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Research article

An innovative approach to improve oil production and quality of mustard (*Brassica juncea* L.) with multi-nutrient-rich polyhalite

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ABSTRACT

Polyhalite popularly known as POLY4 is a multi-nutrient fertiliser containing K, S, Mg, Ca, and micronutrients. POLY4 has a low carbon footprint, is certified for organic agriculture, and has the potential to improve crop productivity and quality attributes Indian mustard which often faces challenges due to imbalanced nutrition supplied in the current fertilisation schedule. The hypothesis of the study was that the multi-nutrient fartiliser POLY4 can ensure balanced nutrition for Indian mustard. Considering this, a field experiment was conducted during the winter seasons of 2017–18 and 2018–19 to evaluate the effect of POLY4 on Indian mustard (*Brassica juncea* L.) with respect to its yield, quality, and nutrient uptake. POLY4 along with conventional sources of nitrogen (N) and phosphorus (P) was compared to recommended fertilisation practices from conventional sources of N, P, K namely urea, di-ammonium phosphate (DAP), and muriate of potash (KCl). With the application of POLY4, seed yield was significantly improved by about 600 kg ha^{-1} compared to NP control (no application of K and S) across the two seasons. Compared to recommended practice of NPK, the yield was increased by about 450 kg ha^{-1} with the application of POLY4. Mustard seed oil and protein percent were also improved with the use of POLY4. POLY4 did not have any adverse effect on the content of anti-nutritional factors and improved the omega-3 fatty acid content of mustard oil. Higher uptakes of macro and micronutrients in the crop were also recorded with POLY4 along with an improved soil nutrient status. From the economic point of view, it was also observed that the application of POLY4 resulted in an increment of net returns of USD 45–60 comparing cultivating mustard with the conventional N, P, K, and S fertilizers only. Therefore, the use of POLY4 as a source of multi-nutrient for balanced nutrition helped to increase the efficiency of applied nutrients which ultimately improved the yield and quality of mustard. This study exhibits the pioneer findings of polyhalite (POLY4) based balanced nutrition in Indian mustard.

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1. Introduction

Oilseeds are important in human diets. They are rich sources of vitamin E and unsaturated as well as essential fatty acids [1]. Oilseeds are the second most important crop in India after cereals [2]. India produces about 7.4% of oilseeds and consumes 9.3% of edible oil in the world [2]. In 2019, India imported about 15 million tonnes (MT) of edible oils annually, which accounted for almost 50% of the total amount spent on agricultural imports [3]. India, the world's second-largest consumer and number one importer of vegetable oil, is projected to maintain a high per capita consumption growth of 2.6% per annum, reaching 14 kg per capita by 2030 [4]. The reliance on vegetable oil imports in a nation with an ever-increasing population emphasises the importance of increasing oilseed production within India. However, oilseed growing areas and overall productivity are jeopardized by an increased focus on cereal grain production, limited and degrading cropping land, and a shift in agricultural land to industrial uses [2,5]. This situation, therefore, requires a plausible alternative to increase oilseed yields as well as quality.

Mustard is the second most important oilseed crop in India after peanut with regard to area and production [5]. Moreover, the low cost of production and high yield potential holds promise for large-scale cultivation in the country. Sulphur (S) and potassium (K) are the most important nutrients that limit oil productivity in India [5,6]. McGrath and Zhao [7] previously reported that although the S requirement of Indian mustard is high, the dominant fertilisation practice is nitrogen (N), ignoring S requirements. Such nutrient management focusing on N requirement only leads to low yield as well as poor oil quality. Kopriva et al. [8] reported the strong interaction between N and S uptake and stated that N-deficiency is increased with a lower supply of sulphur to oilseed crops. Dubuis et al. [9] showed increased fungal disease in canola with sulphur deficiency.

Continuous reductions in soil fertility with imbalanced fertilisation are believed to be responsible for the low productivity of mustard crops. This has led to calls for the adoption of suitable nutrition strategies for crop production [10]. Until now, primary nutrient (N, P, and K) application remains the major focus of Indian farmers. This practice ignores the crop demands for secondary as well as micro-nutrients which are assumed to be met from the soil reserve. In recent years, potassium and sulphur deficiency have been aggravated in the soil after the harvest of mustard [11]. In many cropping systems, a negative potassium balance in soil has been suggested as a reason behind suboptimal yields [12]. Furthermore, there is a decreasing trend in atmospheric S deposition to soil globally. A balanced nutrition approach for crop production is one of the key factors in reducing the existing yield gap, improving nutrient use-efficiency, and producing crops in a sustainable manner [13,14].

Polyhalite has been found to play several vital roles in soil fertility, crop productivity, and crop quality [15]. Polyhalite is a mineral that contains sulphates of potassium (K), calcium (Ca), and magnesium (Mg) with the formula: $K_2SO_4.MgSO_4.2CaSO_4.2H_2O$ [16]. As well as being a multi-nutrient fertiliser source with K, S, Mg, and Ca, polyhalite has a low carbon footprint, is low in chloride, is pH neutral, and has the potential for soil remediation from Ca additions [17]. Polyhalite also has a low salt index which suggests that it can be applied along with crop seeds without salt injury. As a granular product (POLY4) it has excellent spreading characteristics and releases nutrients at a sustained rate to the soil profile as compared to other fertilisers such as KCl, and sulphate of potash (SOP) [17,18].

In India, there is very little published information about POLY4 performance in crop production, especially in mustard. Therefore, a comprehensive assessment of appropriate nutrient management techniques is indispensable in exploring all aspects of balanced nutrition for the mustard crop. This study was performed with the main objective to investigate the efficiency of polyhalite (POLY4) as a fertiliser with special reference to yield, and quality of mustard. The novelty of the study is to generate pioneer information about nutrient management with polyhalite achieving better yield and quality of Indian mustard.

2. Materials and methods

2.1. Experimental site

The field experiment was conducted during the winter seasons of 2017–18 and 2018–19 at Norman E. Borlaug Crop Research

Table 1
Initial soil status at 0–15 cm depth of the experimental site.

Particulars	Value	Method of determination
Texture	Silty clay loam	Hydrometer method [20]
Soil type	*Mollisol*	–
pH (1:2 soil water suspension)	7.52	Beckman Glass Electrode meter [21]
Organic carbon (%)	1.18	Walkley and Black method [22]
Available N (kg ha^{-1})	195.2	Modified Kjeldahl method [23]
Available P (kg ha^{-1})	14.6	Olsen's method [24]
Available K (kg ha^{-1})	161.7	Flame photometer method [21]
Sulphur (kg ha^{-1})	10.19	William and Steinberg [25]
Calcium (mg $100g^{-1}$)	13.5	Titration method
Magnesium (mg $100g^{-1}$)	2.4	Titration method
Iron (mg kg^{-1})	5.11	Atomic Absorption Spectrophotometer
Manganese (mg kg^{-1})	5.28	
Copper (mg kg^{-1})	1.57	
Zinc (mg kg^{-1})	0.61	

Centre, Govind Ballabh Pant University of Agriculture and Technology, Pantnagar, India (latitude: 29°01′08″ N; longitude: 79°28′54″ E; and altitude: 243.84 m a.s.l). The experimental site was located at the foothill of the *Shivalik* range of the Himalayas known as *Tarai*. The climate is subtropical and sub-humid. During the study, the maximum temperature ranged between 15 and 34 °C, and the minimum temperature ranged between 5 and 24 °C. Maximum relative humidity (RH) varied from 80 to 96%, while the minimum RH ranged between 40 and 64%. Annual rainfall of the experimental site varied from 1200 to 1400 mm. The soil of the study area was sandy clay loam in texture belonging to the reference soil group of Gleysols; the principal qualifier is Mollic; and the supplementary qualifier is Mulmic as per the World Reference Base for Soil Resources [19]. The initial soil status (0–15 cm depth) of the experimental field is in Table 1.

2.2. Experimental design and crop management

Eleven treatments were tested for two consecutive years in a randomized complete block design (RCBD) with three replications. Treatment details are as follows: T_1, application of 120, and 40 kg ha^{-1} of N, and P, respectively; T_2, application of 120, 40, and 44 kg ha^{-1} of N, P, and K, respectively; T_3, application of 120, 40, 44, and 40 kg ha^{-1} of N, P, K, and S, respectively; T_4, application of 120, 40, 44, and 60 kg ha^{-1} of N, P, K, and S, respectively; T_5, application of 120, 40, 15, and 207 kg ha^{-1} of N, P, K, and POLY4, respectively; T_6, application of 120, 40, and 315 kg ha^{-1} of N, P, and POLY4, respectively; for T_7 to T_{11}, the application nutrients except N was as same as T_2 to T_6, respectively with only changes made in N application of 160 kg ha^{-1} instead of 120 kg ha^{-1}. Details of the treatment are presented in Table 2. The performance of polyhalite (POLY4) was tested against the recommended application rates of K and S supplied by KCl and elemental S, respectively. N and P were supplied through urea and di-ammonium phosphate (DAP), respectively. Polyhalite was applied before sowing. Urea was top-dressed twice, one after 30 days of sowing (DAS) and another during the flowering stage. Plots were of 18 m^2 of area each (4.0 m × 4.5 m). Mustard variety, NRCHB–101 was used for this study. The crop was sown at 4 kg ha^{-1} of seed rate having 30 cm spaces between two rows and 10 cm spaces between two plants. To maintain plant spacing, thinning of the crop was done at 21 DAS. Two irrigations were provided to the crop at the pre-flowering stage and seed formation stage. One hand-weeding was done during the thinning operation.

2.3. Polyhalite

Polyhalite is a naturally occurring mineral from the evaporate group. It has the chemical formula of $K_2Ca_2Mg(SO_4)_4$, $2H_2O$ with a triclinic crystal system [26]. Polyhalite is being marketed as POLY4 by Anglo American Crop Nutrients, United Kingdom, a new mineral fertiliser, after mining in the UK from deep underground. It contains four important plant nutrients, namely Sulphur (19% S), Potassium (14% K), Magnesium (6% Mg), and Calcium (17% Ca). POLY4 is marketed mainly in powder or granular form. It can be used in most crops both in field or greenhouse conditions [27]. For producing POLY4, mined polyhalite is simply crushed and granulated without using chemicals to produce a low carbon footprint fertiliser that is suitable for organic use. Polyhalite as POLY4 has also been approved for organic farming in many countries like the UK, Brazil, USA, China, Italy, Canada, Germany, France, Netherlands, etc. [28]. POLY4 contains several micronutrients in trace amounts such as B, Zn, Mn, Mo, Fe, and Cu which may significantly improve crop production and soil health with one go [27,29]. The nutrients of POLY4 become available easily in the root zone when there is optimum soil moisture. Sulphur of POLY4 is present in plant available sulphate form.

2.4. Yield and quality analysis

The crop was harvested at maturity from the net plot of 11.9 m^2 of area (3.4 m × 3.5 m), and sun-dried for 2 days before threshing

Table 2
Details of the treatments along with the sources of the nutrients.

Source	Urea	DAP	KCl	Bentonite	Poly-halite (Poly 4)		
Treatments	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})	S (kg ha^{-1})	K (kg ha^{-1})	S (kg ha^{-1})	Mg (kg ha^{-1})
T_1:$N_{120}P_{40}$ (NP control)	120	40	–	–	–	–	–
T_2:$N_{120}P_{40}K_{44}$	120	40	44	–	–	–	–
T_3:$N_{120}P_{40}K_{44}S_{40}$	120	40	44	40	–	–	–
T_4:$N_{120}P_{40}K_{44}S_{60}$	120	40	44	60	–	–	–
T_5:$N_{120}P_{40}K_{15}$ + $POLY4_{207}$	120	40	15	–	29	40	13
T_6:$N_{120}P_{40}K_0$ + $POLY4_{315}$	120	40	–	–	44	60	19
T_7:$N_{160}P_{40}K_{44}$	160	40	44	–	–	–	–
T_8:$N_{160}P_{40}K_{44}S_{40}$	160	40	44	40	–	–	–
T_9:$N_{160}P_{40}K_{44}S_{60}$	160	40	44	60	–	–	–
T_{10}:$N_{160}P_{40}K_{15}$ + $POLY4_{207}$	160	40	15	–	29	40	13
T_{11}:$N_{160}P_{40}K_0$ + $POLY4_{315}$	160	40	–	–	44	60	19

Note: N_{120}, and N_{160} denote application of N-fertiliser at 120, and 160 kg ha^{-1}, respectively; P_{40} denotes application of P-fertiliser at 40 kg ha^{-1}; K_{15}, and K_{44} denote application of K-fertiliser at 15, and 44 kg ha^{-1}, respectively; S_{40} and S_{60} denote application of S-fertiliser at 40, and 60 kg ha^{-1}, respectively; $POLY4_{207}$ and $POLY4_{315}$ denote application of POLY4 at 207, and 315 kg ha^{-1}, respectively; DAP: di-ammonium phosphate; KCl: muriate of potash.

and winnowing. Afterward, the economic yield (seed yield) and byproduct biomass (stalk yield) of mustard were calculated at a 12% moisture level. Harvest index (HI) was calculated as the proportion of economic yield in the total biomass (economic yield + byproduct yield).

Soxhlet's extraction method as described in AOAC [30] was followed to estimate the oil content in mustard seed. Oil yield, protein content, and protein yield were worked out following the formulae described below [5,31]:

Oil yield (kg ha^{-1}) = Oil content (%) × Seed yield (kg ha^{-1})

Protein content (%) = N content in seed (%) × 6.25.

Protein yield (kg ha^{-1}) = Protein content (%) × Seed yield (kg ha^{-1})

Myrosinase hydrolysis released glucose was determined to estimate the total glucosinolate content present in mustard seed as described in Wittstock et al. [32]. The total glucosinolate content was expressed in μ M mg^{-1} fat-free meal. As per the process described in Morrison and Smith [33], 14% BF_3–methanol + methanol + benzene were used for *trans*-methylation to prepare esters of fatty acid methyl which were used to estimate fatty acids present in mustard oil. Gas-liquid chromatography (GLC) mentioned in AOAC [34] was used to profiling fatty acids (%).

2.5. *Nutrient uptake*

Nutrient content (%) in mustard seed and stalk was measured to determine the total nutrient uptake by the mustard crop. Harvested plant samples (both seed and stalk) from each of the experimental plots were put into a hot air oven for air-drying at 70 ± 2 °C for 24 h. After drying, plant samples were ground with a Willey Mill (Star Scientific Instrument, New Delhi, India) to analyze the macro and micronutrients present in the plant using the following protocols described below.

N and S content was measured with a CHNS apparatus. 10 mg of well-prepared plant samples were put into tin-capsules of the CHNS analyzer which was run using a specific software programme. Plant samples were digested for 2 h with a digestion mixture (HNO_3:H_2SO_4:$HClO_4$, 9:1:4). Determination of P content was done spectrophotometrically with yellow phospho-vanado-molybdate complex [21]. Wavelengths of 470 nm at the UV–VIS spectrophotometer (Model 108, Systronics India Limited) as described by Chapman and Parker [35] were used for determining the P absorbance. K content (%) was measured by flame-photometer (Model 126, Systronics India Limited) [21]. Micronutrient analysis was conducted in the second year of the trial. Digested plant samples were mixed with a di-acid mixture, then, these were filtered with filter paper and the micronutrient content was determined by atomic absorption spectrophotometry (PerkinElmer AAS, Model: PinAAcle 900H). Nutrient uptake was estimated by multiplying the nutrient content (%) in respective crops and their yield using the following formulae [5]:

Total nutrient uptake (kg ha^{-1}) = Nutrient uptake by seeds (kg ha^{-1}) + nutrient uptake by stalk (kg ha^{-1})

Nutrient uptake by seeds or stalk (kg ha^{-1}) = [Nutrient content in seed or stalk (%) × seed or stalk yield (kg ha^{-1})]

2.6. *Statistical analysis*

Data were analyzed by using the standard techniques of analysis of variance (ANOVA) for randomized complete block design with the help of statistical software, SAS (version 9.4). Differences were tested for the 'F' test at a 5% level of significance. When the 'F test' was found significant at a 5% level of significance the least significant difference (LSD) was used to test the significance of differences between the two-treatment means [36]. Here the two-year data were presented separately as the year effect was significant which restricted the pooled analysis. All the graphs presented in this manuscript were drawn using the software SigmaPlot v14.0 (Systat Software Inc.).

Table 3
Seed yield, stalk yield, and harvest index (HI) of mustard as influenced by different nutrient management practices.

Treatment	Seed Yield (Mg ha^{-1})		Stalk Yield (Mg ha^{-1})		HI (%)	
	1st year	2nd year	1st year	2nd year	1st year	2nd year
T_1:$N_{120}P_{40}$	1.08^{d}	1.18^{c}	3.64^{c}	4.14^{c}	22.9^{d}	22.2^{a}
T_2:$N_{120}P_{40}K_{44}$	1.23^{cd}	1.32^{c}	4.06^{abc}	4.79^{bc}	23.3^{cd}	21.6^{a}
T_3:$N_{120}P_{40}K_{44}S_{40}$	1.51^{abc}	1.67^{ab}	3.99^{bc}	5.10^{abc}	27.5^{ab}	24.7^{a}
T_4:$N_{120}P_{40}K_{44}S_{60}$	1.55^{ab}	1.68^{a}	3.98^{bc}	5.10^{abc}	28.0^{a}	24.8^{a}
T_5:$N_{120}P_{40}K_{15}$ + $POLY4_{207}$	1.71^{a}	1.73^{a}	4.44^{ab}	5.20^{abc}	27.8^{ab}	25.0^{a}
T_6:$N_{120}P_{40}K_0$ + $POLY4_{315}$	1.75^{a}	1.75^{a}	4.51^{ab}	5.47^{abc}	28.0^{a}	24.2^{a}
T_7:$N_{160}P_{40}K_{44}$	1.31^{bcd}	1.36^{b}	4.13^{abc}	5.03^{abc}	24.1^{bcd}	21.3^{a}
T_8:$N_{160}P_{40}K_{44}S_{40}$	1.54^{ab}	1.68^{a}	4.04^{bc}	5.13^{abc}	27.6^{ab}	24.7^{a}
T_9:$N_{160}P_{40}K_{44}S_{60}$	1.58^{ab}	1.69^{a}	4.14^{abc}	5.24^{abc}	27.6^{ab}	24.4^{a}
T_{10}:$N_{160}P_{40}K_{15}$ + $POLY4_{207}$	1.76^{a}	1.77^{a}	4.53^{ab}	5.36^{ab}	28.0^{a}	24.8^{a}
T_{11}:$N_{160}P_{40}K_0$ + $POLY4_{315}$	1.78^{a}	1.80^{a}	4.63^{a}	5.91^{a}	27.8^{ab}	23.3^{a}
LSD ($P = 0.05$)	0.28	0.31	0.57	1.11	3.7	*Ns*

Values followed by same letter are statistically at par at 5% level of probability; *ns* denotes non-significant.

3. Results

3.1. Yield of mustard

The yield of mustard was documented after harvesting and drying of the crop and the yield data (both seed and stalk) are presented in Table 3. The yield increased compared to the NP control when potassium was added and further increased with the addition of sulphur. Substitution of elemental sulphur and partial or all KCl with POLY4 gave the greatest yield improvements. The highest seed yield of mustard was observed in T_{11} (sources of K and S are POLY4 alone *i.e.*, $N_{160}P_{40}$ + 315 kg POLY4) which had statistically no variation with T_3, T_4, T_5, T_6, T_8, T_9, and T_{10}in both the years (Table 3). This result revealed that a similar yield level was recorded when polyhalite and bentonite were applied with a recommended dose of nitrogen (RDN) or 33% more RDN levels. T_{11} ($N_{160}P_{40}$ + 315 kg POLY4) exhibited yield increments of about 65 and 53% over T_1 (NP control) during the first and second year of study, respectively. It was also attained that application of POLY4 either at 207 or 315 kg ha^{-1} resulted in augmentation of yield to the tune of at least 47% over NP control. Incremental application of POLY4 from 207 to 315 kg ha^{-1} was not increasing seed yield mustard to a significant extent resulting in only a 1%–2% increment during both years. However, it was found that replacing the sources of a similar amount of K and S from KCl and bentonite with POLY4 resulted in yield increment to the tune of about 13% and 6–7% during the first year and second year of study, respectively. A similar trend was observed for stalk yield for both years. Stalk yield was also increased to a considerable extent owing to the application of polyhalite over the same level of N, P, and K chemical fertilisers. The highest amount of stalk yield was observed in T_{11} ($N_{160}P_{40}$ + 315 kg POLY4) during both years; while the minimum amount of mustard-stalk yield was recorded with T_1 (NP control). T_{11} showed an increment in the stalk yield of about 27% and 43% over T_1 during the first and second years of study, respectively. Considerably higher stalk yield was recorded during the second year than that of the first year of study. The harvest index of mustard was found non-significant during the second year of the study. During the first year, the highest value of the harvest index was recorded with T_{10} ($N_{160}P_{40}$ + 315 kg POLY4) and T_6 ($N_{120}P_{40}$ + 315 kg POLY4) (Table 3).

3.2. Quality of mustard

Results on quality parameters, namely oil and protein content (%) and their respective yields (kg ha^{-1}), are depicted in Table 4. Applying either 207 or 315 kg ha^{-1} of POLY4 significantly increased the oil content. Attainments of the highest seed oil content, oil yield, protein content as well as protein yield were recorded in T_{11} ($N_{160}P_{40}$ + 315 kg POLY4) which was closely followed by T_{10} ($N_{160}P_{40}$ + 207 kg POLY4), T_6 ($N_{120}P_{40}$ + 315 kg POLY4) and T_5 ($N_{120}P_{40}$ + 207 kg POLY4) during both the years. At a lower nitrogen regime (120 kg ha^{-1}), partial replacement of nutrient sources with POLY4 (T_5 and T_6) resulted in a 2.5–5.8% increase in oil content; 9.0–14% increase in oil yield; 2.5–4.0% increase in protein content; and 9.0–16% increase in protein yield as compared to similar treatment consisting of conventional nutrient sources (T_4) during both the years. The percent of increment was higher when partial replacement of nutrients was done through POLY4 at a higher nitrogen regime. Comparing recommended dose of NPK for mustard through conventional fertilisers (T_2) with T_{11} ($N_{160}P_{40}$ + 315 kg POLY4), it was witnessed that the increment of oil content, oil yield, protein content, and protein yield were 14–16%, 56–68%, 13–14%, 53–67%, respectively during both the years.

3.3. Lipid and fatty acid profile

Effects of different treatments on glucosinolate content and fatty acid profile were found non-significant except in the case of linolenic acid (Table 5). Lipid profiles, namely glucosinolate content, erucic acid, oleic acid, and palmitic acid in the oil of mustard were not changed significantly with the different treatments during both years. Only linolenic acid, an omega-3 fatty acid, was found to be significantly affected by the treatments. The maximum amount of linolenic acid content was found in the T_{11} ($N_{160}P_{40}$ + 315 kg POLY4) and this treatment was closely followed by other POLY4 applied treatments *i.e.*, T_{10}, T_6, and T_5. T_{11} resulted in the

Table 4
Quality attributes of mustard as influenced by different nutrient management practices.

Treatment	Oil content (%)		Oil yield (kg ha^{-1})		Protein content (%)		Protein Yield (kg ha^{-1})	
	1st year	2nd year	1st year	2nd year	1st year	2nd year	1st year	2nd year
T_1:$N_{120}P_{40}$	38.7[c]	38.2[d]	421[f]	448[e]	18.0[b]	18.3[b]	193[e]	214[d]
T_2:$N_{120}P_{40}K_{44}$	39.9[bc]	39.9[cd]	489[f]	526[de]	18.7[ab]	19.0[ab]	229[de]	251[cd]
T_3:$N_{120}P_{40}K_{44}S_{40}$	42.3[abc]	40.7[cd]	638[de]	678[bc]	19.2[ab]	19.5[ab]	290[bcd]	327[ab]
T_4:$N_{120}P_{40}K_{44}S_{60}$	43.0[abc]	40.8[cd]	664[cd]	682[abc]	19.3[ab]	19.6[ab]	300[bc]	328[ab]
T_5:$N_{120}P_{40}K_{15}$ + $POLY4_{207}$	44.1[abc]	43.2[abc]	757[abcd]	744[ab]	19.8[ab]	20.4[ab]	340[ab]	357[a]
T_6:$N_{120}P_{40}K_0$ + $POLY4_{315}$	44.6[ab]	42.9[abc]	778[abc]	748[ab]	20.0[ab]	20.3[ab]	349[ab]	358[a]
T_7:$N_{160}P_{40}K_{44}$	40.3[bc]	40.3[cd]	525[ef]	549[cde]	20.7[ab]	19.2[ab]	268[cd]	259[bcd]
T_8:$N_{160}P_{40}K_{44}S_{40}$	41.8[abc]	41.8[abcd]	642[de]	702[ab]	19.0[ab]	19.5[ab]	292[bcd]	327[ab]
T_9:$N_{160}P_{40}K_{44}S_{60}$	43.0[abc]	41.2[bcd]	680[bcd]	699[ab]	19.4[ab]	19.8[ab]	304[bc]	330[ab]
T_{10}:$N_{160}P_{40}K_{15}$ + $POLY4_{207}$	45.4[a]	44.9[ab]	798[ab]	793[ab]	19.5[ab]	20.5[ab]	344[ab]	364[a]
T_{11}:$N_{160}P_{40}K_0$ + $POLY4_{315}$	46.2[a]	45.6[a]	823[a]	823[a]	21.4[a]	21.4[a]	382[a]	384[a]
LSD (P = 0.05)	4.4	3.9	123	142	3.2	3.0	64	72

Values followed by same letter are statistically at par at 5% level of probability.

Table 5
Lipid and fatty acid profile of mustard oil as influenced by different nutrient management practices.

Treatment	Glucosinolate (μ mole mg^{-1})		Erucic acid (%)		Oleic acid (%)		Linolenic acid (%)		Palmitic acid (%)	
	1st year	2nd year	1st year	2nd year	1st year	2nd year	1st year	2nd year	1st year	2nd year
T_1:$N_{120}P_{40}$	99^a	97^a	46.2^a	43.4^a	12.7^a	12.6^a	11.0^d	11.0^d	3.28^a	3.04^a
T_2:$N_{120}P_{40}K_{44}$	100^a	99^a	47.9^a	42.6^a	12.6^a	12.6^a	11.2^{cd}	11.4^{cd}	3.15^a	3.15^a
T_3:$N_{120}P_{40}K_{44}S_{40}$	104^a	103^a	49.7^a	42.3^a	12.4^a	12.4^a	12.8^{abcd}	12.8^{abcd}	3.27^a	3.27^a
T_4:$N_{120}P_{40}K_{44}S_{60}$	99^a	100^a	47.8^a	41.3^a	13.1^a	12.7^a	13.0^{abcd}	12.7^{abcd}	3.20^a	3.20^a
T_5:$N_{120}P_{40}K_{15}$ + $POLY4_{207}$	107^a	107^a	46.6^a	41.1^a	12.4^a	12.7^a	13.5^{ab}	13.5^{ab}	3.29^a	3.29^a
T_6:$N_{120}P_{40}K_0$ + $POLY4_{315}$	105^a	105^a	45.2^a	41.6^a	13.0^a	13.0^a	13.9^{ab}	13.9^a	3.77^a	3.77^a
T_7:$N_{160}P_{40}K_{44}$	105^a	99^a	43.4^a	43.3^a	12.0^a	12.0^a	11.8^{bcd}	11.8^{bcd}	3.37^a	3.17^a
T_8:$N_{160}P_{40}K_{44}S_{40}$	105^a	99^a	47.9^a	41.8^a	13.2^a	13.2^a	13.2^{abc}	12.9^{abcd}	3.48^a	3.48^a
T_9:$N_{160}P_{40}K_{44}S_{60}$	98^a	98^a	49.9^a	43.7^a	12.6^a	12.6^a	13.7^{ab}	13.2^{abc}	3.60^a	3.51^a
T_{10}:$N_{160}P_{40}K_{15}$ + $POLY4_{207}Y4$	103^a	106^a	49.2^a	40.0^a	12.9^a	12.9^a	14.3^a	14.3^a	3.71^a	3.73^a
T_{11}:$N_{160}P_{40}K_0$ + $POLY4_{315}$	105^a	106^a	50.3^a	40.6^a	12.2^a	13.1^a	14.4^a	14.4^a	3.56^a	3.60^a
LSD (P = 0.05)	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	2.1	2.0	*ns*	*ns*

Values followed by same letter are statistically at par at 5% level of probability; *ns* denotes non-significant.

augmentation of linolenic acid in mustard seed to the tune of about 26–29% during both years compared with a recommended dose of NPK for mustard through conventional fertilisers (T_2).*3.4 Nutrient uptake*.

Different nutrient management practices significantly increased the uptake of all the nutrients by mustard over control (T_1) and recommended practices (T_2) (Table 6). Application of POLY4 showed significantly greater uptakes of N, P, K, S, Zn, Fe, Mn, and Cu, than the application of standard conventional fertilisers to mustard (Table 6). The highest amounts of total uptake N, P, K, and S, as well as micronutrients like Zn, Fe, and Cu, were recorded with T_{11} ($N_{160}P_{40}$ + 315 kg POLY4) and this treatment was closely followed by T_{10}, T_6, and T_5 during both the years. Concerning total uptake of Mn, T_{10} ($N_{160}P_{40}$ + 207 kg POLY4) exhibited the best result being at pat with T_{11}, T_6, T_5, T_9, and T_8 during both the years of research. Application of POLY4 showed 45–55%, 36–54%, 21–30%, 32–41%, 43–75%, 41–51%, 44–63%, and 47–54% of more uptakes of N, P, K, S, Zn, Fe, Mn, and Cu, respectively over application of recommended conventional fertiliser to mustard (T_2) during both the years. Replacing the source of K and S from KCl and bentonite, respectively to POLY4 with the same level of N and P nutrients resulted in 11–22%, 15–33%, 13–20%, 3–18%, 15–29%, 5–17%, 10–21%, and 12–20% of additional uptakes of N, P, K, S, Zn, Fe, Mn, and Cu, respectively during both the years. The least amounts of all the nutrients were recorded with the NP control plot (T_1) in the first as well as the second year of study.

3.4. Economics

Table 7 illustrates the economics of different treatments. From this table, it has been found that the application of POLY4 over conventional NPK or NPKS fertilizers increased the cost of cultivation to the tune of about USD 25–42. However, due to improvement in the yield of seed and stalk of mustard using POLY4, the gross returns were also increased to the tune of about USD 70–100 comparing the gross returns under using conventional NPK or NPKS fertilizers. Concerning net returns, it was observed that T_5 and T_6 resulted in net returns of USD 45 and 47 more, respectively comparing the net return in T_4, while T_{10} and T_{11} resulted in USD 59 and 61 more net returns, respectively comparing the net returns under T_9. The net return was found the maximum under T_{11} where 315 kg ha^{-1} POLY4 was applied. However, it was also estimated that the application of 15 kg ha^{-1} K through KCl along with 207 kg ha^{-1} POLY4 also resulted in an almost similar net return.

4. Discussion

4.1. Yield of mustard

The combined application of urea, DAP, KCl, and POLY4 supplied the crop with a balanced form of nutrition. Moreover, balanced nutrient management through polyhalite (POLY4) helped in the accomplishment of significantly higher productivity of mustard over the control in the current experiment. Higher nutrient availability in the soils with the application of POLY4 was noted (Fig. 1) which in turn resulted in the increased uptake of several essential nutrients (Table 6). Soil is a very dynamic system and nutrient availability to the crop must not be seen in separation [37]. The use of a multi-nutrient fertiliser like POLY4 not only replenishes the soil with several nutrients but may also have effects on the soil's physical, chemical, and biological properties [38]. The effect of Ca, and Mg on clay flocculation, water holding capacity, and soil aeration as well as beneficial effects on soil biota have been well documented by several workers [39,40]. The effects of primary nutrients and S have been well-documented for growth and yield augmentation for years. Furthermore, other secondary nutrients such as Ca and Mg are also believed to be involved in several quality traits and yield-attributing characteristics of a range of crops [41]. POLY4 is a unique natural combination of Ca, Mg, K, and S that may have the potential to balance nutrient use in plants and harvest the beneficial effects of secondary nutrients. All these findings support the inclusion of Ca, Mg, K, and S-rich POLY4 in the fertilisation schedule for mustard to reduce the problems associated with nutrient limitations of the crop; thereby improvement in the yield of mustard was accomplished.

Table 6
N, P, K, S, Zn, Fe, Mn, and Cu uptake by mustard as influenced by different nutrient management practices.

Treatment	Total N uptake (kg ha^{-1})		Total P uptake (kg ha^{-1})		Total K uptake (kg ha^{-1})		Total S uptake (kg ha^{-1})		Zn (g ha^{-1})		Fe (g ha^{-1})		Mn (g ha^{-1})		Cu (g ha^{-1})	
	1st year	2nd year	1st year	2nd year	1st year	2nd year	1st year	2nd year	1st year	2nd year	1st year	2nd year	1st year	2nd year	1st year	2nd year
T_1	42.6^{g}	47.8^{d}	16.7^{e}	20.9^{e}	79.9^{e}	85.5^{d}	17.4^{f}	22.2^{a}	26.7^{e}	29.1^{e}	145^{e}	142^{b}	37.9^{f}	42.6^{d}	18.2^{d}	19.4^{d}
T_2	50.8^{fg}	56.6^{d}	19.4^{de}	24.4^{de}	88.8^{de}	101.8^{cd}	20.0^{ef}	26.6^{a}	30.9^{de}	33.3^{de}	166^{e}	160^{b}	44.0^{ef}	48.1^{cd}	21.2^{cd}	22.5^{cd}
T_3	61.2^{def}	71.3^{bc}	22.2^{cd}	29.1^{bcd}	92.7^{de}	114.8^{abc}	22.8^{d}	30.0^{a}	38.5^{cd}	42.9^{bcd}	207^{cd}	206^{a}	55.3^{bcde}	62.5^{ab}	25.9^{abcd}	28.7^{abc}
T_4	63.3^{bcd}	72.3^{abc}	23.0^{bcd}	29.7^{bcd}	92.5^{de}	114.5^{abc}	23.3^{cd}	32.0^{a}	40.1^{cd}	45.0^{abc}	211^{bcd}	211^{a}	54.7^{cde}	61.8^{abc}	26.9^{abcd}	28.8^{abc}
T_5	73.8^{abc}	78.1^{ab}	26.4^{ab}	31.9^{abc}	107.6^{abc}	122.0^{abc}	26.3^{abc}	32.9^{a}	44.1^{bc}	43.0^{bcd}	234^{abc}	213^{a}	63.3^{abcd}	65.2^{a}	31.2^{ab}	31.0^{abc}
T_6	73.7^{abc}	80.2^{ab}	28.2^{a}	34.1^{ab}	110.8^{ab}	129.2^{ab}	26.8^{ab}	31.8^{a}	51.6^{ab}	52.0^{ab}	242^{abc}	220^{a}	66.4^{abc}	68.1^{a}	32.2^{a}	32.1^{ab}
T_7	56.4^{def}	59.4^{cd}	20.8^{cde}	26.5^{cd}	96.1^{cd}	107.6^{cd}	20.8^{de}	28.7^{a}	35.8^{cde}	36.4^{cde}	177de	165^{b}	47.6^{def}	50.8^{bcd}	22.5^{bcd}	23.3^{bcd}
T_8	61.4^{cde}	71.4^{bc}	23.8^{bc}	31.4^{bc}	97.7^{bcd}	114.9^{abc}	23.2^{cde}	31.5^{a}	44.1^{bc}	48.6^{ab}	209^{bcd}	210^{a}	56.0^{abcd}	63.6^{ab}	27.2^{abc}	29.4^{abc}
T_9	65.0^{b}	72.9^{ab}	22.4^{bcd}	30.2^{bc}	98.5^{bcd}	118.8^{abc}	23.9^{bcd}	31.0^{a}	45.8^{abc}	47.5^{ab}	215^{abcd}	210^{a}	60.4^{abcd}	66.0^{a}	27.5^{abc}	29.1^{abc}
T_{10}	74.3^{ab}	81.4^{ab}	28.6^{a}	34.4^{ab}	111.4^{ab}	127.2^{abc}	27.3^{a}	34.2^{a}	51.9^{ab}	52.5^{ab}	247^{ab}	225^{a}	71.9^{a}	72.5^{a}	32.0^{a}	32.4^{a}
T_{11}	79.2^{a}	85.6^{a}	29.9^{a}	37.3^{a}	115.1^{a}	140.5^{a}	28.2^{a}	36.0^{a}	54.1^{a}	54.9^{a}	251^{a}	230^{a}	70.7^{abc}	74.2^{a}	32.7^{a}	34.0^{a}
LSD ($P = 0.05$)	12.4	13.5	4.1	5.5	14.5	27.2	3.2	*Ns*	9.2	10.1	38	36	16.0	14.0	8.7	9.0

Values followed by same letter are statistically at par at 5% level of probability; *ns* denotes non-significant; T_1: NP-Control ($N_{120}P_{40}$); T_2: $N_{120}P_{40}K_{44}$; T_3: $N_{120}P_{40}K_{44}S_{40}$; T_4: $N_{120}P_{40}K_{44}S_{60}$; T_5: $N_{120}P_{40}K_{15}$+$POLY4_{207}$; T_6: $N_{120}P_{40}$+$POLY4_{315}$; T_7: $N_{160}P_{40}K_{44}$; T_8: $N_{160}P_{40}K_{44}S_{40}$; T_9: $N_{160}P_{40}K_{44}S_{60}$; T_{10}: $N_{160}P_{40}K_{15}$+$POLY4_{207}$; T_{11}: $N_{160}P_{40}$+$POLY4_{315}$; Values subscripted with N, P, K and POLY4 are denoting the rate of application in kg ha^{-1}.

Table 7
Economics of different treatments.

Treatments	Common cost (USD) [A]	Treatment cost (USD) [B]	Total cost of cultivation (USD) [C = (A + B)]	Gross return (USD) [D]	Net return (USD) [D – C]
T_1:$N_{120}P_{40}$ (NP control)	280	44	324	716	392
T_2:$N_{120}P_{40}K_{44}$	280	55	335	808	474
T_3:$N_{120}P_{40}K_{44}S_{40}$	280	65	345	989	644
T_4:$N_{120}P_{40}K_{44}S_{60}$	280	70	350	1004	654
T_5:$N_{120}P_{40}K_{15}$ + $POLY4_{207}$	280	89	369	1068	699
T_6:$N_{120}P_{40}K_0$ + $POLY4_{315}$	280	107	387	1089	701
T_7:$N_{160}P_{40}K_{44}$	280	61	341	845	504
T_8:$N_{160}P_{40}K_{44}S_{40}$	280	71	351	1002	651
T_9:$N_{160}P_{40}K_{44}S_{60}$	280	76	356	1018	662
T_{10}:$N_{160}P_{40}K_{15}$ + $POLY4_{207}$	280	96	376	1096	721
T_{11}:$N_{160}P_{40}K_0$ + $POLY4_{315}$	280	114	394	1117	723

Mustard seed and stalk prices were USD 567, and 19 per tonne or Mg, respectively; Prices of urea, DAP, KCl, bentonite, and POLY4 were, USD 72, 333, 141, 231, and 200 per tonne or Mg, respectively.

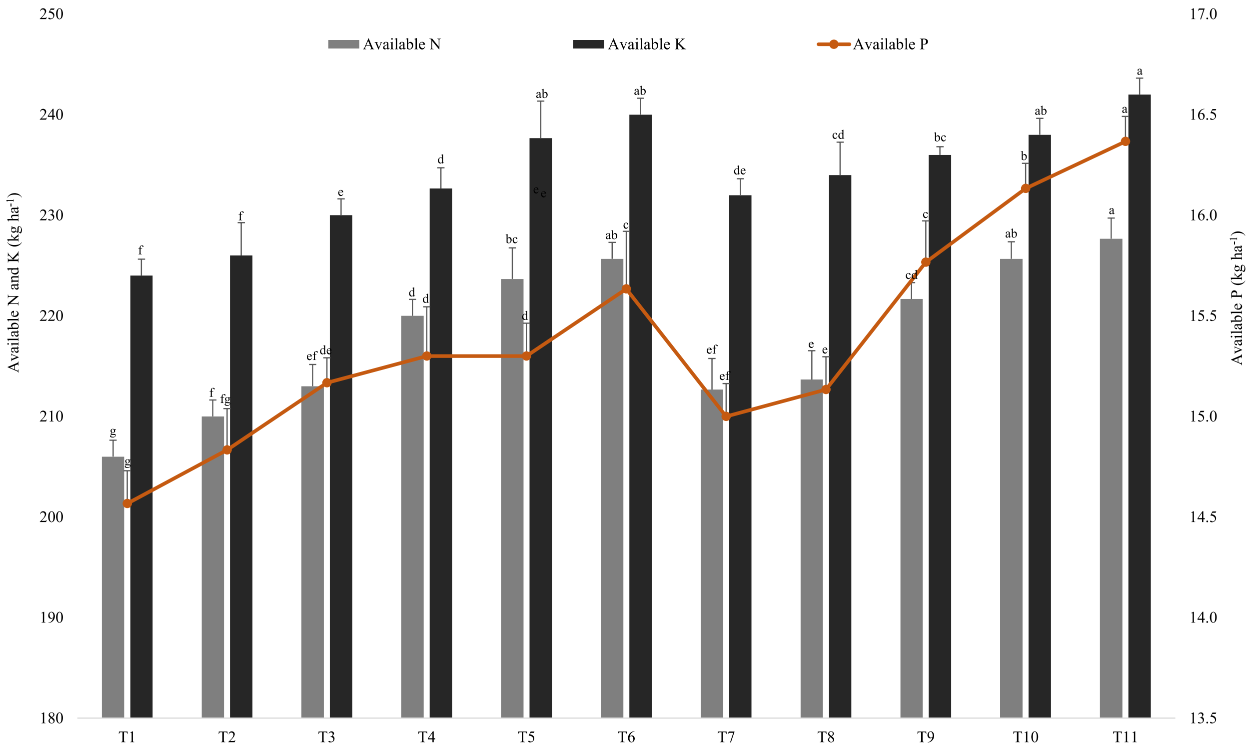

Fig. 1. Soil available N, P, and K status as influenced by different nutrient management practices after completion of the two-year study. [Note– T_1: NP control ($N_{120}P_{40}$); T_2: $N_{120}P_{40}K_{44}$; T_3: $N_{120}P_{40}K_{44}S_{40}$; T_4: $N_{120}P_{40}K_{44}S_{60}$; T_5: $N_{120}P_{40}K_{15}$+$POLY4_{207}$; T_6: $N_{120}P_{40}$+$POLY4_{315}$; T_7: $N_{160}P_{40}K_{44}$; T_8: $N_{160}P_{40}K_{44}S_{40}$; T_9: $N_{160}P_{40}K_{44}S_{60}$; T_{10}: $N_{160}P_{40}K_{15}$+$POLY4_{207}$; T_{11}: $N_{160}P_{40}$+$POLY4_{315}$; Values subscripted with N, P, K, and POLY4 are denoting the rate of application in kg ha^{-1}; the lines above each bar denote standard error (n = 3); different small letters above the lines of each bar represent statistical significance at 5% probability level, otherwise at par].

4.2. Oil quality and fatty acid profiles

In the current study, POLY4 significantly increased oil yield due to both an increase in total seed yield and the oil content of the seeds. The physiological reason behind the improvement in lipid profile might be attributed to the increased availability and absorption of necessary elements like Ca, K, Mg, and S present in POLY4. There is a significant function of K in the plant to improve both the yield and quality through controlling many physiological activities in the plant such as photosynthate transportation through the phloem, ATP synthesis, meristematic growth, and disease resistance [42,43]. Along with these, POLY4 supplies one of the most

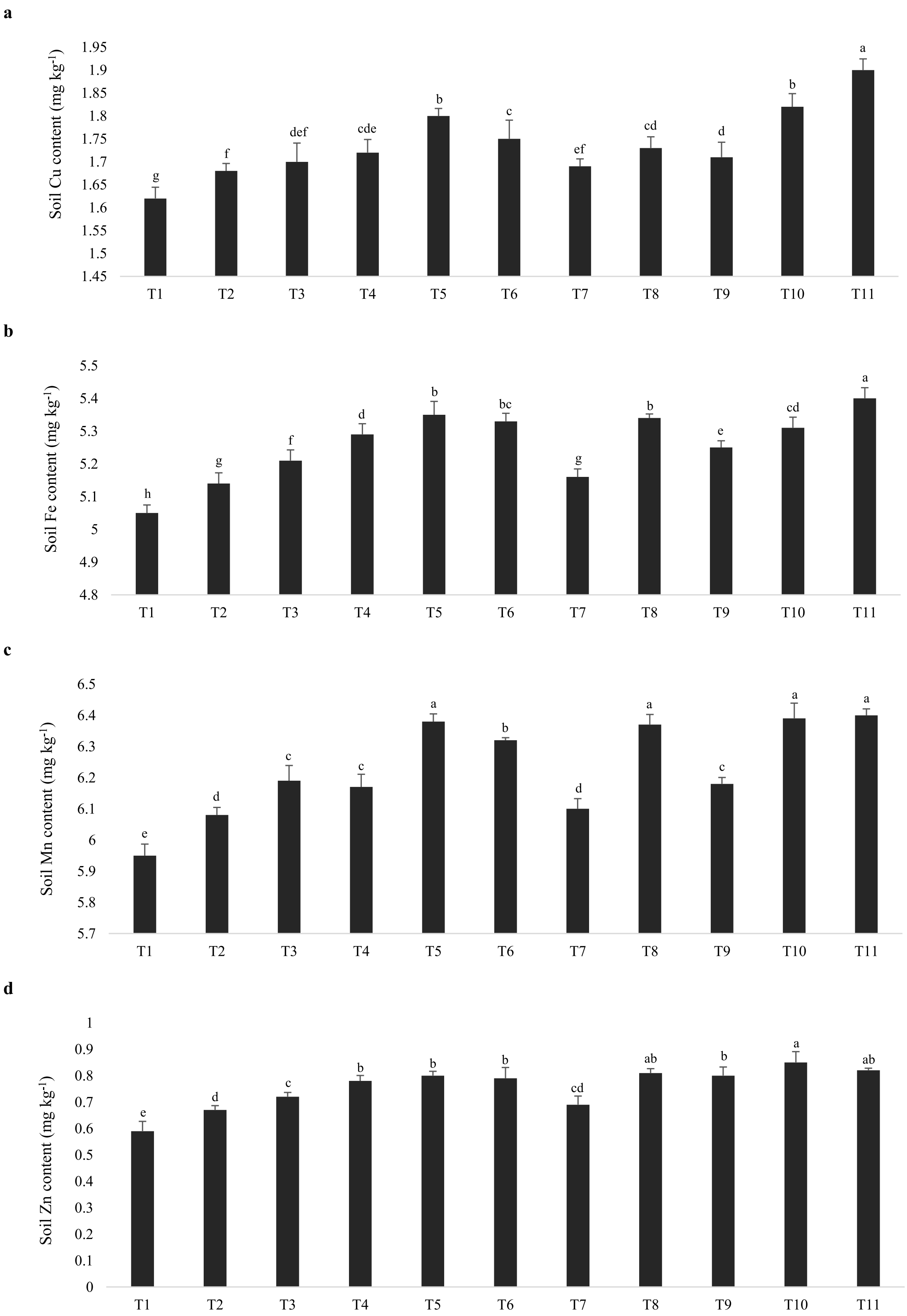

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Fig. 2. Soil micro-nutrient status nutrient management practices after completion of the two-year study, **a.** soil Cu content, **b.** soil Fe content, **c.** soil Mn content, and **d.** soil Zn content. [Note– T_1: NP control ($N_{120}P_{40}$); T_2: $N_{120}P_{40}K_{44}$; T_3: $N_{120}P_{40}K_{44}S_{40}$; T_4: $N_{120}P_{40}K_{44}S_{60}$; T_5: $N_{120}P_{40}K_{15}$+POLY4_{207}; T_6: $N_{120}P_{40}$+POLY4_{315}; T_7: $N_{160}P_{40}K_{44}$; T_8: $N_{160}P_{40}K_{44}S_{40}$; T_9: $N_{160}P_{40}K_{44}S_{60}$; T_{10}: $N_{160}P_{40}K_{15}$+POLY4_{207}; T_{11}: $N_{160}P_{40}$+POLY4_{315}; Values subscripted with N, P, K, and POLY4 are denoting the rate of application in kg ha^{-1}, the lines above each bar denote standard error ($n = 3$); different small letters above the lines of each bar represent statistical significance at 5% probability level, otherwise at par].

important nutrient elements, S which is known to be essential for higher oil yields in oilseed crops [5,44]. The supply of essential plant nutrients to the crops with the combined use of chemical fertiliser and POLY4 was found to be beneficial in narrowing the existing wide gap in the nutrient balance in cropping systems. Such, an approach also ensured balanced nutrition to the crops and thereby, increased crop productivity as well as quality. The use of POLY4 supplementation did not have any significant adverse impact on the erucic acid as well as glucosinolate contents in the current experiment. Indian mustard oil contains a low amount of saturated fatty acids (palmitic and stearic acid) and a high amount of mono-unsaturated fatty acids (oleic, eicosenoic, and erucic acids), and poly-unsaturated fatty acids (linoleic and linolenic acids) [45]. In the POLY4-based treatments, a higher Omega-3 fatty acid viz. linolenic acid content was recorded which may be due to the balancing of the Mg:S ratio in the plant system. Similar findings were also reported by Jahangir et al. [46].

4.3. Nutrient uptake

In the current study, higher levels of uptake of macro, as well as micronutrients, have been recorded with the use of POLY4 (Table 6). This could be attributed to the higher availability of N, P, K, S, Zn, Cu, Mn, etc. in soil (Figs. 1 and Fig. 2a–d) as well as the positive impact of balanced fertilisation on soil properties facilitating greater uptake and recovery of those nutrients by the crop. The higher uptake of nutrients could have increased the photosynthetic activities of plants, which ultimately helped in better crop growth and higher yield [47]. Inclusion of Ca, Mg, K, and S-rich POLY4 with conventional N, P, and K fertilization schedules for mustard might reduce the problems associated with nutrient-limitation factors as evidenced by the augmented yield level as well as nutrient uptake by the crop. Application of POLY4 may increase the stiffness of the stem due to its high K content leading to less lodging which may be helpful in decreasing the extent of yield loss due to stem failures and insect pest damage [48].

5. Conclusions

Polyhalite (POLY4) is a highly efficient fertiliser for supplying K, S, Mg, and C relative to equivalent soluble salts. Integration of polyhalite with N and P or N, P, and K fertilisers could increase nutrient availability in soil compared to the application of conventional N, P, K, and S fertilisers alone. The experiment conducted at Pantnagar on Indian mustard revealed that polyhalite (POLY4) treatments recorded an increase in grain yield of about 400–500 kg ha^{-1} over applying all essential nutrients through conventional fertilisers viz. urea, DAP, and KCl during two years of trials. This seems to be a direct effect of POLY4 which carries soluble nutrients in granular form and fulfills the application of K, Mg, and S in one go. The better secondary nutrition of plants also resulted in better micronutrient uptake, thereby better plant growth, yield, and oil content as evidenced by experimental results using POLY4 on Indian mustard. Besides increasing the productivity of mustard, POLY4 application also resulted in an improvement of oil quality, linolenic acid, and nutrient uptake by the crop. Application of POLY4 with conventional N, P fertilizers also showed an increment in the net returns of about USD 60 comparing net returns with the application of conventional N, P, K, and S fertilizers. Based on this two-year study, it can be concluded that the application of recommended rate of N (120 kg ha^{-1}) and P (40 kg ha^{-1}) through urea and DAP along with the application of 315 kg ha^{-1} POLY4 can be a suitable fertilisation schedule for Indian mustard achieving optimum yield and quality.

Author contribution statement

Biswajit Pramanick, B.S. Mahapatra, S.P. Singh, Neeraj Awasthi: Conceived and designed the experiments.
Debarati Datta, Prithwiraj Dey, Biswajit Pramanick: Performed the experiments.
Debarati Datta, Biswajit Pramanick, Ajay Kumar, Bappa Paramanik: Analyzed and interpreted the data.
B.S. Mahapatra, Ajay Kumar, Neeraj Awasthi: Contributed reagents, materials, analysis tools or data.
Biswajit Pramanick, Bappa Paramanik, Prithwiraj Dey: Wrote the paper.

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Data availability statement

Data included in article/supplementary material/referenced in article.

Declaration of interest's statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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