Research Article

Sustainable Fertilization with Palm Residues, Organic Sulfur and Garlic Extract and its Effect on the Growth, Yield, and Chemical Characteristics of Bunching Onion

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Abstract | This study was conducted to investigate the impact of fertilization with palm residues (0, 20, and 30 tons ha^{-1}), organic sulfur (0, 300, and 600 kg ha^{-1}), and foliar spraying with garlic extract (0 and 6 mL L^{-1}) on selected vegetative traits, yield, and the chemical composition of bunching onion bulbs. The experiment was conducted in a RCBD design using a split-plot layout with three replications, comprising 18 experimental units per replicate, each containing 150 plants. The results revealed that the application of palm residues at 30 tons ha^{-1}, organic sulfur at 600 kg ha^{-1}, and foliar spraying with garlic extract at 6 mL L^{-1}, when applied individually, significantly enhanced nitrogen, phosphorus percentages, and sulfur in the bulbs, leaf chlorophyll content, the height of plant , plant leaf area, in addition to total yield. Regarding the three-way interaction among the studied factors, the combined treatment of palm residues at 30 tons ha^{-1} + organic sulfur at 600 kg ha^{-1} + garlic extract at 6 mL L^{-1} produced the most pronounced improvements, achieving significant increases in nitrogen (3.68%) and phosphorus (0.400%) content in the bulbs, chlorophyll concentration in the leaves (131.4 mg 100 g^{-1} fresh weight), leaf area (15.31 dm^2), and total yield (89.33 tons ha^{-1}).

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Introduction

The global agricultural sector is witnessing a growing trend towards adopting sustainable agricultural practices that aim to achieve a balance between increasing agricultural production and ensuring food safety on the one hand and preserving environmental resources and reducing pollution on the other. In this context, the use of agricultural residues and organic materials is considered an effective alternative to chemical fertilizers, because of its role in improving soil fertility and raising the efficiency of nutrient absorption, in addition to promoting the accumulation of bioactive compounds in plants (Ali *et al.*, 2025). One of the priority vegetable crops is green onions (*Allium fistulosum* L.) a member of Alliaceae family (Mahmood *et al.*, 2021), being a leading crop in Iraq and other countries worldwide.

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This crop is known for its high carbohydrates and mineral contents, specifically sulfur (Liu *et al*., 2024), which is involved in the synthesis of volatile sulfur compounds responsible for the pungent taste and unique aroma of the crop. Clinically, in addition to its food nourishment, the green onion has significant therapeutic effect because of the majority active compound constituents including quercetin (Kim *et al*., 2023). Quercetin is a natural antioxidant that exists in high quantity in green onion and serves as a principal contributor to counter the deleterious action of free radicals, which underlie many chronic diseases such as cardiovascular diseases and some cancers. It's known to also increase immune system responses (Javed, 2025; Kim *et al*., 2023). Green onion also has other biologically active substances, such as kaempferol and phenolics (Zhao *et al*., 2021) and important vitamins such as C, A, B9 (Akbar *et al*., 2024; Amare, 2020).These reinforce the nutritional and medicinal properties of bunching onion.

While heavy use of chemical fertilizers in recent farming systems has resulted in increasing the agricultural productivity, it has also caused several negative impacts for both environment and human health such as groundwater pollution and deterioration of soil fertility. As environmental problems have become more serious and global attention focuses on how to accomplish sustainable food security, it is urgent that safe and natural alternatives which decrease dependence on chemical inputs should be developed (Abdel-Hakim, 2020). In this regard, organic fertilizers are a sustainable and effective choice for enhancing the physical and chemical characteristics of soil and increasing its content of organic matter and available nutrients (Asha *et al*., 2023; Fayhaa *et al*., 2025; Mohammed *et al*., 2025). Moreover, organic fertilizers support the activity of beneficial soil microorganisms and strengthen ecological balance within agroecosystems, making organic farming a strategic approach to producing safe, healthy food while preserving the environment and biodiversity (Al-Hlfie & Hussein, 2024; Du *et al*., 2022).

Among promising organic fertilizers, palm residues stand out as a natural resource capable of improving soil characteristics (Aram & Khattab, 2018; Ghouili *et al*., 2023), increasing nutrient availability and uptake by plants, and consequently enhancing plant nutrition and productivity (Le Guyader *et al*., 2024; Muslat & Salih, 2017). Previous studies have shown that when 32 tons per hectare of palm fronds were added resulted in significant improvements in most vegetative, qualitative, and yield traits of potato compared with other application levels (Shaker & Abdul Rasool, 2023). Likewise, organic sulfur is considered an essential element to support the plants' growth and development (Desouza *et al*., 2015; He *et al*., 2010), particularly in crops such as green onion, where both productivity and quality are highly influenced by sulfur availability (Ogunbode & Tijani, 2020; Taru *et al*., 2025). The importance of sulfur lies in its biological association with nitrogen in the synthesis of amino acids and proteins (Demisse & Shiferaw, 2024). Its deficiency leads to imbalances in plant protein content (Khorsheed & Al-Tamimi, 2018; Sable *et al*., 2024). Research has further demonstrated that applying agricultural sulfur in combination with poultry residues significantly improved all vegetative and productivity traits of red onion (Al-Amri & Al-Abdaly, 2021; Manik *et al*., 2024; Tilahun *et al*., 2021).

In the search for eco-friendly alternatives, recent studies have increasingly focused on the use of plant extracts as effective biostimulants. These extracts contribute to the principles of sustainable agricultural development by utilizing renewable natural resources and minimize the environmental effect of chemical inputs (Lorin & Al-Juboori, 2022). Among these, garlic extract has gained considerable attention due to its richness in bioactive compounds such as allicin, sulfur-containing compounds, phenolics, and flavonoids (Sunanta *et al*., 2023). These compounds exhibit growth-promoting properties, enhance nutrient uptake, and provide resistance against plant diseases (Al-Mousawi *et al*., 2024; Bar *et al*., 2022; Bulgari *et al*., 2019). A recent study on cucumber (Maitig *et al*., 2025) revealed that foliar application containing garlic extract with a concentration of 3.75 mL L^{-1} significantly improved most measured traits, while the concentration of 5 mL L^{-1} resulted in the highest set of fruit percentage. Researchers emphasized the critical role of plant extracts, particularly garlic extract, in enhancing plant growth and productivity.

Despite the progress made in this field, studies examining the combined effects of palm residues, organic sulfur, and garlic extract on green onion remain limited. Therefore, the present study was designed to evaluate the function of these natural sources in enhancing productivity of green onion and boosting its content of bioactive medicinal compounds, thereby supporting sustainable agriculture and the production of safe and healthy food.

Material and Methods

The field trial was conducted at Research Station (A), which is associated with the College of Agricultural Engineering Sciences, University of Baghdad, in the spring growing season from 1 October 2024, to 15 March 2025. The aim was to evaluate the effects of fertilization with palm residues, organic sulfur, and foliar spraying with garlic extract on vegetative traits, total yield, nutrient content, and chlorophyll concentration in bunching onion.

The field was divided into three replications, each comprising 18 experimental units. Each experimental unit was represented by a raised bed measuring 1 × 1 m^2. Plants were grown in rows spaced 10 cm apart, with 7 cm spacing between plants within the row, yielding a combined total of 150 plants per experimental unit. A 0.50 m buffer was left between units to prevent treatment overlap. Well-decomposed palm residue compost was applied according to the designated treatments, followed by the installation of a drip irrigation system. Seeds of the green onion hybrid *Bunching Onion* were sown in Styrofoam trays at a private nursery on 1 October 2024 and transplanted into the permanent field on 15 November once the saplings had developed 2–3 true leaves.

The experiment included three factors:

- Palm residue fertilization at three levels: 0, 20, and 30 tons ha^{-1}.
- Organic sulfur fertilization at three levels: 0, 300, and 600 kg ha^{-1}
- Garlic extract foliar spraying with two concentrations: 0 and 6 ml per liter.

The garlic extract was prepared by blending 150 g of garlic cloves with 150 mL of distilled water using a blender. The mixture passed through two layers of muslin cloth to get a 100% extract, from which the required concentration of 6 mL L^{-1} was prepared (Al-Hajj *et al*., 2022).

The experimental setup as a split-plot arrangement within a RCBD. Palm residue fertilization treatments were assigned to the main plots, while organic sulfur and garlic extract treatments were randomly distributed within the subplots. Treatment averages were compared utilizing the least significant difference test (LSD) at the 0.05 probability level (Elsahooki,. and Waheeb. 1990).

Measured traits

The following vegetative, yield, and nutrient traits were assessed:

- Nitrogen percentage in bulbs, determined according to the method of (Jackson, 1958).
- Phosphorus percentage in bulbs, determined according to the method of (Olsen, and Sommers, 1982).
- Sulfur content in bulbs (mg 100 g^{-1}), determined according to the method of (Williams and Steinbergs, 1959).
- Chlorophyll content in tubular leaves (mg 100 g^{-1} fresh weight), determined according to the method of (Goodwin, 1976).
- Plant height (cm), measured from the point of connection with the soil to the tip of the longest tubular leaf at harvest.
- Leaf area (dm^2) calculated using the specific equation for tubular onion leaves (Gamiely *et al*, 1991).
- Leaf Area = -93.1 + (1.83 × Leaf Length) + (38.6 × Leaf Circumference at 25% from base)
- This formula was used to find the area of a single leaf (cm^2), and the total leaf area per plant (dm^2): was derived as follows:
- Leaf Area per Plant (dm^2) =[Single Leaf Area (cm^2) /100] × No. of Leaves $Plant^{-1}$
- Total Yield (tons ha^{-1})

Results

Nitrogen percentage

The results presented in Table 1 revealed a statistically significant differences were observed in the nitrogen percentage in green onion bulbs due to varying levels of date palm waste fertilizer. The highest value (3.29%) was recorded under treatment T2. Fertilization with organic sulfur also exerted a significant effect on nitrogen content in the bulbs, particularly under treatment S2, which achieved 3.16%. Regarding garlic extract foliar spraying, treatment G1 outperformed others with a nitrogen content of 2.90%.

Concerning the two-way interaction between palm waste and organic sulfur (T × S), the T2S2 combination demonstrated a clear superiority, yielding the highest nitrogen content in bulbs at 3.59%, compared to the lowest value (2.26%) recorded under T1S0.

In the case of the T × G interaction (palm waste × garlic extract), a significant increase was observed in this trait, reaching its peak value of 3.36% under the T2G1 treatment, while the lowest value (2.43%) was recorded under T0G0. For the S × G interaction (organic sulfur × garlic extract), treatment S2G0 gave the highest nitrogen content in bulbs at 3.20%.

Regarding the three-way interaction among all study factors (T × S × G), statistical analysis revealed that the T2S2G1 treatment significantly outperformed all others, elevating nitrogen content in green onion bulbs to 3.68%. In contrast, the lowest nitrogen content (1.75%) was recorded under the T0S0G0 treatment.

Table 1: *Effect of fertilization with palm residues, organic sulfur, and garlic extract spray on the nitrogen percentage in green onion bulbs (%)*

palm residues(T)	organic sulfurb (S)	Garlic extract (G)		T × S
		G_0	G_1	
T_0	S_0	1.75	2.83	2.29
	S_1	2.78	2.80	2.79
	S_2	2.78	3.08	2.93
T_1	S_0	2.30	2.21	2.26
	S_1	2.14	2.48	2.31
	S_2	3.33	2.63	2.98
T_2	S_0	3.27	2.86	3.06
	S_1	2.88	3.53	3.20
	S_2	3.50	3.68	3.59
L.S.D. 0.05		0.1605		0.1135
T × G				T
T_0		2.43	2.90	2.67
T_1		2.59	2.44	2.51
T_2		3.22	3.36	3.29
L.S.D. 0.05		0.0927		0.1387
S × G				
S_0		2.44	2.63	2.54
S_1		2.60	2.93	2.77
S_2		3.20	3.13	3.16
L.S.D. 0.05		0.0927		0.0655
G		2.75	2.90	
L.S.D. 0.05		0.0535		

Phosphorus percentage

The results revealed that the application of date palm waste fertilizer led to an increase in phosphorus percentage in green onion bulbs (Table 2), particularly under treatment T2, which recorded 0.354%. Regarding the effect of organic sulfur fertilization, treatment S2 stood out as the most effective, achieving a phosphorus content of 0.358%. As for garlic extract application, treatment G1 showed superiority, with a phosphorus content of 0.350%.

Table 2: *Effect of fertilization with palm residues, organic sulfur, and garlic extract spray on the phosphorus percentage in green onion bulbs (%)*

palm residues (T)	organic sulfur (S)	Garlic extract (G)		T × S
		G_0	G_1	
T0	S_0	0.310	0.327	0.318
	S_1	0.357	0.310	0.333
	S_2	0.370	0.360	0.365
T1	S_0	0.330	0.367	0.348
	S_1	0.320	0.360	0.340
	S_2	0.380	0.330	0.355
T2	S_0	0.340	0.317	0.328
	S_1	0.380	0.377	0.378
	S_2	0.310	0.400	0.355
L.S.D. 0.05		0.0106		0.0075
T × G				T
T_0		0.346	0.332	0.339
T_1		0.343	0.352	0.348
T_2		0.343	0.364	0.354
L.S.D. 0.05		0.0061		0.0076
S × G				
S_0		0.327	0.337	0.332
S_1		0.352	0.349	0.351
S_2		0.353	0.363	0.358
L.S.D. 0.05		0.0061		0.0043
G		0.344	0.350	
L.S.D. 0.05		0.0035		

In term of the two-way interaction between palm waste and organic sulfur (T × S), treatment T2S1 demonstrated a statistically significant effect, recording the highest phosphorus value in bulbs at 0.378%, compared to the lowest value (0.318%) observed under T0S0. The interaction between palm waste and garlic extract (T × G) also showed significant superiority under treatment T2G1, where phosphorus content reached 0.364%, whilst the minimum value was (0.332%) was for T0G1.

The interaction between organic sulfur and garlic extract (S × G) significantly enhanced phosphorus concentration, with treatment S2G1 achieving the highest content at 0.363%, compared to S0G0, which achieved the minimum value of (0.327%).

In term of three-way interaction (T × S × G) revealed that treatment T2S2G1 was significantly superior in increasing phosphorus percentage, reaching 0.400%. In contrast, the lowest phosphorus concentrations were observed under the triple interaction treatments T0S0G0, T0S1G1, and T2S2G0, all of which recorded the same minimal value of 0.310%.

Sulfur content in green onion bulbs (mg 100g^{-1})

Table 3 reveals clear effects of the individual factors (palm waste, organic sulfur, garlic extract) on the sulfur content in green onion bulbs. For palm waste fertilization treatments, the results showed that treatment T1 (20 tons ha^{-1}) achieved the highest average of 779.6 mg 100g^{-1} compared to treatment T2 (30 tons ha^{-1}), which recorded 749.6 mg 100g^{-1}, and the control treatment T0 (0 tons ha^{-1}), which was the lowest with an average of 707.2 mg 100g^{-1}. The effect of organic sulfur was the most prominent among the individual factors. Treatment S2 (600 kg ha^{-1}) recorded the highest sulfur content value of 900.2 mg 100g^{-1}, while the lowest values were in the control treatment (S0), with an average of 619.0 mg 100g^{-1}. Regarding foliar spraying with garlic extract, its use increased the average sulfur content to 770.1 mg 100g^{-1}, compared to no spraying (G0), which recorded 720.8 mg 100g^{-1}. This indicates its positive effect on improving sulfur content.

Concerning the three-way interactions between the factors (palm waste × organic sulfur × garlic extract), the highest value was recorded for the interaction between the second level of palm waste (T1, 20 tons ha^{-1}), the third level of organic sulfur (S2, 600 kg ha^{-1}), and spraying with garlic extract (G1, 6 ml L^{-1}), where the sulfur content reached 953.4 mg 100g^{-1}. In contrast, the lowest value was recorded for the interaction treatment T2S0G0 (30 tons ha^{-1} + 0 kg ha^{-1} + 0 ml L^{-1}) at 516.4 mg 100g^{-1}.

These results demonstrate that the effect of each individual factor is clearly reflected in the sulfur content, but the highest values were achieved by combining the appropriate levels of these factors together.

Table 3: *Effect of fertilization with palm residues, organic sulfur, and garlic extract spray on the sulfur content of green onion bulbs (mg 100 g^{-1})*

palm residues(T)	organic sulfur(S)	Garlic extract (G)		T × S
		G_0	G_1	
T0	S_0	568.6	582.9	575.8
	S_1	628.6	646.1	637.3
	S_2	905.5	911.7	908.6
T1	S_0	647.9	708.8	678.4
	S_1	736.6	749.3	743.0
	S_2	881.6	953.4	917.5
T2	S_0	516.4	689.5	602.9
	S_1	746.7	795.8	771.3
	S_2	885.4	893.7	874.5
L.S.D. 0.05		24.30		19.35
T × G				T
T_0		700.9	713.6	707.2
T_1		755.4	803.8	779.6
T_2		706.2	793.0	749.6
L.S.D. 0.05		17.89		17.90
S × G				
S_0		577.6	660.4	619.0
S_1		704.0	730.4	717.2
S_2		880.8	919.6	900.2
L.S.D. 0.05		12.79		9.05
G		720.8	770.1	
L.S.D. 0.05		7.39		

Leaf chlorophyll content (mg 100g^{-1} fresh weight)

Results from Table 4 show that variation in palm waste fertilizer application levels had a clear effect on increasing chlorophyll concentration in green onion leaves. Treatment T2 recorded the highest value at 97.9 mg per 100 g fresh weight, significantly outperforming the control treatment T0, where chlorophyll concentration dropped to 69.4 mg per 100 g fresh weight. The application of organic sulfur also stimulated this trait: treatment S2 achieved the highest chlorophyll content at 110.0 mg per 100 g fresh weight, compared to S0, which recorded the lowest value at 63.5 mg per 100 g fresh weight. Regarding garlic extract foliar spraying, treatment G1 significantly surpassed G0, with chlorophyll concentration reaching 91.9 mg per 100 g fresh weight under G1.

Concerning the two-way interaction between date palm waste and organic sulfur (T × S), treatment T2S2 showed clear superiority, yielding the highest chlorophyll content at 124.7 mg 100 g fresh weight. This was significantly higher than the lowest value of 49.8 mg 100 g fresh weight recorded in treatment T0S0. Similarly, the two-way interaction between palm waste and garlic extract (T × G) revealed that treatment T2G1 was superior, achieving 105.1 mg per 100 g fresh weight. The interaction between organic sulfur and garlic extract (S × G) also had a statistically significant effect, with treatment S2G1 recording the highest chlorophyll concentration at 115.4 mg per 100 g fresh weight.

Most notably, the three-way interaction among all three factors (T × S × G) produced the most pronounced effect: treatment T2S2G1 achieved the absolute highest chlorophyll content at 131.4 mg 100 g fresh weight, which was the lowest value a mere 42.4 mg per 100 g fresh weight was recorded under treatment T0S0G0.

Table 4: *Effect of fertilization with palm residues, organic sulfur, and garlic extract spray on leaf chlorophyll content (mg 100 g^{-1} fresh weight)*

palm residues(T)	organic sulfur(S)	Garlic extract (G)		T × S
		G_0	G_1	
T0	S_0	42.4	57.2	49.8
	S_1	69.0	73.3	71.1
	S_2	82.9	91.3	87.1
T1	S_0	62.6	71.6	67.1
	S_1	79.1	94.9	87.0
	S_2	113.0	123.5	118.2
T2	S_0	65.8	81.1	73.5
	S_1	88.5	102.7	95.6
	S_2	118.0	131.4	124.7
L.S.D. 0.05		21.44		17.39
T × G				T
T_0		64.8	73.9	69.4
T_1		84.9	96.9	90.8
T_2		90.8	105.1	97.9
L.S.D. 0.05		16.27		16.39
S × G				
S_0		57.0	70.0	63.5
S_1		78.9	90.3	84.6
S_2		104.6	115.4	110.0
L.S.D. 0.05		11.05		7.81
G		80.2	91.9	
L.S.D. 0.05		6.38		

Plant height (cm)

Results from Table 5 indicate that varying levels of palm waste fertilizer application significantly increased the height of green onion plants. Treatment T2 (30 tons ha^{-1}) recorded the highest average height of 55.21 cm, outperforming treatment T0 (0 tons ha^{-1}), which recorded the lowest height of 50.97 cm. The use of organic sulfur also contributed to improving this trait, with treatment S2 (600 kg ha^{-1}) achieving a height of 54.95 cm compared to treatment S0 (0 kg ha^{-1}), which recorded 50.41 cm. Regarding the effect of foliar spraying with garlic extract, treatment G1 (6 ml L^{-1}) showed clear superiority with a plant height of 53.51 cm.

Table 5: *Effect of fertilization with palm residues, organic sulfur, and garlic extract spray on plant height (cm)*

palm residues (T)	organic sulfur(S)	Garlic extract (G)		T × S
		G_0	G_1	
T0	S_0	45.77	49.30	47.53
	S_1	52.77	52.10	52.43
	S_2	52.53	53.37	52.59
T1	S_0	50.03	50.80	50.42
	S_1	51.73	53.30	52.52
	S_2	53.53	54.77	54.15
T2	S_0	52.97	53.60	53.28
	S_1	54.10	55.10	54.60
	S_2	65.20	59.30	57.75
L.S.D. 0.05		2.713		2.007
T × G				T
T_0		50.36	51.59	50.97
T_1		51.77	52.96	52.36
T_2		56.00	54.42	55.21
L.S.D. 0.05		1.750		1.665
S × G				
S_0		49.59	51.23	50.41
S_1		52.87	53.50	53.18
S_2		54.09	55.81	54.95
L.S.D. 0.05		1.535		1.085
G		52.18	53.51	
L.S.D. 0.05		0.886		

Results of the two-way interaction between organic fertilizer and organic sulfur treatments showed that treatment T2S2 (30 tons ha^{-1} + 600 kg ha^{-1}) recorded the highest height of 57.75 cm, compared to the lowest height in treatment T0S0 (0 tons ha^{-1} + 0 kg ha^{-1}), which reached 47.53 cm. Regarding the two-way interaction between palm waste fertilizer and garlic extract, treatment T2G0 (30 tons ha^{-1} + 0 ml L^{-1}) showed the highest plant height, recording 56.00 cm. Similarly, the interaction between organic sulfur and garlic extract had a significant positive effect, with treatment S2G1 (600 kg ha^{-1} organic sulfur and 6 mL L^{-1} garlic extract) recording a height of 55.81 cm.

The three-way interaction among all factors had the most notable impact. Treatment T2S2G0 achieved the maximum plant height (65.20 cm), while T0G0S0 treatment resulted in the shortest height at 45.77 cm.

Leaf area (dm^2)

Results indicate that varying levels of date palm waste fertilizer led to a clear improvement in leaf area of green onion plants (Table 6). Treatment T1 recorded the highest value at 10.08 dm^2, significantly surpassing the control treatment T0, which showed the lowest leaf area at 8.90 dm^2. Fertilization with organic sulfur also resulted in a statistically significant increase in this trait: treatment S2 achieved the largest leaf area at 11.90 dm^2, compared to S0, which recorded only 8.06 dm^2. Regarding foliar application of garlic extract, treatment G1 outperformed G0, achieving a leaf area of 10.11 dm^2.

Concerning the two-way interaction between date palm waste and organic sulfur (T × S), treatment T2S2 stood out significantly, producing the greatest leaf area at 13.53 dm^2 in contrast to T0S0, which yielded the smallest value at 7.30 dm^2. The two-way interaction between palm waste and garlic extract (T × G) also showed significant superiority under treatment T2G1, which recorded a leaf area of 10.82 dm^2. Similarly, the interaction between organic sulfur and garlic extract (S × G) had a significant positive effect on leaf expansion, with treatment S2G1 achieving a leaf area of 12.76 dm^2.

As for the three-way interaction, the T2S2G1 treatment recorded the highest leaf area of 15.31 dm^2, while the T0S0G0 treatment gave the lowest leaf area of 6.90 dm^2.

These results confirm that each individual input contributes to leaf development, but the most substantial gains in photosynthetic surface area a key indicator of plant vigor and yield potential are achieved only through the synergistic integration of optimal levels of organic fertilizer, sulfur, and biostimulant. This underscores the value of holistic, integrated nutrient and biostimulant management in sustainable green onion production.

Table 6: *Effect of fertilization with palm residues, organic sulfur, and garlic extract spray on leaf area (dm^2)*

palm residues(T)	organic sulfur(S)	Garlic extract (G)		T × S
		G_0	G_1	
T0	S_0	6.90	7.71	7.30
	S_1	9.29	8.42	8.86
	S_2	9.75	11.35	10.55
T1	S_0	8.58	9.37	8.97
	S_1	9.28	10.03	9.65
	S_2	11.60	11.63	11.62
T2	S_0	8.02	7.78	7.90
	S_1	7.77	9.37	8.57
	S_2	11.74	15.31	13.53
L.S.D. 0.05		0.935		0.661
T × G				T
T_0		8.65	9.16	8.90
T_1		9.82	10.34	10.08
T_2		9.18	10.82	10.00
L.S.D. 0.05		0.540		0.698
S × G				
S_0		7.83	8.29	8.06
S_1		8.78	9.27	9.03
S_2		11.03	12.76	11.90
L.S.D. 0.05		0.540		0.382
G		9.21	10.11	
L.S.D. 0.05		0.312		

Total yield (tons per hectare)

Results in Table 7 demonstrate that the application of date palm waste fertilizer had a clear and significant impact on the total yield of green onion plants. Treatment T2 (30 tons ha^{-1}) recorded the highest yield at 78.67 tons ha^{-1}, compared to treatment T0 (0 tons ha^{-1}), which had the lowest yield at 71.67 tons ha^{-1}. Organic sulfur fertilization also had a significant effect, with treatment S2 achieving 82.44 tons ha^{-1} compared with 67.78 tons ha^{-1} in S0. The effect of foliar spraying with garlic extract was evident in treatment G1, which recorded a total yield of 77.07 tons ha^{-1} significantly higher than the unsprayed control (73.19 tons ha^{-1}).

Examining the two-way interaction between date palm waste and organic sulfur (T × S), treatment T2S2 achieved the highest total yield at 88.00 tons ha^{-1}, while the lowest yield (65.83 tons ha^{-1}) was recorded under T0S0. In the two-way interaction between palm waste and garlic extract (T × G), treatment T2G1 produced the highest yield at 79.56 tons ha^{-1}. Similarly, the interaction between organic sulfur and garlic extract (S × G) showed a strong positive effect, with treatment S2G1 achieving the highest yield in this interaction at 84.00 tons ha^{-1}.

The three-way interaction among the three factors resulted in treatment T2S2G1 (30 tons ha^{-1} date palm residues, 600 kg ha^{-1} organic sulfur, and 6 mL L^{-1} garlic extract) producing the highest total yield at 89.33 tons ha^{-1}, while treatment T0S0G0 (no date palm residues, no organic sulfur, and no garlic extract) recorded the lowest total yield at 64.00 tons ha^{-1}.

Table 7: *Effect of fertilization with palm residues, organic sulfur, and garlic extract spray on the total yield of green onion (t ha^{-1})*

palm residues(T)	organic sulfur(S)	Garlic extract (G)		T × S
		G_0	G_1	
T0	S_0	64.00	67.67	65.83
	S_1	69.00	75.00	72.00
	S_2	76.00	78.33	77.17
T1	S_0	67.33	68.67	68.00
	S_1	69.00	81.00	75.00
	S_2	80.00	84.33	82.17
T2	S_0	69.00	70.00	69.50
	S_1	77.67	79.33	78.50
	S_2	86.67	89.33	88.00
L.S.D. 0.05		7.499		5.789
T × G				T
T_0		69.67	73.67	71.67
T_1		72.11	78.00	75.06
T_2		77.78	79.56	78.67
L.S.D. 0.05		5.234		5.157
S × G				
S_0		66.78	68.78	67.78
S_1		71.89	78.44	75.17
S_2		80.89	84.00	82.44
L.S.D. 0.05		4.080		2.885
G		73.19	77.07	
L.S.D. 0.05		2.356		

Discussion

From the results of the above tables (1, 2, 3, 4, 5, 6, 7), we conclude that adding palm waste fertilizer has a positive role in increasing nutrients, chlorophyll, vegetative characteristics and total yield in green onions by improving The soil's physical and chemical characteristics, including increasing the organic matter level and enhancing the ability of soil's to retain water, which positively affects growth and productivity. Similar findings were reported by (Alshamary *et al*., 2023), who observed that incorporating 5% palm residues into the soil significantly improved total yield, leaf area, chlorophyll content, and nutrient accumulation in onion compared with untreated soil. Fertilization with palm residues also promotes the activity of beneficial soil microorganisms and enriches soil with essential nutrients such as nitrogen, phosphorus, and potassium (Kavvadias *et al*., 2024). The decomposition of organic matter further contributes to the formation of amino and organic acids that play a vital role in plant physiological processes and in stimulating the synthesis of secondary metabolites, thereby positively affecting crop yield (Ismail, 2017). These results are consistent with (Fahrurrozi *et al*., 2022), who found that liquid organic fertilizer enhanced vegetative and qualitative traits of green onion, and with (Liu *et al*., 2024), who demonstrated that organic fertilization increased soil sulfur content, consequently improving sulfur compound formation in onion and enhancing productivity.

The observed improvements in vegetative traits associated with organic sulfur application reflect the essential role of sulfur in plant growth. Sulfur is a key element in protein synthesis through its incorporation in amino acids, especially Cysteine and Methionine which are fundamental sulfur-containing amino acids and serve as building blocks for protein formation (Brosnan and Brosnan., 2006). Additionally, sulfur contributes to the formation of disulfide (S–S) linkages between amino acids such as glutamic acid and glycine, and it plays a central role in the synthesis of Coenzyme A (CoA-SH), vitamins, and ferredoxin. The latter acts as a strong reducing agent and an essential component of the electron transport chain during the light reactions of photosynthesis (González-Morales *et al*., 2017).

Positive results above related to spraying with garlic extract may be due to the fact that organic plant extracts contribute to deeper root penetration into the soil, which positively affects the plant's efficiency in nutrient uptake. They also increase soil organic carbon, which enhances the content and activity of soil microorganisms, promoting nitrate reduction and nitrogen absorption by the plant (Bar *et al*., 2022). In addition, Organic plant extracts may help promote growth and enhance leaf mineral elements content because it contains rich in elements and amino acids (Ismail, 2017). Moreover, increase of these characters could be due to the role played by substances in garlic extract which function as biostimulants like growth promoting hormones, such as auxins and gibberellins and salicylates which activates and promote photosynthesis in plants. It directly promotes plant growth and enhances the concentration of bioactive compounds (Golubkina *et al*., 2024; Hayat *et al*., 2022), thus increasing nutritional quality and yield. Moreover, the enhancement of studied traits following application of garlic spray may result from abundance of the polyphenols in garlic which serve as pre-activated compounds when extract is sprayed to the plant (Ei *et al*., 2024; Golubkina *et al*., 2022). The extract also promotes the induction of antioxidant activity (Hamza *et al*., 2024), enhancing the plant's overall health and enhancing its characteristics (Ali *et al*., 2019).

Conclusions

Simultaneous application of palm residues, organic sulfur and garlic extracts showed distinct synergistic behavior on growth, yield and chemical composition of green onion. The palm residues enhanced the soil fertility and water holding capacity, organic sulfur improved protein and enzyme synthesis, and garlic extract formed a natural biostimulant. These combined implications substantially enhanced N, P and S accumulation in bulb, the chlorophyll content of leaves, vegetative growth characters (i.e., plant height and leaf area), which ultimately lead to increasing marketable yield. These results support the implementation of sustainable fertilization practices with organic resources as substitutes to chemical inputs, that could contribute both to sustainability in agriculture and production of safety and nutritional food. The results provide a basis for the application of sustainable fertilization with organic materials as an alternative to the use of chemical inputs and for sustainable agriculture, safe healthy food production.

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Novelty Statement

This study is the first, to our knowledge, to integrate the use of organic fertilizers for date palms and sulfur with garlic extract to improve the growth and productivity of green onions under sustainable farming conditions.

Author's Contribution

Elaf Hamza Wali: fieldwork, sowing, harvesting; wrote abstract, introduction, data collection, data entry in GenStat and analysis, results and discussion, conclusion and references.
Yasamen Fadhil Saloom: Editing of draft, supervised the research, analyzed data, reviewed the manuscript, proofread, reviewed the manuscript, Overall Management of the article, performed proof-reading, and revised the manuscript.

Generative AI and AI-assisted technology statement
The authors declare that no generative AI and AI assisted technology was used in the creation of this manuscript.

Conflict of interest
The authors have declared no conflict of interest

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