



RESEARCH ARTICLE

Effect of POLY4 (polyhalite) and different nutrient levels on growth and productivity of groundnut under irrigated conditions

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Received: 13 May 2026; Accepted: 15 June 2026; Available online: Version 1.0: 31 July 2026

Cite this article: Sweeta AMA, Balasubramanian P, Rajeshkumar A, Sathees KK. Effect of POLY4 (polyhalite) and different nutrient levels on growth and productivity of groundnut under irrigated conditions. Plant Science Today. 2026;13(sp5):01–08. <https://doi.org/10.14719/pst.15532>

Abstract

India is the world's second largest groundnut producer, accounting for 30 % of global production with 119.42 lakh tonnes from 57.62 lakh hectares. Despite its economic significance, the national productivity (2073 kg ha⁻¹) remains low due to sub-optimal nutrient management practices and soil compaction during the pegging stage. In this connection, this study evaluated the efficacy of POLY 4 (polyhalite), a multi-nutrient fertiliser (potassium (K), calcium (Ca), magnesium (Mg) and sulphur (S)), as both a soil amendment and a potential alternative to gypsum for groundnut cultivation. A field experiment was carried out at SRM College of Agricultural Sciences (SRMCAS), SRM Institute of Science and Technology (SRMIST), India during the rabi season of 2025–26 under irrigated conditions. The trial was laid out in a randomised block design (RBD) with 10 treatments and 3 replications on clay loam soil. The groundnut variety GG7 was sown with a spacing of 30 cm × 10 cm. The results revealed that the application of 100 % recommended dose of fertiliser (RDF-nitrogen and phosphorus (NP)- 25:50 kg ha⁻¹) with POLY4 (applied in two splits: 50 % basal and 50 % at 45 days after sowing (DAS)) recorded the highest growth and physiological attributes viz., plant height (45.7 cm), dry matter production (6573 kg ha⁻¹), number of branches plant⁻¹ (13.2), leaf area index (4.20), total chlorophyll content (50.5 μmol m⁻²) and root nodule count plant⁻¹ (273.2), alongside yield and yield attributes such as number of flowers plant⁻¹ (36), number of pegs plant⁻¹ (76), number of pods plant⁻¹ (47), filling percentage (77), number of single seeded pods plant⁻¹ (2.6), number of double seeded pods plant⁻¹ (32.2), number of matured pods plant⁻¹ (34.8), pod yield (2026 kg ha⁻¹), haulm yield (5096 kg ha⁻¹) and harvest index (0.30). Heatmap analysis further confirmed that treatment T₅ (100 % RDF (N and P) + 100 % POLY4 (polyhalite) at 50 % basal and 50 % at 45 DAS) produced strong positive normalised values for growth, physiological and yield parameters, indicating enhanced vegetative growth and reproductive efficiency. The results suggest that polyhalite can improve the yield, leading to higher groundnut productivity under irrigated conditions.

Keywords: groundnut; growth attributes; physiological parameters; polyhalite; yield attributes

Introduction

Globally, the demand for vegetable oils and fats has been rising rapidly at about 6 % per year, while local output has increased at just about 2 % annually. Groundnut is an important oilseed crop in India, primarily grown in semi-arid regions. India is the world's second largest producer of groundnuts, accounting for 30 % of global production. In India groundnut is cultivated in 57.62 lakh hectares with a production of 119.42 lakh tonnes and the average productivity of 2073 kg ha⁻¹ (1). Groundnut responds well to applied nutrients for enhancing its productivity. Hence, in groundnut cultivation, nutrient management and the application of soil amendment are crucial for optimising the growth, development and yield. Nitrogen (N) is important in groundnut for its vegetative growth, such as leaves and stems and plays a key role in photosynthesis, protein synthesis and overall crop growth. In groundnut, adequate N promotes healthy foliage and enhances the crop's ability to utilise sunlight for energy, contributing to improved yield. Phosphorus (P) is essential for energy transfer

within the plant and is critical for a strong root system, which improves flowering and enhances the development of pods.

Gypsum and POLY4 (polyhalite) play a critical role in enhancing groundnut productivity. Gypsum is a widely used source of calcium (Ca) (23 %) and sulfur (S) (18 %) that significantly improves peg penetration, pod development, shelling percentage and nodule formation in groundnut. On the other hand, POLY4 emerges as a multi-nutrient alternative to gypsum and muriate of potash (MOP), providing four macronutrients K (14 %), Ca (17 %), Mg (6 %) and S (18 %) and ensure a steady supply of nutrients (2). Potassium plays a vital role in enhancing plant resilience to biotic and abiotic stresses. It activates more than 60 enzymes and is essential during the reproductive phase of plants. It also involved the remobilisation of carbohydrates and translocation of photosynthates from source to sink. Calcium is essential for cell wall and membrane development and plays vital role in seed development and pod formation. Magnesium is an important nutrient for chlorophyll synthesis, carbohydrate metabolism, protein synthesis and nutrient uptake. Sulphur plays a key role in

enzyme activation, chlorophyll pigment and synthesising proteins, amino acids (cysteine and methionine), DNA and RNA which improves crop yield and quality. The proper management of nutrient levels and soil amendment are of huge importance as judicious and proper use of fertilisers make remarkable improvement in the yield. Keeping this information in view, the present study was conducted to evaluate the response of groundnut to POLY4 (polyhalite) for growth and yield under irrigated conditions.

Materials and Methods

An experiment was conducted at SRM College of Agricultural Sciences (SRMCAS), SRM Institute of Science and Technology (SRMIST), Chengalpattu District, Tamil Nadu during the rabi season of 2025–26. The experimental site is located at 12.38° N latitude and 79.73° E longitude. In this study, 10 treatments with 3 replications were laid out in RBD. The treatment details are furnished in Table 1. The recommended dose of fertiliser (RDF: 25 : 50 : 75 kg N : P₂O₅ : K₂O ha⁻¹) was applied using urea, single super phosphate (SSP) and MOP as sources of nitrogen, phosphorus and potassium (NPK) respectively. Gypsum was applied at a rate of 400 kg ha⁻¹ (Crop Production Guide, TNAU, 2020) and POLY4 at rate of 400 kg ha⁻¹ was applied for uniform comparison. Initial soil samples were collected from the experimental field at a depth of 0–15 cm before sowing and analyses for chemical properties using standard analytical procedures. The experimental soil was clayey loamy soil in texture with pH of 7.9, electrical conductivity (EC) of 0.2 dS m⁻¹, 0.3 % organic carbon (OC), low in available N (123 kg ha⁻¹), high in available P (53 kg ha⁻¹) and medium in available K (150 kg ha⁻¹) respectively. Soil pH and EC were measured using digital pH meter and EC meter (3), OC by chromic acid wet digestion method (4), available N by alkaline permanganate method (5), available P by Bray's method (3) and available K by flame photometer method (6). Groundnut variety GG7, a short-duration Spanish bunch type cultivar released in 2001, the variety matures in 100–105 days and

has a yield potential of 2149 kg ha⁻¹ pod yield and 1633 kg ha⁻¹ kernel yield. The variety is tolerant to rust and late leaf spot disease was used in this study. The crop was sown at a spacing of 30 cm × 10 cm and a seed rate of 120 kg pods ha⁻¹. Irrigation was provided at critical crop growth stages, including sowing, flowering, pegging, pod development and kernel filling stages, to avoid moisture stress. Recommended plant protection measures were followed during the crop period. The observations on growth, physiological and yield attributes were recorded at 25, 50 and 75 days after sowing (DAS) and at harvest from the tagged plants. Data were analysed using analysis of variance (ANOVA) in R-software version 4.4.1 treatment means were compared using Fisher's LSD test ($p \leq 0.05$) through the agricolae package after verifying all the assumptions and heatmap analysis were generated using Python, where all quantitative parameters were normalised to a scale of 0–1 using the Min–Max method to interpret the results (7, 8).

Results and Discussion

Growth attributes

The application of 100 % RDF (NP) + 100 % POLY4 applied as 50 % basal and 50 % at 45 DAS (T₅) significantly increased plant height (10.1, 29.4, 39.3 and 45.7 cm) at 25, 50 and 75 DAS and at harvest respectively (Table 2). This might be due to the better supply of K, Ca, Mg and S along with slow-release nature of polyhalite throughout the crop stage which promotes nutrient translocation during critical stages and improves plant height (9). This was followed by 100 % RDF (NP) + 75 % POLY4 (polyhalite) at 50 % basal and 50 % at 45 DAS (T₆) (9.6, 25.0, 33.6 and 40.6 cm) and 100 % RDF (NP) + 100 % gypsum at 50 % basal and 50 % at 45 DAS (T₉) (9.4, 25.0, 33.1 and 40.2 cm) which were statistically on par. The absolute control treatment (T₁₀) recorded the lowest plant height (7.5, 18.2, 25.8 and 32.2 cm) at 25, 50 and 75 DAS and at harvest respectively. This may be due to absence of essential nutrients required for proper growth and development (10).

Dry matter production significantly increased with the

Table 1. Treatment details

Treatment
T ₁ : 100 % RDF (N and P) + 100 % POLY4 (polyhalite) at basal application
T ₂ : 100 % RDF (N and P) + 75 % POLY4 (polyhalite) at basal application
T ₃ : 100 % RDF (N and P) + 50 % POLY4 (polyhalite) at basal application
T ₄ : 100 % RDF (N and P) + 25 % POLY4 (polyhalite) at basal application
T ₅ : 100 % RDF (N and P) + 100 % POLY4 (polyhalite) at 50 % basal and 50 % at 45 DAS
T ₆ : 100 % RDF (N and P) + 75 % POLY4 (polyhalite) at 50 % basal and 50 % at 45 DAS
T ₇ : 100 % RDF (N and P) + 50 % POLY4 (polyhalite) at 50 % basal and 50 % at 45 DAS
T ₈ : 100 % RDF (N and P) + 25 % POLY4 (polyhalite) at 50 % basal and 50 % at 45 DAS
T ₉ : 100 % RDF (NPK) + 100 % Gypsum at 50 % basal and 50 % at 45 DAS
T ₁₀ : Absolute control

DAS: days after sowing; RDF: recommended dose of fertiliser.

Table 2. Effect of nutrient levels and time of POLY4 application on plant height (cm) of groundnut

Treatment	25 DAS	50 DAS	75 DAS	At harvest
T ₁ : 100 % RDF (N and P) + 100 % POLY4 (polyhalite) at basal application	9.4 ^c	23.4 ^c	31.2 ^c	38.3 ^c
T ₂ : 100 % RDF (N and P) + 75 % POLY4 (polyhalite) at basal application	9.2 ^c	22.8 ^{cd}	31.1 ^{dc}	38.1 ^c
T ₃ : 100 % RDF (N and P) + 50 % POLY4 (polyhalite) at basal application	9.2 ^c	20.7 ^e	30.3 ^c	37.4 ^c
T ₄ : 100 % RDF (N and P) + 25 % POLY4 (polyhalite) at basal application	8.1 ^f	20.3 ^e	29.1 ^c	36.1 ^c
T ₅ : 100 % RDF (N and P) + 100 % POLY4 (polyhalite) at 50 % basal and 50 % at 45 DAS	10.1 ^a	29.4 ^a	39.3 ^a	45.7 ^a
T ₆ : 100 % RDF (N and P) + 75 % POLY4 (polyhalite) at 50 % basal and 50 % at 45 DAS	9.6 ^b	25.0 ^b	33.6 ^b	40.6 ^b
T ₇ : 100 % RDF (N and P) + 50 % POLY4 (polyhalite) at 50 % basal and 50 % at 45 DAS	8.9 ^d	21.1 ^{de}	30.1 ^c	37.2 ^c
T ₈ : 100 % RDF (N and P) + 25 % POLY4 (polyhalite) at 50 % basal and 50 % at 45 DAS	8.4 ^e	21.3 ^{de}	29.6 ^c	36.6 ^c
T ₉ : 100 % RDF (NPK) + 100 % gypsum at 50 % basal and 50 % at 45 DAS	9.4 ^b	25.0 ^b	33.1 ^b	40.2 ^b
T ₁₀ : Absolute control	7.5 ^g	18.2 ^f	25.8 ^d	32.2 ^d
CD ($p \leq 0.05$)	0.35	1.01	2.62	3.94
F value	33.48*	65.82*	13.43*	6.24*

DAS: days after sowing; RDF: recommended dose of fertiliser. *Significant at $p \leq 0.05$; NS: non-significant ($p > 0.05$).

application of 100 % RDF (NP) + 100 % POLY4 (polyhalite) at 50 % basal and 50 % at 45 DAS (T_5) at 25, 50, 75 DAS and at harvest (444, 2373, 4302 and 6573 kg ha⁻¹) (Table 3). The higher dry matter production was due to the balanced application of major nutrients along with application of polyhalite which has improved photosynthetic activity, metabolic process leading to greater biomass accumulation in groundnut. It was followed by 100 % RDF (NP) + 75 % POLY4 (polyhalite) at 50 % basal and 50 % at 45 DAS (T_6) (383, 1944, 3503 and 6200 kg ha⁻¹) and 100 % RDF (NP) + 100 % gypsum at 50 % basal and 50 % at 45 DAS (T_9) (378, 1900, 3422 and 5653 kg ha⁻¹) which were statistically on par, while the lowest dry matter production (DMP) was recorded in the absolute control (T_{10}) (178, 579, 980 and 2066 kg ha⁻¹) indicating that a nutrient deficiency may have occurred during critical stage which leads to low dry matter production (11).

The application of 100 % RDF (NP) + 100 % POLY4 (polyhalite) at 50 % basal and 50 % at 45 DAS (T_5) recorded higher number of branches/plant (9.0, 10.4, 12.5 and 13.2) followed by 100 % RDF (NP) + 75 % POLY4 (polyhalite) at 50 % basal and 50 % at 45 DAS (T_6) (7.9, 9.4, 11.3 and 11.9) and 100 % RDF (NPK) + 100 % gypsum at 50 % basal and 50 % at 45 DAS (T_9) (7.5, 8.4, 10.5 and 11.8) which are significantly on par while the lowest was recorded in T_{10} (4.4, 5.8, 6.9 and 7.9) (Table 4). The growth attributes increased under polyhalite application due to secondary nutrients (Ca^{2+} and Mg^{2+}) available while the reduction of growth attributes were due to the unavailability of K^+ and SO_4^{2-} during critical crop growth stages. Related findings were reported (12).

Physiological parameters

The physiological parameters were significantly influenced by different treatments. Higher leaf area index and total chlorophyll content ($\mu\text{mol m}^{-2}$) (Fig. 1, Table 5) were observed in the application of 100 % RDF (NP) + 100 % POLY4 (polyhalite) at 50 % basal and 50 % at 45 DAS (T_5) on 25, 50, 75 DAS (0.91, 4.32, 4.68, 4.20 and 36.1, 52.5, 50.5 $\mu\text{mol m}^{-2}$). It is followed by 100 % RDF (NP) +

75 % POLY4 (polyhalite) at 50 % basal and 50 % at 45 DAS (T_6) (0.79, 3.95, 4.07, 3.59 and 33.7, 44.7, 42.7 $\mu\text{mol m}^{-2}$) and 100 % RDF (NP) + 100 % gypsum at 50 % basal and 50 % at 45 DAS (T_9) (0.78, 3.90, 4.00, 3.52 and 33.3, 44.3, 42.3 $\mu\text{mol m}^{-2}$) which are significantly on par while the lowest was recorded in absolute control (T_{10}) (0.66, 2.83, 2.93, 2.45 and 28.0, 35.6, 32.7 $\mu\text{mol m}^{-2}$). This indicates that the sustained supply of K, Ca, Mg and S through split application of POLY4 supported chlorophyll synthesis, canopy development and nutrient uptake. The additional nutrient supply at 45 DAS matched the increased demand of crops during active growth and reproductive stages, resulting in improved photosynthetic efficiency and physiological performance. Related research in groundnut was reported (13).

Number of root nodules plant⁻¹

The application of 100 % RDF (NP) + 100 % POLY4 (polyhalite) at 50 % basal and 50 % at 45 DAS (T_5) significant influence on number of root nodules plant⁻¹ with a value of 107.0 and 273.2 (Fig. 2) due to supply of K and S through polyhalite supports cell division, root development, rhizobium activity and increases nodulation. The lowest was observed in absolute control (T_{10}) (55.0 and 205.1). Similar findings regarding the number of root nodules plant⁻¹ under polyhalite application in groundnut were reported earlier (13, 14).

Yield and yield attributes

The yield attributes such as number of flowers per plant, number of pegs plant⁻¹, number of pods plant⁻¹, filling percentage, number of matured pods plant⁻¹, number of single seeded pods plant⁻¹ and number of double seeded pods plant⁻¹ were significantly influenced by different treatments (Tables 6–8). The application of 100 % RDF (NP) + 100 % POLY4 (polyhalite) at 50 % basal and 50 % at 45 DAS (T_5) recorded higher number of flowers plant⁻¹ (36), number of pegs plant⁻¹ (76), number of pods plant⁻¹ (47), filling percentage (77), number of matured pods plant⁻¹ (34.8), number of double seeded pods plant⁻¹ (32.2), lower number of single seeded

Table 3. Effect of nutrient levels and time of POLY4 application on dry matter production (kg ha⁻¹) of groundnut

Treatment	25 DAS	50 DAS	75 DAS	At harvest
T_1 : 100 % RDF (N and P) + 100 % POLY4 (polyhalite) at basal application	318 ^c	1830 ^c	3342 ^c	5533 ^c
T_2 : 100 % RDF (N and P) + 75 % POLY4 (polyhalite) at basal application	300 ^d	1651 ^c	3002 ^c	5213 ^d
T_3 : 100 % RDF (N and P) + 50 % POLY4 (polyhalite) at basal application	300 ^d	1474 ^d	2648 ^d	5146 ^d
T_4 : 100 % RDF (N and P) + 25 % POLY4 (polyhalite) at basal application	233 ^f	981 ^f	1730 ^e	4293 ^f
T_5 : 100 % RDF (N and P) + 100 % POLY4 (polyhalite) at 50 % basal and 50 % at 45 DAS	444 ^a	2373 ^a	4302 ^a	6573 ^a
T_6 : 100 % RDF (N and P) + 75 % POLY4 (polyhalite) at 50 % basal and 50 % at 45 DAS	383 ^b	1943 ^b	3503 ^b	6200 ^b
T_7 : 100 % RDF (N and P) + 50 % POLY4 (polyhalite) at 50 % basal and 50 % at 45 DAS	244 ^e	1291 ^e	2338 ^d	4920 ^e
T_8 : 100 % RDF (N and P) + 25 % POLY4 (polyhalite) at 50 % basal and 50 % at 45 DAS	233 ^f	999 ^f	1765 ^e	4293 ^f
T_9 : 100 % RDF (NPK) + 100 % Gypsum at 50 % basal and 50 % at 45 DAS	378 ^b	1900 ^b	3422 ^b	5653 ^b
T_{10} : Absolute control	177 ^g	579 ^g	980 ^f	2066 ^g
CD ($P \leq 0.05$)	11.69	113.59	313.13	243.95
F value	331.62*	158.11*	74.66*	180.34*

DAS: days after sowing; RDF: recommended dose of fertiliser. *Significant at $p \leq 0.05$; NS: non-significant ($p > 0.05$).

Table 4. Effect of nutrient levels and time of POLY4 application on number of branches/plant of groundnut

Treatment	25 DAS	50 DAS	75 DAS	At harvest
T_1 : 100 % RDF (N and P) + 100 % POLY4 (polyhalite) at basal application	6.7 ^{bc}	8.2 ^c	10.2 ^c	11.2 ^c
T_2 : 100 % RDF (N and P) + 75 % POLY4 (polyhalite) at basal application	6.6 ^{bc}	8.1 ^c	10.1 ^c	11.1 ^c
T_3 : 100 % RDF (N and P) + 50 % POLY4 (polyhalite) at basal application	6.2 ^c	8.1 ^c	9.5 ^d	10.5 ^d
T_4 : 100 % RDF (N and P) + 25 % POLY4 (polyhalite) at basal application	5.3 ^d	7.1 ^c	8.0 ^e	10.0 ^e
T_5 : 100 % RDF (N and P) + 100 % POLY4 (polyhalite) at 50 % basal and 50 % at 45 DAS	9.0 ^a	10.4 ^a	12.5 ^a	13.2 ^a
T_6 : 100 % RDF (N and P) + 75 % POLY4 (polyhalite) at 50 % basal and 50 % at 45 DAS	7.9 ^{ab}	9.4 ^b	11.3 ^b	11.9 ^b
T_7 : 100 % RDF (N and P) + 50 % POLY4 (polyhalite) at 50 % basal and 50 % at 45 DAS	5.6 ^{cd}	7.6 ^c	8.5 ^e	10.3 ^{de}
T_8 : 100 % RDF (N and P) + 25 % POLY4 (polyhalite) at 50 % basal and 50 % at 45 DAS	5.5 ^{cd}	7.3 ^c	8.4 ^e	10.2 ^e
T_9 : 100 % RDF (NPK) + 100 % Gypsum at 50 % basal and 50 % at 45 DAS	7.5 ^b	8.4 ^b	10.5 ^b	11.8 ^b
T_{10} : Absolute control	4.4 ^e	5.8 ^d	6.9 ^f	7.9 ^f
CD ($P \leq 0.05$)	1.04	1.05	1.07	0.39
F value	8.91*	5.15*	13.85*	86.88*

DAS: days after sowing; RDF: recommended dose of fertiliser. *Significant at $p \leq 0.05$; NS: non-significant ($p > 0.05$).

Table 5. Effect of nutrient levels and time of POLY4 application on leaf area index of groundnut

Treatment	25 DAS	50 DAS	75 DAS	At harvest
T ₁ : 100 % RDF (N and P) + 100 % POLY4 (polyhalite) at basal application	0.75 ^c	3.57 ^{bc}	3.38 ^c	3.50 ^c
T ₂ : 100 % RDF (N and P) + 75 % POLY4 (polyhalite) at basal application	0.75 ^c	3.55 ^{ba}	3.36 ^c	3.48 ^c
T ₃ : 100 % RDF (N and P) + 50 % POLY4 (polyhalite) at basal application	0.72 ^d	3.53 ^{bc}	3.34 ^c	3.36 ^c
T ₄ : 100 % RDF (N and P) + 25 % POLY4 (polyhalite) at basal application	0.68 ^e	3.30 ^c	3.61 ^c	3.13 ^c
T ₅ : 100 % RDF (N and P) + 100 % POLY4 (polyhalite) at 50 % basal and 50 % at 45 DAS	0.91 ^a	4.32 ^a	4.68 ^a	4.20 ^a
T ₆ : 100 % RDF (N and P) + 75 % POLY4 (polyhalite) at 50 % basal and 50 % at 45 DAS	0.79 ^b	3.95 ^{ab}	4.07 ^b	3.59 ^b
T ₇ : 100 % RDF (N and P) + 50 % POLY4 (polyhalite) at 50 % basal and 50 % at 45 DAS	0.72 ^d	3.48 ^{bc}	3.33 ^c	3.35 ^c
T ₈ : 100 % RDF (N and P) + 25 % POLY4 (polyhalite) at 50 % basal and 50 % at 45 DAS	0.69 ^e	3.48 ^{bc}	3.80 ^c	3.32 ^c
T ₉ : 100 % RDF (NPK) + 100 % gypsum at 50 % basal and 50 % at 45 DAS	0.78 ^b	3.90 ^{ab}	4.00 ^b	3.52 ^b
T ₁₀ : Absolute control	0.66 ^f	2.83 ^d	2.93 ^d	2.45 ^d
CD ($p \leq 0.05$)	0.02	0.48	0.47	0.44
F value	76.39*	5.83*	7.45*	7.58*

DAS: days after sowing; RDF: recommended dose of fertilizer. *Significant at $p \leq 0.05$; NS: non-significant ($p > 0.05$).

Table 6. Effect of nutrient levels and time of POLY4 application on number of flowers/plant of groundnut

Treatment	25 DAS	50 DAS
T ₁ : 100 % RDF (N and P) + 100 % POLY4 (polyhalite) at basal application	6.7 ^c	26.0 ^c
T ₂ : 100 % RDF (N and P) + 75 % POLY4 (polyhalite) at basal application	6.6 ^c	26.0 ^c
T ₃ : 100 % RDF (N and P) + 50 % POLY4 (polyhalite) at basal application	6.3 ^d	25.0 ^c
T ₄ : 100 % RDF (N and P) + 25 % POLY4 (polyhalite) at basal application	6.0 ^e	24.5 ^c
T ₅ : 100 % RDF (N and P) + 100 % POLY4 (polyhalite) at 50 % basal and 50 % at 45 DAS	9.0 ^a	36.0 ^a
T ₆ : 100 % RDF (N and P) + 75 % POLY4 (polyhalite) at 50 % basal and 50 % at 45 DAS	7.5 ^b	30.8 ^b
T ₇ : 100 % RDF (N and P) + 50 % POLY4 (polyhalite) at 50 % basal and 50 % at 45 DAS	6.0 ^e	24.0 ^c
T ₈ : 100 % RDF (N and P) + 25 % POLY4 (polyhalite) at 50 % basal and 50 % at 45 DAS	6.0 ^e	24.5 ^c
T ₉ : 100 % RDF (NPK) + 100 % Gypsum at 50 % basal and 50 % at 45 DAS	7.3 ^b	29.6 ^b
T ₁₀ : Absolute control	4.5 ^f	18.9 ^d
CD ($P \leq 0.05$)	0.27	2.16
F value	134.30*	36.18*

DAS: days after sowing; RDF: recommended dose of fertiliser. *Significant at $p \leq 0.05$; NS: non-significant ($p > 0.05$).

Table 7. Effect of nutrient levels and time of POLY4 application on number of pods/plant, number of pegs/plant and filling percentage of groundnut

Treatment	Number of pegs/plant	Number of pods/plant	Filling percentage
T ₁ : 100 % RDF (N and P) + 100 % POLY4 (polyhalite) at basal application	68 ^{bc}	40 ^c	70.5 ^c
T ₂ : 100 % RDF (N and P) + 75 % POLY4 (polyhalite) at basal application	68 ^{bc}	40 ^c	69.8 ^c
T ₃ : 100 % RDF (N and P) + 50 % POLY4 (polyhalite) at basal application	66 ^c	43 ^c	66.5 ^d
T ₄ : 100 % RDF (N and P) + 25 % POLY4 (polyhalite) at basal application	54 ^d	35 ^e	64.6 ^f
T ₅ : 100 % RDF (N and P) + 100 % POLY4 (polyhalite) at 50 % basal and 50 % at 45 DAS	76 ^a	47 ^a	77.0 ^a
T ₆ : 100 % RDF (N and P) + 75 % POLY4 (polyhalite) at 50 % basal and 50 % at 45 DAS	71 ^b	45 ^b	74.9 ^b
T ₇ : 100 % RDF (N and P) + 50 % POLY4 (polyhalite) at 50 % basal and 50 % at 45 DAS	64 ^c	43 ^c	65.6 ^e
T ₈ : 100 % RDF (N and P) + 25 % POLY4 (polyhalite) at 50 % basal and 50 % at 45 DAS	56 ^d	41 ^d	64.9 ^f
T ₉ : 100 % RDF (NPK) + 100 % Gypsum at 50 % basal and 50 % at 45 DAS	70 ^b	42 ^b	75.2 ^b
T ₁₀ : Absolute control	44 ^e	28 ^f	59.6 ^g
CD ($P \leq 0.05$)	3.48	2.41	2.04
F value	68.48*	38.59*	2.61*

DAS: days after sowing; RDF: recommended dose of fertiliser. *Significant at $p \leq 0.05$; NS: non-significant ($p > 0.05$).

Table 8. Effect of nutrient levels and time of POLY4 application on number of single seeded pods/plant, number of double seeded pods/plant and number of matured pods/plant of groundnut

Treatment	No. of single seeded pods/plant	No. of double seeded pods/plant	No. of matured pods/plant
T ₁ : 100 % RDF (N and P) + 100 % POLY4 (polyhalite) at basal application	3.8 ^d	24.5 ^c	28.2 ^c
T ₂ : 100 % RDF (N and P) + 75 % POLY4 (polyhalite) at basal application	4.3 ^d	23.6 ^c	27.9 ^c
T ₃ : 100 % RDF (N and P) + 50 % POLY4 (polyhalite) at basal application	6.0 ^c	22.6 ^c	28.6 ^c
T ₄ : 100 % RDF (N and P) + 25 % POLY4 (polyhalite) at basal application	7.0 ^b	15.6 ^e	22.6 ^d
T ₅ : 100 % RDF (N and P) + 100 % POLY4 (polyhalite) at 50 % basal and 50 % at 45 DAS	2.6 ^f	32.2 ^a	34.8 ^a

T ₆ : 100 % RDF (N and P) + 75 % POLY4 (polyhalite) at 50 % basal and 50 % at 45 DAS	3.7 ^e	28.0 ^b	31.7 ^b
T ₇ : 100 % RDF (N and P) + 50 % POLY4 (polyhalite) at 50 % basal and 50 % at 45 DAS	6.3 ^{bc}	21.9 ^c	28.2 ^c
T ₈ : 100 % RDF (N and P) + 25 % POLY4 (polyhalite) at 50 % basal and 50 % at 45 DAS	6.8 ^b	19.8 ^d	26.6 ^{cd}
T ₉ : 100 % RDF (NPK) + 100 % Gypsum at 50 % basal and 50 % at 45 DAS	3.4 ^e	28.2 ^b	31.6 ^b
T ₁₀ : Absolute control	9.5 ^a	7.2 ^f	16.7 ^e
CD ($P \leq 0.05$)	0.67	3.30	2.66
F value	61.70*	31.46*	25.60*

DAS: days after sowing; RDF: recommended dose of fertiliser. *Significant at $p \leq 0.05$; NS: non-significant ($p > 0.05$).

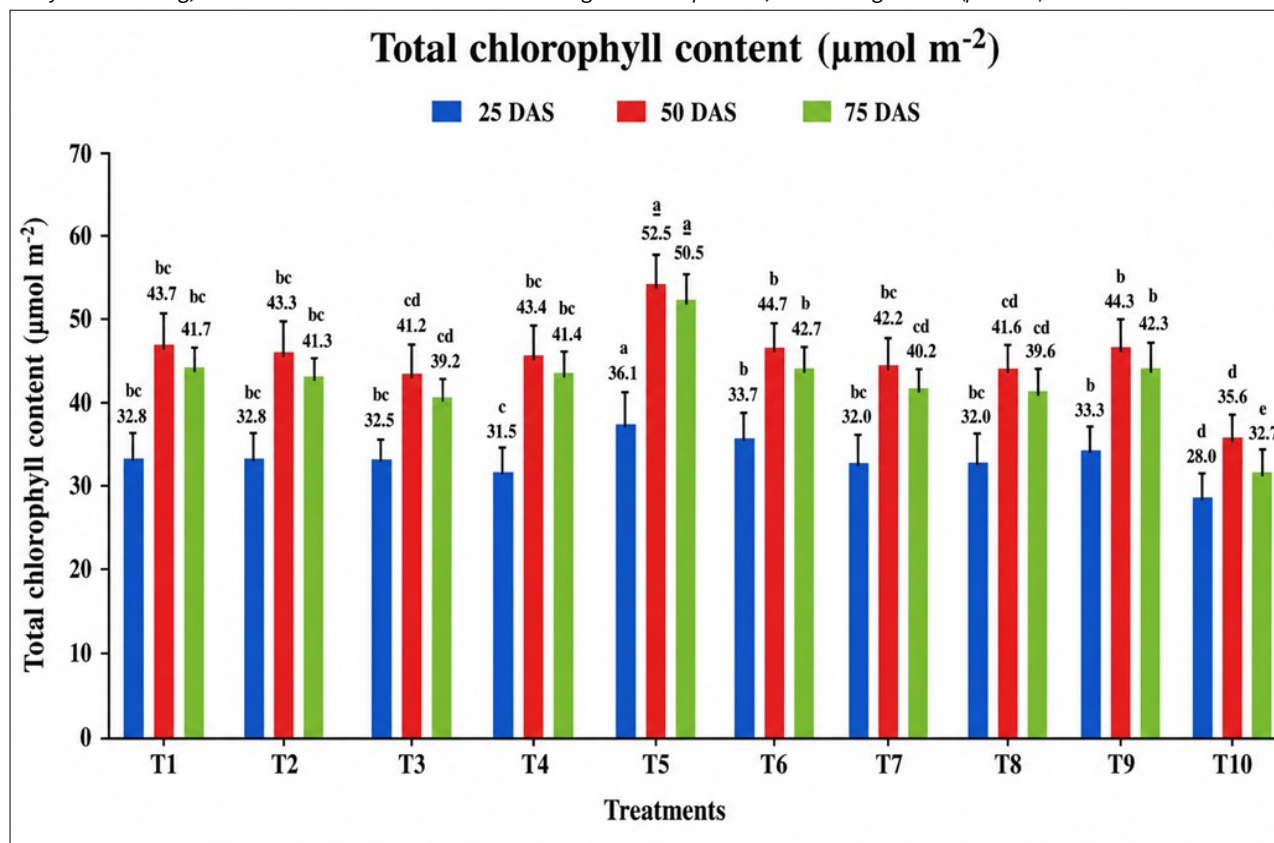


Fig. 1. Effect of nutrient levels and time of POLY4 application on total chlorophyll content ($\mu\text{mol m}^{-2}$) of groundnut.

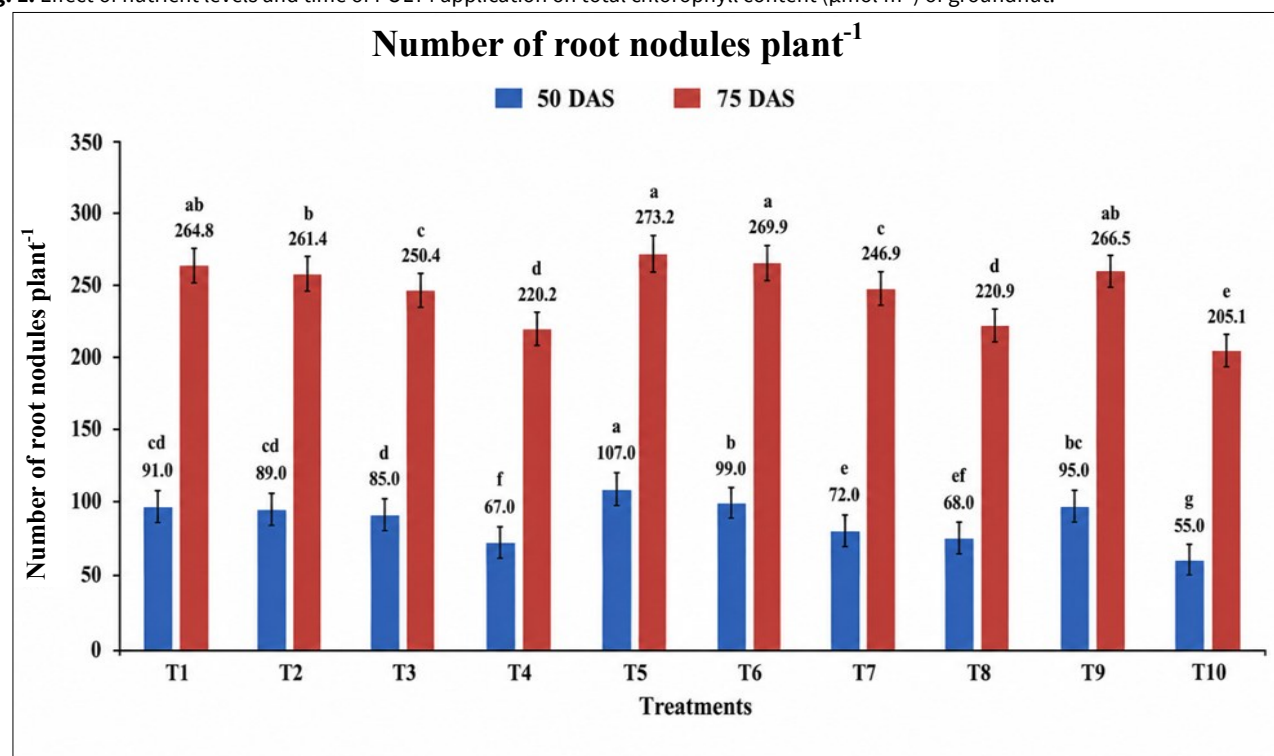


Fig. 2. Effect of nutrient levels and time of POLY4 application on number of root nodules/plant of groundnut.

pods plant⁻¹ (2.6). It was followed by 100 % RDF (NP) + 75 % POLY4 (Polyhalite) at 50 % basal and 50 % at 45 DAS (T₆) (30.8, 71, 45, 74.9, 31.7, 28.0 and 3.7) and 100 % RDF (NPK) + 100 % gypsum at 50 % basal and 50 % at 45 DAS (T₉) (29.6, 70, 42, 75.2, 31.6, 28.2 and 3.4) which are significantly on par. This was due to the balanced supply of nutrients through polyhalite, K improves enzyme activity and movement of photosynthates from source to sink, leading to better peg formation, pod development and filling percentage in groundnut. Calcium supports cell division, flower initiation, peg penetration, loosening of soil, pod development, pod setting and development of filled mature pods while reducing unfilled immature pods. Sulphur and Mg enhanced chlorophyll formation, photosynthetic activity and improves reproductive performance and yield and yield attributes. The lowest was recorded with a treatment of absolute control (T₁₀) (18.9, 44, 28, 59.6, 16.7, 7.2 and 9.5) due to imbalance availability of macro and micronutrient. Similar findings were reported (13, 14).

Pod and haulm yield

The application of 100 % RDF (NP) + 100 % POLY4 (polyhalite) at 50 % basal and 50 % at 45 DAS (T₅) was significantly increased pod yield (2026 kg ha⁻¹), haulm yield (5096 kg ha⁻¹) respectively due to the synergistic role of macronutrients (N and P) and micronutrients (Ca, Mg and S) improves seed formation (15) (Table 9). The slow release and split application of polyhalite prevents excessive K uptake in early stages and ensures continuous nutrient availability during reproductive period by minimising antagonism between cations (K⁺, Ca²⁺ and Mg²⁺), polyhalite allows for better nutrient absorption and translocation which leads to higher nutrient use efficiency and improved physiological performance viz., chlorophyll synthesis, loosening of soil, peg penetration and higher biomass production. These physiological and biological responses improve reproductive performance and results in higher pod and haulm yield in groundnut. It was followed by 100 % RDF (NP) + 75 % POLY4 (polyhalite) at 50 % basal and 50 % at 45 DAS (T₆) (1892 kg ha⁻¹ and 4700 kg ha⁻¹) and 100 % RDF (NPK) + 100 % gypsum at 50 % basal and 50 % at 45 DAS (T₉) (1890 kg ha⁻¹ and 4543 kg ha⁻¹) which were significantly on par. The lower pod yield (1280 kg/ha) and haulm yield (3600 kg ha⁻¹) was observed in (T₁₀) control (Table 8). The higher harvest index was observed in T₅ (0.30) and the lower was observed in T₁₀ (0.26). It might be due to inadequate

nutrient availability, poor physiological activity which leads to poor yield in groundnut. The higher pod and haulm yields recorded under polyhalite fertilisation may be attributed to improved nutrient availability and soil fertility, a response that has also been reported across different cropping systems (16, 17). Heatmap analysis showed strong positive associations among growth, physiological and yield parameters under POLY4 treatments. Overall, the graphical analysis revealed that T₅ treatment was effective treatment compared to other treatments. This suggests a synergetic relationship possibly driven by polyhalite and nutrient levels higher crop growth, more biomass accumulation and higher yield, whereas T₁₀ recorded lower values for several growth and yield parameters (Fig. 3).

Conclusion

In this study, the application of 100 % recommended dose of fertiliser (RDF) nitrogen and phosphorus (NP) along with 100 % POLY4 applied as 50 % basal and 50 % at 45 days after sowing (DAS) significantly increased the plant height, dry matter production, leaf area index, total chlorophyll content (μmol m⁻²), number of branches plant⁻¹, number of root nodules plant⁻¹, number of flowers plant⁻¹, number of pegs plant⁻¹, number of pods plant⁻¹, filling percentage, number of matured pods plant⁻¹, number of single seeded pods plant⁻¹, number of double seeded pods plant⁻¹, pod yield and haulm yield compared to other treatments. Thus, the application of 100 % RDF (25:50 kg ha⁻¹ N, P as basal application) along with 400 kg ha⁻¹ polyhalite at 50 % basal and 50 % at 45 DAS can be recommended to improve growth, physiological attributes and productivity of groundnut under irrigated conditions.

Acknowledgements

We acknowledge the support of the Department of Agronomy, SRM College of Agricultural Sciences, SRM Institute of Science and Technology, for providing facilities, technical help and necessary support during the research work.

Table 9. Effect of nutrient levels and time of POLY4 application on pod yield (kg/ha), haulm yield (kg/ha) and harvest index of groundnut

Treatment	Pod yield (kg/ha)	Haulm yield (kg/ha)	Harvest Index
T ₁ : 100 % RDF (N and P) + 100 % POLY4 (polyhalite) at basal application	1733 ^c	4474 ^c	0.28
T ₂ : 100 % RDF (N and P) + 75 % POLY4 (polyhalite) at basal application	1719 ^c	4417 ^c	0.28
T ₃ : 100 % RDF (N and P) + 50 % POLY4 (polyhalite) at basal application	1647 ^{cd}	4258 ^{cd}	0.28
T ₄ : 100 % RDF (N and P) + 25 % POLY4 (polyhalite) at basal application	1468 ^e	3994 ^d	0.27
T ₅ : 100 % RDF (N and P) + 100 % POLY4 (polyhalite) at 50 % basal and 50 % at 45 DAS	2026 ^a	5096 ^a	0.30
T ₆ : 100 % RDF (N and P) + 75 % POLY4 (polyhalite) at 50 % basal and 50 % at 45 DAS	1892 ^b	4700 ^b	0.29
T ₇ : 100 % RDF (N and P) + 50 % POLY4 (polyhalite) at 50 % basal and 50 % at 45 DAS	1628 ^d	4327 ^c	0.27
T ₈ : 100 % RDF (N and P) + 25 % POLY4 (polyhalite) at 50 % basal and 50 % at 45 DAS	1508 ^e	4128 ^d	0.27
T ₉ : 100 % RDF (NPK) + 100 % Gypsum at 50 % basal and 50 % at 45 DAS	1890 ^b	4543 ^b	0.29
T ₁₀ : Absolute control	1280 ^f	3600 ^e	0.26
CD (<i>P</i> ≤ 0.05)	157.89	360.34	-
F value	13.52*	8.53*	-

DAS: days after sowing; RDF: recommended dose of fertiliser. *Significant at *p* ≤ 0.05; NS: non-significant (*p* > 0.05).

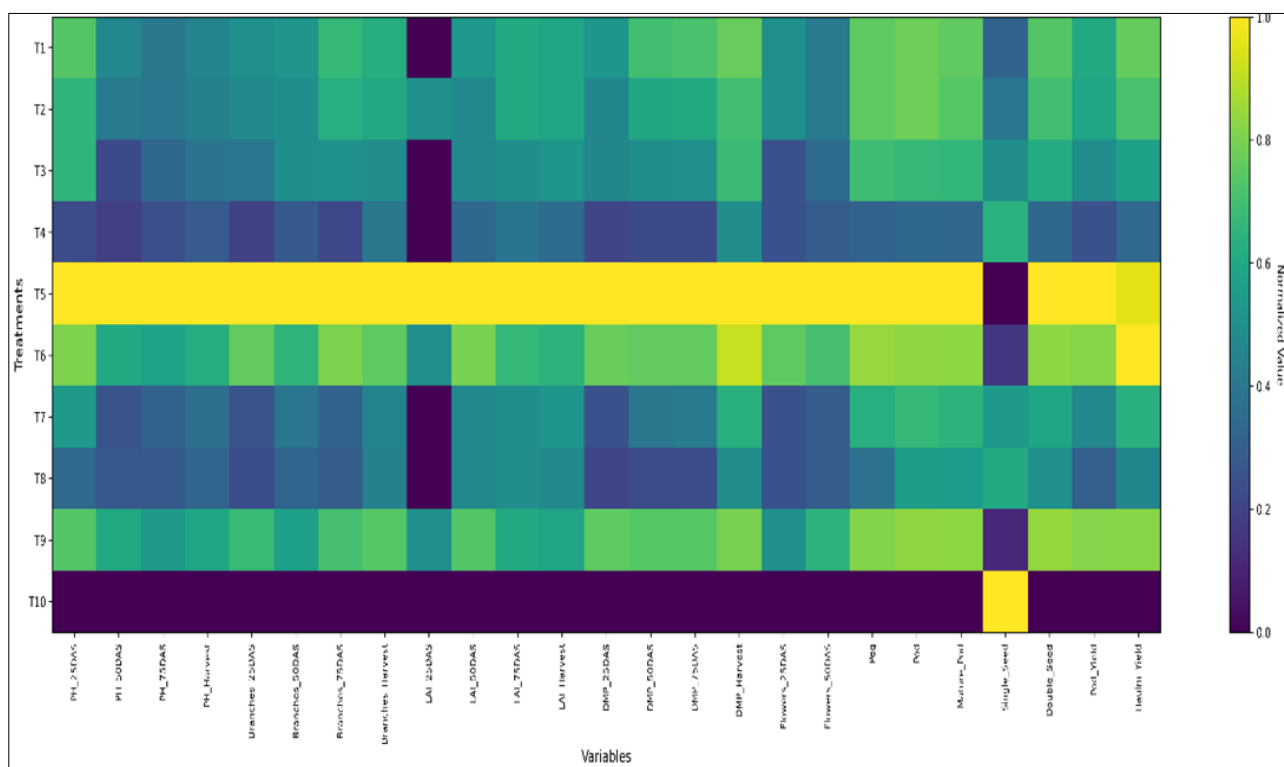


Fig. 3. Heatmap analysis of overall treatments for growth and yield attributes.

Authors' contributions

SAMA conducted field trials, collection of data and performed the design of the research analysis. BP contributed to the collection of literature review and drafting of the manuscript. RA read and communicated for approval of the final manuscript. SKK was involved in the design of the study and carried out the statistical analysis. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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