J. of Soil Sciences and Agricultural Engineering, Mansoura Univ., Vol. 16 (9):263 - 269, 2025

Journal of Soil Sciences and Agricultural Engineering

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

Efficiency of Natural Potassium Sources Accompanied by Potassium Dissolving Bacteria on Garlic Plant Productivity

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Article Information
Received 27/ 7/2025
Accepted 2/ 9/2025

ABSTRACT

Currently, there is an urgent need to use sustainable natural sources of potassium (K) to reduce reliance on chemical fertilizers without causing a significant decline in productivity. Therefore, a field experiment was carried out aiming to evaluate the efficiency of feldspar as a natural potassium source accompanied by potassium solubilizing bacteria (KSB) on garlic productivity as compared to other potassium mineral fertilizers. Seven potassium treatments [T_1: 100% of Potassium Recommended Dose (KRD) from potassium citrate; T_2: 100% of KRD from potassium sulphate; T_3: 100% of KRD from potassium feldspar; T_4: 80% of KRD from potassium feldspar +20% from potassium citrate; T_5: 60% of KRD from potassium feldspar +40% from potassium citrate; T_6: 80% of KRD from potassium feldspar +20% from potassium sulphate; T_7: 60% of KRD from potassium feldspar +40% from potassium sulphate] were studied as main factor, while the KSB type [*B.mucilaginosus*, *B.circulans* and control] were studied as the sub main factor. Results showed that T_1 and T_2 treatments achieved the highest values of growth and productivity traits as well as the *B.mucilaginosus* recorded the highest improvements followed by *B.circulans* then control. As for interaction effect, it was noticed that both T_1 and T_2 treatments without KSB achieved non-significant values compared to the combined treatments of (T_5 x *B.mucilaginosus* or *B.circulans*) and (T_7 x *B.mucilaginosus* or *B.circulans*). Overall, integrating the soluble mineral potassium sources, natural sources *i.e.,* feldspar and inoculation with KSB as an effective strategy to reduce reliance on synthetic fertilizers and improve the sustainability of garlic production.

Keywords: Feldspar*, B.mucilaginosus*, *B.circulans*

INTRODUCTION

Recently, Egypt has been suffering from a shortage of potassium-based mineral fertilizers, which are of great importance to the Egyptian agricultural sector (Sharabin, 2022). They are a rapidly growing source of potassium (K), which all higher plants require in large quantities. Potassium plays a unique role in the movement of water, nutrients and photosynthesis products from the leaves to their locations within the plant. Potassium is a co-enzyme for enzymes involved in vital processes in higher plants, most importantly the synthesis of phytoalexins, which are responsible for the plant's immune system. Therefore, potassium enhances plant resistance to disease. It also works to balance osmotic pressure within plant cells. Additionally, potassium is responsible for opening and closing stomata in the leaf, regulating the exchange of water vapor, oxygen, and carbon dioxide. It also plays a role in promoting root growth and facilitating the formation of protein and starch in plants (Pandey& Mahiwal, 2020). Therefore, all those working in the plant nutrition field must provide natural alternatives or approaches that meet strategic plants' potassium requirements, so their productivity is not affected (Shirale et al. 2019).

Natural sources of potassium are widely available in Egypt, as the largest natural source of potassium is feldspar (Ahmed *et al.* 2016), a naturally occurring mineral with the formula $KAlSi_3O_8$ that contains large quantities of potassium, in addition to other elements (Mansour *et al.* 2024). However, its use in agriculture faces the obstacle of slow solubility, thus its poor ability to meet plants' potassium needs in a timely manner (Zhang *et al.* 2023).

Using potassium-solubilizing bacteria (KSB) with feldspar could be a promising approach to increasing potassium availability to plants, as the KSB can help accelerate the release of potassium to the plant (Rajawat *et al.* 2019). KSBs are bacteria that can convert unavailable potassium into a plant-available form. Each type of KSB has the ability to make potassium available. The dissolution mechanism lies in the ability of these bacteria to secrete organic acids, which dissolve potassium minerals and convert them into a plant-available form (Fawaz & Abo Zaed, 2020; Wang *et al.* 2022).

Garlic (*Allium sativum* .L) is a strategic crop whose productivity is greatly affected by the availability of potassium. Improving garlic productivity is a priority for decision-makers due to its nutritional and export value, as well as its potential to generate hard currency through export. Garlic also has many health benefits. It lowers blood pressure in patients with high blood pressure, regulates blood cholesterol levels, stimulates immunity, and maintains digestive health (El Sayed *et al.* 2024).

Thus, the major aim of this investigation is to evaluate the effect of feldspar as natural potassium source combined with different mineral potassium sources at various rates, in combination with different KSB strains on the quantitative and qualitative traits of garlic plant.

MATERIALS AND METHODS

To achieve the aim of this work, a field experiment was carried out in a privet farm located at Meet-Anter Village, Talkha District, Dakahlia Governorate during seasons of 2023/24 and 2024/25 using split plot experimental design with three replicates. Before planting, a representative soil sample as well as feldspar sample were

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DOI: 10.21608/jssae.2025.407952.1302

analyzed according to the standard methods described by Tandon, (2005), as their properties are shown in Table 1 (a &b). Seven potassium treatments [T_1: 100% of Potassium Recommended Dose (KRD) from potassium citrate; T_2: 100% of KRD from potassium sulphate; T_3: 100% of KRD from potassium feldspar; T_4: 80% of KRD from potassium feldspar +20% from potassium citrate; T_5: 60% of KRD from potassium feldspar +40% from potassium citrate; T_6: 80% of KRD from potassium feldspar +20% from potassium sulphate; T_7: 60% of KRD from potassium feldspar +40% from potassium sulphate] were studied as main factor. Additionally, the type of potassium-solubilizing bacteria KSB [*B.mucilaginosus*, *B.circulans* and control (without KSB)] were studied as the sub main factor. The both studied types of KSB were obtained from the Bio-fertilizer Unit, Faculty of Agriculture, Cairo University, while potassium citrate, potassium sulphate and feldspar were purchased from the Egyptian commercial market.

Table 1a. Initial soil properties

Initial soil	
Characteristics	**Values**
EC dSm^{-1} (suspension 1: 5)	1.350
pH (suspension 1:2.5)	7.990
Organic matter, %	1.250
Potassium, mg K Kg^{-1} soil	139.81
Nitrogen, mg N Kg^{-1}soil	42.20
Phosphorus, mg P Kg^{-1} soil	9.660
Clay,%	49.00
Sand,%	22.00
Silt,%	29.00
Textural class	Clay

Table 1b. Feldspar characteristics

Feldspar	
Characteristics	**Values**
SiO_2	68%
AlO_3	8.5%
MgO	0.1%
K_2O	15%
$P2O_5$	0.08%
NaO_2	1.7%

Garlic cloves "cv. Balady" were sown on October 30th in both growing seasons. Each experimental plot had an area of 10 m2 and consisted of 4 lines, each 5 m long and 0.5 m wide. The planting distance was 15 cm among plants on both sides of a planting row. All plots received calcium superphosphate fertilizer (15% P2O5) and urea (46%N) according to the guides of the Ministry of Agriculture and Soil Reclamation. Additionally, potassium fertilization was done according to MASR, but in different forms (potassium sulphate, potassium citrate and feldspar) according to the studied treatments. Calcium superphosphate fertilizer and feldspar were added before planting with soil preparation, while urea was added at three equal doses with the first, second and third irrigations, respectively. Potassium sulphate and potassium citrate were added according to the studied treatment in two doses; the first was with the first irrigation, while the 2nd dose was with the 2nd irrigation. The feldspar was mixed with KBS according to the studied treatments and then placed in the sowing line immediately before planting. The harvest process was done 180 days after sowing.

Growth criteria such as plant height (cm) and number of leaves $plant^{-1}$, fresh and dry weights (g $plant^{-1}$) and leaf area (cm^2 $plant^{-1}$) were measured at 90 days after planting. Also, chlorophyll a & b and carotene were determined at the same time using spectrophotometer apparatus as described by Picazo *et al.* (2013). Leaf chemical composition (NPK) were estimated at 90 days from planting using a sulphuric acid and perchloric acid mixture (1:1) for digesting leaf samples (Peterburgski, 1968), as N, P and K were quantified by the micro-Kjeldahl method, Olsen method and flame photometer, respectively (Walinga *et al.* 2013). The bacteria content was implemented after 45 and 90 days. At the harvest stage (180 days after planting), the total and marketable bulb yield (ton fed^{-1}) were evaluated as well as the bulb weight (g) and diameter (cm), neck diameter (cm), bulbing ratio (Bulbing ratio = Bulb diameter / Neck diameter), No. of cloves $bulb^{-1}$ were measured. Bulb quality parameters, including carbohydrate content (%), total soluble solids (TSS, %), vitamin C content (mg 100 g^{-1}), dry matter content (%) and pungency (pyruvate content, πmol ml^{-1}), were determined at harvest time (180 days after planting) according to the AOAC (2000) procedures. Additionally, after harvest, the available potassium of the studied soil was analyzed using flame photometer as described by Tandon (2005). The obtained data were statistically analyzed according to Gomez and Gomez (1984) using CoStat software (Version 6.303, CoHort, USA, 1998-2004).

RESULTS AND DISCUSSIONS

1.Growth Criteria

The studied potassium sources, accompanied by potassium-dissolving bacteria, significantly affected the growth criteria of garlic (Table 2), as indicated by the following parameters: Plant height and number of leaves, fresh and dry weights, and leaf area were measured at 90 days after planting during the seasons of 2023/24 and 2024/25. Concerning the individual effect of the potassium sources, it can be noticed that T_1 treatment (100% of the recommended dose from potassium citrate) achieved the highest values of all aforementioned traits, noting that there were no significant differences between it and T_2 treatment (100% of the recommended dose from potassium sulphate). T_3 treatment (100% of the recommended dose from potassium feldspar) recorded the lowest values. T_5 treatment (60% of the recommended dose from potassium feldspar +40% from potassium citrate) as well as T_7 treatment (60% of the recommended dose from potassium feldspar + 40% from potassium sulphate) caused close results in terms of the studied growth parameters. Also, T_4 treatment (80% of the recommended dose from potassium feldspar + 20% from potassium citrate) as well as T_6 (80% of the recommended dose from potassium feldspar + 20% from potassium sulphate) caused close results. Regarding the type of K-solubilizing bacteria, the superior was *B.mucilaginosus* followed by *B.circulans* and lately the control treatment (without K-solubilizing bacteria). As for interaction effect, it was noticed that both T_1 treatment (100% of the recommended dose from potassium citrate) and T_2 treatment (100% of the recommended dose from potassium suphate) without KSB achieved non-significant values compared to the combined treatments of (T_5x *B.mucilaginosus* or *B.circulans)* and (T_7x *B.mucilaginosus* or *B.circulans*) in terms of the studied growth parameters.

2. Photosynthetic Pigments and Chemical Constituents

Table 3 shows the effect of the studied potassium sources accompanied by potassium dissolving bacteria on the photosynthetic pigments (chlorophyll a & b and carotene) and chemical constituents in leaves (NPK) of garlic at 90 days from planting during season of 2023/24 and 2024/25. The obtained results indicated that the T_1 treatment realized the highest values of chlorophyll a & b, carotene N,P and K, with no significant differences between T_1 treatment and T_2 treatment. T_7 treatment came in the third order with most the studied parameters. T_3 treatment came the last order. T_4, T_5 and T_6 treatments came in the middle of the ranking in terms of effectiveness.

Table 2. Effect of the potassium sources accompanied by potassium dissolving bacteria on the growth criteria of garlic at 90 days from planting during seasons of 2023/24 and 2024/25

Treatments		Plant height cm		No. of leaves /plant		Fresh weightg. 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	1st season	2nd season
K-sources											
T_1		83.18a	86.76a	9.44ab	11.56a	89.82a	93.40a	18.95a	19.23a	348.87a	350.43a
T_2		81.75b	85.05b	9.78a	11.33a	89.22a	92.71a	18.79a	19.05a	347.60a	349.13a
T_3		69.97e	72.70e	5.11d	5.67f	77.82d	81.03d	16.81e	17.06e	259.01d	259.89d
T_4		73.97d	77.05d	6.56c	8.11d	82.67c	86.13c	17.51c	17.78c	297.94c	299.38c
T_5		78.80c	82.09c	8.78ab	10.67b	87.35b	91.09b	18.40b	18.69b	335.81b	337.09b
T_6		73.36d	76.47d	6.44c	7.11e	82.05c	85.21c	17.30d	17.57d	296.27c	297.66c
T_7		78.56c	81.62c	8.67b	9.67c	87.09d	90.57b	18.33b	18.67b	335.00b	337.07b
F. test		**	**	*	**	**	**	**	**	**	**
LSD $_{at 5\%}$		0.73	0.82	1.04	0.65	0.94	1.02	0.20	0.19	3.25	5.75
K-solubilizing bacteria											
Without		75.11b	78.24b	7.38b	8.62b	83.69b	87.10b	17.77b	18.03b	303.78b	305.26b
B.circulans		77.98a	81.13a	7.95a	9.29a	85.77a	89.25a	18.08a	18.38a	323.41a	324.96a
B.mucilaginosus		78.15a	81.38a	8.14a	9.57a	85.98a	89.43a	18.19a	18.47a	324.45a	325.77a
F. test		**	**	**	**	**	**	**	**	**	**
LSD $_{at 5\%}$		0.55	0.63	0.51	0.41	0.61	0.62	0.14	0.14	2.53	2.64
Interaction											
T_1	Without	80.56	84.03	9.33	11.33	88.96	92.51	18.71	18.99	347.02	349.04
	B. circulans	84.20	87.48	9.33	11.67	90.29	93.84	19.03	19.32	349.25	351.01
	B.mucilaginosus	84.79	88.77	9.67	11.67	90.22	93.85	19.11	19.37	350.33	351.23
T_2	Without	80.60	83.91	9.33	11.33	88.95	92.30	18.68	18.93	346.57	348.26
	B.circulans	82.18	85.59	10.00	11.00	89.39	92.87	18.75	19.04	347.13	348.67
	B.mucilaginosus	82.48	85.64	10.00	11.67	89.31	92.97	18.94	19.18	349.11	350.46
T_3	Without	69.22	71.78	5.00	5.33	77.30	80.39	16.75	16.98	257.42	257.97
	B.circulans	70.30	73.13	5.00	5.67	78.04	81.23	16.78	17.04	259.15	260.16
	B.mucilaginosus	70.38	73.20	5.33	6.00	78.12	81.48	16.90	17.15	260.46	261.53
T_4	Without	72.70	75.60	6.00	7.33	81.28	84.87	17.19	17.44	274.42	275.78
	B.circulans	74.52	77.59	7.33	8.33	82.98	86.46	17.65	17.93	308.84	310.27
	B.mucilaginosus	74.68	77.97	6.33	8.67	83.76	87.05	17.69	17.96	310.57	312.10
T_5	Without	75.58	78.82	8.33	9.67	84.26	88.24	17.94	18.22	314.23	315.77
	B.circulans	80.45	83.86	9.00	11.33	88.83	92.63	18.59	18.92	346.80	347.38
	B.mucilaginosus	80.37	83.60	9.00	11.00	88.95	92.41	18.66	18.92	346.41	348.11
T_6	Without	71.91	75.26	6.00	6.33	81.18	84.26	17.20	17.48	274.40	275.29
	B.circulans	74.07	77.10	6.00	7.33	82.15	85.35	17.24	17.48	306.63	308.39
	B.mucilaginosus	74.08	77.04	7.33	7.67	82.82	86.04	17.47	17.74	307.77	309.30
T_7	Without	75.24	78.26	7.67	9.00	83.88	87.16	17.89	18.16	312.45	314.71
	B.circulans	80.14	83.18	9.00	9.67	88.72	92.35	18.53	18.90	346.06	348.85
	B.mucilaginosus	80.31	83.44	9.33	10.33	88.67	92.21	18.55	18.96	346.50	347.64
F. test		**	*	*	*	*	*	**	**	*	*
LSD $_{at 5\%}$		1.47	1.67	1.34	1.09	1.61	1.63	0.37	0.38	6.68	7.00

Means within a row followed by a different letter (s) are statistically different at a 0.05 level T1: 100% of Potassium Recommended Dose (KRD) from potassium citrate; T2: 100% of KRD from potassium sulphate; T3: 100% of KRD from potassium feldspar; T4: 80% of KRD from potassium feldspar +20% from potassium citrate; T5: 60% of KRD from potassium feldspar +40% from potassium citrate; T6: 80% of KRD from potassium feldspar +20% from potassium sulphate; T7: 60% of KRD from potassium feldspar +40% from potassium sulphate

Table 3. Effect of the potassium sources accompanied by potassium dissolving bacteria on the photosynthetic pigments and chemical constituents in leaves of garlic at 90 days from planting during seasons of 2023/24 and 2024/25

Treatments		Chlorophyll a mg.g^{-1}		Chlorophyll b mg.g^{-1}		Carotene mg.g^{-1}		N %		P %		K%	
		1st season	2nd season	1st season	2nd season	1st season	2nd season	1st season	2nd season	1st season	2nd season	1st season	2nd season
K-sources													
T_1		0.981a	0.991a	0.699a	0.709a	0.332a	0.337a	3.77a	3.81a	0.365a	0.371a	3.05a	3.10a
T_2		0.968b	0.982a	0.695a	0.705a	0.329a	0.334a	3.70b	3.74b	0.361a	0.366a	3.01a	3.07b
T_3		0.837e	0.849d	0.606e	0.614e	0.268f	0.272f	2.81g	2.86f	0.289e	0.293f	2.36e	2.41g
T_4		0.879d	0.892c	0.637c	0.647c	0.290d	0.294d	3.10e	3.13d	0.321d	0.326d	2.71c	2.76e
T_5		0.935c	0.949b	0.677b	0.688b	0.314b	0.319b	3.48c	3.52c	0.344b	0.350b	2.92b	2.98c
T_6		0.871d	0.885c	0.622d	0.632d	0.281e	0.285e	3.03f	3.08e	0.316d	0.321e	2.63d	2.69f
T_7		0.928c	0.941b	0.670b	0.682b	0.309c	0.313c	3.42d	3.48c	0.339c	0.344c	2.88b	2.93d
F. test		**	**	**	**	**	**	**	**	**	**	**	**
LSD $_{at 5\%}$		0.009	0.014	0.008	0.009	0.004	0.004	0.05	0.05	0.005	0.005	0.04	0.02
K-solubilizing bacteria													
Without		0.897b	0.910b	0.647b	0.657b	0.295c	0.300c	3.20c	3.23c	0.327c	0.332c	2.72c	2.78c
B.circulans		0.920a	0.933a	0.662a	0.671a	0.306b	0.310b	3.37b	3.43b	0.335b	0.340b	2.82b	2.87b
B.mucilaginosus		0.925a	0.938a	0.665a	0.676a	0.309a	0.313a	3.42a	3.47a	0.339a	0.344a	2.84a	2.90a
F. test		**	**	**	**	**	**	**	**	**	**	**	**
LSD $_{at 5\%}$		0.007	0.007	0.005	0.006	0.002	0.003	0.03	0.02	0.003	0.003	0.01	0.01
Interaction													
T_1	Without	0.960	0.974	0.692	0.701	0.325	0.330	3.67	3.70	0.360	0.366	3.00	3.05
	B.circulans	0.989	0.995	0.700	0.709	0.334	0.338	3.78	3.83	0.367	0.372	3.07	3.13
	B.mucilaginosus	0.992	1.005	0.705	0.717	0.337	0.342	3.86	3.89	0.370	0.375	3.07	3.14
T_2	Without	0.955	0.971	0.690	0.700	0.324	0.329	3.65	3.69	0.356	0.361	2.99	3.05
	B.circulans	0.970	0.983	0.697	0.706	0.330	0.335	3.67	3.73	0.363	0.368	3.03	3.08
	B.mucilaginosus	0.978	0.992	0.699	0.709	0.333	0.337	3.77	3.82	0.364	0.369	3.03	3.09
T_3	Without	0.829	0.841	0.601	0.609	0.265	0.269	2.73	2.77	0.282	0.286	2.28	2.33
	B.circulans	0.841	0.853	0.608	0.616	0.268	0.272	2.83	2.89	0.287	0.292	2.39	2.44
	B.mucilaginosus	0.840	0.852	0.609	0.617	0.272	0.276	2.88	2.93	0.297	0.301	2.41	2.46
T_4	Without	0.863	0.875	0.623	0.633	0.275	0.279	3.00	3.03	0.315	0.320	2.60	2.65
	B.circulans	0.884	0.898	0.641	0.650	0.297	0.302	3.13	3.17	0.324	0.329	2.75	2.79
	B.mucilaginosus	0.889	0.901	0.647	0.657	0.298	0.302	3.16	3.20	0.325	0.330	2.78	2.83
T_5	Without	0.903	0.918	0.659	0.669	0.305	0.310	3.22	3.25	0.333	0.338	2.85	2.92
	B.circulans	0.950	0.962	0.684	0.696	0.317	0.322	3.60	3.65	0.349	0.354	2.95	3.01
	B.mucilaginosus	0.952	0.967	0.688	0.699	0.320	0.325	3.62	3.67	0.352	0.358	2.96	3.02
T_6	Without	0.863	0.877	0.615	0.624	0.274	0.278	2.95	2.99	0.312	0.316	2.56	2.60
	B.circulans	0.870	0.883	0.623	0.634	0.282	0.286	3.05	3.10	0.317	0.322	2.63	2.69
	B.mucilaginosus	0.880	0.893	0.629	0.638	0.287	0.292	3.08	3.16	0.320	0.324	2.71	2.77
T_7	Without	0.901	0.913	0.652	0.662	0.300	0.304	3.18	3.18	0.330	0.337	2.81	2.86
	B.circulans	0.937	0.953	0.678	0.687	0.312	0.317	3.54	3.64	0.341	0.346	2.91	2.97
	B.mucilaginosus	0.945	0.957	0.680	0.695	0.315	0.319	3.55	3.63	0.345	0.350	2.92	2.98
F. test		**	**	**	**	**	**	**	**	**	**	**	**
LSD $_{at 5\%}$		0.019	0.019	0.014	0.015	0.006	0.007	0.07	0.04	0.007	0.007	0.03	0.03

Means within a row followed by a different letter (s) are statistically different at a 0.05 level T1: 100% of Potassium Recommended Dose (KRD) from potassium citrate; T2: 100% of KRD from potassium sulphate; T3: 100% of KRD from potassium feldspar; T4: 80% of KRD from potassium feldspar +20% from potassium citrate; T5: 60% of KRD from potassium feldspar +40% from potassium citrate; T6: 80% of KRD from potassium feldspar +20% from potassium sulphate; T7: 60% of KRD from potassium feldspar +40% from potassium sulphate

On the other hand, *B.mucilaginosus* type outperformed *B.circulans* type and the control treatment (without K-solubilizing bacteria) came in the last order in terms of effectiveness. Regarding the interaction effect, the T_1 and T_2 treatments without K-solubilizing bacteria achieved non-significant values compared to the combined treatments of (T_5x *B.mucilaginosus* or *B.circulans)* and (T_7x *B.mucilaginosus* or *B.circulans*) in terms of the photosynthetic pigments (chlorophyll a & b and carotene) and chemical constituents in leaves (NPK) of garlic at 90 days from planting during season of 2023/24 and 2024/25.

3.Bulb Yield and Quality Traits at Harvest

The response of total and marketable bulb yield as well as the physical characteristics of bulb (average bulb weight, bulb diameter, neck diameter, bulbing ratio, No. of cloves / bulb) as affected by the different potassium sources and rates accompanied by potassium dissolving bacteria at 180 days from planting during season of 2023/24 and 2024/25 are shown in Tables 4 and 5. While the quality traits (carbohydrates, total soluble solids TSS, vitamin C, dry matter and pungency) are presented in Table 6. Concerning the individual effect of the potassium sources, it can be noticed that T_1 treatment (100% of the recommended dose from potassium citrate) achieved the highest values of all aforementioned traits, noting that there were no significant differences between it and T_2 treatment (100% of the recommended dose from potassium sulphate). T_3 treatment (100% of the recommended dose from potassium feldspar) recorded the lowest values. T_4, T_5 and T_6 treatments came in the middle of the ranking in terms of effectiveness. The sequence order of the studied K-solubilizing bacteria from top effectiveness to less was *B.mucilaginosus* > *B.circulans* > Control. Regarding the interaction effect, the T_1 and T_2 treatments without K-solubilizing bacteria achieved non-significant values compared to the combined treatments of (T_5x *B.mucilaginosus* or *B.circulans)* and (T_7x *B.mucilaginosus* or *B.circulans*) in terms of the investigated quantitative and qualitative traits.

Table 4. Effect of the potassium sources accompanied by potassium dissolving bacteria on the total and marketable bulb yield of garlic at 180 days from planting during seasons of 2023/24 and 2024/25

Treatments		Bulb yield, ton.fed^{-1}		Marketable yield, ton.fed^{-1}	
		1st season	2nd season	1st season	2nd season
K-sources					
T_1		8.72a	8.86a	7.77a	7.86a
T_2		8.65a	8.82b	7.62b	7.72b
T_3		6.47e	6.56g	6.16g	6.23f
T_4		7.03c	7.13e	6.83e	6.91d
T_5		8.23b	8.36c	7.41c	7.52c
T_6		6.87d	6.98f	6.61f	6.70e
T_7		8.15b	8.29d	7.34d	7.44c
F. test		**	**	**	**
LSD at 5%		0.08	0.02	0.07	0.08
K-solubilizing bacteria					
Without		7.44c	7.55c	6.94c	7.03c
B.circulans		7.84b	7.97b	7.14b	7.23b
B.mucilaginosus		7.92a	8.05a	7.24a	7.33a
F. test		**	**	**	**
LSD at 5%		0.06	0.02	0.06	0.05
Interaction					
T_1	Without	8.60	8.74	7.56	7.64
	B.circulans	8.78	8.92	7.82	7.91
	B.mucilaginosus	8.79	8.91	7.91	8.02
T_2	Without	8.59	8.75	7.51	7.61
	B.circulans	8.62	8.79	7.63	7.71
	B.mucilaginosus	8.73	8.91	7.71	7.82
T_3	Without	6.44	6.53	6.02	6.11
	B.circulans	6.47	6.56	6.15	6.22
	B.mucilaginosus	6.50	6.59	6.30	6.37
T_4	Without	6.83	6.92	6.53	6.63
	B.circulans	7.04	7.15	6.91	6.99
	B.mucilaginosus	7.22	7.34	7.03	7.12
T_5	Without	7.53	7.63	7.30	7.41
	B.circulans	8.58	8.72	7.46	7.57
	B.mucilaginosus	8.60	8.73	7.47	7.56
T_6	Without	6.73	6.84	6.43	6.51
	B.circulans	6.87	6.97	6.62	6.71
	B.mucilaginosus	7.02	7.13	6.79	6.86
T_7	Without	7.34	7.46	7.19	7.28
	B.circulans	8.55	8.70	7.38	7.49
	B.mucilaginosus	8.56	8.72	7.43	7.54
F. test		**	**	**	**
LSD at 5%		0.16	0.06	0.15	0.14

Means within a row followed by a different letter (s) are statistically different at a 0.05 level T1: 100% of Potassium Recommended Dose (KRD) from potassium citrate; T2: 100% of KRD from potassium sulphate; T3: 100% of KRD from potassium feldspar; T4: 80% of KRD from potassium feldspar +20% from potassium citrate; T5: 60% of KRD from potassium feldspar +40% from potassium citrate; T6: 80% of KRD from potassium feldspar +20% from potassium sulphate; T7: 60% of KRD from potassium feldspar +40% from potassium sulphate

Table 5. Effect of the natural potassium sources accompanied by potassium dissolving bacteria on the bulb yield traits of garlic at 180 days from planting during seasons of 2023/24 and 2024/25

Treatments		Average bulb weight, g		Bulb diameter, cm		Neck diameter, cm		Bulbing ratio		No. of cloves / bulb	
		1st season	2nd season	1st season	2nd season	1st season	2nd season	1st season	2nd season	1st season	2nd season
K-sources											
T_1		41.54a	42.18a	4.34a	4.44a	1.30a	1.35a	0.30a	0.30a	30.33a	29.89a
T_2		41.18a	41.98b	4.25b	4.34b	1.24a	1.29a	0.29a	0.30a	29.89ab	29.33a
T_3		30.81e	31.24g	2.97g	3.05g	0.77d	0.80d	0.26c	0.26c	19.33f	19.44e
T_4		33.48c	33.97e	3.73e	3.81e	0.92c	0.96c	0.25d	0.25cd	24.00d	24.00d
T_5		39.21b	39.82c	4.02c	4.11c	1.13b	1.17b	0.28b	0.28b	28.44bc	27.78b
T_6		32.73d	33.22f	3.61f	3.69f	0.88c	0.92c	0.25d	0.25d	22.33e	23.22d
T_7		38.82b	39.48d	3.98d	4.04d	1.10b	1.15b	0.27b	0.28b	27.22c	26.44c
F. test		**	**	**	**	**	**	**	*	**	**
LSD at 5%		0.40	0.08	0.02	0.02	0.06	0.06	0.01	0.01	1.53	0.99
K-solubilizing bacteria											
Without		35.41c	35.96c	3.73b	3.81b	0.99b	1.03b	0.26b	0.27a	25.05c	24.71b
B.circulans		37.35b	37.96b	3.88a	3.96a	1.07a	1.11a	0.27a	0.28a	25.90b	26.00a
B.mucilaginosus		37.70a	38.32a	3.92a	4.01a	1.09a	1.13a	0.28a	0.28a	26.86a	26.48a
F. test		**	**	**	**	**	**	**	N.S	**	*
LSD at 5%		0.30	0.11	0.08	0.08	0.03	0.03	0.01	N.S	0.57	1.01
Interaction											
T_1	Without	40.96	41.63	4.22	4.32	1.23	1.29	0.29	0.30	30.00	29.67
	B.circulans	41.79	42.47	4.37	4.46	1.31	1.35	0.30	0.30	30.33	29.67
	B.mucilaginosus	41.86	42.43	4.42	4.53	1.35	1.40	0.31	0.31	30.67	30.33
T_2	Without	40.90	41.66	4.18	4.26	1.20	1.25	0.29	0.29	30.33	29.00
	B.circulans	41.05	41.88	4.28	4.38	1.25	1.30	0.29	0.30	29.67	29.67
	B.mucilaginosus	41.59	42.41	4.30	4.39	1.28	1.33	0.30	0.30	29.67	29.33
T_3	Without	30.67	31.08	2.91	2.99	0.74	0.77	0.25	0.26	18.33	18.00
	B.circulans	30.79	31.25	2.98	3.06	0.78	0.81	0.26	0.26	18.67	19.33
	B.mucilaginosus	30.96	31.39	3.02	3.09	0.79	0.82	0.26	0.26	21.00	21.00
T_4	Without	32.50	32.94	3.61	3.68	0.88	0.93	0.24	0.25	22.00	23.00
	B.circulans	33.54	34.03	3.79	3.87	0.94	0.97	0.25	0.25	24.33	24.33
	B.mucilaginosus	34.39	34.95	3.79	3.89	0.95	0.99	0.25	0.25	25.67	24.67
T_5	Without	35.85	36.35	3.85	3.94	1.04	1.08	0.27	0.27	27.00	25.67
	B.circulans	40.85	41.52	4.09	4.18	1.16	1.21	0.28	0.29	28.33	28.67
	B.mucilaginosus	40.93	41.58	4.12	4.22	1.18	1.23	0.29	0.29	30.00	29.00
T_6	Without	32.06	32.55	3.53	3.61	0.85	0.89	0.24	0.25	21.33	22.33
	B.circulans	32.72	33.17	3.63	3.70	0.89	0.93	0.25	0.25	22.67	24.00
	B.mucilaginosus	33.43	33.94	3.68	3.75	0.91	0.95	0.25	0.25	23.00	23.33
T_7	Without	34.97	35.52	3.81	3.86	0.98	1.03	0.26	0.27	26.33	25.33
	B.circulans	40.72	41.42	4.04	4.09	1.14	1.20	0.28	0.29	27.33	26.33
	B.mucilaginosus	40.78	41.51	4.08	4.17	1.17	1.21	0.28	0.29	28.00	27.67
F. test		**	**	**	**	**	**	*	*	*	*
LSD at 5%		0.79	0.29	0.21	0.22	0.08	0.09	0.02	0.03	1.50	2.66

Means within a row followed by a different letter (s) are statistically different at a 0.05 level T1: 100% of Potassium Recommended Dose (KRD) from potassium citrate; T2: 100% of KRD from potassium sulphate; T3: 100% of KRD from potassium feldspar; T4: 80% of KRD from potassium feldspar +20% from potassium citrate; T5: 60% of KRD from potassium feldspar +40% from potassium citrate; T6: 80% of KRD from potassium feldspar +20% from potassium sulphate; T7: 60% of KRD from potassium feldspar +40% from potassium sulphate

Table 6. Effect of the natural potassium sources accompanied by potassium dissolving bacteria on the bulb quality of garlic at 180 days from planting during seasons of 2023/24 and 2024/25

Treatments		Carbohydrates %		TSS %		Vitamin C mg/100g		Dry matter %		Pungency (purvate content πmol.ml^{-1})	
		1st season	2nd season	1st season	2nd season	1st season	2nd season	1st season	2nd season	1st season	2nd season
K-sources											
T_1		26.49a	26.87a	27.59a	28.17a	16.64a	17.27a	25.77a	26.11a	13.38a	13.65a
T_2		26.26a	26.60a	27.23b	27.75a	16.42b	17.08a	25.28b	25.62a	13.23b	13.49a
T_3		22.23e	22.53d	23.91g	24.41d	13.64e	14.22d	20.83f	21.12d	9.35g	9.54f
T_4		23.63c	23.97c	25.09e	25.61c	15.23d	15.87c	22.81d	23.14c	11.51e	11.74d
T_5		25.43b	25.83b	26.52c	27.02b	15.90c	16.56b	24.21c	24.57b	12.75c	13.00b
T_6		23.27d	23.61c	24.75f	25.26c	15.07d	15.68c	22.51e	22.85c	11.22f	11.45e
T_7		25.31b	25.76b	26.02d	26.59b	15.76c	16.42b	24.00c	24.44b	12.50d	12.76c
F. test		**	**	**	**	**	**	**	**	**	**
LSD at 5%		0.27	0.46	0.30	0.62	0.17	0.30	0.24	0.64	0.13	0.22
K-solubilizing bacteria											
Without		24.05b	24.37b	25.48c	26.02b	15.27c	15.90c	23.13c	23.45b	11.65c	11.89c
B.circulans		24.89a	25.27a	25.95b	26.46a	15.58b	16.22b	23.77b	24.12a	12.07b	12.31b
B.mucilaginosus		25.04a	25.43a	26.19a	26.72a	15.72a	16.36a	23.99a	24.37a	12.25a	12.49a
F. test		**	**	**	**	**	**	**	**	**	**
LSD at 5%		0.18	0.20	0.18	0.41	0.12	0.13	0.19	0.32	0.10	0.10
Interaction											
T_1	Without	26.19	26.56	27.05	27.59	16.29	16.93	25.27	25.57	13.15	13.41
	B.circulans	26.55	26.95	27.78	28.36	16.79	17.43	25.91	26.31	13.36	13.65
	B.mucilaginosus	26.73	27.10	27.93	28.57	16.84	17.47	26.13	26.45	13.62	13.90
T_2	Without	26.17	26.50	27.05	27.57	16.27	16.95	24.81	25.15	13.14	13.40
	B.circulans	26.25	26.58	27.25	27.77	16.42	17.08	25.35	25.67	13.26	13.52
	B.mucilaginosus	26.36	26.72	27.38	27.90	16.57	17.22	25.67	26.04	13.29	13.53
T_3	Without	22.06	22.31	23.68	24.18	13.47	14.06	20.53	20.82	9.05	9.23
	B.circulans	22.16	22.47	23.94	24.40	13.52	14.10	20.96	21.21	9.28	9.46
	B.mucilaginosus	22.46	22.80	24.12	24.65	13.93	14.51	21.01	21.34	9.71	9.91
T_4	Without	23.10	23.42	24.74	25.31	14.99	15.59	22.40	22.69	11.11	11.37
	B.circulans	23.85	24.22	25.08	25.56	15.29	15.97	22.99	23.36	11.60	11.81
	B.mucilaginosus	23.93	24.27	25.46	25.95	15.42	16.07	23.05	23.38	11.81	12.05
T_5	Without	24.06	24.47	26.01	26.47	15.54	16.16	23.44	23.81	12.16	12.40
	B.circulans	26.07	26.48	26.60	27.15	16.05	16.68	24.39	24.73	12.99	13.26
	B.mucilaginosus	26.16	26.54	26.96	27.45	16.12	16.83	24.79	25.18	13.09	13.34
T_6	Without	22.74	23.05	24.34	24.94	14.85	15.46	22.07	22.40	10.95	11.20
	B.circulans	23.42	23.74	24.89	25.32	15.17	15.80	22.52	22.84	11.24	11.45
	B.mucilaginosus	23.65	24.03	25.01	25.53	15.20	15.79	22.93	23.30	11.48	11.70
T_7	Without	24.01	24.31	25.52	26.10	15.46	16.16	23.38	23.69	11.98	12.23
	B.circulans	25.93	26.46	26.08	26.66	15.81	16.46	24.27	24.76	12.74	13.03
	B.mucilaginosus	25.97	26.53	26.47	27.02	16.00	16.62	24.36	24.87	12.77	13.02
F. test		**	*	**	**	**	**	**	**	**	**
LSD at 5%		0.47	0.54	0.48	1.08	0.33	0.35	0.49	0.86	0.25	0.27

Means within a row followed by a different letter (s) are statistically different at a 0.05 level T1: 100% of Potassium Recommended Dose (KRD) from potassium citrate; T2: 100% of KRD from potassium sulphate; T3: 100% of KRD from potassium feldspar; T4: 80% of KRD from potassium feldspar +20% from potassium citrate; T5: 60% of KRD from potassium feldspar +40% from potassium citrate; T6: 80% of KRD from potassium feldspar +20% from potassium sulphate; T7: 60% of KRD from potassium feldspar +40% from potassium sulphate

4.Bacteria Content

Table 7 illustrates the bacteria content after 45 and 90 days as affected by the studied potassium sources accompanied by potassium dissolving bacteria. Bacterial counts were performed 45 days after planting, representing the early vegetative stage, to assess the stability and success of bacterial inoculation. Additionally, bacterial counts were performed 90 days after planting, representing the garlic head formation and active growth stage, to assess the persistence and activity of bacteria in the soil. The population density of both types of KSB in the rhizosphere of garlic plants was significantly impacted due to the investigated treatments. Under all studied potassium treatments, the data in Table 7 show that the both studied bacterial inoculants (*B.circulans* and *B.mucilaginosus*) resulted in a remarkable increase in colony-forming units (CFU) compared to the control treatment (uninoculated). *B. mucilaginosus* inoculant consistently achieved the highest CFU values under all studied potassium treatments at 45 and 90 days after planting. Additionally the *B. circulans* enhanced the bacterial population in comparison with the control, though to a lesser extent than *B. mucilaginosus* at 45 and 90 days after planting. The control treatment (without inoculation) maintained relatively low CFU values at 45 and 90 days after planting under all studied potassium treatments. In addition, it can be noticed a slight decrease in numbers from 45 to 90 days, reflecting a relative stability of bacterial activity in the soil.

Table 7. Bacteria content after 30 and 90 days as affected by the studied potassium sources accompanied by potassium dissolving bacteria during seasons of 2023/24 and 2024/25 (combined data over both seasons as averages)

Potassium treatments	Bacteria type	CFU ($\times10^6$ g^{-1}) at 45 Days	CFU($\times10^6$ g^{-1}) at 90 Days
100% of K recommended dose from K citrate	Without	1.524	1.218
	B.circulans	5.706	4.992
	B.mucilaginosus	6.522	5.910
100% of K recommended dose from K sulphate	Without	1.626	1.320
	B.circulans	5.910	5.094
	B.mucilaginosus	6.828	6.114
100% of K recommended dose from K feldspar	Without	1.830	1.422
	B.circulans	6.216	5.400
	B.mucilaginosus	7.134	6.420
80% of K recommended dose from K feldspar +20% from K citrate	Without	1.728	1.422
	B.circulans	6.420	5.706
	B.mucilaginosus	7.338	6.624
60% of K recommended dose from K feldspar +40% from K citrate	Without	1.626	1.320
	B.circulans	6.522	5.910
	B.mucilaginosus	7.440	6.828
80% of K recommended dose from K feldspar +40% from Ksulphate	Without	1.830	1.524
	B.circulans	6.726	6.114
	B.mucilaginosus	7.644	7.032
60% of K recommended dose from K feldspar +40% from K sulphate	Without	1.728	1.422
	B.circulans	6.828	6.318
	B.mucilaginosus	7.746	7.236

5.Availability of Potassium in Soil at Harvest Stage

At harvest stage in both studied seasons, the availability of potassium in soil was determined to evaluate the response to the studied potassium treatments and bacteria inoculation as shown in Fig 1.

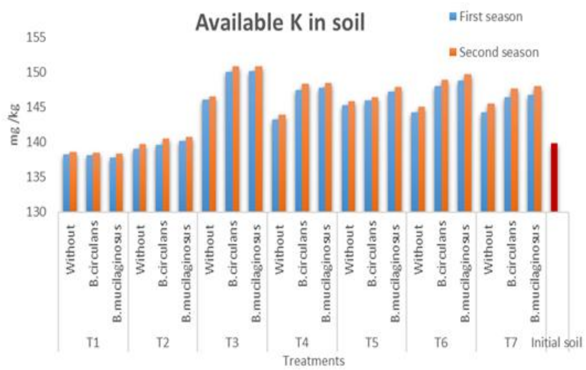

Fig 1. Effect of the natural potassium sources accompanied by potassium dissolving bacteria on the availability of potassium in soil at harvest stage during seasons of 2023/24 and 2024/25

It can be said that all studied treatments caused an increase in the availability of potassium in the soil at harvest compared to its availability in the soil before planting. Noting a relative increase in the availability of potassium in the second season compared to the first season, perhaps due to the long-term impact. Moreover, both types of bacteria caused an increase in the availability of potassium compared to the control, where the type *B. mucilaginosus* caused the highest values under all potassium treatments. Also, the treatments containing feldspar had the highest values, perhaps due to the slow supply of potassium and the increase in its availability.

Discussion

According to the results of this research, the potassium citrate and potassium sulphate treatments showed a significant superiority compared to feldspar treatment alone. This may be due to their easy solubility and availability to the grown garlic plant, which quickly improved garlic performance and nutrient absorption, thus increasing plant growth and improving its chemical constituents. Feldspar also improved garlic performance, perhaps because it is a silicate mineral rich in potassium, but it has low solubility. Therefore, the 100% potassium treatment in the form of feldspar did not rank highly compared to the mineral forms studied (potassium citrate and potassium sulphate), as it showed a limited effect on garlic performance when used alone. However, feldspar can be considered an alternative natural source of potassium, given its potential, as highlighted by these results, when it was combined with potassium-dissolving bacteria (*B. mucilaginosus or B. circumlans*). Overall, inoculation with the aforementioned bacteria resulted in a significant improvement in garlic plant growth, bulb yield and nutrients absorption, especially potassium. This remarkable improvement can be explained by the ability of both studied inoculants to solubilize potassium from feldspar through the secretion of organic acids by these bacteria (each according to its ability, as the ability of *B. mucilaginosus* was probably greater than that of *B. circularans*), as well as by chemical and organic decomposition, and by lowering the pH in the root zone, which may have helped release potassium from the feldspar crystal lattice. This explains the absence of significant effect among the T_1 and T_2 treatments without K-solubilizing bacteria and the combined treatments of (T_5 x *B.mucilaginosus* or *B.circulans*) and (T_7 x *B. mucilaginosus or B. circulans*). Also ,this can be explained by the fact that combining feldspar with a soluble mineral source (potassium citrate or potassium sulphate) led to more distinctive results, as this combination helped improve potassium availability by making available a rapidly soluble portion of the mineral source (either potassium citrate or potassium sulphate) and a graded portion of the feldspar that was dissolved by the bacteria (either *B. mucilaginosus or B. circularans*). This balance in availability was reflected in improved potassium uptake, increased plant physiological efficiency, and higher yields and improved quality. The obtained results are in harmony with those of Rajawat *et al*. (2019); Fawaz & Abo Zaed, (2020); Wang *et al.* (2022); Mansour *et al.* (2024).

CONCLUSION

According to the obtained findings, there are no significant among the treatment of 100% K recommended dose as potassium citrate or potassium sulphate without K-solubilizing bacteria and the combined treatments of (T_5x *B.mucilaginosus* or *B.circulans)* and (T_7x *B.mucilaginosus* or *B.circulans*). Moreover, the type of *B.mucilaginosus* was more effective than B.circulans in raising the availability of soil potassium. Finally, it can be concluded that integrating the use of soluble mineral potassium sources, natural sources such as feldspar and inoculation with potassium-dissolving bacteria (either *B. mucilaginosus* or *B. circularans*) as an effective strategy to reduce reliance on synthetic fertilizers and improve the sustainability of garlic production.

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كفاءة مصادر البوتاسيوم الطبيعية المصحوبة بالبكتيريا المذيبة للبوتاسيوم على إنتاجية نبات الثوم

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الملخص

في الوقت الحالي، هناك حاجة ملحة لاستخدام مصادر طبيعية مستدامة للبوتاسيوم (K) وذلك لتقليل الاعتماد على الأسمدة الكيماوية دون التسبب في انخفاض معنوي في الإنتاجية .لذلك، أجريت تجربة حقلية بهدف تقييم كفاءة الفلسبار كمصدر طبيعي للبوتاسيوم مصحوبًا ببكتيريا مذيبة للبوتاسيوم (KSB) على إنتاجية نبات الثوم مقارنةً بأسمدة البوتاسيوم المعدنية الأخرى .سبع معاملات بوتاسيوم تم دراستهم كعامل رئيسي[T_1:١٠٠ % من الجرعة الموصى بها من البوتاسيوم (KRD) في صوره سترات البوتاسيوم؛ T_2:100% من KRDفي صورة كبريتات البوتاسيوم؛T_3: 100% من KRD في صورة فلسبار بوتاسيوم؛T_4: ٨٠ % من KRD في صورة فلسبار بوتاسيوم + ٢٠٪ من سترات البوتاسيوم؛T_5: ٦٠ % من KRD في صورة فلسبار بوتاسيوم + ٤٠٪ من سترات البوتاسيوم، T_6: ٨٠٪ من KRD في صورة فلسبار بوتاسيوم + ٢٠٪ من كبريتات البوتاسيوم؛T_7: ٦٠ % من KRDفي صورة فلسبار بوتاسيوم + ٤٠٪ من كبريتات البوتاسيوم]. بالإضافة إلى ذلك، تمت دراسة نوعين من البيكتريا المذيبه للبوتاسيوم KSB كعامل فرعي (B.mucilaginosusو B.circulans والكنترول) . أظهرت النتائج أن المعاملات T_1 و T_2حققت أعلى قيم لجميع الصفات المرتبطة بالنمو والإنتاجية .حقق نوع B.mucilaginosus اعلي التحسنات في اداء النبات متفوقا على نوع .B.circulans أما بالنسبة لتأثير التداخل، فقد لوحظ أن كل من معاملات T_1 و T_2بدون KSB حققت فروقا في القيم غير معنوية مع المعاملات المشتركة لـ (T_5 x B.mucilaginosus or B.circulans) و (T_7x B.mucilaginosus أو B.circulans) . بشكل عام، يمكن استنتاج ان دمج مصادر البوتاسيوم المعدنية القابلة للذوبان والمصادر الطبيعية مثل الفلسبار والتلقيح بـ KSB يعد استراتيجية فعالة لتقليل الاعتماد على الأسمدة الصناعية وتحسين استدامة إنتاج الثوم.