



Article

Impact of Potassium Solubilizing Bacteria on Growth and Yield of Sweet Potato

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Abstract: The purpose of this work is to evaluate the impact of potassium solubilizing bacteria (KSB) as biofertilizer combined with varying levels of potassium sulphate (K_2SO_4) soil fertilization, on the growth, yield, chemical composition and storability of sweet potato plants (*Ipomoea batatas*L.), cv. Minufia 6. It also aims to confirm the potentiality of KSB to partially replace mineral fertilizers without affecting the end product quality and examining the effects of KSB on nutrients (NPK) availability in the soil. Trials were conducted during the summers of 2023 and 2024 under clay soil conditions. The experiment carried out in a randomized complete block design with 3 replicates of 6 treatments namely and two 100% K_2SO_4 and KSB as controls treatments and four treatments of K_2SO_4 at rates 100%, 75%, 50%, and 25% K_2SO_4 of the recommended dose each combined with KSB. Plant length, number of branches per plant, plant fresh and dry weight, total chlorophyll content, carotenoids content, tuber root length, tuber root diameter, and number of tuber roots per plant were noticeably higher for treatments (100% K_2SO_4), (100% K_2SO_4 +KSB), (75% K_2SO_4 +KSB), and to a lesser extent (50% K_2SO_4 +KSB). In addition, the highest average fresh tuber root weight, fresh tuber roots weight per plant, total yield, and marketable yield, together with the lowest non-marketable yield, were achieved under the treatments (100% K_2SO_4), (100% K_2SO_4 +KSB), and (75% K_2SO_4 +KSB). Also, the best results of total carbohydrate, NPK, and protein contents in sweet potato tuber roots were recorded by applying KSB with 100% or 75% of the recommended K_2SO_4 dose. While, throughout the different storage periods the treatment consisting of 50% K_2SO_4 combined with KSB exhibited the lowest percentage of tuber roots weight loss. Soils treated with KSB exhibited an increase in available N with rate of (6-11%), and available P (17-23%) higher than untreated soil after the first and second growing seasons. Furthermore, soils receiving 100% K_2SO_4 combined with KSB showed a significant increase in available K, with levels of 26-37% higher than

those treated only with 100% K₂SO₄, across the two growing seasons. The results clearly demonstrated that KSB based biofertilizers can successfully achieve partial substitution of mineral K inputs, allowing a reduction of 25% in chemical K₂SO₄ fertilization without compromising tuber roots yield or quality, while simultaneously contributing to long term soil health. The application of KSB in combination with 75% of the recommended K₂SO₄ dose is recommended as the optimal and most sustainable practice

Key words: Soil health, Biofertilizer, K₂SO₄, Tuber roots yield, Productivity, Chemical components, storability.

1. Introduction

Sweet potato (*Ipomoea batatas* L.) are a vital globally economic crop, playing a significant role in ensuring food security (El-Sheikha and Ray, 2017; Sapakhova *et al.*, 2023). Ranked as the world's 7th most significant food crop, they follow wheat, rice, maize, potato, barley, and cassava (FAO, 2016). As a staple food, sweet potatoes are consumed widely, including during ceremonies, and by adults, children, and infants (Suparno *et al.*, 2016), due to their high carbohydrate content, which provides essential energy. They also include a lot of vitamins and micronutrients (B vitamins, vitamin C, folate, K, P, and Mn). Additionally, their polyphenols offer health benefits, including liver protection, anti-inflammatory, anticancer, and antidiabetic properties (Hu *et al.*, 2016; Khalil, 2025). Beyond consumption by humans, sweet potatoes serve as important livestock feed and production of starch and sugar, owing to their adaptability to a variety of agricultural management conditions-including low-technology and low-cost practices with reasonable yields-sweet potatoes have significant recognition as a viable contender for the market for accessible functional foods (Bach *et al.*, 2021). In 2023, Egypt cultivated sweet potatoes on more than 29.58 feddan (4200 m²), yielding approximately 423,423 tons (FAOSTAT, 2025).

Potassium is a vital macronutrient for various organisms, ranking as the Earth's crust's 7th most plentiful element, with soil concentrations ranging from 0.04% to 3% as a total. It plays critical roles in plants, including enhancing resistance to biotic and abiotic stresses, supporting biochemical and physiological processes such as promoting water uptake, maintaining osmotic balance and turgor pressure in cells, regulating stomata function, facilitating the transport of carbohydrates produced during photosynthesis from leaves to storage organs, aiding nitrate reduction, controlling cell membrane permeability, and ensuring proper protoplasm hydration (Gallegos-Cedillo *et al.*, 2016; Hasanuzzaman *et al.*, 2018; Subhash *et al.*, 2022). Although, soil contains abundant K, only 1-2% is available to plants, with the majority certain to minerals in an unavailable form (Jalali *et al.*, 2021). Reduced soil K levels negatively impact plant growth and yield (Meena *et al.*, 2014; Xiao *et al.*, 2017). K is the most critical nutrient for sweet potato due to its high uptake requirements. In Egypt, sweet potatoes are typically cultivated on old soils rich in total K but deficient in available, making efficient K management crucial for these soils.

Soil degradation from continuous cultivation has become a major issue in producing high-quality bulbous and root crops. The limited availability of chemical fertilizers, combined with their negative effects on soil fertility and the environment due to prolonged use, Gouda *et al.* (2018) has highlighted the need for alternatives. Biofertilizers offer an eco-friendly, cost-effective, and sustainable substitute for synthetic fertilizers, boosting agricultural productivity while reducing environmental pollution (Sattar *et al.*, 2018). Soil hosts a variety of microorganisms, or rhizosphere microflora, which impact soil fertility by decomposition, mineralization, nutrient analysis, and its storage (Parmar and Sindhu, 2013; Waseem *et al.*, 2025).

Potassium solubilizing bacteria (KSB) are increasingly recognized for their potential as a sustainable approach to improve plant growth, root development, flowering, yield, and quality by enhancing K availability in soil (Zhang *et al.*, 2013; Bahadur *et al.*, 2019; Basak *et al.*, 2020). These biofertilizers aid in lowering environmental contamination brought on by overuse of chemical fertilizers. KSB produce organic acids, which aid in the transformation of insoluble K into soluble forms (e.g.,

oxalic, tartaric, gluconic, 2-ketogluconic, lactic, citric, malonic, and fumaric acids), inorganic acids, and protons via an acidolysis mechanism (Maurya *et al.*, 2014; Meena *et al.*, 2015). This process makes potassium more accessible to plants. Additionally, organic acids produced by KSB generate ammonia and hydrogen sulfide, which can oxidize in soil to form strong acids as nitric and sulfuric acids, promoting ion exchange involving hydrogen, K, Mg, Ca, and Mn (Huang *et al.*, 2013). KSB also store K in their biomass, transferring it to plants, and form biofilms around microbial cells. These biofilms accelerate mineral weathering, protect against ion loss, and enhance the release of K, silicon, and aluminum from potassium-bearing rocks (Meena *et al.*, 2016; Jain *et al.*, 2022). In contrast, combining KSB with potassium sulphate can ensure a rapid and steady potassium supply, improving plant growth, yield, and product quality (Osman and Soltan, 2021). Among the most effective potassium solubilizing bacteria is *Bacillus mucilaginosus*, which can extract K from feldspar and aluminosilicate minerals. Also breaking it down from organic matter (OM) and crop residues (Merwad, 2016; Adwani *et al.*, 2024).

Understanding nutrient requirements is crucial for maximizing sweet potato yields, improving resource efficiency, and minimizing nutrient leaching. Integrated nutrient management offers an eco-friendly approach for sustainable agriculture and optimal crop production with minimal environmental impact, building upon previous research on rationalizing chemical fertilizer consumption. Consequently, the current study aimed to determine the effects of potassium-solubilizing bacteria (KSB) biofertilizer, combined with different potassium sulphate (K_2SO_4) soil fertilization levels, on sweet potato growth, yield, chemical composition, and storability. It also assesses the potential for biofertilizers to reduce K chemical fertilizer inputs without compromising product quality. It moreover examines the effect of KSB on soil NPK availability.

2. Material and Methods

2.1. Field Experiment

There were two field tests carried out at the Qaha Vegetable Research Farm, Qaliobia Governorate, Horticulture Research Institute (HRI), ARC, Egypt, situated at 30°17'22.5" N latitude and 31°11'53.8" E longitude. These trials took place in clay soil during the summers of 2023 and 2024. The study aimed to assess the potential of partially replacing mineral potassium fertilizers with biofertilizers. Potassium was applied to the soil as potassium sulphate (K_2SO_4 , 48% K_2O) at four levels (100%, 75%, 50%, and 25% of the recommended dose) combined with inoculation by the biofertilizer potassium solubilizing bacteria (KSB, *Bacillus circulans*). To assessing its effects on vegetative growth, yield and its components, chemical composition of tuberous roots, storage capacity and of sweet potato (*Ipomoea batatas* L.) cultivar Minufia 6 from HRI, ARC. In addition to examining its impact on the residual amount of available K in the soil. The experiment followed a randomized complete block design with 3 replicates, each comprising six treatments as follows: 100% K_2SO_4 (as a positive control), 100% K_2SO_4 +KSB, 75% K_2SO_4 +KSB, 50% K_2SO_4 +KSB, 25% K_2SO_4 +KSB and KSB.

Stem cutting of sweet potato cv. Minufia 6 were planted on May 20th in both 2023 and 2024. Each experimental plot covered an area of 13.5 m², consisting of 4 ridges (0.75 m wide and 4.5 m long each). Stem cuttings, measuring 25 cm in length with 3-4 nodes, were planted at a slant, inserted halfway into the soil on one side of the ridge, spaced 25 cm apart.

Bacterial strains and growth condition: An active strain of KSB (*Bacillus circulans*), in two hundred ml conical flask were incubated at 28 °C for 72 h. Homogenous suspensions containing microbial load $\geq 10^9$ C Fu ml⁻¹ were prepared, following Priyanka and Sindhu (2013). Mowlation method, the stem cuttings were soaked for 30 to 60 seconds before planting at liquid inoculant of *Bacillus circulans* culture. A base dressing of the previous inoculant was repeat after 21 days of planting at the rate of 5 liter per feddan to guarantee their function. The KSB (*Bacillus circulans*) used were supplied by the Department of Soil Microbiology and SWERI, ARC, Egypt.

Potassium sulphate (48% K_2O) was applied at 100%, 75%, 50%, and 25% of the recommended potassium fertilizer rates (200 kg/feddan), with each treatment split into two equal doses and incorporated into the soil at 30 and 60 days after planting. All experimental plots received 100 kg/feddan

of ammonium sulphate (20.6% N) as a nitrogen source and 300 kg/feddan of calcium superphosphate (15% P₂O₅) as a phosphorus source. The recommended NPK rates were adjusted based on the soil's available nutrient content, with the amount of available NPK in the soil measured and deducted from the mineral fertilizers added (**Ganzour *et al.*, 2020; Ganzour *et al.*, 2025**). Other agricultural practices for sweet potato cultivation, including disease and pest control, followed the standard recommendations of the Egyptian Ministry of Agriculture.

Soil Analysis: Prior to planting and following the first and second seasons, topsoil samples (0-30 cm) from the experimental plots were collected. Laboratory analyses were then performed following the procedures described by the **Soil Survey Staff (2014)** to determine key physicochemical properties, including particle size distribution, pH, OM content, CaCO₃, EC, and soluble ions in the soil paste extract (Ca²⁺, Mg²⁺, Na⁺, K⁺, Cl⁻, HCO₃⁻, and CO₃²⁻). Available K was measured using a flame photometer, available N was determined via the Kjeldahl method (**Page *et al.*, 1982**), and available P was extracted using the **Olsen *et al.* (1954)** and measured by a spectrophotometer and (Table 1).

Water Analysis: A sample of the irrigation water source was analyzed to determine its chemical properties, including pH, EC, cations, anions, and SAR, following the methodology outlined by the **USDA (2004)** as shown in Table 1.

Table (1). Physicochemical soil properties and chemical analyses for irrigation water

Physicochemical properties of the soil											
Particle size distribution (%)				Chemical properties				Available macronutrients (mg kg ⁻¹)			
Sand	Silt	Clay	Texture (Class)	pH (1:2.5)	OM (g kg ⁻¹)	Total CaCO ₃ (g kg ⁻¹)	N	P	K		
12.87	28.41	58.72	Clay	7.76	9.35	48.16	35.69	5.38	218.22		
Soluble cations and anions (mmolc L ⁻¹)											
ECe (dSm ⁻¹)	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	Cl ⁻	HCO ₃ ⁻	CO ₃ ²⁻	SO ₄ ²⁻	SAR	ESP	
2.40	7.33	4.49	11.86	0.52	11.28	1.21	---	11.71	4.88	5.60	
Chemical analyses of irrigation water											
Soluble cations and anions (mmolc L ⁻¹)											
pH	ECe (dSm ⁻¹)	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	Cl ⁻	HCO ₃ ⁻	CO ₃ ²⁻	SO ₄ ²⁻	SAR	
7.36	1.28	3.83	3.14	5.74	0.15	7.20	0.55	---	5.11	3.07	

2.2. Data recording

Vegetative growth parameters: At 90 days after transplanting, vegetative growth measurements were recorded. Five plants were randomly chosen to measure average plant length (cm), number of branches per plant, fresh weight of the plant (kg), and dry weight of the plant (g).

Chlorophyll (Chl) and Carotenoids: Levels of Chl a, Chl b, total Chl (a+b), and carotenoids (mg/g fresh weight) in leaves were determined 105 days after planting, following the method described by **Wettstein (1957)**.

Yield and its components: At harvest (130 days after planting), random crop samples were collected to measure tuber root length and diameter (cm), number of tuber roots per plant, average fresh tuber root weight (g), total fresh tuber roots weight per plant (kg/plant), total yield (ton/feddan), and marketable yields (suitable size and good shape) have a weight about 100 to 300 g and non-marketable (small and malformed roots) have a weight of less than 100 g or more than 300 g crop yields (ton/feddan).

2.3. Chemical plant analyses

Total Carbohydrates (%): These were determined in tuber roots using a colorimetric method as described by **Dubois *et al.* (1956)**.

Nutrient contents and proteins (%): Randomly selected tuber roots from each plot were oven-dried at 70°C until constant weight, then crushed to pass through a 1 mm sieve. Following **A.O.A.C. (2016)**, 0.5 g of dried tuber root samples were digested using a mixture of H₂SO₄ and HClO₄. In the digested

samples, N was determined using a micro-Kjeldahl device, P by spectrophotometer, and K by flame photometer (Page *et al.*, 1982). Protein content was calculated by multiplying the N content by 6.25 (Pregl, 1945).

2.4. Tubers roots storability

The tuber roots were placed in perforated, numbered bags and stored randomly in three replicates for 4 months (120 days). All treatments were kept in a prepared warehouse, thoroughly cleaned of pathogens and insects, maintained at ambient room temperature with adequate airflow through the tubers to prevent heat accumulation that could cause soft rots. Each replicate was inspected monthly to determine the weight loss percentage at 30, 60, 90, and 120 days of storage, as well as the weight loss percentage averaged over the entire storage period for both seasons. The following formula was used to get the weight loss percentage:

$$\text{Weight loss \%} = \frac{\text{initial tuber roots weight} - \text{tuber roots weight at sampling date}}{\text{initial tuber roots weight}} \times 100$$

2.5. Statistical analysis

InfoStat modeling software was used to perform statistical analysis for this investigation (V. 2014), as outlined by Di Rienzo *et al.* (2012). The means of different experimental treatments were compared using Duncan's Multiple Comparisons Test. Furthermore, Duncan's multiple range test at a 5% significance level was applied, where values in columns or rows sharing the same lowercase letter(s) indicate no significant differences.

3. Results

3.1. The field experiment

3.1.1. Soil and irrigation water properties

The soil exhibited a clayey texture, with 58.72% clay content. It had a Sodium Adsorption Ratio (SAR) of 4.88, an Exchangeable Sodium Percentage (ESP) of 5.60, a pH of 7.76, and an EC of 2.40 dSm⁻¹, indicating slightly saline and non-alkaline conditions. The soil was non-calcareous, with a total carbonate content of 4.82%. Additionally, the organic matter content was low at 0.94%. Among the available macronutrients, nitrogen (N) was low at 35.69 mg kg⁻¹, while phosphorus (P) and potassium (K) were moderate at 5.38 mg kg⁻¹ and 218.22 mg kg⁻¹, respectively (Table 1). Surface irrigation was utilized for the current field experiment. For the irrigation water, which was slightly saline (EC of 1.28 dSm⁻¹) and non-alkaline (SAR of 3.07), making it generally suitable for irrigation. However, according to FAO (1985), water with EC values between 0.75 and 3.00 dSm⁻¹ may pose increasing challenges for irrigation over time (Table 1).

3.2. Vegetative growth parameters

3.2.1. Plant length and number of branches

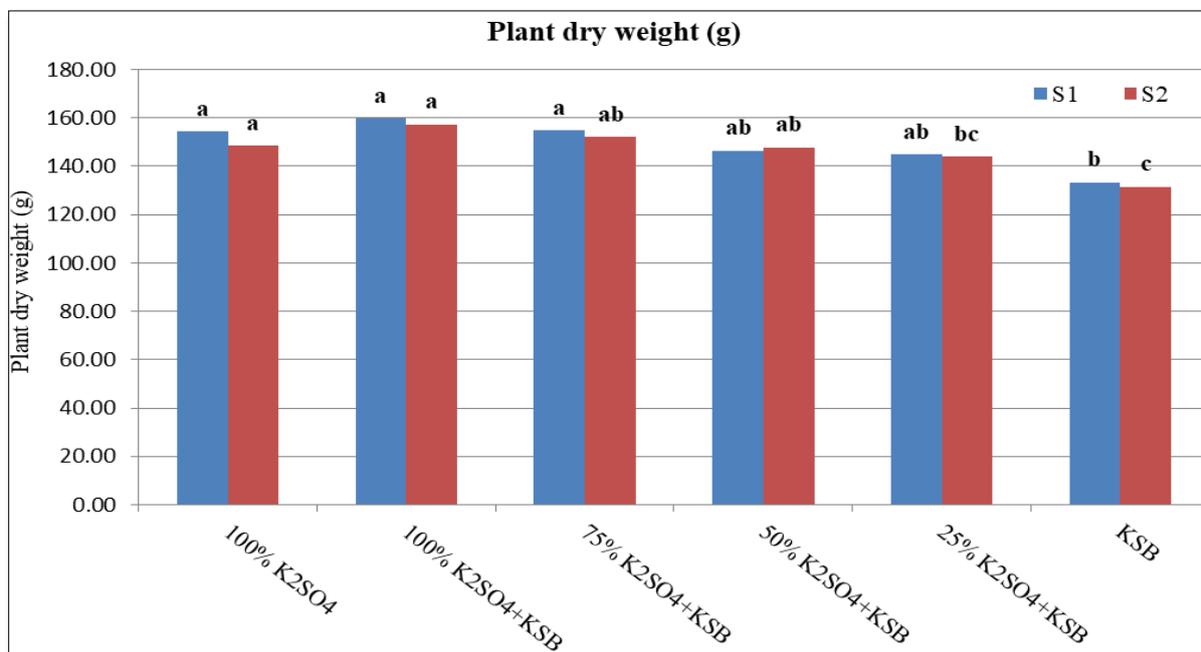
The treatments of 100% K₂SO₄, 100% K₂SO₄+KSB, and 75% K₂SO₄+KSB resulted in the highest plant length, and number of branches per plant during the two seasons (Table 2). Adding, 50% K₂SO₄+KSB gave a non-significant difference for number of branches per plant in the first season compared to these three treatments (100% K₂SO₄, 100% K₂SO₄+KSB, and 75% K₂SO₄+KSB). Conversely, the lowest plant length and branches number were recorded for the KSB treatment only in both seasons.

3.2.2. Plant fresh and dry weight

Data in Table 2 designated that the sweet potato plants supplemented with 100% K₂SO₄ or 100% K₂SO₄+KSB or 75% K₂SO₄+KSB had higher plant fresh weight in the both seasons. As well, all treatments showed the highest plant dry weight except 25% K₂SO₄+KSB in the 2nd season, and KSB in the two-seasons (Figure 1).

Table (2). Effect of K₂SO₄ combinations with KSB on plant length (cm), number of branches per plant, and plant fresh weight (kg) of sweet potato plants in 2023 and 2024 seasons

Treatments	Plant length (cm)		Number of branches (per plant)		Plant fresh weight (kg)	
	S1	S2	S1	S2	S1	S2
100% K ₂ SO ₄	161.00 a	160.33 a	20.70 ab	18.67 a	1.002 a	0.976 a
100% K ₂ SO ₄ +KSB	166.67 a	162.00 a	21.77 a	19.67 a	1.009 a	0.994 a
75% K ₂ SO ₄ +KSB	156.33 a	154.00 a	21.00 ab	18.63 a	0.985 a	0.959 ab
50% K ₂ SO ₄ +KSB	137.33 b	130.67 b	19.33 abc	17.37 b	0.904 b	0.912 bc
25% K ₂ SO ₄ +KSB	132.67 b	126.67 bc	18.77 bc	16.23 c	0.879 bc	0.899 c
KSB	126.67 b	122.33 c	17.00 c	15.00 d	0.819 c	0.802 d

**Figure (1).** Effect of K₂SO₄ combinations with KSB on plant dry weight (g) of sweet potato plants in 2023 and 2024 seasons

3.2.3. Chlorophyll content

It is evident from the data presented in Table 3 that all treatments made a non-significant difference in Chlorophyll a, in the two years. The same results in Chlorophyll b except for KSB treatment, scored the lowest Chlorophyll b in both seasons. The addition of K₂SO₄ only or combined with biofertilizer led to the highest total Chlorophyll content as relative values (1.99 and 1.89 mg g⁻¹) in both years (Table 3). The optimal total Chlorophyll level of 1.99mg g⁻¹ obtained under the 100% K₂SO₄+KSB treatment in the 1st season, with non-significant differences were found under (100% K₂SO₄, and 75% K₂SO₄+KSB treatments, in the both seasons) and (50% K₂SO₄+KSB, and 25% K₂SO₄+KSB treatments, in the 2nd season).

3.2.4. Carotenoids content

Carotenoids content of sweet potato differed significantly under the K₂SO₄ and/or KSB treatments in both tested seasons (Figure 2). Fertilizing with 100% K₂SO₄ and 100% K₂SO₄+KSB rates

produced the highest carotenoids content in the tow tested season, without significant differences between 75% K₂SO₄+KSB and 50% K₂SO₄+KSB, in the second year. However, the lowest carotenoids content was obtained under the treatments of 75% K₂SO₄+KSB and 50% K₂SO₄+KSB, in first year and 25% K₂SO₄+KSB and KSB alone, in both years.

Table (3). Effect of K₂SO₄ combinations with KSB on Chlorophyll a, Chlorophyll b, and total Chlorophyll (mg g⁻¹) of sweet potato plants in 2023 and 2024 seasons

Treatments	Chlorophyll a (mg g ⁻¹)		Chlorophyll b (mg g ⁻¹)		Total Chlorophyll (mg g ⁻¹)	
	S1	S2	S1	S2	S1	S2
100% K₂SO₄	1.11 a	1.09 a	0.850 ab	0.820 a	1.96 ab	1.91 a
100% K₂SO₄+KSB	1.13 a	1.08 a	0.863 a	0.817 a	1.99 a	1.90 ab
75% K₂SO₄+KSB	1.10 a	1.08 a	0.793 ab	0.813 a	1.89 abc	1.89 ab
50% K₂SO₄+KSB	1.06 a	1.07 a	0.750 ab	0.797 ab	1.81 bc	1.86 ab
25% K₂SO₄+KSB	1.06 a	1.06 a	0.747 ab	0.797 ab	1.81 bc	1.86 ab
KSB	1.05 a	1.03 a	0.733 b	0.700 b	1.78 c	1.73 b

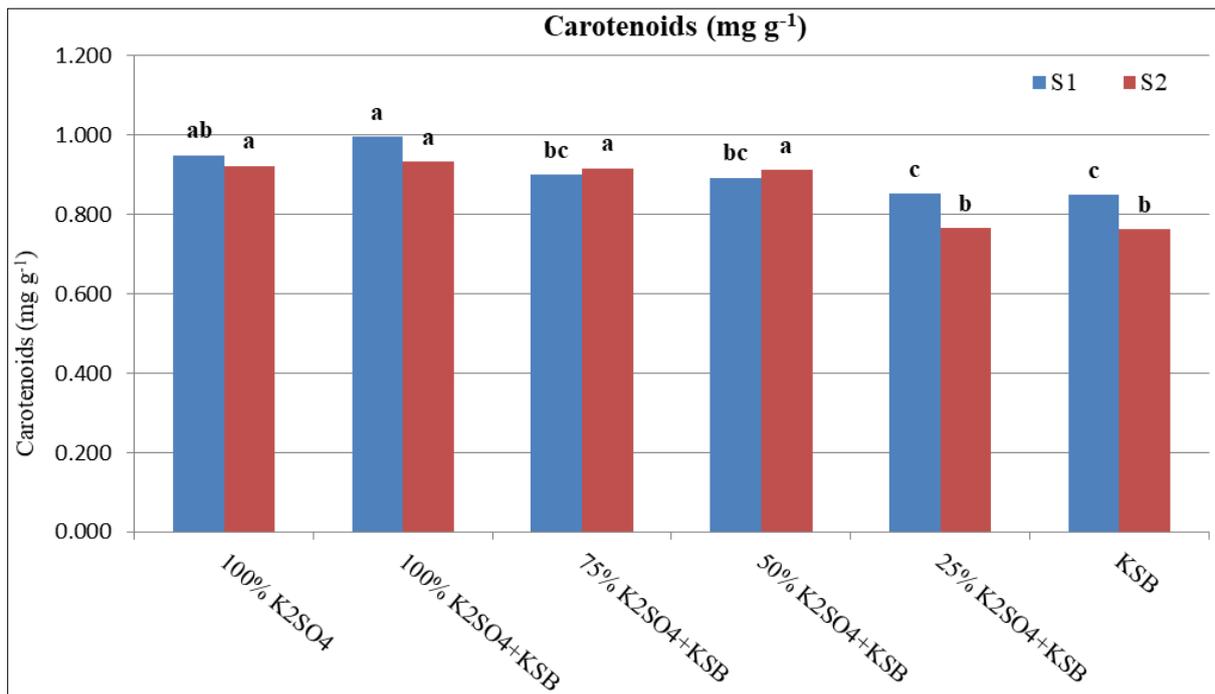


Figure (2). Effect of K₂SO₄ combinations with KSB on carotenoids content (mg g⁻¹) of sweet potato plants in 2023 and 2024 seasons

3.3. Yield and its components

3.3.1. Tuber root length and diameter, and number of tuber roots per plant

The quality parameters and tuber root length, tuber root diameter and number of tuber roots per plant were significantly maximized by applying K₂SO₄ combined with KSB as compared to the KSB treatments in both growing seasons. Tuber root length, tuber root diameter and number of tuber roots per plant increased in response to (100% K₂SO₄), (100% K₂SO₄+KSB), and (75% K₂SO₄+KSB), also

with (50% K₂SO₄+KSB) no significant differences were observed, except in the 2nd season for tuber root diameter (Table 4). While the lowest results were obtained under (25% K₂SO₄+KSB) or (KSB), in both growing seasons.

3.3.2. Average weight of fresh tuberous roots and fresh tuberous roots weight per plant

The results presented in Figure 3 and Table 5 indicate that addition of 100% K₂SO₄ or 100% K₂SO₄+KSB or 75% K₂SO₄+KSB led to the highest average fresh tuber root weight (259.45 to 267.78 g) and fresh tuber roots weight per plant (1.58 to 1.88 kg), of sweet potato plants in both seasons.

Table (4). Effect of K₂SO₄ combinations with KSB on tuber root length and diameter (cm), and number of tuber roots (per plant) of sweet potato plant in 2023 and 2024 seasons

Treatments	Tuber root length (cm)		Tuber root diameter (cm)		Number of tuber roots (per plant)	
	S1	S2	S1	S2	S1	S2
100% K ₂ SO ₄	18.00 ab	18.00 a	5.60 a	5.33 a	5.43 a	5.58 a
100% K ₂ SO ₄ +KSB	18.33 ab	17.67 ab	5.67 a	5.40 a	5.63 a	5.17 a
75% K ₂ SO ₄ +KSB	18.88 a	18.03 a	5.87 a	5.47 a	5.84 a	5.64 a
50% K ₂ SO ₄ +KSB	17.83 ab	17.50 ab	5.07 ab	4.73 b	5.39 a	4.76 ab
25% K ₂ SO ₄ +KSB	16.67 bc	16.33 bc	4.63 b	4.67 b	4.60 b	3.94 bc
KSB	15.05 c	15.06 c	4.40 b	3.97 c	4.40 b	3.67 c

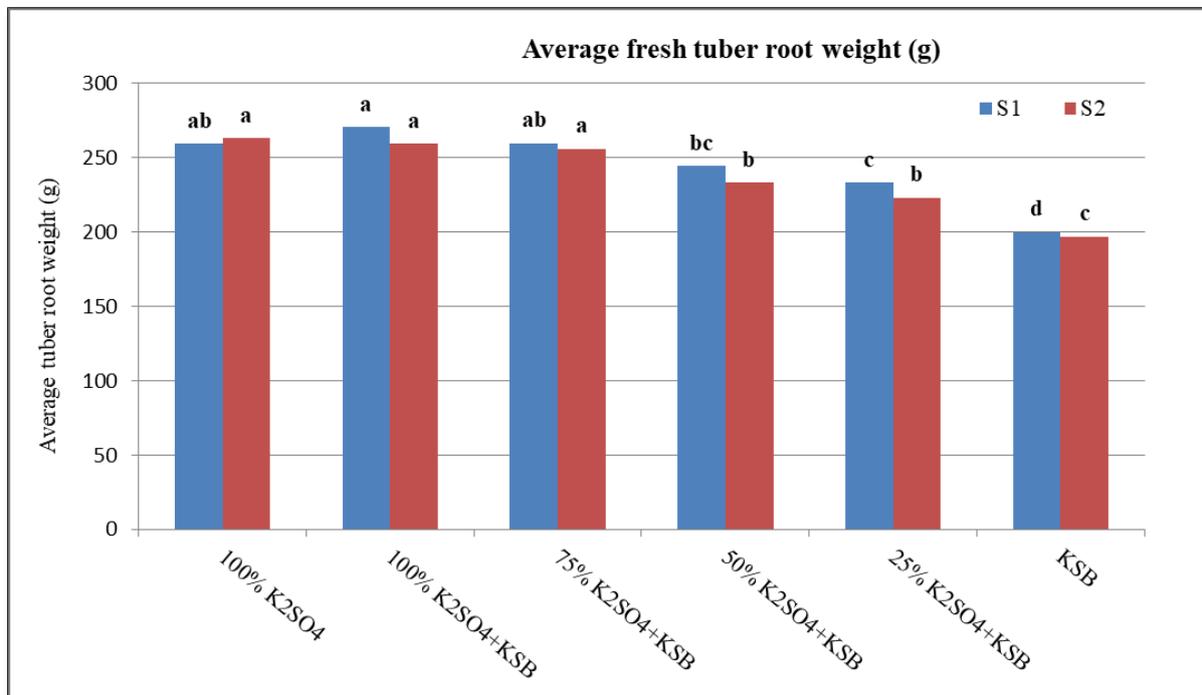


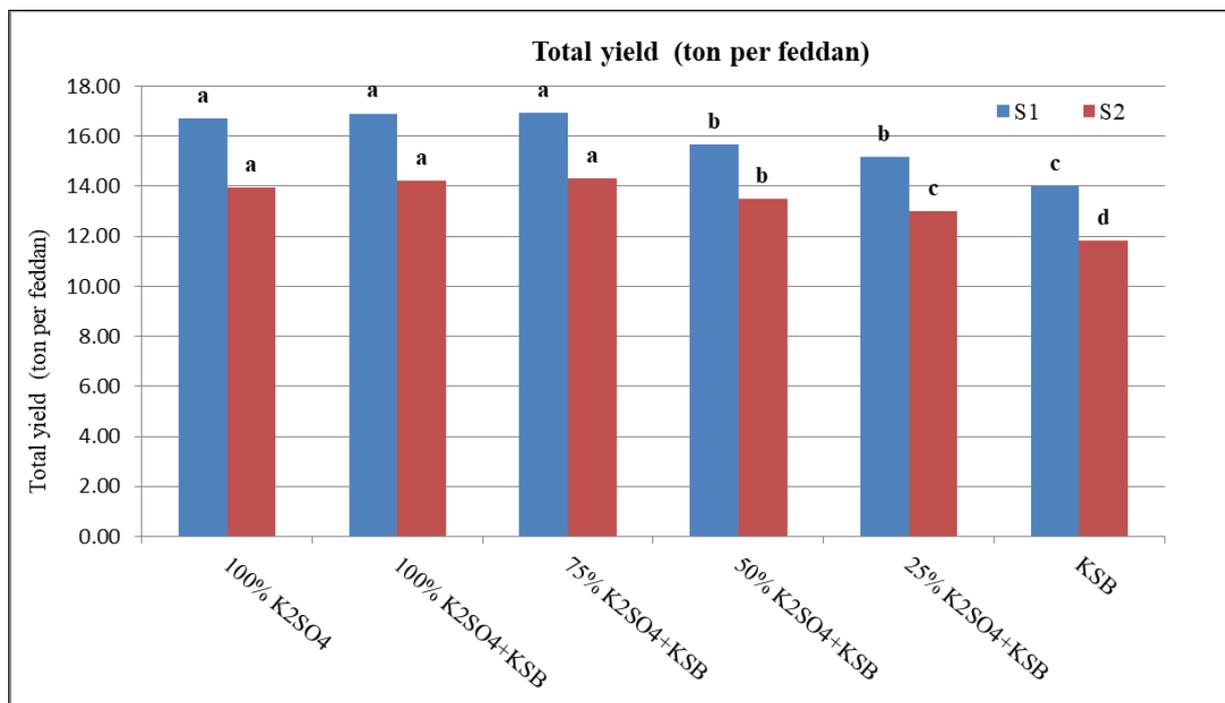
Figure (3). Effect of K₂SO₄ combinations with KSB on average fresh tuber root weight (g) of sweet potato plants in 2023 and 2024 seasons

Table (5). Effect of K₂SO₄ combinations with KSB on fresh tuber roots weight plant (kg per plant), marketable yield (ton per feddan), and non-marketable yield (ton per feddan) of sweet potato plant in 2023 and 2024 seasons

Treatments	Fresh tuber roots weight plant (kg per plant)		Marketable yield (ton per feddan)		Non-marketable yield (ton per feddan)	
	S1	S2	S1	S2	S1	S2
100% K ₂ SO ₄	1.86 a	1.59 a	15.975 a	13.328 a	0.723 ab	0.605 c
100% K ₂ SO ₄ +KSB	1.88 a	1.58 a	16.139 a	13.597 a	0.773 ab	0.630 bc
75% K ₂ SO ₄ +KSB	1.88 a	1.59 a	16.252 a	13.735 a	0.672 b	0.571 c
50% K ₂ SO ₄ +KSB	1.74 b	1.50 b	14.790 b	12.782 b	0.840 a	0.702 ab
25% K ₂ SO ₄ +KSB	1.69 b	1.44 c	14.332 b	12.214 c	0.866 a	0.773 a
KSB	1.55 c	1.31 d	13.101 c	11.034 d	0.882 a	0.777 a

3.3.3. Total yield, marketable and non-marketable yield

Adding K₂SO₄ plus KSB produced the greatest total and marketable yield, followed by applied KSB only in both tested seasons (Figure 4 and Table 5). In addition, the best interaction for total and marketable yield in both seasons were gained by applying 75% K₂SO₄+KSB with non-significantly differences under 100% K₂SO₄, and 100% K₂SO₄+KSB. In contrary, the lowest total and marketable yield were recorded for the KSB treatment alone in the both seasons. On the other hand, data show that applied 25% of K₂SO₄ combined with KSB and/ or KSB only scored the highest non marketable yield of sweet potato plants in both seasons.

**Figure (4).** Effect of K₂SO₄ combinations with KSB on sweet potato total yield (ton per feddan) in 2023 and 2024 seasons

3.4. Chemical constituents in tuber roots

3.4.1. Total carbohydrate

As shown in Figure 5, the total carbohydrate content in sweet potato tuber root was maximally enhanced under 100% K_2SO_4 +KSB as compared to the other treatments in the two growing seasons, without significant with 75% K_2SO_4 +KSB in the two tested seasons. While, the lowest total carbohydrate content recorded with both 25% K_2SO_4 +KSB, and KSB treatments.

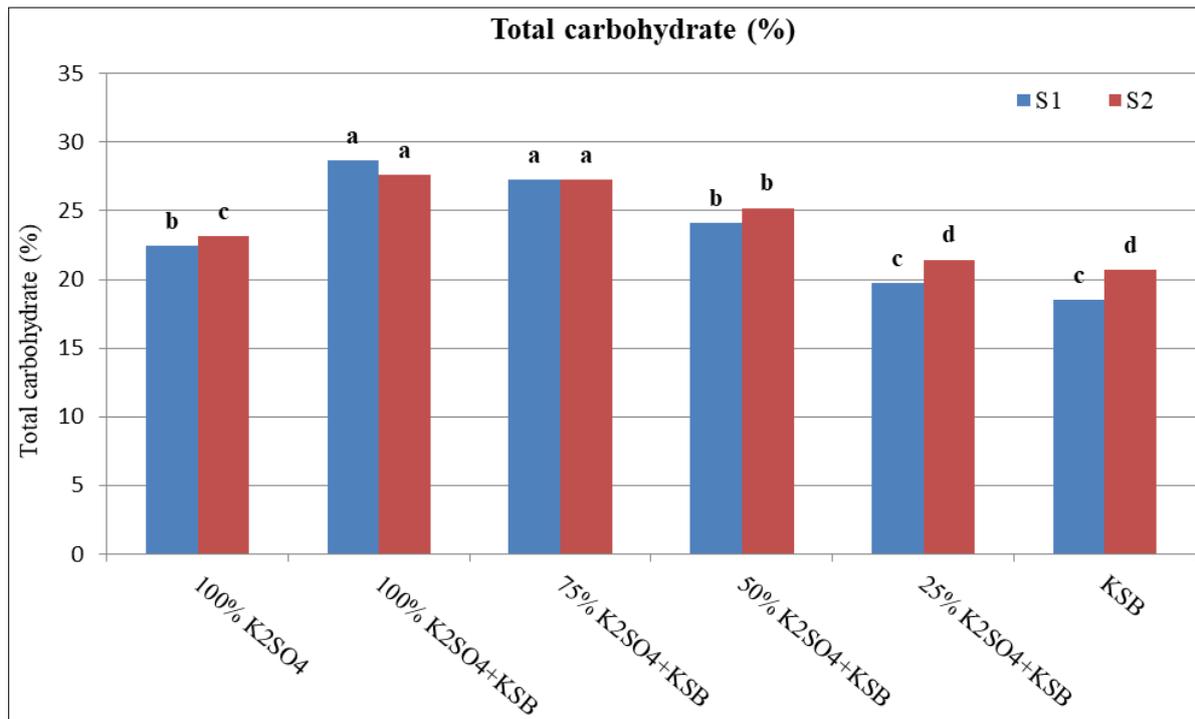


Figure (5). Effect of K_2SO_4 combinations with KSB on total carbohydrate content (%) of sweet potato tuber roots in 2023 and 2024 seasons

3.4.2. Nutrients and protein contents

Nitrogen and protein contents: As presented in Table 6 and Figure 6, applying (100% K_2SO_4 +KSB, in the both seasons) resulted in the highest nitrogen (2.06 and 2.10%, respectively) and protein (12.90 and 13.12%, respectively) contents in sweet potato tuber root.

Phosphorus content: The obtained data revealed that 100% K_2SO_4 and/or 75% K_2SO_4 rates combined with KSB resulted in the highest value of phosphorus percentage in both tested seasons (Table 6) with non-significant differences from the 50% K_2SO_4 +KSB treatment in the first season. In contrast, applying 100% K_2SO_4 or KSB individually, as well as the 25% K_2SO_4 +KSB treatment, resulted in the lowest values.

Potassium content: Data in Table 6 reveal significant differences in the K content of sweet potato tuber root under treatments involving K_2SO_4 alone or in combination with KSB across both growing seasons. The highest K content was achieved under 100% K_2SO_4 +KSB and 75% K_2SO_4 +KSB treatments in both seasons, followed by 100% K_2SO_4 and 50% K_2SO_4 +KSB, whereas the lowest K content was recorded under KSB alone in both seasons.

Table (6). Effect of K₂SO₄ combinations with KSB on nutrient contents% (N, P, K) of sweet potato tuber roots in 2023 and 2024 seasons

Treatments	N (%)		P (%)		K (%)	
	S1	S2	S1	S2	S1	S2
100% K ₂ SO ₄	1.97 bc	2.07 a	0.286 b	0.283 d	2.87 ab	2.67 b
100% K ₂ SO ₄ +KSB	2.06 a	2.10 a	0.318 a	0.313 ab	3.02 a	2.96 a
75% K ₂ SO ₄ +KSB	2.02 ab	1.98 b	0.313 a	0.317 a	3.07 a	2.81 ab
50% K ₂ SO ₄ +KSB	1.93 c	1.92 b	0.314 a	0.307 b	2.78 b	2.72 b
25% K ₂ SO ₄ +KSB	1.78 d	1.81 c	0.293 b	0.297 cd	2.43 c	2.50 c
KSB	1.75 d	1.73 d	0.277 c	0.290 cd	2.10 d	2.26 d

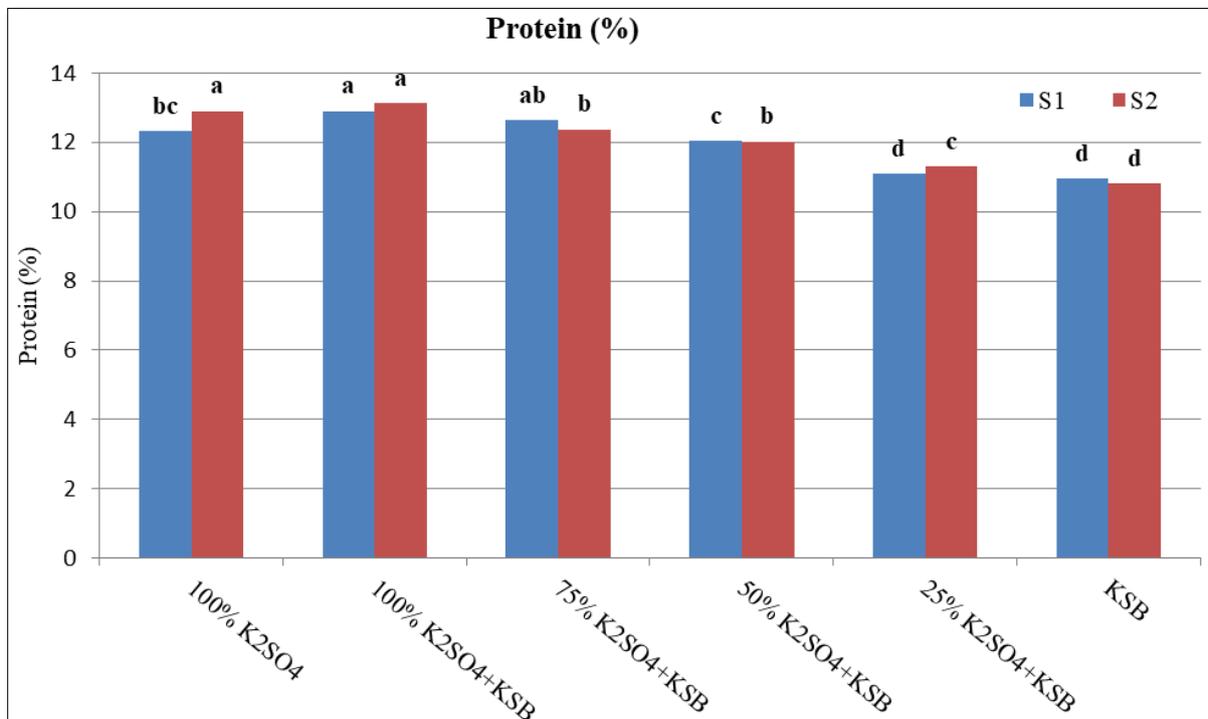


Figure (6). Effect of K₂SO₄ combinations with KSB on protein content (%) of sweet potato tuber roots in 2023 and 2024 seasons

3.5. Storage of tuber roots

As presented in Table 7, applying 50% K₂SO₄+KSB resulted in the lowest tuber roots weight loss after 30, 60, 90, and 120 days of sweet potato tuber root storage in both tested seasons. Furthermore, the fertilizing by 100% K₂SO₄, or KSB, had negative effect on the tuber roots weight loss of sweet potato in both growing periods.

Table (7). Effect of K₂SO₄ combinations with KSB on tuber roots weight loss (%) after 30, 60, 90, and 120 day of sweet potato plant in 2023 and 2024 seasons

Treatments	Tuber roots weight loss (%) after							
	30 days		60 days		90 days		120 days	
	S1	S2	S1	S2	S1	S2	S1	S2
100% K₂SO₄	2.89 a	3.30 ab	5.31 a	6.30 a	7.88 ab	8.77 a	12.85 a	13.76 ab
100% K₂SO₄+KSB	2.32 ab	3.12 abc	5.11 a	6.01 ab	7.00 ab	7.71 ab	11.55 a	12.88 b
75% K₂SO₄+KSB	2.30 ab	2.90 abc	5.01 a	5.68 ab	6.71 bc	7.50 abc	9.90 b	10.56 c
50% K₂SO₄+KSB	1.44 c	2.44 c	3.79 b	4.69 b	5.32 c	6.32 c	7.46 c	8.13 d
25% K₂SO₄+KSB	1.97 bc	2.63 bc	4.80 a	5.57 ab	6.63 bc	7.30 bc	9.82 b	10.49 c
KSB	2.99 a	3.59 a	5.59 a	6.42 a	8.44 a	8.21 ab	12.90 a	14.18 a

3.6. Nutrient contents in the soil

3.6.1. Available nitrogen content

Table 8 shows that soil N levels remained low (< 40 mg kg⁻¹) after both growing seasons under all treatments, with the sole exception of the (100% K₂SO₄+KSB) after the first season, and (75% K₂SO₄+KSB) after the second season, treatments, which reached a moderate level (40.28 and 41.19 mg kg⁻¹) albeit with only a very slight increase.

3.6.2. Available phosphorus content

The analyses confirmed that all treatments increased soil P content after the two growing seasons, with the sole exception of the treatment involving 100% K₂SO₄ applied alone (Table 8).

3.6.3. Available potassium content

Table 8 illustrates that the highest soil available K content after both growing seasons was achieved with the 100% K₂SO₄+KSB treatment, followed closely by the 75% K₂SO₄+KSB treatment.

Table (8). Effect of K₂SO₄ combinations with KSB on available nutrient contents (mg kg⁻¹) in soil after first season (2023) and after second seasons (2024)

Treatments	N (mg kg ⁻¹)		P (mg kg ⁻¹)		K (mg kg ⁻¹)	
	S1	S2	S1	S2	S1	S2
100% K₂SO₄	36.64 d	34.58 d	5.87 b	5.69 d	212.97 c	206.32 c
100% K₂SO₄+KSB	40.28 a	38.12 bc	7.02 a	7.40 ab	268.62 a	283.07 a
75% K₂SO₄+KSB	38.24 bc	41.19 a	7.14 a	7.46 ab	235.81 b	246.93 b
50% K₂SO₄+KSB	39.79 ab	37.64 c	6.94 a	7.24 c	213.86 d	220.28 c
25% K₂SO₄+KSB	37.66 c	38.79 bc	7.10 a	7.63 a	190.04 e	199.77 d
KSB	38.77 abc	39.34 b	7.17 a	7.36 bc	168.79 f	180.34 e

5. Discussion

5.1. Vegetative growth

Sweet potato plants exhibited the highest responses to the applied treatments in terms of plant length, number of branches per plant, plant fresh and dry weight, total Chl content and carotenoids content when 100% K₂SO₄ was applied alone or in combination with KSB, particularly in the treatments 100% K₂SO₄+KSB and 75% K₂SO₄+KSB, and to a lesser extent under 50% K₂SO₄+KSB. These findings confirm the effective role of KSB in enhancing K availability in the soil and compensating for reduced rates of mineral K fertilizer. The results clearly demonstrate that KSB-based biofertilizers can successfully achieve partial substitution, enabling a reduction in the usage of K mineral fertilization by 25–50%. These observations are consistent with those reported by **Ali *et al.* (2019)**; **Ali *et al.* (2021a)**; **Anjanadevi *et al.* (2016)**, who found that biofertilization with KSB significantly improved potato growth. Similarly, inoculation of potato with potassium solubilizing microorganisms has been shown to exert beneficial effects on plant growth (**Parmar and Sindhu, 2013**). The observed increases in vegetative growth may be attributed to the enhanced soil microbial activity that solubilizes K from insoluble sources (e.g., feldspar), providing a continuous supply of available K to the plants as a result of biofertilization. K plays a crucial role in promoting plant growth through several fundamental physiological processes, including stimulation of root development, activation of numerous enzyme systems, maintenance of cell turgor, reduction of water loss and wilting, enhancement of photosynthesis and assimilate production, reduction of respiration and energy losses, improved translocation of sugars and starch, increased starch content in grains, strengthened cellulose synthesis, reduced lodging, and greater resistance to crop diseases (**Meena *et al.*, 2016**). Additionally, **Osman and Soltan (2021)** reported that the application of KSB significantly increased the contents of photosynthetic pigments (total Chl and carotenoids) in carrot plants. Where, KSB plays a critical role in sustaining stronger photosynthetic capacity, enhancing resistance to photoinhibition, protecting the PSII reaction center from damage, and maintaining significantly higher stomatal conductance (**Jia *et al.*, 2008**).

5.2. Yield components

The present study revealed strong positive interactions between KSB as biofertilizer and the applied rates of K₂SO₄, significantly enhancing sweet potato yield components. The highest tuber root length, tuber root diameter, and number of tuber roots per plant were obtained with the treatments 100% K₂SO₄, 100% K₂SO₄+KSB, 75% K₂SO₄+KSB, and 50% K₂SO₄+KSB. In addition, the highest average fresh tuber root weight, fresh tuber roots weight per plant, total yield, and marketable yield, together with the lowest non-marketable yield, were achieved with the treatments 100% K₂SO₄, 100% K₂SO₄+KSB, and 75% K₂SO₄+KSB. The observed improvements in yield parameters were consistent with the effects of the applied treatments on vegetative growth characteristics, indicating that enhanced plant growth in this study directly contributed to higher yields through the production of a greater number of larger roots. These findings align with numerous studies emphasizing the critical role of K fertilization in achieving high tuber/or root yields. **Scherer *et al.* (2003)**, in a long-term experiment examining K availability across various crops, demonstrated that K deficiency can lead to a significant reduction in potato tuber yield. The positive effects of K fertilization on tuber/ or root yield parameters are linked to its involvement in key physiological processes, including osmotic regulation, maintenance of ionic balance, stomatal function, and enzyme activation. Adding the function of K in photosynthesis, translocation through phloem, and the synthesis of large molecular weight materials (like starch) in storage organs, all of which contribute to the tubers' quick growth (**Youssef and Eissa, 2017**; **Almaroai and Eissa, 2020**; **Al-Sayed *et al.*, 2020**), and promote vigorous plant growth and support tuber root development and bulking (**Bishwoyog and Swarnima, 2016**). Furthermore, the integrated use of mineral K fertilizers with biofertilizers containing KSB has been shown to further enhance potato growth and tuber root yield (**Singh *et al.*, 2017**; **Lallawmkima, 2018**; **Ali *et al.*, 2021a**; **Ali *et al.*, 2021b**). These results align with the sweet potato research released by **Abd El-Hakeem and Fekry (2014)**.

5.3. Chemical properties

The chemical composition of sweet potato tuber roots was significantly improved by the application of biofertilizers. Specifically, inoculation with KSB, combination with 100% or 75% of the recommended K₂SO₄ dose, markedly increased total carbohydrate, NPK, and protein contents. In some

cases, the treatments 50% K₂SO₄ + KSB and/or 100% K₂SO₄ alone produced comparable results with no significant differences in certain quality parameters during one of the growing seasons. Similar findings were reported by **Ali *et al.* (2021b)**, who demonstrated that biofertilization of potato plants with *Bacillus cereus* significantly enhanced the availability and uptake of N, P, and K. Likewise, inoculation with *Bacillus circulans* as a biofertilizer has been shown to increase P and K availability through the production of organic acids and other chelating compounds that promote nutrient solubilization and plant uptake (**Eissa *et al.*, 2013**). Consistent results were also observed by **Ali *et al.* (2019)**, who recorded elevated N, P, and K concentrations in potato tissues following biofertilizer application. These improvements can be attributed to the high activity of KSB, which proliferate in the rhizosphere especially in the presence of feldspar and efficiently convert insoluble mineral forms of nutrients into plant-available forms (**Shovitri *et al.*, 2021; Adwani *et al.*, 2024**). Moreover, **Merwad (2016)** in maize, **Abd El-Hakeem and Fekry (2014)** in sweet potato, and **Mounir *et al.* (2020)** trialing with garlic reported that the application of KSB significantly improved the protein and carbohydrate contents of the crops. These improvements can be attributed to the vital regulatory roles of K in various biochemical processes, involving the metabolism of carbohydrates, the production of proteins, and the activation of enzymes (**Hasanuzzaman *et al.*, 2018**).

5.4. Storage of tuber roots

Throughout the different storage periods (after harvest, 30, 60, 90, and 120 days), the treatment consisting of 50% K₂SO₄ combined with KSB exhibited the lowest percentage of tuber roots weight loss in sweet potato. Regarding the storage period, the percentage of weight loss in sweet potato tuber roots increased significantly as the storage duration progressed. This increase can be primarily attributed to respiration and transpiration processes, which lead to a reduction in dry matter content through both internal physiological changes and external moisture loss (**Emam and Attia, 2010; El-Sayed *et al.*, 2013**). Similarly, **EL-Sayed and Abd El Wadod (2023)** revealed that the loss increased linearly over time of storage in sweet potato tuber roots.

5.5. Nutrient contents in soil

Soils treated with biofertilizers containing KSB exhibited a slight increase in available N, with levels rising 6-11% higher than untreated (uninoculated) soil after the first and second growing seasons. Perhaps this is due to increase in soil organic matter (SOM) and specifically, **Ali *et al.* (2021b)** reported that inoculation with *Bacillus cereus* as a biofertilizer raised SOM content by approximately 10% compared to the uninoculated control. Comparable findings were reported by **Meena *et al.* (2016)**, who attributed the increase in SOM to the ability of free-living bacteria to produce various bioactive substances. **Youssef and Eissa (2017)** also recorded a slight, though non-significant, increase in SOM in biofertilizer-treated soils compared by without biofertilizers. This modest rise in SOM may be explained by enhanced vegetative growth and greater total plant biomass, resulting from improved photosynthesis and more efficient translocation and accumulation of nutrients (**Youssef and Eissa, 2017; Abou-Zaid and Eissa, 2019; Rekaby *et al.*, 2020**).

Soils amended with biofertilizers containing KSB showed a modest increase in available P, with levels 17-23% higher than those in untreated soils at the end of both the first and second growing seasons. Furthermore, soils receiving 100% K₂SO₄ combined with KSB showed a substantial increase in available K, with levels 26–37% higher than those treated with 100% K₂SO₄ alone across the two growing seasons. These increases can be attributed to the microbial activity of KSB, which alter the soil pH in the rhizosphere microenvironment, thereby promoting the solubilization of mineral potassium and phosphorus and efficiently converting their insoluble forms into plant-available forms. These results are in line with those published by **Ali *et al.* (2019); Shovitri *et al.* (2021); Adwani *et al.* (2024)**.

6. Conclusion

The findings of this investigation underscore the significant potential of KSB as a biofertilizer in sweet potato cultivation. KSB application positively influenced not only plant growth and tuber roots yield but, more importantly, also improved the nutritional quality of the harvested tuber roots and enhanced storability. The beneficial effects are primarily attributed to the increased availability of key

nutrients particularly K and P in the soil, driven by the production of organic acids and other chelating compounds by KSB that facilitate nutrient solubilization and uptake by plants. The most effective treatments involved the combined application of KSB with 100%, 75%, or in some cases 50% of the recommended dose of K₂SO₄. These findings confirm the crucial role of KSB in enhancing soil K availability and its ability to compensate for reduced rates of mineral potassium fertilizer. Overall, the results clearly demonstrate that KSB based biofertilizers can successfully achieve partial substitution of mineral K inputs, allowing a reduction of 25% in chemical K₂SO₄ fertilization without compromising tuber roots yield or quality, while simultaneously contributing to long term soil health. Based on the consistent performance across parameters, the application of KSB in combination with 75% of the recommended K₂SO₄ dose is recommended as the optimal and most sustainable practice. This study highlights KSB as an effective, eco-friendly tool for sustainable sweet potato production, offering both agronomic and economic benefits while supporting soil fertility preservation.

Conflicts of interest

The authors declare that there are no conflicts of interest.

Author contribution

Each author authorized the final article for publication and made an equal contribution to this study.

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