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Effect of Mineral and Biological Potassium Fertilization Levels on The Growth, Yield and Quality of Garlic (Cultivar Seds 50)

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Abstract

The field experiment was conducted on garlic (Allium sativum L.) cultivar seds 50 during winter seasons 2022/2023 and 2023/2024 growing seasons on a private farm located in Shanasha village, Aga District, Dakahlia Governorate, Egypt. A field experiment was designed in randomiz complete block design to assess the impact of varying potassium fertilization levels (50%, 75% and 100% of the recommended dose KRD as K_2SO_4) combined with bio-fertilization using potassium-solubilizing bacteria (KSB). Additionally, a control treatment of 100% of KRD without PSB was included. These treatments were applied to evaluate their effects on garlic growth and yield. Results showed that applying 75% of KRD with KSB significantly enhanced plant growth indicators, such as plant height, and fresh and dry weights compared to other combined treatments. This combination also led to higher nutrient concentrations (N, P, K, B) in leaves and SPAD chlorophyll readings compared to other combined treatments. At harvest, the same combined treatment achieved the highest values for yield components and bulb quality traits such as vitamin C and dry matter. In contrast, using only 50% of KRD resulted in the lowest growth and yield outcomes, emphasizing the necessity of adequate potassium supplementation. Overall, the study demonstrates that using 75% KRD combined with PSB is an effective, sustainable approach to boost garlic yield and quality while reducing environmental impact.

Key words: K_2SO_4, PSB, garlic, levels, fertilization.

Introduction

Garlic (*Allium sativum* L.) is a widely valued crop with significant economic and health benefits due to its high levels of essential nutrients, antioxidants, and sulfur-containing compounds (**Kareem *et al.* 2024**). As a staple ingredient in culinary applications and a source of medicinal compounds, garlic cultivation holds substantial agricultural importance globally. Egypt, being one of the leading producers, emphasizes the need for cultivation practices that not only enhance yield but also improve quality parameters to meet both domestic demands and export requirements (**Rizk and Deshesh, 2021; Baddour *et al.* 2024)**.

Potassium is an essential macronutrient that plays a critical role in the physiological and biochemical processes of plants. It supports enzymatic functions, osmoregulation, photosynthesis, and the regulation of water and nutrient transport within the plant (**Jiku *et al.* (2020**). For garlic, potassium has been linked to improved bulb quality, increased weight, and enhanced resistance to environmental stressors. However, the precise dosage and the most efficient forms of potassium application remain an active area of research for maximizing growth and productivity (**Wang *et al.* (2022**).

Bio-fertilization, particularly through the use of potassium-solubilizing bacteria (KSB), presents an environmentally friendly alternative to traditional mineral fertilization. These beneficial bacteria help convert soil-bound potassium into forms that plants can readily absorb, thus reducing dependency on chemical fertilizers **(Mounir *et al.* 2020)**.

Objective of the Study

This study aims to evaluate the effects of different potassium fertilization levels, bio-fertilization with potassium-solubilizing bacteria on the growth, productivity, and quality of garlic. The goal is to determine the optimal combination of these treatments to enhance yield and bulb quality in garlic under the local agro-environmental conditions of Dakahlia Governorate, Egypt.

Materials and Methods

1. Experimental Site and Soil Analysis

The field experiment was conducted during the 2022/2023 and 2023/2024 growing seasons on a private farm located in Shanasha village, Aga District, Dakahlia Governorate, Egypt. Prior to planting garlic, soil samples were collected from a depth of 0–30 cm to analyze its physical and chemical properties. The standard analytical methods described by **Sparks *et al.* (2020) and Dane and Topp (2020)** were employed for soil analysis, and the results are presented in Table 1.

Table 1. Fundamental initial soil characteristics

Particle size distribution (%)			Texture class	Field capacity	Saturation	Organic matter	Available soil nutrients			EC, dSm^{-1}	pH
Sand	**Silt**	**Clay**			**(%)**		**N**	**P**	**K**		
							(mg kg^{-1})				
27.8	23.2	49.0	Clay	35	70	1.3	42.93	0.75	250.9	3.95	7.90

2. Plant Material

The garlic cultivar used in this experiment was Balady Seds-50, commonly known as Egyptian garlic, obtained from the Horticulture Research Institute, Agricultural Research Center, Egypt. This variety is widely grown in Egypt due to its adaptability and local demand.

3. Isolation of Potassium Solubilizing Bacteria (KSB)

The isolation of potassium solubilizing bacteria (KSB) from agricultural wastes involved several systematic steps aimed at identifying and cultivating effective strains for agricultural applications. In this process, agricultural waste materials, such as compost and soil, were collected for microbial analysis. To isolate KSB, samples were cultured on selective media designed to promote the growth of potassium-solubilizing microorganisms. One common method utilizes Aleksandrov medium, which contains potassium sources that are insoluble, allowing researchers to identify bacteria that can solubilize potassium effectively. After inoculating the medium with the collected samples, the cultures were incubated under controlled conditions, optimizing factors like temperature and pH to encourage the growth of KSB. Colonies exhibiting clear zones around them, indicative of potassium solubilization, were selected for further study. Among the isolated strains, Bacillus mucilaginous HQ013329 has shown significant potential. This strain is notable for its high potassium solubilization capacity. Ultimately, the isolation and characterization of Bacillus mucilaginous HQ013329 as a potassium-solubilizing bacterium highlighted its potential role in developing biofertilizers that can enhance potassium availability in soils, thereby improving crop growth and yield in potassium-deficient environments **(Parmar and Sindhu, 2013).**

4. Treatments and Experimental Design

A field experiment was designed in randomiz complete block design with three replicates was used to evaluate the effect of mineral and biological potassium fertilization levels on the growth, yield and quality of garlic comprising four treatments were used in three replicates, total of comprising 12 was used to evaluate the effect oftreatment combinations of potassium fertilization, bio fertilization. Each experimental plot covered an area of 10.5 m², consisting of three rows, each 3.5 m in length and 1 m in width. Garlic cloves were planted at a spacing of 7 cm, with each row containing 150 cloves, resulting in 450 cloves per plot.

Treatments: Mineral and bio-fertilization

T_1:100 % of the recommended potassium dose (KRD) as potassium sulphate (50% K_2SO_4) + Bio-fertilizer (potassium-solubilizing bacteria, Bacillus mucilaginous HQ013329) applied at 2 L fed^{-1}.

T_2:100 % of the recommended potassium dose (KRD) as potassium sulphate (50% K_2SO_4) without Bio-fertilizer.

T_3:75 % of the recommended potassium dose (KRD) as potassium sulphate (50% K_2SO_4) + Bio-fertilizer (potassium-solubilizing bacteria, Bacillus mucilaginous HQ013329) applied at 2 L fed^{-1}.

T_4:50 % of the recommended potassium dose (KRD) as potassium sulphate (50% K_2SO_4) + Bio-fertilizer (potassium-solubilizing bacteria, Bacillus mucilaginous HQ013329) applied at 2 L fed^{-1}.

The recommended dose of potassium sulphate (50% K_2SO_4) was set at 150 kg per fed^{-1}, as per agricultural guidelines provided by the Ministry of Agriculture and Soil Reclamation (MASR). All other agricultural practices were carried out, including the application of fertilization and pest control, herbicide, according to the technical recommendations for the crop issued by the Egyptian Ministry of Agriculture and Land Reclamation.

5. Planting and Agricultural Practices

Garlic planting was conducted on October 1 in the 2022 season and on October 2 in the 2023 season. Standard agricultural practices, as recommended by

MASR, were followed throughout the experiment to ensure optimal growth conditions for garlic.

6. Protocol for Applying the Treatments

Potassium fertilization was applied in three stages: the first dose, comprising 25% of the studied mineral potassium requirement, was applied at planting (October 1st in 2022 and October 2nd in 2023). The second application, consisting of 50% of the studied potassium dose, was administered 30 days after planting. The final 25% was applied 60 days after planting. Bio-fertilizer (KSB) was applied at planting time (1st October for 2022, and 2nd October for 2023) by incorporating it into the soil alongside the first potassium application.

7. Harvest Process

The garlic crop was harvested 150 days after planting to ensure optimal bulb maturity

8. Measurements

Data were collected at two growth stages: 150 days and 200 days post-planting**.**

8.1. At 150 days post-planting

Growth parameters, including plant height (cm), number of leaves plant^{-1}, fresh weight (g plant^{-1}) and dry weight (g plant^{-1}) were measured. Leaf chemical compositions such as nitrogen (N %), phosphorus (P, %, potassium (K, %) and boron (B, mg kg^{-1} DW) contents in leaves were determined. Leaf samples were digested with a mixture of $HClO_4$ + H_2SO_4 according to **Peterburgski, (1968)**. Nitrogen was measured by Micro-Kjeldahl, phosphorus by spectrophotometry and potassium by flame photometry as per the methods of **Walinga *et al.* (2013),** while boron was estimated using hot water extraction with a spectrophotometer as described by **Sah and Brown, (1997).** Chlorophyll content was estimated using a Minolta Chlorophyll Meter (SPAD-502).

8.2. At 200 days post-planting

Bulb traits like fresh and dry weights (g plant^{-1}), bulb and neck diameters (cm) and clove weight (g) were measured. Also, yield measures such as total yield (ton fed^{-1}), treated yield (ton fed^{-1}), weight loss percentage (after 200 days of planting) and bulbing ratio (neck diameter/bulb diameter) were measured.

Vitamin C content (mg 100g^{-1}), carbohydrate percentage, total dissolved solids (TDS %), pungency (pyruvate content, µmol m^{-1} and dry matter percentage were determined following **A.O.A.C (2000)** protocols.

Statistical Analysis

The data obtained were subjected to analysis of variance (ANOVA) as outlined by **Snedecor and Cochran (1980).** Mean comparisons were carried out using the Least Significant Difference (LSD) test to establish statistical significance among treatments

Results and Discussion

The findings of this research work will be presented and discussed under the following headings:

1. Plant vegetative growth characteristics at 150 Days from Planting

1.1. Growth parameters

Table 2 demonstrates the impact of varying ratios of mineral potassium fertilizer combined with bio-fertilization and different foliar supplements on garlic growth performance during the 2022/23 and 2023/24 seasons. The parameters measured include plant height (cm), the number of leaves plant^{-1}, fresh and dry weights (g plant^{-1}).

Effect of potassium fertilizer and bio-fertilization treatments

The findings show that the combination of 75% of the recommended potassium dose as $K_2SO_4$with bio-fertilization using potassium-solubilizing bacteria (T_3) resulted in the highest values of plant height, leaf number, fresh weight, and dry weight across both seasons. This combination highlights the potential of bio-fertilization to supplement lower potassium fertilizer levels effectively. In contrast, the treatment with only 50% of the potassium dose and bio-fertilization (T_4) resulted in the lowest values for all growth parameters. These results suggest that reducing potassium levels may limit growth, even with bio-fertilization, emphasizing the importance of an adequate potassium supply in garlic cultivation. It is also worth noting that the T_1 treatment [100% of the recommended potassium dose (K_2SO_4) combined with bio-fertilization using potassium-solubilizing bacteria] ranked second in growth performance, following the T_3 treatment. This result highlights the beneficial role of bio-fertilization in supporting plant growth when potassium is applied at full-recommended levels. The T_1 treatment consistently outperformed the T_2 treatment (100% of the recommended potassium dose without bio-fertilization), indicating that the presence of potassium-solubilizing bacteria likely enhanced potassium availability, leading to improved growth metrics in garlic plants. This finding supports the potential of bio-fertilizers as a complementary tool to enhance nutrient efficiency, especially in systems where full mineral fertilization is applied.

Table 2. The impact of various ratios of mineral potassium fertilizer and bio-fertilization on plant height, number of leaves/plant and leaves fresh, **Dry** weight of garlic plants growth performance during the 2022/23 and 2023/24 seasons

Treatments	Plant height, cm		No. of leaves plant^{-1}		Fresh weight, g plant^{-1}		Dry weight, g plant^{-1}	
	1st season	2nd season	1st season	2nd season	1st season	2nd season	1st season	2nd season
100 % of KRD (K_2SO_4 50%) + Bio (KSB)	122.70b	109.62b	10.73ab	10.33a	105.34b	93.55b	21.32b	19.26b
100 % of KRD (K_2SO_4 50%) without Bio (KSB)	118.76c	104.16c	10.07bc	9.40c	83.43c	80.84c	16.87c	15.98c
75% of KRD (K_2SO_4 50%) +Bio (KSB)	126.32a	116.35a	11.60a	10.93a	123.67a	110.34a	25.32a	23.12a
50% of KRD (K_2SO_4 50%) +Bio (KSB)	109.95d	96.13d	9.40c	8.53b	72.70d	69.98d	14.25d	13.40d
LSD at 5%	**0.85**	**0.80**	**0.91**	**0.35**	**0.44**	**0.44**	**0.15**	**0.21**

Means within a row followed by a different letter (s) are statistically different at 5%
NS*= Non-significant

The T_3 treatment was superior to both the T_1 treatment (which involves 100% of the recommended potassium dose (K_2SO_4) combined with bio-fertilization using potassium-solubilizing bacteria) and the T_2 treatment (which consists of 100% of the recommended potassium dose without bio-fertilization). This superiority is attributed to the fact that applying 100% of the mineral potassium fertilizer along with potassium-solubilizing bacteria can disrupt the nutrient balance in the soil, leading to antagonism between potassium and other critical elements like calcium and magnesium.**(Jakobsen. 1992).** This situation suggests that high potassium levels may hinder the garlic plant's ability to absorb calcium and magnesium, negatively impacting its overall health. Calcium is essential for constructing and maintaining cell wall stability, while magnesium is crucial for chlorophyll production and photosynthesis.

In contrast, using 75% of the mineral potassium fertilizer together with potassium-solubilizing bacteria allows for a better balance and enables the plant to absorb nutrients more effectively.

Moreover, the application of 100% mineral potassium fertilizer may inhibit microbial activity in the soil, as the high concentration of potassium can decrease the activity of beneficial bacteria, including potassium-solubilizing bacteria, which play a crucial role in enhancing nutrient availability to the plant **(Parmar.2013).** Therefore, using 75% of the mineral potassium fertilizer can contribute to improving microbial activity, thereby enhancing nutrient absorption efficiency.

Overall, the application of 75% of the mineral potassium fertilizer combined with solubilizing bacteria provides a better nutritional balance compared to using 100% of the mineral fertilizer, whether accompanied by potassium-solubilizing bacteria or not. The obtained results are in accordance with those of **Mounir *et al.* (2020)**; **El-Shal and Ahmed (2021)**. **Soltan and Osman (2021)**.

1.2.Chemical constituents of plant folige in l eaves and chlorophyll SPAD reading

The chemical composition [N, P, K (%), B (mgkg^{-1})] of garlic leaves and chlorophyll content, measured as SPAD readings, were analyzed across different treatments, including mineral potassium fertilizer combined with bio-fertilization and various foliar supplements. Results, presented in Table 3, reflect data collected over the 2022/23 and 2023/24 seasons.

Effect of potassium fertilizer and bio-fertilization treatments

In both seasons, T_3 produced the highest values for nitrogen (N,%), phosphorus (P,%), potassium (K,%), boron (B, mgkg^{-1}) and chlorophyll content (SPAD reading), showing significant superiority over other treatments. T_1followed in effectiveness, with T_2 and T_4ranking third and fourth, respectively.

Table 3. The impact of various ratios of mineral potassium fertilizer and bio-fertilization, on chemical constituents in leaves of garlic and photosynthetic pigment during the 2022/23 and 2023/24 seasons

Treatments	N, %		P, %		K, %		B, mg kg^{-1}		Chlorophyll, SPAD	
	1st season	**2nd season**	**1st season**	**2nd season**	**1st season**	**2nd season**	**1st season**	**2nd season**	**1st season**	**2nd season**
100 % of KRD (K_2SO_4 50%) + Bio (KSB)	**3.21b**	**3.35b**	**0.348b**	**0.362b**	**2.58b**	**2.69b**	**26.37b**	**26.78b**	**65.88b**	**65.66b**
100 % of KRD (K_2SO_4 50%) without Bio	**3.03c**	**3.15c**	**0.319c**	**0.331c**	**2.42c**	**2.52c**	**25.64c**	**26.01c**	**64.50b**	**63.80c**
75% of KRD (K_2SO_4 50%) +Bio (KSB)	**3.40a**	**3.55a**	**0.368a**	**0.383a**	**2.69a**	**2.79a**	**27.05a**	**27.47a**	**69.10a**	**68.37a**
50% of KRD (K_2SO_4 50%) +Bio (KSB)	**2.81d**	**2.94d**	**0.299d**	**0.310d**	**2.09d**	**2.17d**	**24.89d**	**25.27d**	**61.87c**	**60.58d**
LSD at 5%	**0.04**	**0.02**	**0.003**	**0.005**	**0.03**	**0.06**	**0.50**	**0.14**	**1.56**	**1.28**

Means within a row followed by a different letter (s) are statistically different at 5%
NS*= Non-significant

This significant superiority of T_3 treatment over other treatments can be attributed to the application of bio-fertilizers, such as potassium-solubilizing bacteria (KSB), which may have enhanced the bioavailability of essential nutrients in the soil. These microorganisms can solubilize potassium and other nutrients, making them more accessible to plant roots. This increased availability can lead to higher nutrient concentrations in plant tissues, as observed with T_3 treatment.

Also, bio-fertilizers may have led to promote better root growth and development, which further facilitates nutrient absorption **(Vessey, 2003).** An extensive root system allows for greater soil exploration, leading to improved uptake of nitrogen, phosphorus, potassium, and boron. The higher levels of these nutrients in T_3 can be linked to enhanced root biomass and root activity due to the application of bio-fertilization.

The combination of potassium fertilization and bio-fertilization treatments may have created a synergistic effect that enhances the uptake and utilization of other nutrients. Potassium is crucial for many physiological processes, including enzyme activation, photosynthesis, and protein synthesis**.(Fekry, 2009).**Adequate potassium levels can improve the efficiency of nitrogen and phosphorus utilization, leading to overall better plant growth and higher nutrient content.

Potassium plays a vital role in the synthesis of chlorophyll and enhances the plant's ability to carry out photosynthesis effectively. Higher chlorophyll content, as indicated by SPAD readings, suggests better photosynthetic capacity, which can directly influence growth and yield. The improved chlorophyll content in T3 treatment aligns with findings that link potassium availability to enhanced photosynthetic efficiency. these results are in harmony with those of **Jiku *et al.* (2020)**;**Octaviany and Fuskhah, (2020)**;**Soltan and Osman (2021)**;**Mohamed *et al.* (2022)**;**Wang *et al.* (2022);Kour *et al.* (2023)**;**Zail and Abdaly (2023).**

1.3. Yield and its components (150 days)

Table 4 presents the impact of various ratios of mineral potassium fertilizer and bio-fertilization, along with foliar supplements, on physical bulb traits and yield of garlic plants at 150 days after planting during the 2022/23 and 2023/24 seasons. The measured traits included bulb fresh weight (g plant^{-1}), bulb dry weight (g plant^{-1}), number of cloves per bulb, bulb diameter (cm), neck diameter (cm), bulb yield (kg plot^{-1}) and bulbing ratio.

Effect of potassium fertilizer and bio-fertilization treatments

The results indicate that the treatment combining 75% of the potassium recommended dose (KRD) with bio-fertilization (KSB) (T_3) consistently produced the highest values for bulb fresh weight (g plant^{-1}), bulb dry weight (g plant^{-1}), number of cloves per bulb, bulb diameter (cm), neck diameter (cm), bulb yield (kg plot^{-1}) and bulbing ratioacross both seasons. This suggests a significant positive effect of optimized potassium levels and bio-fertilization on garlic growth and development**.**

In contrast, the lowest values were observed in the treatment with 50% KRD plus bio-fertilization (T_4), indicating a detrimental effect of insufficient potassium application on bulb traits and yield.

Table 4. The impact of various ratios of mineral potassium fertilizer and bio-fertilization, on physical bulb traits and yield of garlic plant at150 days from planting during the 2022/23 and 2023/24 seasons

Treatments	Bulb fresh weight, g $plant^{-1}$		Bulb dry weight, g $plant^{-1}$		No. of cloves $bulb^{-1}$	
	1st season	**2nd season**	**1st season**	**2nd season**	**1st season**	**2nd season**
T_1: 100 % of KRD (K_2SO_4 50%) + Bio (KSB)	**57.16b**	**54.98b**	**22.21b**	**19.03b**	**33.40b**	**31.07b**
T_2: 100 % of KRD (K_2SO_4 50%) without Bio (KSB)	**51.59c**	**48.13c**	**21.31c**	**17.43c**	**31.53c**	**28.93c**
T_3: 75% of KRD (K_2SO_4 50%) +Bio (KSB)	**67.11a**	**67.96a**	**24.64a**	**21.96a**	**37.07a**	**34.33a**
T4: 50% of KRD (K_2SO_4 50%) +Bio (KSB)	**41.47d**	**42.22d**	**18.57d**	**15.70d**	**28.47d**	**26.60d**
LSD at 5%	**1.12**	**1.08**	**0.33**	**0.45**	**0.78**	**0.30**

Means within a row followed by a different letter (s) are statistically different at 5%
NS*= Non-significant

Table 4. Cont.

Treatments	Bulb diameter, cm		Neck diameter, cm		Bulb yield, Kg $plot^{-1}$		Bulbing ratio	
	1st season	**2nd season**	**1st season**	**2nd season**	**1st season**	**2nd season**	**1st season**	**2nd season**
100 % of KRD (K_2SO_4 50%) + Bio (KSB)	5.48b	5.30b	1.15b	1.22b	44.88b	40.27b	0.31b	0.44b
100 % of KRD (K_2SO_4 50%) without Bio (KSB)	4.86c	4.76c	0.96c	1.11c	40.80c	37.63c	0.30c	0.44b
75% of KRD (K_2SO_4 50%) +Bio (KSB)	6.16a	6.02a	1.40a	1.49a	49.14a	44.55a	0.34a	0.43b
50% of KRD (K_2SO_4 50%) +Bio (KSB)	4.24d	4.13d	0.76d	0.97d	34.50d	30.76d	0.27d	0.47a
LSD at 5%	**0.13**	**0.21**	**0.03**	**0.05**	**0.85**	**0.43**	**0.01**	**0.02**

Means within a row followed by a different letter (s) are statistically different at 5%
NS*= Non-significant

2. Yield and its Components at Harvest Stage (200 days)

Effect of potassium fertilizer and bio-fertilization treatments

Table 5 presents the effects of various ratios of mineral potassium fertilizer and bio-fertilization on garlic yield and physical bulb traits at harvest. The findings show that the combination of 75% KRD (K_2SO_4 50%) with Bio (KSB) (T_3) achieved the highest values for most measured parameters, including bulb fresh and dry weights (g), bulb and neck diameters (cm), clove weight (g), yield (ton fed^{-1}), treated yield (ton fed^{-1}), and bulbing ratio. Additionally, this treatment recorded the lowest weight loss percentage across both seasons. The treatment with 100% KRD and Bio (KSB) (T_1) also performed well but yielded lower values compared to T_3. In contrast, treatments with 50% KRD (T_4) showed the least favorable results for bulb fresh and dry weights (g), bulb and neck diameters (cm), clove weight (g), yield (ton fed^{-1}), treated yield (ton fed^{-1}) and bulbing ratio, alongside the highest weight loss percentage during both studied seasons.

Table 5. The impact of various ratios of mineral potassium fertilizer and bio-fertilization, along on physical bulb traits and yield of garlic plant at 200 days from planting during the 2022/23 and 2023/24 seasons

Treatments	Bulb fresh weight, g plant^{-1}		Bulb dry weight, g plant^{-1}		Bulb diameter, cm		Neck diameter, cm	
	1st season	**2nd season**	**1st season**	**2nd season**	**1st season**	**2nd season**	**1st season**	**2nd season**
100 % of KRD (K_2SO_4 50%) + Bio (KSB)	95.33b	83.77b	28.81b	19.53b	5.88b	4.16b	1.87b	1.82b
100 % of KRD (K_2SO_4 50%) without Bio (KSB)	84.43c	77.10c	24.68c	12.66c	5.63c	3.62c	1.73c	1.59c
75% of KRD (K_2SO_4 50%) +Bio (KSB)	103.75a	91.03a	32.72a	29.32a	6.23a	4.85a	2.15a	2.08a
50% of KRD (K_2SO_4 50%) +Bio (KSB)	75.43d	66.24d	19.73d	7.68d	5.22d	3.07d	1.45d	1.43d
LSD at 5%	**0.71**	**0.50**	**0.14**	**0.16**	**0.04**	**0.10**	**0.05**	**0.06**

Means within a row followed by a different letter (s) are statistically different at 5%
NS*= Non-significant

Table 5. Cont.

Treatments	Weight of clove, g		Yield, ton fed^{-1}		Treated yield, ton fed^{-1}		Weight loss, %		Bulbing ratio	
	1st season	**2nd season**	**1st season**	**2nd season**	**1st season**	**2nd season**	**1st season**	**2nd season**	**1st season**	**2nd season**
100 % of KRD (K_2SO_4 50%) + Bio (KSB)	1.78b	1.84b	17.95b	16.11b	10.72b	10.03b	40.32b	37.75c	0.21b	0.23b
100 % of KRD (K_2SO_4 50%) without Bio	1.62c	1.68c	16.32c	15.05c	10.05c	9.07c	38.45c	39.71b	0.20bc	0.24ab
75% of KRD (K_2SO_4 50%) +Bio (KSB)	2.18a	2.26a	19.66a	17.82a	12.89a	12.03a	34.46d	32.62d	0.23a	0.25a
50% of KRD (K_2SO_4 50%) +Bio (KSB)	1.36d	1.40d	13.80d	12.30d	7.50d	6.80d	45.80a	44.81a	0.18d	0.24ab
LSD at 5%	**0.09**	**0.08**	**0.34**	**0.17**	**0.16**	**0.10**	**0.26**	**0.46**	**0.01**	**0.01**

Means within a row followed by a different letter (s) are statistically different at 5%
NS*= Non-significant

3.1. Chemical constituents of bulb

The chemical composition of garlic bulbs at harvest was significantly influenced by various treatments involving mineral potassium fertilizers, bio-fertilization, and foliar supplements. The results summarized in Table 6 highlight the effects of these treatments on nitrogen (N, %), phosphorus (P, %), potassium (K, %) and boron (B, mgkg^{-1}) concentrations in the bulbs across two growing seasons (2022/23 and 2023/24).

Effect of potassium fertilizer and bio-fertilization treatments

The application of 75% of KRD as K_2SO_4 combined with bio-fertilization (KSB) (T_3) realized the maximum concentrations of N, P, K and B in garlic bulbs, with values of 2.83and 2.88% for nitrogen, 0.323and 0.335% for phosphorus, 2.57 and 2.63% for potassium and 22.44and 22.79 mg kg^{-1} for boron in the first and second seasons, respectively. Conversely, the treatment with 50% KRD plus bio-fertilization (T_4) showed the lowest concentrations for all chemical constituents, emphasizing the critical role of potassium levels in enhancing nutrient accumulation in garlic.

Table 6. The impact of various ratios of mineral potassium fertilizer and bio-fertilization on chemical constituents of garlic bulbs during the 2022/23 and 2023/24 seasons

Treatments	N, %		P, %		K ,%		B, mg kg^{-1}	
	1st season	**2nd season**	**1st season**	**2nd season**	**1st season**	**2nd season**	**1st season**	**2nd season**
100 % of KRD (K_2SO_4 50%) + Bio (KSB)	2.63b	2.69b	0.303b	0.315b	2.44b	2.49b	21.51b	21.83b
100 % of KRD (K_2SO_4 50%) without Bio (KSB)	2.44c	2.50c	0.282c	0.293c	2.29c	2.34c	20.47c	20.79c
75% of KRD (K_2SO_4 50%) +Bio (KSB)	2.83a	2.88a	0.323a	0.335a	2.57a	2.63a	22.44a	22.79a
50% of KRD (K_2SO_4 50%) +Bio (KSB)	2.26d	2.31d	0.262d	0.273d	2.10d	2.15d	19.40d	19.74d
LSD at 5%	**0.05**	**0.05**	**0.006**	**0.003**	**0.05**	**0.05**	**0.44**	**0.28**

Means within a row followed by a different letter (s) are statistically different at 5%
NS*= Non-significant

Potassium-solubilizing bacteria (KSB) may have contributed to converting unavailable nutrients into forms that can be readily absorbed by plants. According to the results, the application of 75% of mineral potassium fertilizer combined with bio-fertilization resulted in a significant increase in the concentrations of nitrogen (N), phosphorus (P), potassium (K) and boron (B) in garlic bulbs. This highlights the critical role of bacteria in enhancing nutrient uptake and providing approximately 25% of the plants' nutritional requirements, thereby improving their productivity and quality (**Mounir *et al.* 2020;El-Shal and Ahmed 2021; Osman and Soltan 2021**; **Mohamed *et al.* 2022**; **Kour *et al.* 2023**).

3.2.Quality of bulb

Table 7 illustrates the impact of various ratios of mineral potassium fertilizer and bio-fertilization, along with foliar supplements and their interactions on the quality traits of garlic bulbs during the 2022/23 and 2023/24 growing seasons.

Table 7. The impact of various ratios of mineral potassium fertilizer and bio-fertilization on bulb quality traits of garlic growth performance during the 2022/23 and 2023/24 seasons

Treatments	Vitamin C, mg $100g^{-1}$		Carbohydrates, %		TDS, %		Pungency (purvate content $\pi mol.ml^{-1}$)		Dry matter, %	
	1st season	**2nd season**	**1st season**	**2nd season**	**1st season**	**2nd season**	**1st season**	**2nd season**	**1st season**	**2nd season**
100 % of KRD (K_2SO_4 50%) + Bio (KSB)	13.89b	14.11b	22.61b	23.07b	24.35b	24.78b	10.70b	10.92b	21.88b	23.52b
100 % of KRD (K_2SO_4 50%) without Bio (KSB)	13.50c	13.69c	21.60c	22.06c	23.56c	23.97c	9.94c	10.15c	20.64c	22.38c
75% of KRD (K_2SO_4 50%) +Bio (KSB)	14.34a	14.56a	23.58a	24.04a	25.30a	25.96a	11.42a	11.65a	22.80a	24.73a
50% of KRD (K_2SO_4 50%) +Bio (KSB)	12.92d	13.11d	20.98d	21.38d	22.76d	23.15d	9.18d	9.35d	19.32d	20.91d
LSD at 5%	**0.13**	**0.16**	**0.25**	**0.13**	**0.57**	**0.50**	**0.21**	**0.15**	**0.50**	**0.55**

Means within a row followed by a different letter (s) are statistically different at 5%
NS*= Non-significant

Effect of potassium fertilizer and bio-fertilization treatments

The application of potassium fertilizers in conjunction with bio-fertilization significantly influenced the quality traits of garlic bulbs. Among the treatments, using 75% of KRD as K_2SO_4 combined with bio-fertilization (T_3) resulted in the highest concentrations of vitamin C (14.34 and 14.56 mg $100g^{-1}$), carbohydrates (23.58, 24.04%), total dissolved solids (TDS) (25.30, 25.96%), pungency (11.42 11,65 µmol ml^{-1}) and dry matter (22.80, 24.73%) across both seasons, respectively. In contrast, the treatment involving 50% KRD combined with bio-fertilization (T_4) recorded the lowest concentrations across all measured quality parameters, indicating that higher levels of potassium and the presence of bio-fertilizers play a crucial role in enhancing garlic bulb quality.**3.4. Weight Loss Percentage after Harvest**

The results presented in Table 8 provide a comprehensive overview of the impact of different ratios of mineral potassium fertilizer and bio-fertilization treatments, along with foliar supplements, on the weight loss percentage of stored produce over time during both studied seasons.

Effect of potassium fertilizer and bio-fertilization treatments

The data in Table 8 reveals a clear trend regarding the effectiveness of potassium fertilizer and bio-fertilization treatments in minimizing weight loss during storage. Specifically, the treatment with 50% potassium fertilizer combined with bio-fertilizer (T_4) consistently resulted in the highest weight loss percentages, suggesting that insufficient potassium may lead to suboptimal post-harvest quality. Following this, the treatment with 100% KRD (K_2SO_4) without bio-fertilizer (T_2) exhibited high weight loss percentages, along with the combination of 100% potassium fertilizer without bio-fertilization (T_1). In contrast, the combination of 75% potassium fertilizer with bio-fertilization (T_3) demonstrated the lowest weight loss percentages across all months of storage. This indicates that adequate potassium levels, particularly when complemented with bio-fertilizers, can significantly enhance the produce's ability to resist weight loss during storage.

Table 8. The impact of various ratios of mineral potassium fertilizer and bio-fertilization on weight loss percentage after two, three, four,five, six, seveneight and ninemonths of the storage periods during the 2022/23 and 2023/24 seasons

Treatments	May		June		July		August		September		October		November		December	
	1st season	2nd season	1st season	2nd season	1st season	2nd season	1st season	2nd season	1st season	2nd season	1st season	2nd season	1st season	2nd season	1st season	2nd season
100 % of KRD (	6.87c	6.57c	2.76c	2.87c	1.68c	1.74c	1.19c	1.25c	1.00bc	1.05c	0.88c	0.93c	0.81c	0.85c	0.73c	0.76c
100 % of KRD (	7.61b	7.44b	3.06b	3.18b	2.20b	2.29b	1.46b	1.54b	1.03b	1.08b	0.91b	0.96b	0.86b	0.90b	0.75b	0.78b
75% of KRD (	5.94d	5.66d	2.46d	2.56d	1.29d	1.34d	1.10d	1.16d	0.97c	1.02d	0.84d	0.88d	0.79c	0.82d	0.71d	0.74d
50% of KRD (	8.91a	8.79a	3.36a	3.49a	2.70a	2.81a	2.52a	2.65a	1.07a	1.12a	0.94a	0.99a	0.93a	0.97a	0.76a	0.80a
LSD at 5%	0.16	0.05	0.05	0.09	0.01	0.06	0.06	0.05	0.03	0.02	0.03	0.02	0.04	0.01	0.02	0.01

Means within a row followed by a different letter (s) are statistically different at 5%
NS*= Non-significant

The observed differences in weight loss across treatments can be attributed to the role of potassium and bio-fertilizers in physiological and biochemical processes that influence post-harvest quality. Potassium is essential for osmoregulation, enzyme activation, and maintaining cell turgor, which are critical in reducing dehydration and weight loss in stored produce (**Abdel-Latif *et al* 2019**). When potassium levels are insufficient, as seen in the T_4 treatment (50% potassium fertilizer with bio-fertilizer), cellular processes may be compromised, leading to increased water loss and reduced tissue integrity during storage. Conversely, the T_3 treatment (75% potassium with bio-fertilizer) provided a more balanced potassium level, which may have strengthened cell walls and improved water retention, resulting in minimal weight loss.Bio-fertilizers further enhance these effects by promoting beneficial microbial activity that can improve nutrient uptake and stimulate the production of plant growth-promoting substances. These microbes may also help maintain a favorable microbial environment around the roots, which supports sustained nutrient supply and overall plant health. This combination, especially in T_3, likely contributed to the plant's resilience to post-harvest weight loss. In contrast, treatments without bio-fertilizer (T_1) might lack these added benefits, resulting in less effective resistance to weight loss during storage.

Conclusion

Based on the obtained results, it can be concluded that applying a using 75% of the recommended dose of potassium (KRD) in conjunction with biofertilization significantly enhanced growth indicators such as plant height, fresh and dry weight compared to other compound treatments. This compound treatment also led to an increase in the concentration of nutrients (N, P, K, B) in the leaves and SPAD chlorophyll readings compared to the other studied combinations. At harvest, the same compound treatment achieved the highest values for yield, its components, and the quality characteristics of garlic heads, such as vitamin C content and dry matter, highlighting its potential in maintaining quality. In contrast, using only 50% of the recommended dose of potassium with biofertilization resulted in the lowest growth and productivity rates, emphasizing the importance of having a sufficient amount of potassium.

Overall, the study demonstrates that using 75% of the recommended dose of potassium along with biofertilization is an effective and sustainable approach to improving garlic productivity and quality while reducing environmental impact.

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