

GROWTH, YIELD AND QUALITY PARAMETERS OF GROUNDNUT (*ARACHIS HYPOGAEA* L.) AS INFLUENCED BY DIFFERENT LEVELS OF PHOSPHORUS, SULPHUR AND BIOFERTILIZERS IN LATERITIC SOILS OF ODISHA

Sushma Mahato¹, Anwesha Mohanty², Lipsa Mohanty³, Aishwarya Sahoo⁴, Gayatri Sahu^{5*}

¹PG scholar, Dept of soil science and agricultural chemistry, Siksha O Anusandhan University, Bhubaneswar, Odisha-751029, mahatosushma376@gmail.com

²PG scholar, Dept of soil science and agricultural chemistry, Siksha O Anusandhan University, Bhubaneswar, Odisha-751029, anwesha.mohanty99@gmail.com

³PG scholar, Dept of soil science and agricultural chemistry, Siksha O Anusandhan University, Bhubaneswar, Odisha-751029, lipsamohanty1397@gmail.com

⁴PG scholar, Dept of soil science and agricultural chemistry, Siksha O Anusandhan University, Bhubaneswar, Odisha-751029, aishwarya.sahoo01@gmail.com

^{5*}Assistant Professor, Siksha O Anusandhan University, Bhubaneswar, Odisha-751029, gayatrisahu@soa.ac.in

ABSTRACT

A field experiment entitled “Effect of different level of phosphorus, Sulphur & Bio-fertilizers on the growth, yield and quality parameters of groundnut in lateritic soil of Odisha” was conducted during 2025 at Agricultural Research Station, Binjhagiri, Chhatabar, Faculty of Agricultural Sciences, Siksha ‘O’ Anusandhan (Deemed to be University), Bhubaneswar Odisha. The experiment was laid out in randomized block design (RBD) with three replications, and nine treatments i.e. T₁:Control, T₂: S_(Phosphogypsum), T₃: P_(100%), T₄: P_(50%) + S_(Phosphogypsum) + Rhizobium, T₅: P_(50%) + S_(Phosphogypsum) + PSB, T₆: P_(50%) + S_(Phosphogypsum) + Rhizobium+PSB, T₇: P_(100%) + S_(Phosphogypsum) + Rhizobium, T₈: P_(100%) + S_(Phosphogypsum) + PSB, T₉: P_(100%) + S_(Phosphogypsum) + Rhizobium+PSB. The soil of the experimental site was sandy clay loam in texture with particle size groups of 32 % clay, 15 % silt and 53 % sand. The soil was non-saline (EC = 0.12 dSm⁻¹) and slightly acidic in reaction (pH = 5.5). The initial soil recorded an available Bray’s P 12.25 kg ha⁻¹ (low), available Nitrogen 248 kg ha⁻¹ (low), available Potassium 155 kg ha⁻¹ (medium), available Sulphur 14.8 kg ha⁻¹ (medium), and available Calcium Ca 3.1meq/100g of soil. . This integrated nutrient management approach notably enhanced growth parameters like plant height, dry matter accumulation, nodulation as well as yield attributes. Pod yield of ground nut ranged from 1.12 to 3.26 t/ha. Maximum pod yield was recorded in T₉ (P_(100%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 3.26 t/ha followed by T₆ (P_(50%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 2.95t/ha whereas T₇ (P_(100%) + S_(Phosphogypsum) + Rhizobium) i.e. 2.54t/ha and T₈ (P_(100%) + S_(Phosphogypsum) + PSB) i.e. 2.78 t/ha were found statistically at par and minimum was reported in control i.e. 1.12 t/ha. The haulm yield of groundnut varied between 1.75 to 3.65 t/ha. Significantly Maximum haulm yield was recorded in T₉ (P_(100%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 3.65 t/ha followed by T₆ (P_(50%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 3.36 t/ha which was statistically at par with T₈ (P_(100%) + S_(Phosphogypsum) + PSB) i.e. 3.27 t/ha whereas minimum was found in control i.e. 1.75 t/ha. Moreover, T₉ recorded the highest nutrient concentrations and uptake for nitrogen, phosphorus, potassium, and sulphur in both pods and haulm. Quality parameters such as protein content (32.19%) and oil content (20.97%) in pods were also significantly superior in T₉, confirming the beneficial effect of balanced fertilization and microbial synergy. In summary, the combination of 100% phosphorus + sulphur (phosphogypsum) + Rhizobium + PSB emerged as the most effective treatment in enhancing growth, yield, nutrient uptake, and quality of groundnut in lateritic soils, and is therefore recommended for sustainable groundnut cultivation in similar agro-ecological zones.

KEYWORDS: Phosphorus, Sulphur, Biofertilizer, Groundnut, Yield, Uptake.

INTRODUCTION

Groundnut (*Arachis hypogaea*), commonly known as peanut, holds immense importance both nutritionally and economically, making it one of the most valuable legume and oilseed crops cultivated worldwide. It is globally known as the fourth oilseed crop, the third most significant source of vegetable protein after soybean, and the thirteenth most important food crop (Akpoti et al. 2023). As a leguminous crop, groundnut has the unique ability to fix atmospheric nitrogen through symbiotic relationships with Rhizobium bacteria in its root nodules. This natural process enriches soil fertility and reduces the need for chemical fertilizers, thereby lowering input costs for farmers and minimizing environmental pollution. Phosphorus is essential for the formation of chlorophyll and protoplasm, cell division and development of meristematic tissues, also helps in the seed development and maturity of plant (Lincoln, 2022). Phosphorus (P) is the second most important essential macronutrient for plants, it is a crucial nutrient that, in many soils, restricts plant growth and is necessary for increased and sustained agricultural productivity (Puttaswamy-et-al, 2024). Phosphorus is involved in all the growth and developmental processes at both cellular and whole plant levels as, for example, cell division/elongation, membrane structure maintenance, enzyme activation, photosynthesis, respiration, seed germination, seedling establishment, root and shoot development, flower and seed formation (Sharmin -et-al, 2024).

Sulphur is now widely accepted as fourth major plant nutrient along with N, P and K. It involves in the synthesis of essential amino acids and oil in oilseed crops, being vital component of co-enzyme involved in oil synthesis (Nayee, 2022). In recent years, sulphur has gained increasing attention in crop management due to its direct impact on both yield and quality of agricultural produce. Sulfur deficiency can have severe ramifications for crop quality and yield (Hinckley-et-al, 2023). For instance, in oilseed crops, sulphur contributes directly to oil content and fatty acid composition, while in pulses and cereals, it enhances grain protein quality. In sustainable agriculture, the application of sulphur-containing amendments, such as gypsum or elemental sulphur, can help improve soil structure, reduce soil pH in alkaline soils, and enhance soil aeration and water infiltration. In natural ecosystem a sufficient amount of sulfur in the soil is required for the proper maintenance of the soil organic matter stocks and soil fertility (Magnucka -et-al, 2023). Phospho-gypsum not only supplies sulphur but also provides calcium, which is essential for cell wall development, root health, and enzyme activation. Phosphogypsum in split applications considered optimum due to both yield enhancement and environmental considerations. (Vaishnav -et-al, 2023).

Bio-fertilizer has been considered as a competitive option to synthetic fertilizer to enhance the soil fertility and crop production in sustainable agriculture. The inoculation of phosphorous solubilizing bacteria secretes phosphate solubilizer which helps in conversion of unavailable to available form of phosphorus which intern increase in yield of crops by 10-30 per cent (Baburao & Singh, 2024). Phosphate Solubilizing Bacteria (PSB) play an important role in plant nutrition by increasing phosphorus availability through solubilization and mineralization of inorganic and organic soil P pools (Singh et al., 2021). In addition to solubilizing inorganic phosphorus, microorganisms also play a key role in the mineralization of organic phosphorus. Rhizobium-mediated nitrogen fixation in legumes accounts for a significant portion of overall biological nitrogen fixation. Green gram roots have nodules capable of fixing atmospheric nitrogen through symbiotic interaction with the bacteria Rhizobium (Mandale et al., 2021).

MATERIALS AND METHODS

A field experiment was conducted during 2025 at Agricultural Research Station, Binjhagiri, Chhatabar, Faculty of Agricultural Sciences, Siksha 'O' Anusandhan (Deemed to be University), Bhubaneswar Odisha. The research site is at an altitude of around 196m above the mean sea level and falls under tropical wet and dry climatic region (also known as the savanna climate). This region experiences distinct wet and dry seasons, with significant rainfall during the monsoon months and dry conditions for the rest of the year. The proximity to the Bay of Bengal influences its climate, contributing to the area's biodiversity. Soil samples (0-15 cm depth) were collected from different spots of the experimental field systematically in a zigzag manner from the field and bulked to form a composite sample prior to land preparation and also after harvest of the crop from each plot. The composite soils sample thus collected were air dried, sieved through 2 mm sieve and stored in polythene bag, subjected to mechanical, physical and chemical analysis for obtaining initial analysis data using standard analytical procedure. Plant samples were ground into a powder and utilized to determine their nutritional value. Following harvest, the necessary quantity of powdered plant samples was gathered in order to analyze the nutrient content. The seeds were coated with Rhizobium @ 1.5 kg/ha and treated with PSB @ 1.23 kg/ha. To ensure adequate coating, the groundnut seeds were spread out on a jute mat and dusted with PSB culture solution. The seeds were dipped by hand and sown in a line after being allowed to dry in the shade. The data collected from field observation and recorded in laboratory were subjected to statistical analysis by standard analysis of variance technique as described in "Statistical Procedure for Agricultural Research" by Gomez and Gomez (1984) for significant treatment effects, standard error of means (SEm $\pm$) and critical differences were calculated at 5% level of significance.

Results and Discussion

Effect of different level of phosphorus, sulphur and bio-fertilizers on soil pH, EC and OC

The effect of different level of phosphorus in combination with sulphur and biofertilizers on soil pH (Table 1). It was observed that the pH decreased gradually from flowering to pod formation and harvest stage. The soil pH ranged from 5.71 to 5.91 at flowering, with the highest pH recorded in treatment T6 (P(50%) + S(Phosphogypsum) + Rhizobium + PSB). At pod formation, the pH ranged from 5.54 to 5.82, with the highest pH observed in treatment T5 (P(50%) + S(Phosphogypsum) + PSB). At harvest stage, the pH ranged from 5.42 to 5.68, and the highest pH was recorded in T8 (P(100%) + S(Phosphogypsum) + PSB).

Table 1 Effect of different level phosphorus, sulphur and bio-fertilizers on soil pH

Treatments	pH		
	Flowering	Pod formation	At harvest
T ₁ – Control (No fertilizer)	5.81	5.73	5.62
T ₂ - S _(Phosphogypsum)	5.71	5.54	5.42
T ₃ - P _(100%)	5.84	5.76	5.53
T ₄ - P _(50%) + S _(Phosphogypsum) + Rhizobium	5.83	5.81	5.65
T ₅ - P _(50%) + S _(Phosphogypsum) + PSB	5.86	5.82	5.62
T ₆ - P _(50%) + S _(Phosphogypsum) + Rhizobium + PSB	5.91	5.76	5.67

T ₇ - P _(100%) + S _(Phosphogypsum) + Rhizobium	5.85	5.71	5.55
T ₈ - P _(100%) + S _(Phosphogypsum) + PSB	5.73	5.72	5.68
T ₉ - P _(100%) + S _(Phosphogypsum) + Rhizobium + PSB	5.78	5.63	5.51
SEm±	0.09	0.06	0.07
CD (P=0.05)	0.14	0.18	0.16

However, the lowest pH was observed in treatment T₂ (S(Phosphogypsum)) in all the growth stages. This gradual decline in soil pH during crop growth stages can be attributed to root exudation of organic acids and enhanced microbial activity, particularly by phosphate-solubilizing bacteria (PSB), which produce acids like gluconic acid to solubilize phosphorus, thereby acidifying the rhizosphere (Chen et al., 2006). The combined application of phosphogypsum (a sulphur source) and biofertilizers further accelerates acidification due to microbial oxidation of elemental sulphur to sulphuric acid (Kandpal et al., 2019). Additionally, the higher pH in treatments with PSB and Rhizobium may be due to balanced nutrient supply and moderated acidification through buffering capacity of organic matter produced by microbial activity (Zaidi et al., 2009).

The effect of different level of phosphorus in combination with sulphur and biofertilizers on soil EC was recorded (Table 2). It was observed that EC in soil decreased gradually from flowering to pod formation and harvest stage. The soil EC ranged from 0.16 to 0.29 dS m⁻¹ at flowering,

Table 2. Effect of different level phosphorus, sulphur and bio-fertilizers on Electrical Conductivity of soil

Treatments	EC (dS m ⁻¹)		
	Flowering	Pod formation	At harvest
T ₁ – Control (No fertilizer)	0.16	0.15	0.12
T ₂ - S _(Phosphogypsum)	0.20	0.18	0.15
T ₃ - P _(100%)	0.21	0.20	0.18
T ₄ - P _(50%) + S _(Phosphogypsum) + Rhizobium	0.26	0.24	0.19
T ₅ - P _(50%) + S _(Phosphogypsum) + PSB	0.27	0.24	0.20
T ₆ - P _(50%) + S _(Phosphogypsum) + Rhizobium + PSB	0.29	0.25	0.22
T ₇ - P _(100%) + S _(Phosphogypsum) + Rhizobium	0.24	0.22	0.18
T ₈ - P _(100%) + S _(Phosphogypsum) + PSB	0.22	0.21	0.18
T ₉ - P _(100%) + S _(Phosphogypsum) + Rhizobium + PSB	0.25	0.23	0.19
SEm±	0.07	0.09	0.08
CD (P=0.05)	0.04	0.06	0.03

with the highest EC recorded in treatment T₆ (P(50%) + S(Phosphogypsum) + Rhizobium + PSB). At pod formation, the EC ranged from 0.15 to 0.25 dS m⁻¹, with the highest EC observed in treatment T₆. At harvest stage, the EC ranged from 0.12 to 0.22 dS m⁻¹, and again the highest EC was recorded in T₆. However, the lowest EC was observed in the control treatment at all growth stages.

The gradual decline in EC over the crop growth period may be attributed to nutrient uptake by plants, leaching of soluble salts, and improved microbial assimilation of ions (Reddy et al., 2011). The higher EC observed in T₆ treatment may be due to the solubilization of phosphorus and sulphur compounds by phosphate-solubilizing bacteria (PSB) and Rhizobium, which increase the concentration of ionic species in the soil solution (Subbarao et al., 2020). Phosphogypsum, being a source of calcium and sulphate, may also contribute to increased EC by releasing ions into the soil (Kandpal et al., 2019). Conversely, the control treatment, lacking nutrient amendments and biofertilizers, maintains a lower ionic concentration, resulting in the lowest EC throughout the stages.

Effect of different level of phosphorus, sulphur and bio-fertilizers on soil organic carbon (g kg⁻¹) of soil

Table 3. Effect of different level phosphorus, sulphur and bio-fertilizers on organic carbon (g kg⁻¹) of soil

Treatments	OC (g kg ⁻¹)		
	Flowering	Pod formation	At harvest

T ₁ – Control (No fertilizer)	7.6	6.5	6.2
T ₂ - S _(Phosphogypsum)	8.1	7.5	6.5
T ₃ - P _(100%)	8.2	7.0	6.8
T ₄ - P _(50%) + S _(Phosphogypsum) + Rhizobium	8.5	7.4	6.7
T ₅ - P _(50%) + S _(Phosphogypsum) + PSB	8.7	7.5	6.8
T ₆ - P _(50%) + S _(Phosphogypsum) + Rhizobium + PSB	8.9	7.6	6.9
T ₇ - P _(100%) + S _(Phosphogypsum) + Rhizobium	7.9	7.2	6.8
T ₈ - P _(100%) + S _(Phosphogypsum) + PSB	8.2	7.1	6.6
T ₉ - P _(100%) + S _(Phosphogypsum) + Rhizobium + PSB	9.1	8.3	7.9
SEm±	0.04	0.05	0.04
CD (P=0.05)	0.02	0.03	0.05

As per Table 3, the soil organic carbon ranged from 7.6 to 9.1 g kg⁻¹ at flowering, 6.5 to 8.3 g kg⁻¹ at pod formation, and 6.2 to 7.9 g kg⁻¹ at harvest. In all the stages, the highest soil organic carbon was recorded in treatment T₉ (P_(100%) + S_(Phosphogypsum) + Rhizobium + PSB), followed by T₆ (P_(50%) + S_(Phosphogypsum) + Rhizobium + PSB), whereas the lowest was found in the control. The higher organic carbon content in treatments T₉ and T₆ can be attributed to the synergistic effect of phosphorus, sulphur, and biofertilizers. Rhizobium enhances biological nitrogen fixation and root biomass production, which contributes to higher organic matter input in the soil (Kaur et al., 2005). PSB not only solubilize bound phosphorus but also secrete polysaccharides that support microbial biomass and organic matter retention (Zaidi et al., 2009). Additionally, phosphogypsum indirectly improves SOC by enhancing soil structure and promoting microbial activity (Kandpal et al., 2019). The gradual decrease in SOC from flowering to harvest could be due to increased mineralization and decomposition of organic matter during crop growth (Bhattacharyya et al., 2013).

Effect of different level of phosphorus, sulphur and bio-fertilizers on available nutrient status at critical growth stages of ground nut

The available nitrogen in the soil followed a decreasing trend from flowering to pod formation and harvest stage (Table 4). There was a significant variation in available N among the treatments ranging from 305.4 to 392.8 kg ha⁻¹ at flowering. The highest available N was recorded in treatment T₉ (P_(100%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 392.8 kg ha⁻¹ followed by T₆ (P_(50%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 377.5 kg ha⁻¹ while the lowest value was recorded in T₁ (control) i.e. 305.4 kg ha⁻¹. At pod formation, the highest available N was observed in T₉ (P_(100%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 355.6 kg ha⁻¹ followed by T₆ (P_(50%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 342.8 kg ha⁻¹ which was statistically at par with T₇ (P_(100%) + S_(Phosphogypsum) + Rhizobium) i.e. 341.2 kg ha⁻¹ while the lowest value was recorded in T₁ (control) i.e. 281.5 kg ha⁻¹. At harvest stage, the highest available N was observed in T₉ (P_(100%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 339.1 kg ha⁻¹ followed by T₈ (P_(100%) + S_(Phosphogypsum) + PSB) i.e. 324.9 kg ha⁻¹ while the lowest value was recorded in T₁ (control) i.e. 265.3 kg ha⁻¹.

The overall decreasing trend of available nitrogen during the crop growth period can be attributed to the progressive uptake of nitrogen by plants and possible leaching losses over time (Singh et al., 2011). The significantly higher available nitrogen in treatments T₉ and T₆ may be due to the role of Rhizobium, a symbiotic nitrogen-fixing bacterium, which converts atmospheric nitrogen into plant-available forms, thereby enriching the soil nitrogen pool (Zahran, 1999). The presence of PSB may have enhanced root growth and nutrient absorption through improved phosphorus availability, which supports better nitrogen uptake and assimilation (Zaidi et al., 2009). Furthermore, phosphogypsum provides calcium and sulphur that can stimulate microbial activity and nitrogen transformation processes such as mineralization and nitrification (Kandpal et al., 2019). The control plots showed the lowest nitrogen levels due to the absence of nutrient inputs and biological enhancements.

Table 4 Effect of different level phosphorus, sulphur and bio-fertilizers on available nitrogen (kg ha⁻¹) at critical growth stages of groundnut

Treatments	Available nitrogen (kg ha ⁻¹)		
	Flowering	Pod formation	At harvest
T ₁ – Control (No fertilizer)	305.4	281.5	265.3
T ₂ - S _(Phosphogypsum)	316.7	301.4	280.7
T ₃ - P _(100%)	325.3	303.7	287.1
T ₄ - P _(50%) + S _(Phosphogypsum) + Rhizobium	334.2	312.5	282.5
T ₅ - P _(50%) + S _(Phosphogypsum) + PSB	346.4	327.8	301.8

T ₆ - P _(50%) + S _(Phosphogypsum) + Rhizobium + PSB	377.5	342.8	312.6
T ₇ - P _(100%) + S _(Phosphogypsum) + Rhizobium	362.5	341.2	321.6
T ₈ - P _(100%) + S _(Phosphogypsum) + PSB	371.8	335.8	324.9
T ₉ - P _(100%) + S _(Phosphogypsum) + Rhizobium + PSB	392.8	355.6	339.1
SEm±	11.56	14.23	15.17
CD (P=0.05)	35.41	42.56	48.51

The available phosphorus in the soil followed a decreasing trend from flowering to pod formation and harvest stage (Table 5). The soil available P varied from 16.8 to 86.5 kg ha⁻¹ at flowering stage. The highest available P was recorded in T₉ (P_(100%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 86.5 kg ha⁻¹ followed by T₈ (P_(100%) + S_(Phosphogypsum) + PSB) i.e. 78.2 kg ha⁻¹ while the lowest value was recorded in T₁ (control) i.e. 16.8 kg ha⁻¹. At pod formation, the soil available P varied from 13.3 to 58.9 kg ha⁻¹. Highest available P was observed in T₉ (P_(100%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 58.9 kg ha⁻¹ followed by T₈ (P_(100%) + S_(Phosphogypsum) + PSB) i.e. 55.6 kg ha⁻¹ while the lowest value was recorded in T₁ (control) i.e. 13.3 kg ha⁻¹. At harvest stage, treatment T₉ (P_(100%) + S_(Phosphogypsum) + Rhizobium + PSB) showed significantly highest soil available P (39.6 kg ha⁻¹) among all the treatments followed by T₈ (P_(100%) + S_(Phosphogypsum) + PSB) i.e. 36.4 kg ha⁻¹ which was statistically at par with T₇ (P_(100%) + S_(Phosphogypsum) + Rhizobium) i.e. 35.7 kg ha⁻¹ where as lowest value was found in control i.e. 10.8 kg ha⁻¹.

Table 5 Effect of different level phosphorus, sulphur and bio-fertilizers on available phosphorus (kg ha⁻¹) at critical growth stages of groundnut

Treatments	Available phosphorus (kg ha ⁻¹)		
	Flowering	Pod formation	At harvest
T ₁ – Control (No fertilizer)	16.8	13.3	10.8
T ₂ - S _(Phosphogypsum)	25.7	22.1	14.7
T ₃ - P _(100%)	30.6	25.4	16.5
T ₄ - P _(50%) + S _(Phosphogypsum) + Rhizobium	36.2	29.1	20.1
T ₅ - P _(50%) + S _(Phosphogypsum) + PSB	50.3	32.6	21.7
T ₆ - P _(50%) + S _(Phosphogypsum) + Rhizobium + PSB	62.8	45.8	32.1
T ₇ - P _(100%) + S _(Phosphogypsum) + Rhizobium	75.7	51.6	35.7
T ₈ - P _(100%) + S _(Phosphogypsum) + PSB	78.2	55.6	36.4
T ₉ - P _(100%) + S _(Phosphogypsum) + Rhizobium + PSB	86.5	58.9	39.6
SEm±	2.54	3.16	3.58
CD (P=0.05)	5.61	6.12	3.17

The decreasing trend of available phosphorus from flowering to harvest is likely due to the progressive uptake of P by the growing crop and potential fixation of P in unavailable forms as the season progresses (Holford, 1997). The significantly higher available P in treatments T₉ and T₈ can be attributed to the combined application of phosphorus fertilizers, phosphogypsum, and phosphate-solubilizing bacteria (PSB). PSB produce organic acids such as gluconic and citric acids, which solubilize the otherwise insoluble phosphorus compounds, thereby increasing the availability of P to plants (Chen et al., 2006). Additionally, phosphogypsum contributes to improving soil structure and calcium supply, which in turn can enhance the effectiveness of applied phosphorus (Kandpal et al., 2019). The inclusion of Rhizobium in T₉ may further support microbial activity and organic acid production through symbiotic interactions, leading to better P availability. In contrast, the control treatment lacked any phosphorus input or microbial inoculants, resulting in the lowest P content throughout all growth stages.

The available potassium in the soil followed a decreasing trend from flowering to pod formation and harvest stage (Table 6). The highest available potassium was recorded in T₉ (P_(100%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 286.3 kg ha⁻¹ followed by T₆ (P_(50%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 232.8 kg ha⁻¹ while the lowest value was recorded in T₁ (control) i.e. 158.6 kg ha⁻¹. At pod formation, the soil available potassium varied from 133.3 to 238.9 kg ha⁻¹. Highest available P was observed in T₉ (P_(100%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 238.9 kg ha⁻¹ followed by T₆ (P_(50%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 185.8 kg ha⁻¹ while the lowest value was recorded in T₁ (control) i.e. 133.3 kg ha⁻¹. At harvest stage, treatment T₉ (P_(100%) + S_(Phosphogypsum) + Rhizobium + PSB) showed significantly highest soil available

potassium i.e. 197.6 kg ha⁻¹ among all the treatments followed by T₆ (P_(50%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 162.1 kg ha⁻¹ whereas lowest value was found in control i.e 101.8 kg ha⁻¹.

Table 6. Effect of different level phosphorus, sulphur and bio-fertilizers on available potassium (kg ha⁻¹) at critical growth stages of groundnut

Treatments	Available potassium (kg ha ⁻¹)		
	Flowering	Pod formation	At harvest
T ₁ – Control (No fertilizer)	158.6	133.3	101.8
T ₂ - S _(Phosphogypsum)	175.7	122.1	114.7
T ₃ - P _(100%)	170.6	135.4	106.5
T ₄ - P _(50%) + S _(Phosphogypsum) + Rhizobium	186.2	159.1	110.1
T ₅ - P _(50%) + S _(Phosphogypsum) + PSB	191.3	162.6	121.7
T ₆ - P _(50%) + S _(Phosphogypsum) + Rhizobium + PSB	232.8	185.8	162.1
T ₇ - P _(100%) + S _(Phosphogypsum) + Rhizobium	182.7	151.6	128.7
T ₈ - P _(100%) + S _(Phosphogypsum) + PSB	178.2	155.6	136.4
T ₉ - P _(100%) + S _(Phosphogypsum) + Rhizobium + PSB	286.3	238.9	197.6
SEm±	12.24	9.06	15.58
CD (P=0.05)	25.61	16.12	13.07

The gradual decline in soil potassium from flowering to harvest is largely attributed to continuous plant uptake and possible leaching losses, especially in lighter-textured soils (Prasad & Power, 1997). The significantly higher levels of available K in T₉ and T₆ treatments can be attributed to the synergistic effects of phosphogypsum, biofertilizers, and phosphorus fertilization. Phosphogypsum supplies calcium and improves soil structure, which enhances cation exchange capacity and retention of potassium ions in the root zone (Kandpal et al., 2019). Moreover, phosphate-solubilizing bacteria (PSB) and Rhizobium enhance root proliferation and nutrient absorption, indirectly contributing to better uptake and cycling of potassium (Zaidi et al., 2009). The control treatment recorded the lowest available K due to the absence of nutrient inputs and biological activity, limiting K availability and mobility in soil.

The available sulphur in the soil followed a decreasing trend from flowering to pod formation and harvest stage (Table 7). The highest available sulphur was recorded in T₉ (P_(100%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 82.3 kg ha⁻¹ followed by T₈ (P_(100%) + S_(Phosphogypsum) + PSB) i.e. 74.2 kg ha⁻¹ which was statistically at par with T₇ (P_(100%) + S_(Phosphogypsum) + Rhizobium) i.e. 73.7 kg ha⁻¹ while the lowest value was recorded in T₁ (control) i.e. 15.6 kg ha⁻¹. At pod formation, the soil available sulphur varied from 12.5 to 58.4 kg ha⁻¹. Highest available P was observed in T₉ (P_(100%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 58.4 kg ha⁻¹ followed by T₈ (P_(100%) + S_(Phosphogypsum) + PSB) i.e. 56.1 kg ha⁻¹ while the lowest value was recorded in T₁ (control) i.e. 12.5 kg ha⁻¹. At harvest stage, treatment T₉ (P_(100%) + S_(Phosphogypsum) + Rhizobium + PSB) showed significantly highest soil available sulphur i.e. 37.1 kg ha⁻¹ among all the treatments followed by T₈ (P_(100%) + S_(Phosphogypsum) + PSB) i.e. 35.9 kg ha⁻¹ which was statistically at par with T₇ (P_(100%) + S_(Phosphogypsum) + Rhizobium) i.e. 35.4 kg ha⁻¹ while the lowest value was recorded in T₁ (control) i.e. 9.2 kg ha⁻¹.

Table 7. Effect of different level phosphorus, sulphur and bio-fertilizers on available sulphur (kg ha⁻¹) at critical growth stages of groundnut

Treatments	Available sulphur (kg ha ⁻¹)		
	Flowering	Pod formation	At harvest
T ₁ – Control (No fertilizer)	15.6	12.5	9.2
T ₂ - S _(Phosphogypsum)	27.5	14.1	11.7
T ₃ - P _(100%)	30.6	23.4	13.5
T ₄ - P _(50%) + S _(Phosphogypsum) + Rhizobium	46.2	35.4	20.6
T ₅ - P _(50%) + S _(Phosphogypsum) + PSB	52.3	40.7	23.4
T ₆ - P _(50%) + S _(Phosphogypsum) + Rhizobium + PSB	65.8	46.8	30.1
T ₇ - P _(100%) + S _(Phosphogypsum) + Rhizobium	73.7	51.7	35.4

T ₈ - P _(100%) + S _(Phosphogypsum) + PSB	74.2	56.1	35.9
T ₉ - P _(100%) + S _(Phosphogypsum) + Rhizobium + PSB	82.3	58.4	37.1
SEm±	16.12	10.14	13.31
CD (P=0.05)	28.11	22.02	24.07

The decreasing trend of available sulphur from flowering to harvest stage is likely due to plant uptake and possible leaching losses, especially in sulphate forms that are mobile in the soil profile (Scherer, 2001). The significantly higher available S in T₉, T₈, and T₇ treatments can be attributed to the application of phosphogypsum, which is a readily available source of sulphur in the form of calcium sulphate (Kandpal et al., 2019). Additionally, phosphate-solubilizing bacteria (PSB) can promote sulphur mineralization by enhancing microbial activity and organic matter turnover, thereby contributing to a higher sulphur pool in the soil (Zaidi et al., 2009). Rhizobium, although not directly involved in sulphur cycling, supports overall plant and root biomass, which indirectly improves nutrient uptake efficiency, including that of sulphur. The control treatment lacked both sulphur input and biological inoculants, resulting in minimal available sulphur throughout the crop stages.

Effect of different level of phosphorus, sulphur and bio-fertilizers on yield of ground nut

Pod yield (t/ha):

Pod yield of ground nut ranged from 1.12 to 3.26 t/ha which was shown in table 4.8. Maximum pod yield was recorded in T₉ (P_(100%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 3.26 t/ha followed by T₆ (P_(50%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 2.95t/ha whereas T₇ (P_(100%) + S_(Phosphogypsum) + Rhizobium) i.e. 2.54t/ha and T₈ (P_(100%) + S_(Phosphogypsum) + PSB) i.e. 2.78 t/ha were found statistically at par and minimum was reported in control i.e. 1.12 t/ha. The superior yield performance of T₉ and T₆ may be attributed to the integrated application of phosphorus, phosphogypsum, and biofertilizers (Rhizobium and PSB), which enhanced nutrient availability and uptake, particularly nitrogen, phosphorus, sulphur, and calcium—key elements for reproductive development and pod filling. Rhizobium enhances biological nitrogen fixation, improving vegetative growth and reproductive success. PSB increases the solubilization of soil-bound phosphorus, making it more accessible for plant use, which is essential for energy metabolism and seed formation (Gyaneshwar et al., 2002; Zaidi et al., 2009). Phosphogypsum provides calcium and sulphur, which promote root development, pod formation, and overall plant health (Tiwari et al., 2016). In contrast, the control plot suffered from nutrient deficiencies, leading to poor plant performance and significantly reduced yield.

Haulm yield (t/ha):

Table 4.8 shown that the haulm yield of groundnut varied between 1.75 to 3.65 t/ha. Significantly Maximum haulm yield was recorded in T₉ (P_(100%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 3.65 t/ha followed by T₆ (P_(50%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 3.36 t/ha which was statistically at par with T₈ (P_(100%) + S_(Phosphogypsum) + PSB) i.e. 3.27 t/ha whereas minimum was found in control i.e. 1.75 t/ha. The enhanced haulm yield in T₉ and T₆ is attributed to the synergistic effect of integrated nutrient management involving phosphorus, sulphur (from phosphogypsum), and biofertilizers (Rhizobium and PSB). Rhizobium inoculation significantly improves nitrogen availability via biological nitrogen fixation, which supports vigorous vegetative growth and biomass accumulation. Phosphorus is essential for energy transfer, cell division, and root development, all of which influence overall plant biomass (Rao & Reddy, 2010). PSB enhances phosphorus solubilization, increasing its availability to the crop. Sulphur, supplied through phosphogypsum, plays a critical role in protein synthesis and chlorophyll production, thereby improving overall plant growth and haulm yield (Tiwari et al., 2016). The control treatment yielded the lowest haulm production due to nutrient limitations and lack of microbial activity.

Table 8 Effect of different level phosphorus, sulphur and bio-fertilizers on yield of groundnut

Treatments	Yield (t/ha)		Harvest index (%)
	Pod yield (t/ha)	Haulm yield (t/ha)	
T ₁ – Control (No fertilizer)	1.12	1.75	39.02
T ₂ - S _(Phosphogypsum)	1.75	2.06	45.93
T ₃ - P _(100%)	1.86	2.24	45.37
T ₄ - P _(50%) + S _(Phosphogypsum) + Rhizobium	2.11	2.62	44.61
T ₅ - P _(50%) + S _(Phosphogypsum) + PSB	2.18	2.71	44.58
T ₆ - P _(50%) + S _(Phosphogypsum) + Rhizobium + PSB	2.95	3.36	46.75
T ₇ - P _(100%) + S _(Phosphogypsum) + Rhizobium	2.54	3.05	45.44
T ₈ - P _(100%) + S _(Phosphogypsum) + PSB	2.78	3.27	45.95
T ₉ - P _(100%) + S _(Phosphogypsum) + Rhizobium + PSB	3.26	3.65	47.18

SEm±	0.08	0.21	1.14
CD (P=0.05)	0.27	0.53	1.19

Harvest Index (%)

An in-depth analysis of the data reveals that there were no significant variations in the harvest index based on different levels of Phosphorus, Rhizobium and PSB (table 8). However, the highest harvest index was observed in T₉ (P_(100%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 47.18% followed by T₆ (P_(50%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 46.75% and minimum was reported in control i.e. 39.02%. The higher harvest index in T₉ and T₆ suggests a more efficient partitioning of assimilates towards reproductive structures (pods) rather than vegetative parts. This improvement can be linked to better nutrient uptake facilitated by Rhizobium-induced nitrogen fixation and enhanced phosphorus availability through PSB. Phosphorus plays a pivotal role in energy transfer (ATP synthesis), root growth, and grain filling, all of which contribute to higher economic yield without disproportionately increasing vegetative biomass (Gyaneshwar et al., 2002). Furthermore, phosphogypsum supplies sulphur and calcium, which support balanced growth and reproductive development, thus influencing harvest index positively (Tiwari et al., 2016). Although not statistically significant, the consistent numerical advantage in treatments involving biofertilizers and phosphorus suggests a trend worth noting for future research.

Effect of different level of phosphorus, sulphur and bio-fertilizers on nutrient uptake of ground nut

Nitrogen Content and Uptake

The results obtained from the present study revealed a significant difference on content of nitrogen (%) with various treatments at harvest stage (table 9). A perusal of the results highlights that the content of nitrogen (%) in pod was higher than the nitrogen content in haulm of groundnut. The N content in pod ranged from 3.05 to 5.15% with the highest content observed in T₉ (P_(100%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 5.15% followed by T₆ (P_(50%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 4.94% and lowest content observed in T₁ (control) i.e. 3.05%. The N content in haulm ranged 1.49 to 3.18 %. Highest content observed in T₉ (P_(100%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 3.18% followed by T₆ (P_(50%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 2.94% and lowest content observed in T₁ (control) i.e. 1.49%. Similar trend was followed in uptake of nitrogen in pods of groundnut. The uptake of nitrogen (kg/ha) in pod was higher than the nitrogen content in haulm of groundnut (table 9). The N uptake in pod ranged from 34.2 to 167.9 kg/ha with the highest content observed in T₉ (P_(100%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 167.9 kg/ha followed by T₆ (P_(50%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 145.7 kg/ha and lowest content observed in T₁ (control) i.e. 34.2 kg/ha. The N uptake in haulm ranged 26.08 to 116.07 kg/ha. Highest content observed in T₉ (P_(100%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 116.07 kg/ha followed by T₆ (P_(50%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 98.78 kg/ha and lowest content observed in T₁ (control) i.e. 26.08 kg/ha.

The superior performance of T₉ and T₆ treatments can be attributed to the combined application of phosphorus, sulphur (via phosphogypsum), and biofertilizers (Rhizobium and PSB). Rhizobium enhances atmospheric nitrogen fixation, directly increasing plant nitrogen content, while PSB increases the availability of phosphorus, a nutrient that aids in nitrogen metabolism and overall plant energy flow (Zaidi et al., 2009; Gyaneshwar et al., 2002). Additionally, phosphogypsum contributes sulphur, which is essential for amino acid synthesis and protein formation, thereby supporting higher biomass and nitrogen accumulation (Tiwari et al., 2016). The control plot, devoid of these inputs, showed poor nutrient availability and uptake, resulting in lower nitrogen content and uptake in both pod and haulm.

Table 9 Effect of different level phosphorus, sulphur and bio-fertilizers on nitrogen content (%) and uptake (kg/ha) of groundnut

Treatments	Pod		Haulm	
	Content (%)	Uptake (kg/ha)	Content (%)	Uptake (kg/ha)
T ₁ – Control (No fertilizer)	3.05	34.2	1.49	26.08
T ₂ - S _(Phosphogypsum)	3.72	65.1	1.83	37.70
T ₃ - P _(100%)	3.28	61.0	2.12	47.49
T ₄ - P _(50%) + S _(Phosphogypsum) + Rhizobium	4.45	93.9	2.43	63.67
T ₅ - P _(50%) + S _(Phosphogypsum) + PSB	4.48	97.7	2.35	63.69
T ₆ - P _(50%) + S _(Phosphogypsum) + Rhizobium + PSB	4.94	145.7	2.94	98.78
T ₇ - P _(100%) + S _(Phosphogypsum) + Rhizobium	4.83	122.7	2.67	81.44
T ₈ - P _(100%) + S _(Phosphogypsum) + PSB	4.75	132.1	2.81	91.89
T ₉ - P _(100%) + S _(Phosphogypsum) + Rhizobium + PSB	5.15	167.9	3.18	116.07

SEm±	0.09	6.32	0.12	10.12
CD (P=0.05)	0.23	18.15	0.27	22.43

Phosphorus Content and Uptake

The results obtained from the present study revealed a significant difference on content of phosphorus (%) with various treatments at harvest stage (table 10). A perusal of the results highlights that the content of phosphorus (%) in pod was higher than the phosphorus content in haulm of groundnut. The phosphorus content in pod ranged from 0.21 to 0.45% with the highest content observed in T₉ (P_(100%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 0.45% followed by T₆ (P_(50%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 0.42% and lowest content observed in T₁ (control) i.e. 0.21%. The phosphorus content in haulm ranged 0.09 to 0.28 %. Highest content observed in T₉ (P_(100%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 0.28% followed by T₆ (P_(50%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 0.25% and lowest content observed in T₁ (control) i.e. 0.09%.

Similar trend was followed in uptake of phosphorus in pods of groundnut. The uptake of phosphorus (kg/ha) in pod was higher than the phosphorus content in haulm of groundnut (table 10). The phosphorus uptake in pod ranged from 2.4 to 14.7 kg/ha with the highest content observed in T₉ (P_(100%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 14.7 kg/ha followed by T₆ (P_(50%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 12.4 kg/ha and lowest content observed in T₁ (control) i.e. 2.4 kg/ha. The phosphorus uptake in haulm ranged 1.58 to 10.22 kg/ha. Highest content observed in T₉ (P_(100%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 10.22 kg/ha followed by T₆ (P_(50%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 8.40 kg/ha and lowest content observed in T₁ (control) i.e. 1.58 kg/ha.

Table 10. Effect of different level phosphorus, sulphur and bio-fertilizers on phosphorus content (%) and uptake (kg/ha) of groundnut

Treatments	Pod		Haulm	
	Content (%)	Uptake (kg/ha)	Content (%)	Uptake (kg/ha)
T ₁ – Control (No fertilizer)	0.21	2.4	0.09	1.58
T ₂ - S _(Phosphogypsum)	0.27	4.7	0.12	2.47
T ₃ - P _(100%)	0.26	4.8	0.14	3.14
T ₄ - P _(50%) + S _(Phosphogypsum) + Rhizobium	0.35	7.4	0.17	4.45
T ₅ - P _(50%) + S _(Phosphogypsum) + PSB	0.38	8.3	0.18	4.88
T ₆ - P _(50%) + S _(Phosphogypsum) + Rhizobium + PSB	0.42	12.4	0.25	8.40
T ₇ - P _(100%) + S _(Phosphogypsum) + Rhizobium	0.37	9.4	0.21	6.41
T ₈ - P _(100%) + S _(Phosphogypsum) + PSB	0.39	10.8	0.23	7.52
T ₉ - P _(100%) + S _(Phosphogypsum) + Rhizobium + PSB	0.45	14.7	0.28	10.22
SEm±	0.05	0.36	0.02	0.88
CD (P=0.05)	0.08	1.45	0.05	2.13

This increase in phosphorus content and uptake under integrated treatment can be attributed to the synergistic effects of PSB, Rhizobium, and phosphogypsum. PSB (Phosphate-Solubilizing Bacteria) enhances phosphorus availability by converting insoluble phosphorus forms to soluble ones through organic acid production and phosphatase activity (Zaidi et al., 2009). Rhizobium, while primarily involved in nitrogen fixation, also aids phosphorus acquisition by stimulating root growth and enhancing rhizosphere activity (Gyaneshwar et al., 2002). Phosphogypsum contributes sulphur and calcium, both of which are vital for improving nutrient absorption and root efficiency, especially in acidic or phosphorus-fixing soils (Tiwari et al., 2016). The control treatment consistently underperformed due to the absence of external nutrient inputs, leading to poor availability and uptake of phosphorus by the groundnut crop.

Potassium Content and Uptake

The results obtained from the present study revealed a significant difference on content of potassium (%) with various treatments at harvest stage (table 11). A perusal of the results highlights that the content of potassium (%) in haulm was higher than the phosphorus content in pod of groundnut. The phosphorus content in haulm ranged from 1.28% to 1.87% with the highest content observed in T₉ (P_(100%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 1.87% followed by T₈ (P_(100%) + S_(Phosphogypsum) + PSB) i.e. 1.62% which was statistically at par with T₆ (P_(50%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 1.61% and lowest content observed in T₁ (control) i.e. 1.28%. The potassium content in pod ranged 0.45 to 1.13 %. Highest content observed in T₉ (P_(100%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 1.13% followed by T₆ (P_(50%) +

$S_{(Phosphogypsum)} + Rhizobium + PSB$ i.e. 0.96% whereas $T_7(P_{(100\%)} + S_{(Phosphogypsum)} + Rhizobium)$ and $T_8 (P_{(100\%)} + S_{(Phosphogypsum)} + PSB)$ were found statistically similar. Lowest content of potassium was observed in T_1 (control) i.e. 0.45%. Similar trend was followed in uptake of potassium in groundnut. The uptake of potassium (kg/ha) in haulm was higher than the potassium content in pod of groundnut (table 11). The potassium uptake in haulm ranged from 22.40 to 68.26 kg/ha with the highest content observed in $T_9 (P_{(100\%)} + S_{(Phosphogypsum)} + Rhizobium + PSB)$ i.e. 68.26 kg/ha followed by $T_6 (P_{(50\%)} + S_{(Phosphogypsum)} + Rhizobium + PSB)$ i.e. 54.10 kg/ha which was statistically at par with $T_8 (P_{(100\%)} + S_{(Phosphogypsum)} + PSB)$ i.e. 52.97 kg/ha and lowest content observed in T_1 (control) i.e. 22.40 kg/ha. The potassium uptake in pod ranged 5.0 to 36.8 kg/ha. Highest content observed in $T_9 (P_{(100\%)} + S_{(Phosphogypsum)} + Rhizobium + PSB)$ i.e. 36.8 kg/ha followed by $T_6 (P_{(50\%)} + S_{(Phosphogypsum)} + Rhizobium + PSB)$ i.e. 28.3 kg/ha and lowest content observed in T_1 (control) i.e. 5.0 kg/ha.

The enhanced potassium content and uptake in integrated treatments can be attributed to multiple synergistic effects i.e. PSB and Rhizobium improve nutrient availability by modifying the rhizosphere environment and root physiology, enhancing both uptake and translocation (Zaidi et al., 2009), Phosphogypsum, a rich source of calcium and sulphur, improves soil structure and cation exchange capacity, thereby facilitating potassium retention and absorption (Tiwari et al., 2016), Improved root growth and microbial activity due to these treatments also promote better K acquisition, especially under conditions of limited availability or soil fixation (Subba Rao, 2008). These findings demonstrate the importance of integrated nutrient management using inorganic fertilizers and bio-inoculants for optimizing nutrient uptake and improving groundnut productivity.

Table 11. Effect of different level phosphorus, sulphur and bio-fertilizers on potassium content (%) and uptake (kg/ha) of groundnut

Treatments	Pod		Haulm	
	Content (%)	Uptake (kg/ha)	Content (%)	Uptake (kg/ha)
T_1 – Control (No fertilizer)	0.45	5.0	1.28	22.40
$T_2 - S_{(Phosphogypsum)}$	0.58	10.2	1.37	28.22
$T_3 - P_{(100\%)}$	0.53	9.9	1.38	30.91
$T_4 - P_{(50\%)} + S_{(Phosphogypsum)} + Rhizobium$	0.81	17.1	1.45	37.99
$T_5 - P_{(50\%)} + S_{(Phosphogypsum)} + PSB$	0.82	17.9	1.48	40.11
$T_6 - P_{(50\%)} + S_{(Phosphogypsum)} + Rhizobium + PSB$	0.96	28.3	1.61	54.10
$T_7 - P_{(100\%)} + S_{(Phosphogypsum)} + Rhizobium$	0.88	22.4	1.57	47.89
$T_8 - P_{(100\%)} + S_{(Phosphogypsum)} + PSB$	0.87	24.2	1.62	52.97
$T_9 - P_{(100\%)} + S_{(Phosphogypsum)} + Rhizobium + PSB$	1.13	36.8	1.87	68.26
SEm±	0.04	0.54	0.07	2.16
CD (P=0.05)	0.09	2.35	0.22	15.67

Sulphur Content and Uptake

The results obtained from the present study revealed a significant difference on content of sulphur (%) with various treatments at harvest stage (table 12). A perusal of the results highlights that the content of sulphur (%) in pod was than the sulphur content in haulm of groundnut. The sulphur content in pod ranged from 0.22% to 0.75% with the highest content observed in $T_9 (P_{(100\%)} + S_{(Phosphogypsum)} + Rhizobium + PSB)$ i.e. 0.75% followed by $T_6 (P_{(50\%)} + S_{(Phosphogypsum)} + Rhizobium + PSB)$ i.e. 0.61% whereas $T_7(P_{(100\%)} + S_{(Phosphogypsum)} + Rhizobium)$ and $T_8 (P_{(100\%)} + S_{(Phosphogypsum)} + PSB)$ were found statistically similar. Lowest content observed in T_1 (control) i.e. 0.22%. The sulphur content in haulm ranged 0.18 to 0.54 %. Highest content observed in $T_9 (P_{(100\%)} + S_{(Phosphogypsum)} + Rhizobium + PSB)$ i.e. 0.54% followed by $T_6 (P_{(50\%)} + S_{(Phosphogypsum)} + Rhizobium + PSB)$ i.e. 0.45% whereas $T_7(P_{(100\%)} + S_{(Phosphogypsum)} + Rhizobium)$ and $T_8 (P_{(100\%)} + S_{(Phosphogypsum)} + PSB)$ were found statistically similar. Lowest content of sulphur was observed in T_1 (control) i.e. 0.18%.

Table 12. Effect of different level phosphorus, sulphur and bio-fertilizers on sulphur content (%) and uptake (kg/ha) of groundnut

Treatments	Pod		Haulm	
	Content (%)	Uptake (kg/ha)	Content (%)	Uptake (kg/ha)

T ₁ – Control (No fertilizer)	0.22	2.5	0.18	3.15
T ₂ - S _(Phosphogypsum)	0.35	6.1	0.32	6.59
T ₃ - P _(100%)	0.37	6.9	0.28	6.27
T ₄ - P _(50%) + S _(Phosphogypsum) + Rhizobium	0.46	9.7	0.37	9.69
T ₅ - P _(50%) + S _(Phosphogypsum) + PSB	0.48	10.5	0.36	9.76
T ₆ - P _(50%) + S _(Phosphogypsum) + Rhizobium + PSB	0.61	18.0	0.45	15.12
T ₇ - P _(100%) + S _(Phosphogypsum) + Rhizobium	0.53	13.5	0.42	12.81
T ₈ - P _(100%) + S _(Phosphogypsum) + PSB	0.54	15.0	0.43	14.06
T ₉ - P _(100%) + S _(Phosphogypsum) + Rhizobium + PSB	0.75	24.5	0.54	19.71
SEm±	0.08	0.25	0.04	0.29
CD (P=0.05)	0.28	1.19	0.18	1.34

The uptake of sulphur (kg/ha) in haulm ranged from 3.15 to 19.71 kg/ha with the highest content observed in T₉ (P_(100%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 19.71 kg/ha followed by T₆ (P_(50%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 15.12 kg/ha which was statistically at par with T₈ (P_(100%) + S_(Phosphogypsum) + PSB) i.e. 14.06 kg/ha and lowest content observed in T₁ (control) i.e. 3.15 kg/ha. The sulphur uptake in pod ranged 2.5 to 24.5 kg/ha. Highest content observed in T₉ (P_(100%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 24.5 kg/ha followed by T₆ (P_(50%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 18.0 kg/ha and lowest content observed in T₁ (control) i.e. 2.5 kg/ha.

These results clearly indicate the positive influence of phosphogypsum and bioinoculants (especially Rhizobium and PSB) on sulphur availability, uptake, and translocation in groundnut. Phosphogypsum, being a rich source of sulphate-S, enhances the sulphur pool in the soil, particularly in acidic or lateritic soils where native S is low. Meanwhile, PSB and Rhizobium not only promote phosphorus mobilization but also improve overall nutrient use efficiency by enhancing microbial activity in the rhizosphere (Khan et al., 2010; Tiwari et al., 2016). This integrated nutrient strategy thus plays a crucial role in maximizing sulphur nutrition, which is essential for oil synthesis, protein formation, and nodulation in legumes like groundnut.

Effect of different level of phosphorus, sulphur and bio-fertilizers on oil and protein content of ground nut

Protein content and yield

The effect of different level of phosphorus, sulphur and biofertilizers on quality parameters of groundnut such as protein and oil content in pods of groundnut was recorded (Table 13). The result showed that the protein content in pods ranged from 19.06 to 32.19 % with highest value obtained with T₉ (P_(100%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 32.19% followed by T₆ (P_(50%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 30.88 % which was statistically at par with T₇ (P_(100%) + S_(Phosphogypsum) + Rhizobium) i.e. 30.19%. The lowest protein content was observed in T₁ (control) i.e. 19.06 % The values of protein yield in groundnut crop varied from 21.4 to 104.9 kg/ha. The highest protein yield was found in T₉ (P_(100%) + S_(Phosphogypsum) + Rhizobium + PSB) followed by T₆ (P_(50%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 91.1 kg/ha and lowest was found in control i.e. 21.4 kg/ha. There was a remarkable improvement in protein yield than control plot and sole application of phosphogypsum and phosphorus in groundnut crop. This increase in protein yield with integrated nutrient management (phosphorus + sulphur + bioinoculants) is attributed to improved nitrogen fixation and nutrient assimilation facilitated by Rhizobium and PSB, enhancing protein biosynthesis (Kumar et al., 2017).

Oil content and yield

The oil content in groundnut ranged from 12.32 to 20.97 %. The highest oil content was recorded in T₉ (P_(100%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 20.97% followed by T₈ (P_(100%) + S_(Phosphogypsum) + PSB) i.e. 19.92% which was statistically at par with T₆ (P_(50%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 19.87% and lowest content observed in T₁ (control) i.e. 12.32%. The values of oil yield in groundnut crop varied from 138.0 to 683.6 kg/ha. The highest protein yield was found in T₉ (P_(100%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 683.6 kg/ha followed by T₆ (P_(50%) + S_(Phosphogypsum) + Rhizobium + PSB) i.e. 586.2 kg/ha and lowest was found in control i.e. 138.0 kg/ha. The improvement in oil yield may be due to enhanced sulphur availability from phosphogypsum, which plays a critical role in the synthesis of oil and sulfur-containing amino acids (Jat et al., 2018).

Table 13 Effect of different level of phosphorus, sulphur and bio-fertilizers on oil and protein content of ground nut

Treatments	Oil Content (%)	Oil Yield (kg/ha)	Protein Content (%)	Protein Yield (kg/ha)
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T ₁ – Control (No fertilizer)	12.32	138.0	19.06	21.4
T ₂ - S _(Phosphogypsum)	15.31	267.9	23.25	40.7
T ₃ - P _(100%)	15.03	279.6	20.50	38.1
T ₄ - P _(50%) + S _(Phosphogypsum) + Rhizobium	18.04	380.6	27.81	58.7
T ₅ - P _(50%) + S _(Phosphogypsum) + PSB	18.42	401.6	28.00	61.0
T ₆ - P _(50%) + S _(Phosphogypsum) + Rhizobium + PSB	19.87	586.2	30.88	91.1
T ₇ - P _(100%) + S _(Phosphogypsum) + Rhizobium	19.12	485.6	30.19	76.7
T ₈ - P _(100%) + S _(Phosphogypsum) + PSB	19.92	553.8	29.69	82.5
T ₉ - P _(100%) + S _(Phosphogypsum) + Rhizobium + PSB	20.97	683.6	32.19	104.9
SEm±	1.97	18.18	1.82	12.34
CD (P=0.05)	3.12	37.52	3.01	23.18

CONCLUSION

The integrated application of phosphorus (100% recommended dose), sulphur (as phosphogypsum), and biofertilizers (Rhizobium + PSB), especially in treatment T9, significantly improved the soil chemical properties, nutrient availability, and plant nutrient uptake. This integrated nutrient management approach notably enhanced growth parameters (plant height, dry matter accumulation, nodulation), yield attributes (pods per plant, seeds per pod), and ultimately resulted in maximum pod yield (3.26 t/ha) and haulm yield (3.65 t/ha) of groundnut. Moreover, T9 recorded the highest nutrient concentrations and uptake for nitrogen, phosphorus, potassium, and sulphur in both pods and haulm. Quality parameters such as protein content (32.19%) and oil content (20.97%) in pods were also significantly superior in T9, confirming the beneficial effect of balanced fertilization and microbial synergy. In summary, the combination of 100% phosphorus + sulphur (phosphogypsum) + Rhizobium + PSB emerged as the most effective treatment in enhancing growth, yield, nutrient uptake, and quality of groundnut in lateritic soils, and is therefore recommended for sustainable groundnut cultivation in similar agro-ecological zones.

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