7.13a	7.33a
F-test			**	**	**	**	**	**	**	**
Sub main factor: Spraying potassium supplements										
K_0: Without K (Control)			10.42d	10.78d	10.68d	10.83d	26.27d	26.88d	5.66d	5.79d
K_1: Potassium nitrate			10.85c	11.19c	11.08c	11.23c	26.57c	27.20c	6.01c	6.15c
K_2: Potassium citrate			11.25b	11.49b	11.41b	11.54b	26.88b	27.49b	6.45b	6.65b
K_3: Potassium silicate			11.77a	12.03a	11.83a	11.97a	27.39a	27.97a	6.80a	6.99a
F-test			**	**	**	**	**	**	**	**
Sub-sub main factor: Spraying the methionine amino acid										
M_0: Without methionine (Control)			10.97b	11.27b	11.15b	11.29b	26.67b	27.25a	6.14b	6.29b
M_1: With methionine			11.18a	11.47a	11.36a	11.50a	26.89a	27.52a	6.32a	6.50a
F-test			**	**	**	**	**	*	**	**
Interaction										
S_0	**K_0**	**M_0**	9.10	9.58	9.57	9.68	25.03	25.54	4.63	4.70
		M_1	9.31	9.78	9.75	9.90	25.05	25.92	4.79	4.93
	K_1	**M_0**	9.52	9.99	9.89	9.98	25.14	25.82	4.96	5.07
		M_1	9.71	10.05	10.05	10.14	25.28	25.90	5.14	5.25
	K_2	**M_0**	9.90	10.11	10.16	10.29	25.34	26.16	5.51	5.62
		M_1	10.12	10.33	10.32	10.42	25.56	26.10	5.70	5.92
	K_3	**M_0**	10.57	10.80	10.61	10.72	25.76	26.31	5.88	6.00
		M_1	10.78	11.05	10.84	10.98	26.31	26.93	6.05	6.18
S_1	**K_0**	**M_0**	11.54	11.77	11.54	11.68	27.39	27.89	6.52	6.67
		M_1	11.74	11.98	11.87	12.05	27.60	28.17	6.72	6.85
	K_1	**M_0**	11.98	12.24	12.06	12.29	27.86	28.41	6.90	7.03
		M_1	12.19	12.47	12.30	12.51	28.00	28.66	7.05	7.23
	K_2	**M_0**	12.40	12.65	12.49	12.64	28.19	28.72	7.22	7.42
		M_1	12.60	12.85	12.66	12.83	28.43	28.97	7.38	7.62
	K_3	**M_0**	12.78	13.03	12.85	13.03	28.64	29.18	7.53	7.81
		M_1	12.95	13.22	13.03	13.15	28.87	29.47	7.72	7.98
F-test			**	**	**	**	**	**	**	**

Means within a column followed by a different letter (s) are statistically different at 5%

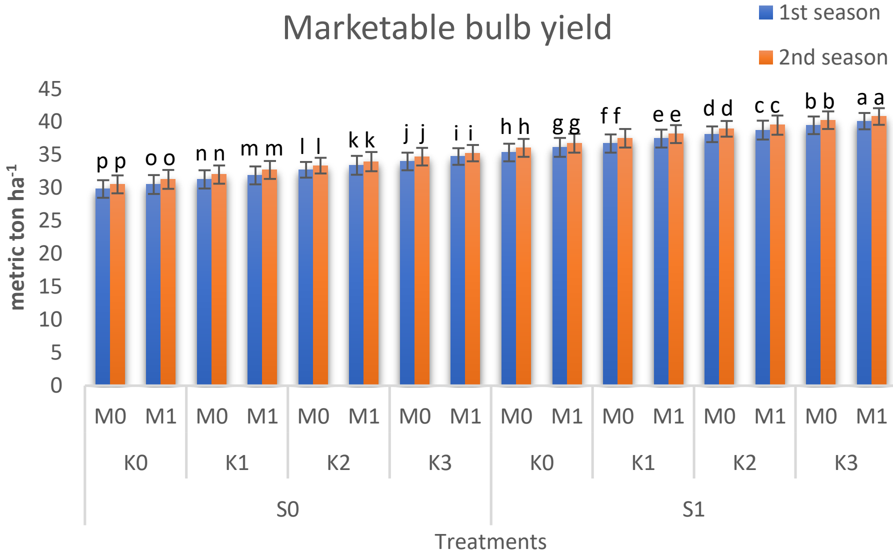

Fig. 2. Synergistic effect of elemental sulfur, diverse potassium supplements and methionine amino acid on marketable yield of onion at 160 days after transplanting (harvest stage) during the studied seasons.

Where, S_0: Without elemental sulfur (Control), **S_1:** With elemental sulfur**, K_0:** Without K (Control), **K_1:** Potassium nitrate, **K_2:** Potassium citrate**, K_3:** Potassium silicate**, M_0:** Without methionine (Control), **M_1:** With methionine.

4. Discussion

In this study, elemental sulfur played a vital role in onion nutrition through several mechanisms. Firstly, elemental sulfur can act as a soil acidifier, leading to a reduction in soil pH. This decrease in pH creates a more acidic environment, which is favorable for the availability and uptake of essential nutrients by onion plants. The lowered pH facilitates the release of bound nutrients in the soil, making them more accessible to the plants. Additionally, sulfur itself is an essential element for plant growth, being a component of amino acids, vitamins, and enzymes involved in various metabolic processes **(González-Morales et al. 2017; Przygocka-Cyna *et al.* 2020; Sałata *et al.* 2021).**

Potassium silicate emerged as the superior potassium supplement in this study due to its unique properties. Potassium silicate provides not only potassium but also silicon, which plays a crucial role in enhancing plant resilience against various biotic and abiotic stresses. Silicon strengthens cell walls, making plants more resistant to diseases, pests, and environmental stresses such as drought and heat. This dual benefit of potassium and silicon likely contributed to the superior performance of potassium silicate-treated plants in terms of growth, yield, and quality **(Sarhan and Shehata, 2023; Metwally *et al.* 2024).**

Potassium citrate, which ranked second in effectiveness, is a potassium source that also provides citrate, an organic acid. Citrate acts as a chelating agent, enhancing the availability of micronutrients in the soil and promoting their uptake by plants. Additionally, citrate can facilitate the transport of potassium within the plant, improving its distribution and utilization. These mechanisms likely contributed to the positive impact of potassium citrate on onion growth and development observed in the study **(Ali *et al.* 2021; Fawaz *et al.* 2024; Metwally *et al.* 2024).**

Potassium nitrate, although ranked third, still provided beneficial effects on onion nutrition. Nitrate serves as a crucial nitrogen source for plant growth and is readily taken up by onion roots. Additionally, potassium nitrate contributes to the osmotic regulation of cells and is involved in various metabolic processes. While potassium nitrate may not have outperformed potassium silicate and potassium citrate in this study, its role in supplying both potassium and nitrogen to the plants remains essential for overall growth and development **(Alebidi *et al.* 2021; Khudhair and Hamza, 2024).**

Methionine amino acid, when applied as a supplement, played a vital role in enhancing onion nutrition. Methionine is an essential amino acid involved in protein synthesis and various metabolic pathways. By providing an additional source of methionine, the supplemented plants likely experienced improved protein synthesis, leading to enhanced growth, development, and quality traits (**Faiyad *et al.* 2020; Khater *et al.* 2024**).

Lastly, the synergistic effect observed when combining elemental sulfur, potassium silicate, and methionine highlights the importance of integrated nutrient management. Each component likely complemented the others, leading to enhanced nutrient availability, uptake, and utilization by onion plants. This synergistic effect underscores the significance of considering multiple nutrient sources and their interactions in optimizing crop nutrition and performance.

5. Conclusion

Based on the results obtained, it can be inferred that the utilization of elemental sulfur, potassium supplements (especially potassium silicate) and methionine yield beneficial outcomes for enhancing onion performance. Looking ahead, there is a need to delve deeper into the precise mechanisms governing the interactions among these nutrients to refine their application in onion cultivation. Conducting prolonged field trials across diverse environmental settings will aid in gauging the durability and efficacy of these nutrient management approaches over time. Moreover, exploring alternative sources of elemental sulfur, potassium supplements and amino acids holds promise for fostering more sustainable practices in onion cultivation.

Conflicts of interest

The authors have declared that no competing interests exist. The authors have declared that no competing interests exist. The authors contributed equally to put the research methodology and implementation at all stages.

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6. References

Abd El-Hady, M. A. M., Doklega, S. M. A., & El-Ezz, S. A. (2021). Influence of organic and potassium fertilization on potato yield and quality. Plant Archives, 21(Supplement 1), 560-568.

Alebidi, A., Almutairi, K., Merwad, M., Mostafa, E., Saleh, M., Ashour, N., ... & Elsabagh, A. (2021). Effect of spraying algae extract and potassium nitrate on the yield and fruit quality of Barhee date palms. Agronomy, 11(5), 922.

Ali, M. M., Petropoulos, S. A., Selim, D. A. F. H., Elbagory, M., Othman, M. M., Omara, A. E. D., & Mohamed, M. H. (2021). Plant growth, yield and quality of potato crop in relation to potassium fertilization. Agronomy, 11(4), 675.

Anthon, A & Barrett, D (2003). Modified method for the determination of pyruvic acid with di-nitrophenyl hydrazine in the assessment of onion pungency. J Sci. Food Agric., 83:1210-1213.

AOAC, (2000). ˝ Official Methods of Analysis˶. 18th Ed. Association of Official Analytical Chemists, Inc., Gaithersburg, MD, Method 04.

Awad, A. H., El-Wahed, A., Ahmed, H. M., Elateeq, A. A., Moustafa, M. M., Ullah, S., ... & Badawi, T. A. (2024). Response of yield, quality, and bioactive constituents of green onion to foliar spraying with *Moringa oleifera* leaf extract and yeast extract. Egyptian Journal of Soil Science, 64(2), 543-560.

CoStat, Version 6.303, Copyright (1998-2004), CoHort Software, Monterey, CA, USA.

Dane, J. H., & Topp, C. G. (Eds.) (2020). ″Methods of soil analysis", Part 4: Physical methods (Vol. 20). John Wiley & Sons.

Dey, P. M. (1990). Oligosaccharides. In Methods in plant biochemistry (Vol. 2, pp. 189-218). Academic Press.

El Shafei, W. A., Mohamed, M. M., Ibrahim, A. A. E., & Nossier, M. I. (2023). Evaluation of the efficiency of foliar potassium applications as drought mitigation. Egyptian Journal of Soil Science, 63(2), 187-196.

El-Bauome, H. A., Abdeldaym, E. A., Abd El-Hady, M. A., Darwish, D. B. E., Alsubeie, M. S., El-Mogy, M. M., & Doklega, S. M. (2022). Exogenous proline, methionine, and melatonin stimulate growth, quality, and drought tolerance in cauliflower plants. Agriculture, 12(9), 1301.

El-Beltagi, H. S., Abdeldaym, E. A., Farag, H. A., Doklega, S. M., Abd El-Hady, M. A., Abdelaziz, S. M.; El-Mogy, M. M.; Maryam, A.; EL-Bauome, H. A. (2023). Pre-harvest application of proline, methionine, and melatonin improves shelf-life and maintains nutritional quality of *Brassica oleracea* florets during cold storage. Notulae Botanicae Horti Agrobotanici Cluj-Napoca, 51(2), 13218-13218.

Elmasry, H. M., & Marey, R. A. (2024). Vegetative growth, yield, and quality of onion as influenced by nitrogen rates and natural stimulators. Egyptian Journal of Soil Science, 64(1), 49-62.

Faiyad, R., El-Azeiz, A., Eman, H., & El-Mahdy, R. E. (2020). Integrated management of nitrogen and sulfur sources in combination with amino acids amelioration for onion plants production under alluvial soil condition. Journal of Soil Sciences and Agricultural Engineering, 11(9), 489-496.

Fawaz, D. M., El-Salhy, A. F. M., Saeed, H. H., & El-Harith, O. (2024). Effect of foliar spray of urea and potassium citrate on fruiting of Barhee Date palm. Aswan University Journal of Sciences and Technology, 46-56.

Garnier, E., Shipley, B., Roumet, C., & Laurent, G. (2001). A standardized protocol for the determination of specific leaf area and leaf dry matter content. Functional Ecology, 688-695.

Gomez, K. A., & Gomez, A. A. (1984). “Statistical procedures for agricultural research”. John Wiley and Sons, Inc., New York.pp:680.

González-Morales, S., Pérez-Labrada, F., García-Enciso, E. L., Leija-Martínez, P., Medrano-Macías, J., Dávila-Rangel, I. E., & Benavides-Mendoza, A. (2017). Selenium and sulfur to produce Allium functional crops. Molecules, 22(4), 558.

Hamaiel, A. F., Abd El-Hady, M. A. M., & Hussien, Kh. R. (2020). Impact of sulfur rates and some foliar applications on broccoli. J. Plant Production, Mansoura Univ., 11 (9): 835 – 839.

Hedge JE, Hofreiter BT (1962). In: Carbohydrate Chemistry (Eds Whister RL and Be Miller, J N) Academic Press, New York

Hekal, M. A., & Moussa, M. G. (2023). The role of gamma radiation on the productivity of sesame plants and potassium efficiency under different rates of potassium fertilization. Egyptian Journal of Soil Science, 63(3), 301-310.

Khater, M. A., Zaki, F. S., Dawood, M. G., El-Awadi, M. E., & Elsayed, E. A. (2024). Comparing physiological role of l-methionine and its encapsulated nanoform on growth and crop productivity of onion (*Allium Cepa* L.). Egyptian Journal of Chemistry, 67(4), 291-307.

Khudhair, M. M., & Hamza, J. H. (2024). Effect of potassium nitrate, licorice extract and planting date on field emergence and growth of maize (*Zea mays* L.) in spring season. In *IOP* .Conference Series: Earth and Environmental Science (Vol. 1325, No. 1, p. 012011). IOP Publishing. **DOI** 10.1088/1755-1315/1325/1/012011.

Lee, S. K., Lee, Y. S., Ji, S. H., Kim, P. H., Kim, J. H., Kim, S. J., ... & Lee, J. W. (2023). Nutritional and functional constituents and antioxidant activity in whole onion (*Allium cepa* L.) by growth stage. Food Science and Preservation, 30(5), 833-846.

Metwally, A. K. B., Yousef, A. F., El-Raheem, A., & El-Rehim, A. (2024). Exploring the influence of supplemental potassium fertilizer types and rates on garlic quality and yield. Archives of Agriculture Sciences Journal, 47-63.

Ndiaye, N. A., Niang, L., Dieng, M., & Touré, N. C. K. (2024). Physicochemical and biochemical characterization, total phenolic and energy value from bulbs of different onion (*Allium cepa* L.) varieties in Senegal. Food and Nutrition Sciences, 15(2), 129-139.

Peterburgski, A. V. (1968)."Handbook of Agronomic Chemistry". Kolos Puplishing House, Moscow, (in Russian, pp. 29-86).

Przygocka-Cyna, K., Barłóg, P., Grzebisz, W., & Spiżewski, T. (2020). Onion (*Allium cepa* L.) yield and growth dynamics response to in-season patterns of nitrogen and sulfur uptake. Agronomy, 10(8), 1146.

Sadasivam, S. Manickam,A (1996). In: Biochemical methods for Agricultural Sciences. Wiley Eastern Limited, New Delhi, pp.6-7;11-12.

Sałata, A., Buczkowska, H., Papliński, R., & Rutkowska, A. (2021). The effects of using sulfur and organic bedding on the content of macro-and micronutrients and biologically active substances in winter garlic bulbs. Agriculture, 11(5), 399.

Sami, R., Elhakem, A., Alharbi, M., Benajiba, N., Almatrafi, M., & Helal, M. (2021). Nutritional values of onion bulbs with some essential structural parameters for packaging process. Applied Sciences, 11(5), 2317.

Sarhan, M. G., & Shehata, A. M. (2023). Effect of compost along with spraying of methyl Jasmonate and potassium silicate on the productivity of French basil under sandy soil conditions. Egyptian Journal of Soil Science, 63(2), 225-241.

Schoefs, B. (2004). Determination of pigments in vegetables. Journal of chromatography, 1054 (1-2): 217-226.

Sharma, M., Delta, A. K., & Kaushik, P. (2022). Effects of *Funneliformis mosseae* and potassium silicate on morphological and biochemical traits of onion cultivated under water stress. Horticulturae, 8(7), 663.

Sparks, D. L., Page, A. L., Helmke, P. A., & Loeppert, R. H. (Eds.). (2020).”Methods of soil analysis”, part 3: Chemical methods (Vol. 14). John Wiley & Sons.

Walinga, I., Van Der Lee, J. J., Houba, V. J., Van Vark, W., & Novozamsky, I. (2013). Plant analysis manual. Springer Science & Business Media.

Wellburn, A. R. (1994). The spectral determination of chlorophylls a and b, as well as total carotenoids, using various solvents with spectrophotometers of different resolution. Journal of plant physiology, 144(3), 307-313.