scientific reports

Check for updates

OPEN

Polyhalite as an alternate nutrient source for improving growth, yield, and nutrient use efficiency in onion and garlic

Thangasamy Arunachalam[1]✉, Komal Gade[1], Payal Arun Mahadule[1], Abhishek Khalate[1], Neeraj K. Awasti[2], Vipin Mishra[2] & Vijay B. Mahajan[1]

Polyhalite (POLY4), a naturally occurring multi-nutrient source with a low salt index, has potential as a replacement for muriate of potash (MOP). A field experiment was conducted to assess the effect of POLY4 on the growth, yield, quality, and nutrient use efficiency of onion and garlic, comparing nine fertilizer treatments. The results indicated that applying 100% POLY4 alone significantly enhanced the yield and nutrient uptake of both crops compared to plots treated with 100% K and S from MOP and bentonite S. Notably, potassium uptake in the POLY4 treatment exceeded the amount of potassium applied through fertilization, indicating that the crops may have mobilized additional potassium from soil reserves, which could raise concerns regarding the long-term sustainability of soil nutrient levels. However, the combination of 100% POLY4 with additional K resulted in a 6.3% yield increase in 2022–2023 and a 4.0% increase in 2023–2024 compared to the MOP treatment. This combined treatment produced statistically similar results to the MOP treatment for garlic in both years. Additionally, it significantly enhanced pyruvic acid and total protein concentrations in both crops and resulted in higher total dry matter yield and N, P, K, and S uptake. Moreover, agronomic efficiency, partial factor productivity, and recovery efficiency were notably higher in plots receiving 100% POLY4 with K. Due to its lower cost and reduced chloride content, 100% recommended S through POLY4, supplemented with K from MOP, could be recommended for sustainable onion and garlic production and improved soil health.

Keywords POLY4, Potassium, Nutrient use efficiency, Biochemical quality, Sustainability

Onion (*Allium cepa* L.) and garlic (*Allium sativum* L.) are important vegetable crops worldwide. Globally, the onion crop occupies about 5.84 million hectares, with a total production of 111.3 million tons, while garlic occupies 1.69 million hectares, with a production of 28.67 million tons. In India, the onion crop covered 1.74 million hectares, with a total production of 30.21 million tons, whereas garlic occupied 0.41 million hectares, producing 3.27 million tons[1]. Despite their extensive cultivation, onion and garlic productivity in India remains well below that of leading onion- and garlic-producing countries, mainly due to challenges such as poor soil fertility, unbalanced fertilizer use, and a high incidence of pests and diseases[2]. Among these challenges, improper fertilizer application significantly contributes to reduced onion and garlic productivity and to the declining soil fertility across the country[3].

Fertilizer application in India is predominantly limited to nitrogen (N), phosphorus (P), and potassium (K) fertilizers, leading to an imbalance where nitrogen use exceeds that of phosphorus and potassium[4,5]. This unbalanced application not only reduces crop yield but also adversely affects biochemical qualities, nutrient availability, and plant nutrient uptake, thereby increasing the cost of cultivation and resulting in multi-nutrient deficiencies[6–8]. Balanced fertilization is crucial for addressing these issues and sustaining the agroecosystem in onion- and garlic-growing regions[9–11].

Currently, farmers are using complex fertilizers like di-ammonium phosphate (DAP), 10:26:26, and straight fertilizers like urea and muriate of potash (MOP)[12]. However, MOP, which contains 60% potassium and 46% chloride, poses challenges[13]. Continuous application of MOP can lead to chloride accumulation in soils,

[1]ICAR–Directorate of Onion and Garlic Research, Rajgurunagar, Pune, Maharashtra 410505, India. [2]Anglo-American Crop Nutrients Pvt. Ltd., New Delhi, India. ✉email: astsamy1978@gmail.com

potentially contributing to soil salinity[14]. Moreover, MOP's high salt index of 116 can adversely affect plant growth by hindering water absorption and reducing soil microbial activity and nutrient transformations[15].

Furthermore, straight and complex fertilizers primarily supply nitrogen, phosphorus, and potassium, often neglecting other essential nutrients such as sulfur (S), calcium (Ca), and magnesium (Mg). Sulfur, in particular, is crucial for plant growth, bulb development, and enhancing bulb quality in these two crops[16–18]. It plays a key role in amino acid and protein synthesis, as well as the formation of secondary metabolites[19,20]. Plants deficient in sulfur often exhibit inefficient use of nitrogen, phosphorus, and potassium, highlighting the importance of adequate sulfur application to improve yield and bulb quality[20,21]. Additionally, magnesium is essential for plant metabolism[22], while calcium significantly contributes to both physiological functions and structural stability in plants[23]. Each of these nutrients must be supplied separately according to crop requirements, posing challenges for farmers who seek a simplified solution for applying all essential nutrients. Farmers often face difficulties in selecting appropriate fertilizers for each nutrient and in determining the optimal application rates required for their crops.

Polyhalite (POLY4), a naturally occurring mineral, contains potassium, calcium, magnesium, and sulfur. POLY4 releases its nutrients gradually, matching crop demand across different stages and reducing leaching losses[13,24]. Research at the University of Nottingham, UK, indicated that 50–60% of the sulfur present in POLY4 is readily available to plants, with the remainder released gradually[24]. Being a natural mineral extracted without chemical processing, POLY4 has a low carbon footprint compared to synthetic fertilizers, thereby reducing environmental impact[13,25]. Many experiments across different crops, including studies by Singh et al.[25], Pramanick et al.[26], and Gopinath et al.[13], demonstrated the benefits of POLY4 on crop yield and quality. Importantly, POLY4 is more cost-effective compared to other fertilizers and provides four nutrients that support plant growth and development.

In the context of onion and garlic cultivation, POLY4 has the potential to replace MOP and elemental sulfur as a source of potassium and sulfur, respectively. However, studies evaluating the specific efficacy of polyhalite as a fertilizer for these crops remain limited. Hence, the present study was undertaken with two hypotheses: (1) Polyhalite application may improve plant growth, yield, nutrient uptake, and biochemical quality of onion and garlic compared to MOP and elemental sulfur. (2) Polyhalite could effectively substitute MOP and elemental sulfur as a source of potassium and sulfur in these crops. To test these hypotheses, a field experiment was conducted to assess the effect of POLY4 on crop growth, yield, nutrient uptake, and biochemical quality and to assess its suitability as a source of potassium and sulfur for onion and garlic.

Materials and methods

Experimental site

The field experiment was conducted at the research farm of the Indian Council of Agricultural Research-Directorate of Onion and Garlic Research (ICAR-DOGR), located near Pune, Maharashtra, India (18.32° N, 73.51° E; elevation 645 m) (Fig. 1). The experimental site has a hot semi-arid climate with tropical wet and dry periods. The long-term average rainfall at the site is 820 mm per year, with approximately 98.5% of it occurring during the southwest monsoon season (June-September). The mean maximum and minimum air temperatures at the location range from 27.0 to 39.5 °C and 9.3 to 22.3 °C, respectively. The soil at the site is classified as *Typic Haplustepts* with a clay loam texture, slightly alkaline pH, medium concentrations of soil organic carbon (SOC), low available N and S, and high available P and K (Table 1).

Experimental details

The experiment was conducted during the *rabi* seasons of 2022–2023 and 2023–2024 on both onion and garlic crops. It was laid out in a randomized block design with nine treatments, and each treatment was replicated four times. The treatments included T1—100% K alone (no S); T2—100% S alone (no K); T3—100% K (from MOP) and S (from Bentonite S); T4—75% S (from POLY4); T5—100% S (from POLY4); T6—150% S (from POLY4); T7—75% S (from POLY4) + K (from MOP); T8—100% S (from POLY4) + K (from MOP); and T9—150% S (from POLY4) + K (from MOP). The recommended fertilizer rates for onion were 110:40:60:40 kg NPKS ha^{-1}, and for garlic, 100:50:50:40 kg NPKS ha^{-1}. The quantity of each nutrient supplied for each treatment for onion and garlic is presented in Table 2. Before planting, the full dose of P, K, and S and 16% of N were applied as basal, with the remaining N applied in three equal split doses at 15, 30, and 45 days after planting (DAT). Di-ammonium phosphate, complex fertilizer 10:26:26, MOP, urea, bentonite S, and POLY4 were used as fertilizer sources. The quantity of each fertilizer applied under the respective treatments is presented in Table S1. POLY4 contains 11.13% K, 11.79% Ca, 3.32% Mg, and 18.50% S[13,27]. Onion seedlings were prepared using the standard ICAR-DOGR practices. Simultaneously, the main field was prepared by ploughing with a mouldboard plough, followed by tilling with a cultivator. The soil was then pulverized with a rotavator, and flat beds measuring 3 × 2 m were formed. Organic manure was applied at a rate of 5 t ha^{-1} for all the treatments. A pre-emergence herbicide, oxyfluorfen 23.5% emulsifiable concentrate, was applied before planting to the flat beds. In the first year, onion seedlings of the cultivar Bhima Shakti (45 days old) were transplanted on December 11, 2022. Bhima Shakti is a red onion variety suitable for cultivation during the winter season. It matures in 115–120 days and has a high yield potential of approximately 45–50 t ha^{-1}. Similarly, the garlic cultivar Bhima Purple was planted on November 7, 2022. Bhima Purple is a pink-colored garlic variety with a yield potential of 12–14 t ha^{-1} and matures in 140–150 days after planting. In the subsequent year, the onion crop was transplanted on December 8, 2023, and garlic was planted on November 1, 2023. Spacing for both crops was set at 15 × 10 cm, with a plant population of 66 plants per square meter. Standard practices for plant protection and irrigation management were followed as per ICAR-DOGR recommendations. Onion harvesting was completed on April 16, 2023, in the first year, and on April 5, 2024, in the second year, after 50% neck fall; bulbs were harvested with a 2.5 cm neck left intact. Garlic harvesting was completed on March 29, 2023, in the first year, and on March 26, 2024, in

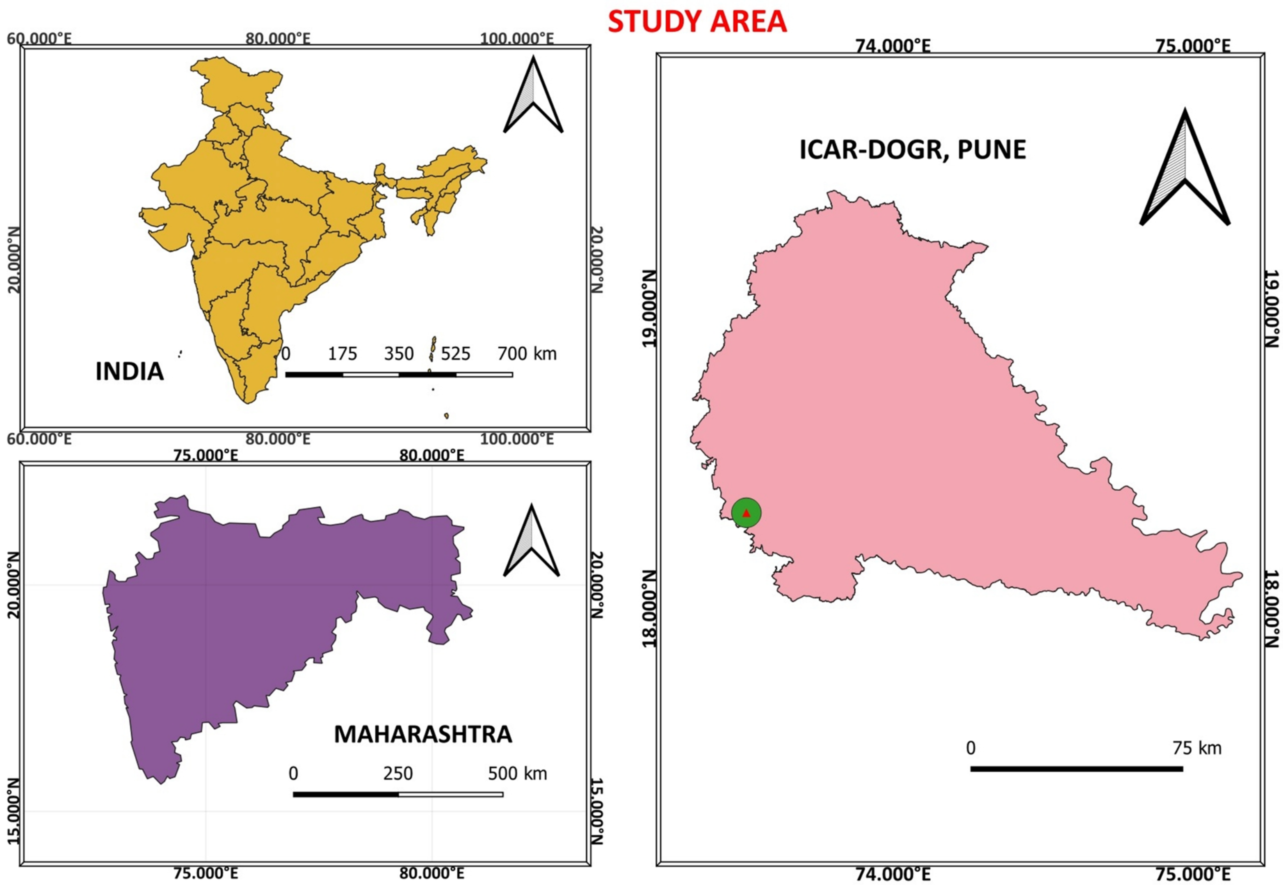


Fig. 1. Experimental location.

Soil parameters	Method	Onion	Garlic
pH	1:2 Soil water ratio	7.87 ± 0.47	7.78 ± 0.50
Soil organic carbon (g kg^{-1})	Wet oxidation method	0.72 ± 0.11	0.65 ± 0.05
EC (dS m^{-1})	1:2 Soil water ratio	0.13 ± 0.05	0.14 ± 0.04
Available N (mg kg^{-1})	Alkaline permanganate method	61.6 ± 6.11	71.1 ± 2.64
Available P (mg kg^{-1})	Olsen's method	14.3 ± 5.19	14.9 ± 6.00
Available K (mg kg^{-1})	1 N Ammonium acetate method	237.9 ± 44.78	286.0 ± 20.80
Available S (mg kg^{-1})	0.12% CaCl2 extraction method	8.2 ± 0.51	9.4 ± 0.28
Exchangeable Ca (Cmol (p^+) kg^{-1})	EDTA method	2.79 ± 0.03	2.71 ± 0.10
Exchangeable Mg (Cmol (p^+) kg^{-1})	EDTA method	0.75 ± 0.00	0.82 ± 0.01
Available B (mg kg^{-1})	Hot water extraction method	1.16 ± 0.05	1.26 ± 0.05
Available Cu (mg kg^{-1})	DTPA method	3.12 ± 0.42	3.17 ± 0.16
Available Fe (mg kg^{-1})	DTPA method	3.53 ± 0.56	3.84 ± 0.12
Available Mn (mg kg^{-1})	DTPA method	5.82 ± 2.36	5.52 ± 2.04
Available Zn (mg kg^{-1})	DTPA method	0.89 ± 0.26	0.87 ± 0.07

Table 1. Initial soil fertility status. Initial soil fertility status values are the mean with standard error from two years of data (2022–2023 and 2023–2024).

the second year. Onion bulbs were cured in the field for three days, while garlic bulbs were cured for one month after harvesting. After curing, the total bulb yield for both crops was recorded and expressed in tons per hectare (t ha^{-1}).

Soil sampling and analysis

Soil samples were collected initially and after harvest from a depth of 0–15 cm at four spots within each plot and thoroughly mixed to prepare a representative composite. The samples were air-dried, processed, and sieved

Treatments	The quantity of each nutrient supplied (kg ha^{-1}) for onion							The quantity of each nutrient supplied (kg ha^{-1}) for garlic						
	N	P_2O_5	K_2O	S	CaO	MgO	Cl	N	P_2O_5	K_2O	S	CaO	MgO	Cl
100% K alone (No S)	110	40	60	0	0	0	46	100	50	50	0	0	0	41
100% S alone (No K)	110	40	0	40	0	0	0	100	50	0	40	0	0	0
100% K (MOP) and S (Bentonite S)	110	40	60	40	0	0	46	100	50	50	40	0	0	41
75% S (POLY4)	110	40	22	30	27	8	3	100	50	22	30	27	8	3
100% S (POLY4)	110	40	37	40	46	16	5	100	50	37	40	46	16	5
150% S (POLY4)	110	40	44	60	54	24	8	100	50	44	60	54	24	8
75% S (POLY4) + K (MOP)	110	40	60	30	27	8	33	100	50	50	30	27	8	25
100% S (POLY4) + K (MOP)	110	40	60	40	46	16	23	100	50	50	40	46	16	15
150% S (POLY4) + K (MOP)	110	40	60	60	54	24	21	100	50	50	60	54	24	13

Table 2. The quantity of each nutrient supplied for onion and garlic.

through a 2.0 mm mesh, and analyzed for various parameters using standard procedures[28]. Soil pH and electrical conductivity (EC) were measured using a pH meter and conductivity bridge, respectively, in a 1:2 soil-to-water suspension. SOC was determined by the wet oxidation method. Available N was measured using the alkaline permanganate method, available P by the Olsen method, K by the 1 N ammonium acetate method, and S by the 0.15 M $CaCl_2$ extraction method. Micronutrients (Zn, Fe, Mn, Cu) were extracted using the DTPA extractant and analyzed by atomic absorption spectrometry.

Plant sampling and analysis

In both onion and garlic, sixteen plant samples were collected from a single middle row of the bed, excluding border rows and diseased plants. The plant samples were rinsed, and bulbs and leaves were separated, chopped into small pieces, air-dried, and then oven-dried at 60 °C until a constant weight was achieved. The dry matter yield of leaves and bulbs was recorded and added to calculate the total dry matter yield. The dried samples were ground and passed through a 2.0 mm sieve for nutrient analysis following standard procedures[29]. N was determined by the Kjeldahl method[30]. For other nutrients (P, K, S, Ca, Mg, and micronutrients), 0.5 g of plant samples was digested using a di-acid mixture of HNO_3 and $HClO_4$. P was determined by the vanadomolybdate yellow color method, K by flame photometry, and S by the turbidimetric method. Micronutrients (Fe, Mn, Zn, Cu) were analyzed using atomic absorption spectrometry. Nutrient uptake was calculated by multiplying the nutrient concentration by the dry weight.

Biochemical analysis.

At harvest, twenty-four bulbs per plot were collected for biochemical analysis, including total soluble solids (TSS, ˚Brix), pyruvic acid (μmol g^{-1}), total phenol concentration, antioxidant activity, and protein concentration. TSS was measured using a digital refractometer, with readings in ˚Brix. Selected onion bulbs and garlic cloves were prepared, crushed, and blended. Pyruvic acid was measured using the Schwimmer and Weston method[16]. Total phenol concentration and antioxidant activity were determined by extracting samples with 80% methanol, followed by centrifugation and analysis using the Folin–Ciocalteau (FC) reagent for phenols and the FRAP assay for antioxidant activity[16]. Protein concentration was measured using Lowry's method after extraction with phosphate buffer and centrifugation[31].

Statistical analysis

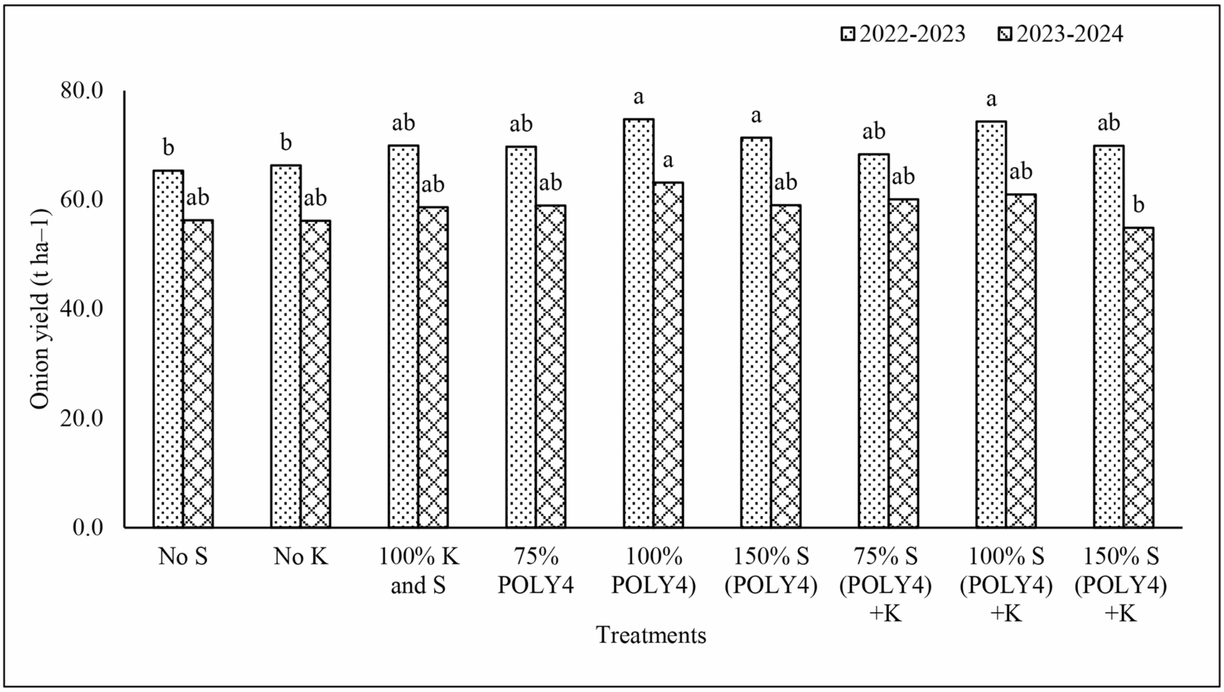
Data from both years were tested for homogeneity using Bartlett's test. If the data were not homogeneous, they were transformed using Atkinson's transformation. A pooled analysis was conducted with year and treatment considered as random effects in R software version 4.4.1. As the data showed significant differences at the 5% significance level, year-wise data were analyzed using one-way analysis of variance (ANOVA)[32]. Significant treatment effects were further analyzed using Tukey's honestly significant difference test for mean comparison. QGIS Version 3.28.3 was used to prepare the experimental location map[33].

Results

Yield

Fertilizer treatments significantly affected onion yield, whereas they had no effect on garlic yield (Fig. 2). In onion, the highest yield was observed in the plot that received 100% S supplied through POLY4 alone (100% POLY4 alone), followed by the plot treated with 100% S through POLY4 plus additional K through MOP (100% POLY4 + K). These treatments produced significantly higher yields than the plot that did not receive either K or S. Additionally, the application of 100% POLY4 alone increased onion yield by 14.4% and 12.7% in 2022–2023 and by 12.2% and 12.3% in 2023–2024, compared to the plots that did not receive either K or S, respectively. Similarly, the treatment that received 100% POLY4 + K resulted in a yield increase of 13.8% and 12.1% in 2022–2023 and 8.4% and 8.6% in 2023–2024, compared to the plots that did not receive either K or S, respectively. However, the onion yield from these treatments was statistically similar to the yields obtained with the application of 100% K and S through MOP and bentonite S (100% K (MOP) and S (bentonite sulfur)). Even though the values were statistically comparable, the application of 100% POLY4 alone still showed a 6.9%

2a Onion



2b Garlic

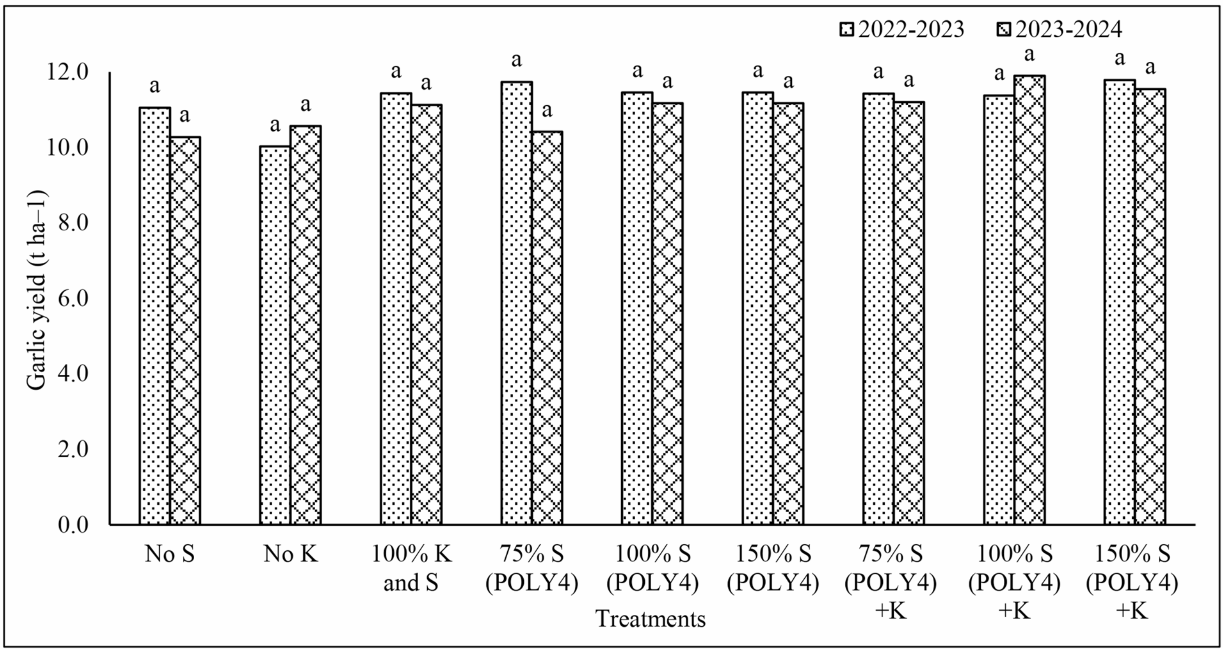


Fig. 2. Effect of POLY4 on yield of onion (**a**) and garlic (**b**). Different lowercase letters above the bars indicate significant differences ($P<0.05$) among treatments. 100% K (MOP) and S (BS): 100% recommended potassium applied through muriate of potash and sulfur through bentonite sulfur.

increase in bulb yield in 2022–2023 and a 7.7% increase in bulb yield in 2023–2024, compared to the treatment with 100% K (MOP) and S (bentonite sulfur). Similarly, the application of 100% POLY4 + K showed a 6.3% increase in 2022–2023 and a 4.0% increase in 2023–2024 compared to the plot treated with 100% K (MOP) and S (bentonite sulfur).

In garlic, the highest yield was observed in the plots that received 150% S through POLY4 plus additional K through MOP (150% POLY4 + K) and in the plot that received 75% S through POLY4 (75% POLY4 alone) in 2022–2023. These treatments resulted in increases of 6.6% and 17.6% and 3.3% and 14.0%, respectively, compared to the control plots without K or S. The application of 100% POLY4 + K also increased yields by 2.9–3.6% and 13.5–14.3%, respectively, compared to the control plots without K or S. In 2023–2024, the highest yields were obtained from the plots treated with 100% POLY4 alone and 100% POLY4 + K, which showed yield increases of 8.8% and 5.8% and 15.8% and 12.6%, respectively, compared to the control plots without K or S. However, these treatments produced yields that were statistically similar to those from the plot treated with 100% K (MOP) and S (bentonite sulfur) in both years.

Pyruvic acid and total protein

Fertilizer treatments significantly influenced both pyruvic acid and total protein concentrations in onion and garlic. Generally, pyruvic acid concentration increased with the S dose, ranging from 75 to 150% S (POLY4), in both crops, except during the 2022–2023 season (Table 3). In 2022–2023, the highest pyruvic acid concentration in onion was recorded in the plot treated with 100% K (MOP) and S (bentonite sulfur), followed by 150% POLY4 alone and 75% S through POLY4 plus additional K through MOP (75% POLY4 + K). These treatments increased pyruvic acid concentrations by 11.8%, 5.6%, and 5.1%, respectively, compared to the treatment that received 100% K alone. However, in 2023–2024, all treatments that received POLY4 + K showed higher pyruvic concentrations compared to the rest of the treatments. The highest concentration was recorded in the treatment that received 150% POLY4 + K, followed by 100% POLY4 + K and 75% POLY4 + K, with increases of 20.4%, 16.2%, and 11.4%, respectively, compared to the plot treated with 100% K alone. In garlic, increasing the S dose through POLY4 alone or 100% POLY4 + K, from 75 to 150%, generally led to higher pyruvic acid concentrations compared to the plot that received 100% K. The increase in pyruvic acid ranged from 25.0% (75% POLY4) to 41.7% (150% POLY4) in 2022–2023 and 3.7% (75% POLY4) to 45.4% (150% POLY4) in 2023–2024, compared to the plot treated with K without S. Similarly, treatment that received the POLY4 + K also showed increases in pyruvic acid concentration, with an increase of 20.8% (75% POLY4 + K) to 29.2% (100% POLY4 + K) in 2022–2023 and 19.5% (100% POLY4 + K) to 24.0% (150% POLY4 + K) in 2023–2024, compared to the plot treated with 100% K without S.

The highest total protein concentration in onion was recorded in the plot that received 75% POLY4 alone, showing a 19.6% increase in 2022–2023. The plot that received 150% POLY4 alone showed a 12.0% increase compared to the plot that received 100% K. Similarly, the plot that received 75% POLY4 + K and 150% POLY4 + K showed increases of 16.3% and 5.2%, respectively, compared to the treatment that received 100% K without S. In garlic, the highest total protein concentrations were recorded in the treatment that received 100% K (MOP) and S (bentonite sulfur), showing a 12.5% increase compared to the plot that received 100% K without sulfur in 2022–2023. In 2023–2024, the highest total protein concentrations were observed in the plot that received 150% POLY4 alone (15.2%), followed by the treatment that received 150% POLY4 + K (6.0%), and the treatment that received 100% K (MOP) and S (bentonite sulfur) (5.2%).

Antioxidant activity and total phenol concentrations

Antioxidant activity and total phenol concentrations were significantly influenced by the fertilizer treatments, whereas they did not affect total soluble solids in both onion and garlic (Table 4 and Table S2). In 2022–2023, the plot treated with 75% POLY4 alone showed the highest antioxidant activity and total phenol concentrations. In the 2023–2024 season, the highest antioxidant activity was observed in the plot treated with 150% POLY4 alone, while the highest total phenol concentration was found in the treatment that received 100% POLY4 + K. For garlic, in 2022–2023, the highest antioxidant concentration was recorded in the treatment that received 150%

	Pyruvic acid (µmoles g fresh weight^{-1})				Total protein (%)			
	Onion		Garlic		Onion		Garlic	
Treatments	2022–2023	2023–2024	2022–2023	2023–2024	2022–2023	2023–2024	2022–2023	2023–2024
100% K alone (No S)	5.94 abc	4.99 f	38.40 c	32.35 e	3.68 b	3.93 g	16.87 bcd	17.25 de
100% S alone (No K)	5.58 bc	5.20 e	43.20 bc	32.45 e	3.77 b	3.94 g	17.82 b	17.65 bcd
100% K (MOP) and S (BS)	6.64 a	5.22 e	49.60 ab	45.95 a	3.59 b	4.44 d	18.98 a	18.15 bc
75% S (POLY4)	5.41 c	5.44 cd	48.00 ab	36.65 cd	4.77 a	4.32 e	16.01 d	16.30 f
100% S (POLY4)	5.89 abc	4.60 g	49.60 ab	33.55 de	4.40 ab	4.11 f	16.32 cd	16.53 ef
150% S (POLY4)	6.27 ab	5.35 de	54.40 a	47.05 a	4.12 ab	4.86 b	17.16 bc	19.88 a
75% S (POLY4) + K (MOP)	6.24 ab	5.56 c	46.40 abc	31.80 e	4.28 ab	4.40 de	16.67 cd	14.15 g
100% S (POLY4) + K (MOP)	6.00 abc	5.80 b	49.60 ab	38.65 bc	3.81 b	5.61 a	16.33 cd	17.33 cde
150% S (POLY4) + K (MOP)	5.63 bc	6.01 a	44.80 bc	40.10 b	3.87 b	4.65 c	14.89 e	18.28 b
P value	< 0.0001	< 0.0001	< 0.0001	< 0.0001	0.002	< 0.0001	< 0.0001	< 0.0001
CV (%)	5.28	1.21	7.93	3.47	9.07	1.04	2.65	2.05

Table 3. Effect of POLY4 on pyruvic acid and total protein concentrations of onion and garlic. Different lowercase letters indicate significant differences ($P < 0.05$) among treatments. 100% K (MOP) and S (BS): 100% recommended potassium applied through muriate of potash and sulfur through bentonite sulfur.

Treatments	Antioxidant activity mg of Trolox equivalents (TE) kg^{-1} of fresh weight				Total phenol mg of gallic acid equivalent (GAE) kg^{-1} of garlic (fresh weight)			
	Onion		Garlic		Onion		Garlic	
	2022–2023	2023–2024	2022–2023	2023–2024	2022–2023	2023–2024	2022–2023	2023–2024
100% K alone (No S)	267.0 c	321.0 g	118.75 d	300.28 c	719.3 ab	545.0 d	326.50 d	547.50 bc
100% S alone (No K)	253.0 d	316.6 g	153.75 bc	297.33 cd	663.3 e	482.5 e	433.50 bc	562.50 b
100% K (MOP) and S (BS)	203.3 e	323.6 fg	144.00 c	352.90 a	486.0 g	545.0 d	426.50 bc	602.50 a
75% S (POLY4)	304.0 a	354.5 e	144.75 c	335.73 b	730.0 a	572.5 c	406.50 c	537.50 c
100% S (POLY4)	288.3 b	393.4 d	164.25 b	242.83 f	694.0 cd	540.0 d	516.50 a	427.50 e
150% S (POLY4)	243.7 d	485.0 a	181.25 a	302.30 c	624.7 f	672.5 b	463.50 b	567.50 b
75% S (POLY4) + K (MOP)	278.0 bc	447.1 c	148.00 c	271.98 e	702.7 bc	692.5 b	430.00 bc	482.50 d
100% S (POLY4) + K (MOP)	276.7 bc	458.2 b	157.25 bc	288.63 d	675.3 de	755.0 a	410.00 c	492.50 d
150% S (POLY4) + K (MOP)	277.0 bc	330.9 f	144.00 c	274.48 e	714.7 abc	575.0 c	453.50 b	550.00 bc
P value	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
CV (%)	2.02	0.97	4.46	1.44	1.51	1.48	4.09	1.93

Table 4. Effect of POLY4 on antioxidant activity and total phenol concentrations of onion and garlic. Different lowercase letters indicate significant differences ($P < 0.05$) among treatments. 100% K (MOP) and S (BS): 100% recommended potassium applied through muriate of potash and sulfur through bentonite sulfur.

POLY4 alone, and the highest total phenol concentration was in the plot that received 100% POLY4 alone. In the 2023–2024 season, the highest levels of antioxidant activity and total phenol concentrations were recorded in the treatment that received 100% K (MOP) and S (bentonite sulfur).

Total dry matter yield and plant nutrient uptake

The application of fertilizers significantly influenced total dry matter yield in both onion and garlic (Fig. 3) and macronutrient uptake in onions in both experimental years (Table 5). In garlic, fertilizer application affected nutrient uptake during the 2022–2023 growing season; however, it had no significant effect in 2023–2024. In both years, the highest total dry matter yields were produced with the application of 100% POLY4 alone and with 100% POLY4 + K, compared to the control plots that received neither K nor S. In 2022–2023, applying 100% S through POLY4 resulted in an 8.3% increase in total dry matter yield, while in 2023–2024, it led to a 0.8% increase relative to plots treated with 100% potassium alone via MOP. When 100% POLY4 + K was applied, total dry matter yield increased by 13.6% in 2022–2023 and by 11.4% in 2023–2024. For garlic, the application of 100% POLY4 alone increased total dry matter yield by 9.2% in 2022–2023 and by 2.7% in 2023–2024. Similarly, when 100% POLY4 + K was applied, the total dry matter yield in garlic increased by 14.9% in 2022–2023 and by 1.3% in 2023–2024, compared to the plots that received 100% potassium alone via MOP. Both of these treatments produced total dry matter yields that were statistically comparable to those achieved with 100% K (MOP) and S (bentonite sulfur).

The highest total uptake of N, P, K, and S was recorded with the application of 100% or 150% POLY4, either alone or with K, in both years and for both crops. The application of 150% POLY4 alone resulted in higher total K uptake compared to 100% POLY4 alone in both crops, while the application of 100% POLY4 + K and 100% K (MOP) and S (bentonite sulfur) showed nearly similar total K uptake values. The application of 100% POLY4 + K increased total K uptake by 16.5–18.3% in onion and 1.8–7.9% in garlic compared to the plot that received 100% S alone through bentonite sulfur. In the case of S, the application of 150% POLY4 alone increased total S uptake by 16.8% in onion and 40.8% in garlic in 2022–2023 and by 14.7% in onion and 3.2% in garlic in 2023–2024. Similarly, the plot that received 150% POLY4 + K increased total S uptake by 23.5% in onion and 30.6% in garlic in 2022–2023 and 27.2% in onion and 5.3% in garlic in 2023–2024 compared to the plot treated with 100% K (MOP) and S (bentonite sulfur).

Nutrient use efficiency indicators

The application of 100% potassium (MOP) and sulfur (bentonite sulfur), as well as 75–150% POLY4 alone, resulted in higher partial factor productivity and agronomic efficiency of K and S in both crops across both years (Table 6) compared to the control (no K or S). Additionally, 75–150% POLY4 alone produced higher values for both indicators than the treatment with 100% K (MOP) and S (bentonite sulfur). In contrast, combining POLY4 with additional K (POLY4 + K) reduced both partial factor productivity and agronomic efficiency compared to POLY4 alone. However, the 75% and 100% POLY4 + K treatments still showed higher partial factor productivity and agronomic efficiency than the 100% K (MOP) and S (bentonite sulfur) treatment. The 100% POLY4 + K treatment also showed higher recovery efficiency for K and S than both 150% POLY4 + K and 100% K (MOP) with S (bentonite sulfur) across both years and crops.

Post-harvest soil properties

Soil-available nutrients decreased significantly compared to the initial values recorded before planting in both crops, except for S, which increased in both years (Table 7). Additionally, soil available S and electrical conductivity showed an increase compared to the initial values. The application of POLY4 did not significantly

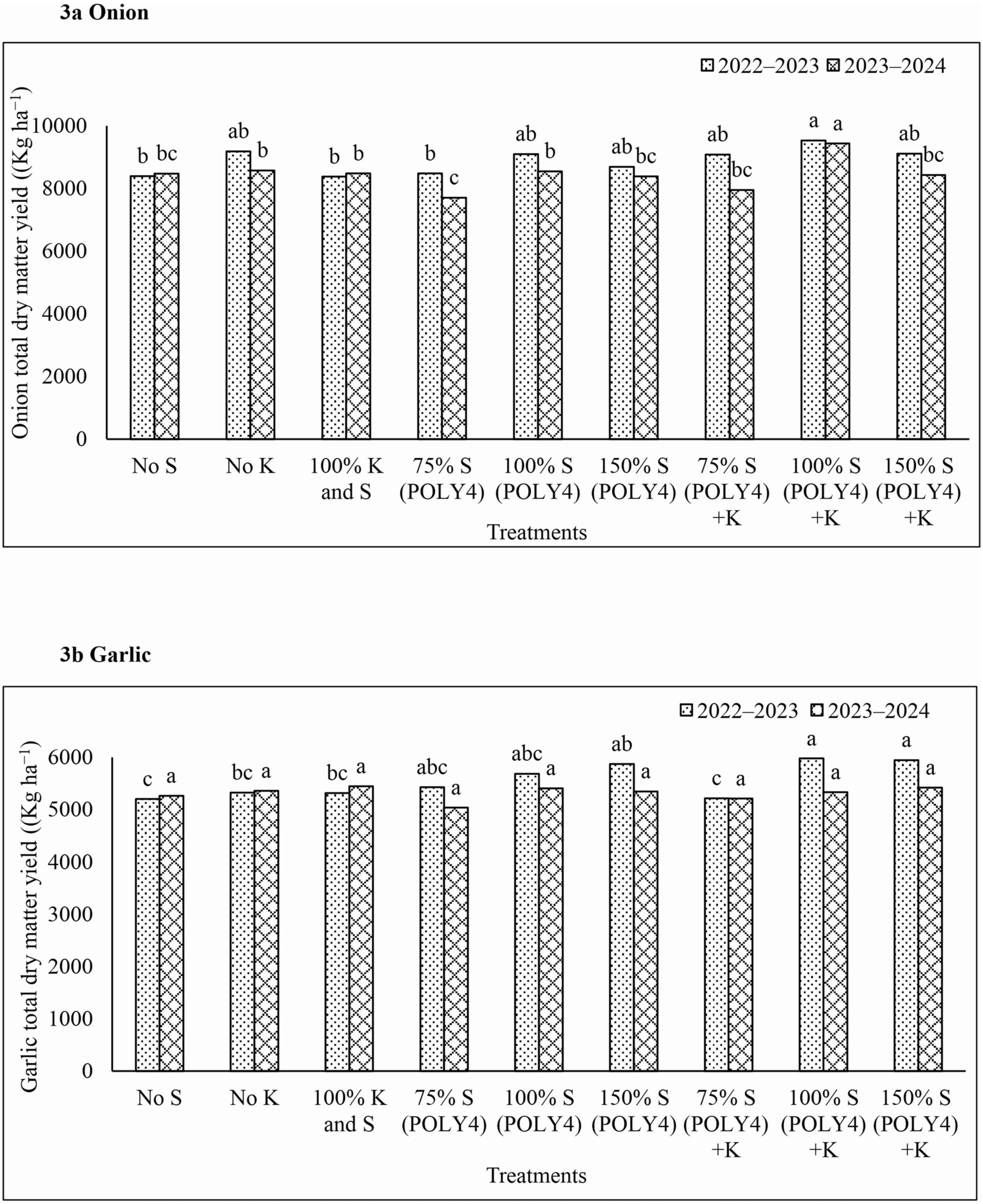


Fig. 3. Effect of POLY4 on total dry matter yield of onion (**a**) and garlic (**b**). Different lowercase letters above bars indicate significant differences ($P < 0.05$) among treatments. 100% K (MOP) and S (BS): 100% recommended potassium applied through muriate of potash and sulfur through bentonite sulfur.

Treatments	N		P		K		S	
	2022–2023	2023–2024	2022–2023	2023–2024	2022–2023	2023–2024	2022–2023	2023–2024
Onion								
100% K alone (No S)	84.1 bc	103.1 bc	25.8 bc	21.3 bc	73.0 c	102.7 bc	16.1 f	23.0 c
100% S alone (No K)	92.8 ab	104.3 bc	32.3 ab	19.0 cd	67.7 c	99.4 bc	24.8 bcd	25.7 bc
100% K (MOP) and S (BS)	89.4 ab	100.2 bc	26.1 bc	21.5 bc	74.9 bc	104.2 bc	23.2 de	24.6 bc
75% S (POLY4)	77.9 c	90.8 c	19.2 c	18.1 d	72.2 c	96.0 bc	22.1 e	23.5 c
100% S (POLY4)	90.4 ab	102.1 bc	37.3 a	24.2 a	74.1 bc	107.0 b	26.6 abc	26.8 bc
150% S (POLY4)	91.1 ab	101.2 bc	31.0 ab	23.2 ab	89.9 a	107.3 b	27.1 ab	27.6 ab
75% S (POLY4) + K (MOP)	92.0 ab	95.7 bc	21.0 c	20.9 bc	92.5 a	99.4 bc	24.4 cde	23.3 c
100% S (POLY4) + K (MOP)	96.4 a	122.7 a	27.1 bc	22.4 ab	84.2 ab	120.9 a	26.7 abc	30.9 a
150% S (POLY4) + K (MOP)	97.1 a	108.7 ab	34.1 ab	23.5 ab	90.7 a	102.1 bc	28.4 a	31.0 a
P value	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
CV (%)	4.6	6.5	13.0	5.1	5.3	3.6	6.6	6.2
Garlic								
100% K alone (No S)	77.4 c	77.8 a	12.2 d	12.5 a	80.0 b	64.5 a	24.5 b	29.1 a
100% S alone (No K)	80.3 bc	78.0 a	11.8 d	11.9 a	78.0 b	65.8 a	25.4 b	31.2 a
100% K (MOP) and S (BS)	75.2 c	86.5 a	13.8 bcd	11.8 a	78.8 b	67.2 a	26.2 b	30.9 a
75% S (POLY4)	75.2 c	76.5 a	12.9 cd	10.9 a	77.7 b	59.8 a	29.1 b	28.5 a
100% S (POLY4)	85.5 abc	79.5 a	14.2 abcd	11.8 a	82.3 ab	67.1 a	24.5 b	31.6 a
150% S (POLY4)	93.8 a	79.5 a	16.3 a	12.0 a	88.0 a	67.5 a	36.9 a	31.9 a
75% S (POLY4) + K (MOP)	77.9 c	75.4 a	12.3 d	12.3 a	70.1 c	62.6 a	24.5 b	30.5 a
100% S (POLY4) + K (MOP)	89.8 ab	79.5 a	15.4 abc	11.7 a	86.2 a	65.7 a	35.3 a	31.2 a
150% S (POLY4) + K (MOP)	90.5 ab	77.8 a	15.7 ab	12.0 a	87.4 a	67.4 a	35.1 a	32.4 a
P value	< 0.0001	0.49	< 0.0001	0.85	< 0.0001	0.13	< 0.0001	0.48
CV (%)	5.6	8.2	7.34	10.2	5.0	6.0	5.0	8.4

Table 5. Effect of POLY4 on total major nutrient uptake (kg ha^{-1}) of onion and garlic. Different lowercase letters indicate significant differences ($P < 0.05$) among treatments. 100% K (MOP) and S (BS): 100% recommended potassium applied through muriate of potash and sulfur through bentonite sulfur.

affect the available soil nutrients. When applied either alone or in combination with MOP, POLY4 resulted in soil nutrient levels that were statistically comparable to those in plots that received 100% K (MOP) and S (bentonite sulfur).

Discussion

Polyhalite, a naturally occurring mineral, emerged as a potential source for supplying multiple essential nutrients simultaneously, containing four major nutrients, namely K, S, Ca, and Mg[34], making it a suitable option for efficient fertilization. Previous studies showed that the application of POLY4 increased plant growth, yield, biochemical qualities, and nutrient use efficiencies in various crops[13,25,26,35]. This study assessed the effect of POLY4 on plant growth, yield, biochemical qualities, and nutrient use efficiencies in onion and garlic through a two-year field experiment.

The results highlighted that the application of POLY4, either alone or with K, increased the yield of onion and garlic, which could be due to the supply of four essential nutrients, namely K, S, Ca, and Mg, through this source[25,36]. Additionally, POLY4 slowly releases these nutrients into the soil solution, making it available to the plants throughout the growing season[25]. Singh et al.[25] reported a similar yield increase in maize and wheat with the application of POLY4 in the Indo-Gangetic plains of India. They found that POLY4 showed a better response compared to treatment with no K, due to K deficiency in those regions. In contrast, in the present study on onion and garlic, the application of POLY4, either alone or with K, increased yields compared to treatments without S, as the experimental soils were low in 1% $CaCl_2$-extractable S, suggesting that S deficiency might have caused more yield reduction than the K deficiency. The soils were rich in K, allowing the plants to use native soil reserves and produce better yield than treatment without S[4].

Furthermore, the application of 100% POLY4, either alone or with K, resulted in higher yields compared to treatments that received 100% K and S standard sources[26]. This may be due to the presence of micronutrients and S in SO_4^{2-} form in POLY4[25]. Since the soils were deficient in S, the S supplied in SO_4^{2-} form may have facilitated better S uptake, enhancing biomass production and crop yields in both onion and garlic. This is further supported by the increased S uptake observed in the 100% or 150% POLY4, either alone or with K, compared to the treatment receiving 100% S alone in the present study. A similar increase in S uptake with the application of SO_4^{2-} forms was noted by Sharma et al.[37] and Nguyen et al.[17].

The increased S uptake in these treatments may have contributed to enhanced leaf area, a higher number of leaves, higher plant height, and improved root growth compared to the control and the treatment with 100% K (MOP) and S (bentonite sulfur)[38]. This enhanced leaf area and plant growth might have supported higher

Treatments	PFP-K		PFP-S		AE-K		AE-S		RE-K		RE-S	
	2022–2023	2023–2024	2022–2023	2023–2024	2022–2023	2023–2024	2022–2023	2023–2024	2022–2023	2023–2024	2022–2023	2023–2024
Onion												
100% K alone (No S)	1087.9	937.5	–	–	− 17.1	1.7	–	–	8.9	5.6	–	–
100% S alone (No K)	–	–	1657.5	1403.8	–	–	25.6	− 2.5	–	–	43.3	6.6
100% K (MOP) and S (BS)	1165.0	977.1	1747.5	1465.6	60.0	41.3	90.0	61.9	11.9	8.1	34.9	4.0
75% S (POLY4)	3167.0	2679.5	2322.5	1965.0	153.4	127.3	146.7	90.0	20.6	-15.2	39.5	1.3
100% S (POLY4)	2018.9	1706.1	1867.5	1578.1	227.0	188.5	235.6	171.9	-1.9	7.6	50.1	9.3
150% S (POLY4)	1621.6	1340.9	1189.2	983.3	114.8	64.8	101.3	45.8	50.5	18.1	34.8	7.5
75% S (POLY4) + K (MOP)	1138.3	1001.3	2276.7	2002.5	33.3	65.4	100.8	127.5	41.4	0.0	50.3	0.8
100% S (POLY4) + K (MOP)	1238.3	1015.8	1857.5	1523.8	133.3	80.0	225.6	117.5	27.5	35.8	49.0	19.6
150% S (POLY4) + K (MOP)	1163.8	914.2	1163.8	914.2	58.8	− 21.7	75.8	− 23.3	38.4	4.6	38.6	13.3
Garlic												
100% K alone (No S)	220.9	205.5	–	–	20.6	− 5.7	–	–	4.0	− 14.6	–	–
100% S alone (No K)	–	–	250.4	263.9	–	–	− 25.8	7.1	–	–	3.4	5.4
100% K (MOP) and S (BS)	228.6	222.5	285.7	278.1	28.3	11.3	9.6	21.3	1.6	− 12.4	4.6	4.5
75% S (POLY4)	533.3	473.0	391.1	346.8	78.1	− 6.9	22.9	4.4	− 1.4	− 66.8	27.3	− 1.9
100% S (POLY4)	309.5	301.9	286.3	279.3	38.9	16.6	10.2	22.4	11.6	4.6	− 3.9	6.3
150% S (POLY4)	260.2	253.8	190.8	186.1	32.6	13.9	6.8	14.9	22.7	− 3.6	37.5	4.7
75% S (POLY4) + K (MOP)	228.5	224.0	380.8	373.3	28.2	12.9	12.6	30.9	− 15.8	− 11.8	0.0	4.9
100% S (POLY4) + K (MOP)	227.5	237.7	284.3	297.1	27.2	26.6	8.2	40.3	16.4	− 11.4	52.6	5.4
150% S (POLY4) + K (MOP)	235.6	230.8	196.3	192.3	35.3	19.6	12.2	21.1	18.8	1.8	32.5	5.5

Table 6. Nutrient use efficiency as affected by different sources of fertilizers. *PEP-K* Partial factor productivity of potassium, *PEP-S* Partial factor productivity of sulfur, *AE-K* Agronomic efficiency of potassium, *AE-S* Agronomic efficiency of sulfur, *RE-K* Recovery efficiency of potassium, and *RE-S* Recovery efficiency of sulfur.

photosynthetic activity, increased N and P uptake, and higher total dry matter yield, ultimately leading to the higher yields in the present study[39]. Since N and S are essential components of amino acids and protein, the increased uptake of these nutrients may have increased the total protein content in both crops[40]. Furthermore, S, as an important constituent of S-containing secondary metabolites, contributed to higher pyruvic acid concentrations in treatments with 100% or 150% POLY4, either alone or with K. The S application has also been shown to increase S-containing secondary metabolites and protein concentrations in various crops[16,41]. However, when compared to the control, the increase in antioxidant activity, total phenol, and total protein concentrations were lower in the 150% POLY4 alone or with K compared to 100% POLY4 alone or with K. This difference may be attributed to an imbalance in the N: S ratio in both onion and garlic, which could have contributed to the reduced yields observed in 150% POLY4 treatments. Similar reductions in antioxidant activity, total phenol, total protein concentrations, and yield at higher S doses in garlic were reported by[16]. Furthermore, the reduction in onion yield in the treatment that received 100% K (MOP) and S (bentonite sulfur) could be attributed to the addition of more chloride from MOP. Chloride negatively affects dry matter production[35,42,43] and leaf nitrate concentration[44]. Partial factor productivity, agronomic efficiency, and recovery efficiency were lower in the treatment that received 150% POLY4 + K and 100% K (MOP) and S (bentonite sulfur) compared to 100% POLY4 + K[25]. The cost of POLY4 is also low (₹16) compared to the MOP (₹36).

Although applying 100% POLY4 alone produced higher yields, increased nutrient uptake, enhanced nutrient use efficiency, and improved biochemical quality, continuous cropping with the sole application as a source of K and S may deplete the soil's native K reserves in the long term. This concern arises because the onion crop removed approximately 66.2–92.5 kg K ha^{-1} in 2022–2023 and 86.9–120.9 kg K ha^{-1} in 2023–2024, while garlic removed 68.8–88.0 kg K ha^{-1} in 2022–2023 and 62.0–67.5 kg K ha^{-1}. However, only 37–44 kg K ha^{-1} was applied through 100% POLY4 alone. This indicates that applying 100% POLY4 alone is insufficient to sustain crop yields and soil health over time. Since POLY4 contains higher levels of S and Ca than K, relying solely on it for K supplementation would result in excessive additions of S and Ca to the soil. This nutrient imbalance, particularly with S in the present study, affected plant growth and crop yield by disrupting the balance between N and S. Therefore, POLY4 needs to be supplemented with other K fertilizers to supply the additional K removed by these crops[34,36]. Soil available S and electrical conductivity at harvest of both crops increased, which could be due to capillary rise of soluble salts and S along with soil water[45], whereas the initial available N, P, and K values were maintained across all treatments. Even though plants deplete readily available soil nutrients, nutrients in an unavailable form may be released to maintain equilibrium[4], suggesting that immediate changes in soil fertility might not be noticeable. Medium- to long-term experiments are therefore needed to assess the effects of fertilizer application on soil fertility status.

Additionally, treatments with 100% POLY4 + K exhibited higher partial factor productivity, agronomic efficiency, and recovery efficiency than those with 100% K (MOP) and S (bentonite sulfur)[25]. This treatment also helps to replenish K, S, Ca, Mg, and micronutrients removed by the crops[26]. Additionally, POLY4 adds less chlorides into the soil compared to K through MOP[25,35]. Overall, applying 100% S through POLY4, supplemented with additional K from MOP, will support sustaining the productivity of onion and garlic, improve nutrient uptake and biochemical quality, and help in maintaining soil health.

Conclusion

Applying 100% sulfur through POLY4 alone increased the yield, nutrient uptake, biochemical quality, and agronomic efficiency of onion and garlic. However, this treatment provided only 37–44 kg K ha^{-1}, which was insufficient to meet the actual potassium uptake of 66–121 kg K ha^{-1} for onion and 62–88 kg K ha^{-1} for garlic. This shortfall may lead to depletion of native soil potassium if used continuously. Furthermore, since POLY4 contains higher amounts of sulfur and calcium than potassium, applying it in excess to meet the crop's potassium needs may disrupt the nitrogen-to-sulfur balance, resulting in reduced bulb quality and overall yield. The results indicate that POLY4 can effectively provide 100% of the recommended sulfur, while additional potassium should be supplemented from MOP. This combined application would support in sustaining productivity of onion and garlic, enhancing nutrient uptake and biochemical quality, and maintaining soil health. Hence, applying 100% sulfur through PLOY4, along with additional potassium, may be recommended for these crops. Further medium- to long-term studies are required to assess the impact of these nutrient applications through POLY4 + K on soil health.

Treatments	Soil pH		EC (dS m^{-1})		SOC (g kg^{-1})		Soil available nutrients							
							N (kg ha^{-1})		*P* (kg ha^{-1})		K (kg ha^{-1})		S (mg kg^{-1})	
	2022–2023	2023–2024	2022–2023	2022–2023	2023–2024	2022–2023	2023–2024	2022–2023	2022–2023	2023–2024	2022–2023	2022–2023	2023–2024	2022–2023
Onion														
100% K alone (No S)	8.40 ab	7.92 b	0.23 b	0.22 f	5.47 c	4.93	61.1 a	64.8 a	12.5 a	16.6 b	177.9 cd	221.7 a	11.1 bc	10.9 e
100% S alone (No K)	8.32 abc	7.85 c	0.22 b	0.27 c	5.42 cd	4.87	59.2 a	64.8 a	11.7 a	16.9 ab	185.4 bc	213.4 a	11.1 bc	11.2 de
100% K (MOP) and S (BS)	8.38 ab	7.82 c	0.25 b	0.25 d	5.28 cd	4.93	61.1 a	64.8 a	10.7 a	17.3 a	200.9 b	208.5 a	11.1 bc	12.4 c
75% S (POLY4)	8.26 bc	7.91 b	0.22 b	0.24 e	5.18 d	5.37	62.9 a	66.6 a	11.8 a	15.6 d	185.4 bc	210.9 a	11.1 bc	11.7 d
100% S (POLY4)	8.20 c	7.94 b	0.31 a	0.22 f	5.32 cd	4.93	62.9 a	61.1 a	11.4 a	15.8 cd	198.4 b	208.5 a	12.0 ab	12.6 bc
150% S (POLY4)	8.28 abc	7.93 b	0.23 b	0.29 b	5.39 cd	5.43	64.8 a	61.1 a	10.3 a	16.3 bc	165.5 d	209.0 a	12.4 ab	12.4 c
75% S (POLY4) + K (MOP)	8.36 abc	8.00 a	0.23 b	0.18 g	5.26 cd	5.27	61.1 a	64.8 a	12.2 a	16.6 b	174.1 cd	213.9 a	13.4 a	13.1 ab
100% S (POLY4) + K (MOP)	8.42 a	7.92 b	0.14 c	0.30 a	6.11 a	5.23	62.9 a	66.6 a	11.6 a	15.8 cd	225.3 a	209.6 a	10.0 c	12.8 abc
150% S (POLY4) + K (MOP)	7.99 d	7.89 b	0.25 b	0.26 d	5.74 b	4.93	44.4 a	62.9 a	11.1 a	17.3 a	183.9 bc	213.3 a	13.4 a	13.4 a
P value	0.19	0.05	0.6	0.01	0.02	0.02	NS	NS	NS	0.9	15.8	NS	3.1	0.6
CV (%)	1.39	0.34	14.19	2.04	2.54	2.32	14.3	5.1	9.8	3.2	5.0	3.8	7.9	2.7
Garlic														
100% K alone (No S)	8.40 abc	8.01 a	0.19 a	0.26 a	5.11 cd	5.23 d	62.9 a	55.5 c	11.2 a	18.6 c	161.1 cde	211.9 b	12.00 a	10.91 b
100% S alone (No K)	8.37 bcd	7.86 f	0.18 a	0.23 b	4.96 d	4.93 e	62.9 a	55.5 c	11.3 a	19.3 bc	152.1 e	206.0 b	11.21 a	12.39 a
100% K (MOP) and S (BS)	8.27 de	7.96 cd	0.23 a	0.26 a	5.42 b	6.23 a	61.1 a	61.1 a	12.0 a	19.2 bc	189.1 a	217.4 b	13.86 a	11.06 b
75% S (POLY4)	8.35 cd	8.01 ab	0.20 a	0.22 c	5.79 a	5.73 c	62.9 a	61.1 a	10.1 a	19.9 ab	153.0 e	217.4 b	11.71 a	9.96 d
100% S (POLY4)	8.20 e	7.98 abc	0.18 a	0.20 d	5.00 d	5.93 bc	57.4 a	61.1 a	11.9 a	19.3 bc	189.8 a	217.1 b	11.85 a	12.39 a
150% S (POLY4)	8.42 abc	7.89 ef	0.21 a	0.20 e	5.26 bc	5.97 bc	61.1 a	59.2 ab	11.9 a	19.3 bc	175.1 bc	215.2 b	12.36 a	9.88 d
75% S (POLY4) + K (MOP)	8.47 ab	7.98 abc	0.18 a	0.19 f	5.12 cd	5.87 bc	62.9 a	59.2 ab	9.9 a	18.6 c	152.5 e	241.3 a	11.42 a	10.69 bc
100% S (POLY4) + K (MOP)	8.47 ab	7.93 de	0.19 a	0.19 f	5.16 cd	6.03 ab	62.9 a	57.4 bc	11.0 a	20.4 a	156.1 de	214.6 b	10.34 a	10.18 cd
150% S (POLY4) + K (MOP)	8.50 a	7.97 bc	0.19 a	0.21 d	5.47 b	5.43 d	61.1 a	61.1 a	10.7 a	20.3 a	168.5 cd	214.3 b	12.72 a	10.91 b
P value	0.10	0.04	NS	0.01	0.03	0.02	NS	3.2	NS	0.7	20.3	13.7	NS	0.68
CV (%)	0.73	0.28	11.03	1.47	2.93	2.46	5.1	3.2	11.6	2.0	7.3	3.7	9.73	3.58

Table 7. Effect of POLY4 on physico-chemical properties and soil fertility status. Different lowercase letters indicate significant differences ($P < 0.05$) among treatments. 100% K (MOP) and S (BS): 100% recommended potassium applied through muriate of potash and sulfur through bentonite sulfur.

Data availability

All original data supporting the findings of this study are included in the article and its supplementary materials. Additional datasets generated and analyzed during the current study are available from the corresponding authors upon reasonable request.

Received: 19 October 2024; Accepted: 7 July 2025
Published online: 22 July 2025

References

1. FAOSTAT. Crops and livestock products. *Food and Agriculture Organization of the United Nations* (2025). https://www.fao.org/faostat/en/#data/QCL (Accessed 24 May 2025).
2. Gopal, J. Onion research in india: status and challenges. *Progress. Hortic.* **47** (1), 1–10. https://doi.org/10.5958/2249-5258.2015.00001.9 (2015).
3. Thangasamy, A. et al. Optimizing plant growth, nutrient uptake, and yield of onion through the application of phosphorus solubilizing bacteria and endophytic fungi. *Front. Microbiol.* **15**, 1442912. https://doi.org/10.3389/fmicb.2024.1442912 (2024).
4. Das, D., Sahoo, J., Raza, M. B., Barman, M. & Das, R. Ongoing soil potassium depletion under intensive cropping in India and probable mitigation strategies: A review. *Agron. Sustain. Dev.* **42** (4). https://doi.org/10.1007/s13593-021-00728-6 (2022).
5. Penuelas, J., Coello, F. & Sardans, J. A better use of fertilizers is needed for global food security and environmental sustainability. *Agric. Food Secur.* **12**, 5. https://doi.org/10.1186/s40066-023-00409-5 (2023).
6. Dass, A., Jinger, D., Kaur, R., Kumar, S. V. & Kumari, K. Addressing multinutrient deficiency in crops using customized fertilizer. *Indian Farm*. **67** (3), 22–25 (2017).
7. Bisht, N. & Singh, C. P. Excessive and disproportionate use of chemicals cause soil contamination and nutritional stress. *IntechOpen*. https://doi.org/10.5772/intechopen.94593 (2021).
8. Vijayakumar, S., Gobinath, R., Kannan, P. & Murugaiyan, V. Optimizing potassium mining in rice–wheat system: strategies for promoting sustainable soil health – A review. *Farm. Syst.* **2** (3), 100099. https://doi.org/10.1016/j.farsys.2024.100099 (2024).
9. Thangasamy, A. Nutrient management in onion and garlic—review. *J. Allium Res.* **1**, 107–115 (2018).
10. Krasilnikov, P., Taboada, M. A. & Amanullah. Fertilizer use, soil health and agricultural sustainability. *Agriculture*. **12** (4), 462. https://doi.org/10.3390/agriculture12040462 (2022).
11. Divya, S., Rusyn, I., Solorza–Feria, O. & Kamaraj, S. K. Sustainable SMART fertilizers in agriculture systems: A review on fundamentals to in–field applications. *Sci. Total Environ.* **904**, 166729. https://doi.org/10.1016/j.scitotenv.2023.166729 (2023).
12. The Fertilizer Association of India. Annual review of fertilizer production and consumption 2022–23. *Indian J. Fertil.* **19** (9), 918–978 (2023).
13. Gopinath, K. A. et al. Exploring the use of POLY4 for the improvement of productivity, peanut quality, and soil properties in Southern India. *Front. Plant Sci.* **15**, 1448909. https://doi.org/10.3389/fpls.2024.1448909 (2024).
14. Pereira, D. G. C., Santana, I. A., Megda, M. M. & Megda, M. X. V. Potassium chloride: impacts on soil microbial activity and nitrogen mineralization. *Ciência Rural*. **49** (5), e20180556. https://doi.org/10.1590/0103-8478cr20180556 (2019).
15. Marcel, B. et al. Characterizing polyhalite plant nutritional properties. *Agric. Res. Technol. Open. Access. J.* **6** (3), 555690. https://doi.org/10.19080/ARTOAJ.2017.06.555690 (2017).
16. Thangasamy, A. et al. Effects of sulfur fertilization on yield, biochemical quality, and thiosulfinate content of Garlic. *Sci. Hort.* **289**, 110442. https://doi.org/10.1016/j.scienta.2021.110442 (2021).
17. Nguyen, B. T., Harper, S. M., O'Hare, T. J., Menzies, N. W. & Wehr, B. Sulfur nutrition affects Garlic bulb yield and allicin concentration. *Plants*. **11** (19), 2571. https://doi.org/10.3390/plants11192571 (2022).
18. Mahmoud, S. H. & El-Tanahy, A. M. M. Effect of carbon nanoparticles in Biochar and sulphur as a foliar spray on onion plants: A new orientation. *Gesunde Pflanzen*. **75**, 1361–1368. https://doi.org/10.1007/s10343-022-00768-2 (2023).
19. Traynor, A. M., Sheridan, K. J., Jones, G. W., Calera, J. A. & Doyle, S. Involvement of sulfur in the biosynthesis of essential metabolites in pathogenic fungi of animals, particularly *Aspergillus* spp.: molecular and therapeutic implications. *Front. Microbiol.* **10**, 2859. https://doi.org/10.3389/fmicb.2019.02859 (2019).
20. Narayan, O. P., Kumar, P., Yadav, B., Dua, M. & Johri, A. K. Sulfur nutrition and its role in plant growth and development. *Plant Signal. Behav.* **18** (1). https://doi.org/10.1080/15592324.2022.2030082 (2022).
21. Grzebisz, W., Zielewicz, W. & Przygocka–Cyna, K. Deficiencies of secondary nutrients in crop plants—A real challenge to improve nitrogen management. *Agronomy*. **13** (1), 66. https://doi.org/10.3390/agronomy13010066 (2023).
22. Ishfaq, M. et al. Physiological essence of magnesium in plants and its widespread deficiency in the farming system of China. *Front. Plant Sci.* **13**, 802274. https://doi.org/10.3389/fpls.2022.802274 (2022).
23. de Bang, T. C., Husted, S., Laursen, K. H., Persson, D. P. & Schjoerring, J. K. The molecular–physiological functions of mineral macronutrients and their consequences for deficiency symptoms in plants. *New Phytol.* https://doi.org/10.1111/nph.17074 (2020).
24. Vale, F. & Girotto, E. S. Fertilization efficiency with polyhalite mineral: A multi-nutrient fertilizer. In *Electronic International Fertilizer Correspondent (e-ifc)*, March 2022, No. 66 (2022).
25. Singh, V. K. et al. Optimizing polyhalite (POLY4) use in the maize–wheat system: A comparative case study from upper and trans Indo–Gangetic plains of India. *Heliyon*. **9** (12), e22566. https://doi.org/10.1016/j.heliyon.2023.e22566 (2023).
26. Pramanick, B. et al. An innovative approach to improve oil production and quality of mustard (Brassica juncea L.) with multi–nutrient rich polyhalite. *Heliyon*. **9** (3), e13997. https://doi.org/10.1016/j.heliyon.2023.e13997 (2023).
27. Sirius Minerals. *POLY4 brochure*. (2016). http://siriusminerals.com/site/flexpaper/Publications/POLY4_brochure/docs/POLY4_brochure.pdf (accessed 17 Oct 2024).
28. Mahendru, K. G., Sachan, R., Singh, D. & Kumar, A. *Fundamentals of Soil Science (Laboratory Manual of Soil analysis)* (Bhavya Books, 2023).
29. Piper, C. S. *Soil and Plant Analysis* (Scientific, 2019).
30. Goulding, D. A., Fox, P. F. & O'Mahony, J. A. *Milk Proteins: An Overview. Milk Proteins*, 21–98. https://doi.org/10.1016/b978-0-12-815251-5.00002-5 (2020).
31. Shen, C. H. Quantification and analysis of proteins. *Diagn. Mol. Biol.* 187–214. https://doi.org/10.1016/b978-0-12-802823-0.00008-0 (2019).
32. R Core Team. *R: A Language and Environment for Statistical Computing.* (R Foundation for Statistical Computing, 2024). http://www.r-project.org/index.html.
33. QGIS Development Team. *QGIS Geographic Information System* (Version 3.28.3) [Software]. Open-Source Geospatial Foundation. (2023). https://qgis.org/.
34. Yermiyahu, U. et al. Polyhalite as a multi-nutrient fertilizer—potassium, magnesium, calcium, and sulfate. *Isr. J. Plant. Sci.* **64** (3–4), 145–157. https://doi.org/10.1163/22238980-06401001 (2017).
35. Mello, S. C. et al. Potato response to polyhalite as a potassium source fertilizer in brazil: yield and quality. *HortScience*. **53** (3), 373–379. https://doi.org/10.21273/HORTSCI12738-17 (2018).
36. Tan, H. et al. Toward the replacement of conventional fertilizer with polyhalite in Eastern China to improve peanut growth and soil quality. *Chem. Biol. Technol. Agric.* **9**, 94. https://doi.org/10.1186/s40538-022-00363-7 (2022).

37. Sharma, R. K., Cox, M. S., Oglesby, C. & Dhillon, J. S. Revisiting the role of sulfur in crop production: A narrative review. *J. Agric. Food Res.* **15**, 101013. https://doi.org/10.1016/j.jafr.2024.101013 (2024).
38. Bhatt, R. et al. Polyhalite positively influences the growth, yield, and quality of sugarcane (*Saccharum officinarum* L.) in potassium and calcium-deficient soils in the semi-arid tropics. *Sustainability*. **13**, 10689. https://doi.org/10.3390/su131910689 (2021).
39. Li, Y. et al. Quantifying contributions of leaf area and longevity to leaf area duration under increased planting density and nitrogen input regimens during maize yield improvement. *Field Crops Res.* **283**, 108551. https://doi.org/10.1016/j.fcr.2022.108551 (2022).
40. Liu, S. et al. Synergistic regulation of nitrogen and sulfur on redox balance of maize leaves and amino acids balance of grains. *Front. Plant Sci.* **11**, 576718. https://doi.org/10.3389/fpls.2020.576718 (2020).
41. Czerniawski, P. & Bednarek, P. Glutathione *S*-Transferases in the biosynthesis of Sulfur–Containing secondary metabolites in Brassicaceae plants. *Front. Plant. Sci.* **9**, 1639. https://doi.org/10.3389/fpls.2018.01639 (2018).
42. Roy, T. S. et al. Yield, dry matter and specific gravity of exportable potato: response to salt. *Univers. J. Agric. Res.* **5** (2), 98–103 (2017).
43. Torabian, S. et al. Potassium: A vital macronutrient in potato production—A review. *Agronomy*. **11** (3), 543. https://doi.org/10.3390/agronomy11030543 (2021).
44. Rosales, M. A. et al. Chloride improves nitrate utilization and NUE in plants. *Front. Plant Sci.* **11**, 442. https://doi.org/10.3389/fpls.2020.00442 (2020).
45. Liu, Z. et al. Effects of long–term saline water irrigation on soil salinity and crop production of winter wheat–maize cropping system in the North China plain: A case study. *Agric. Water Manag.* **303**, 109060. https://doi.org/10.1016/j.agwat.2024.109060 (2024).

Author contributions

T.A.: Conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, supervision, validation, writing—original draft, writing—review and editing. K.G.: Formal analysis, investigation, methodology, writing—original draft. P.M.: Formal analysis, investigation, methodology, writing—original draft, A.K.: Formal analysis, investigation, methodology, writing—original draft, N.A.: Conceptualization, resources, writing—review and editing, V.M.: Conceptualization, resources, writing—review and editing, V.B.M.: Project administration, resources, writing—review and editing.

Funding

The project was funded by Anglo-American Crop Nutrients Pvt. Ltd., New Delhi.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1038/s41598-025-10889-z.

Correspondence and requests for materials should be addressed to T.A.