



RESEARCH ARTICLE

Response of sesame varieties to phosphorus fertilisation and phosphobacteria inoculation: Effects on nutrient uptake, availability, use efficiency and yield of sesame

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Abstract

A field experiment was conducted at a farmers' field from April to August 2021 in Korakottai Village, Vandavasi Taluk, Tiruvannamalai District, to evaluate the effects of phosphorus fertilisation and phosphobacteria inoculation on nutrient uptake, availability, use efficiency and productivity of sesame varieties (TMV 3 and ASWIN 3). The study followed a factorial randomised block design with six phosphorus levels, viz., Control, 25 % RDP, 50 % RDP, 75 % RDP, 100 % RDP and 125 % RDP and two levels of phosphobacteria application, viz., control and phosphobacteria at 2 kg ha⁻¹, replicated thrice. The results revealed that both individual and combined applications of 100 % recommended phosphorus dose along with phosphobacteria at 2 kg ha⁻¹ significantly enhanced nitrogen, phosphorus and potassium uptake and availability, phosphobacteria population, response ratio and apparent recovery, as well as seed and stalk yields in both varieties. Considering these benefits, the application of 100 % recommended phosphorus dose along with phosphobacteria at 2 kg ha⁻¹ is recommended for sesame farmers in Tiruvannamalai district, Tamil Nadu, to achieve higher yields and profitability.

Keywords: nutrient availability; sesame; uptake; use efficiency; yield

Introduction

Sesame (*Sesamum indicum* L.) is one of the most important oilseed crops in Indian agriculture and is considered the oldest cultivated oilseed crop globally. It is widely grown in tropical and subtropical regions, with a significant share of its cultivated area in developing countries. Sesame has been cultivated since the ancient Harappan, Mesopotamian and Anatolian civilisations for over 5,000 years and is a versatile crop that thrives in semi-arid and arid regions with temperatures between 25 and 35 °C (1). Sesame prefers well-drained, sandy loam to loam soils with a pH of 5.5 to 8.0 and is sensitive to waterlogged and excessive moisture conditions. The genus *Sesamum* comprises approximately 36 species, with *Sesamum indicum* being the most commonly cultivated. It is a self-pollinated edible oilseed crop belonging to the family Pedaliaceae. India ranks first in global sesame production, contributing approximately 7.50 lakh tons in 2019–2020, with Tamil Nadu cultivating sesame over an area of 0.3 lakh ha, producing 0.189 lakh Mt with a productivity of 630 kg ha⁻¹(2).

Sesame seeds are nutritionally rich, containing 42–45 % edible oil, 20 % protein, 14–20 % carbohydrates and 15–20 % hull materials (3–6). They possess antioxidant properties due to lignin, tocopherols, sesamin and sesamol (7, 8) along with essential

amino acids like methionine and tryptophan. Sesame oil, known as the queen of oils, is highly resistant to oxidative rancidity and is widely used in ayurvedic preparations and cosmetic formulations. It is also referred to as the poor mans' substitute for ghee (9). White-seeded sesame is primarily used in bakery products, whereas black-seeded sesame has medicinal applications (8, 10). Despite its advantages, sesame productivity remains low, necessitating the adoption of improved nutrient management strategies to enhance yield potential.

Phosphorus (P) is a critical macronutrient that plays a vital role in plant growth and development. It is essential for various physiological processes, including photosynthesis, energy transfer (ATP- Adenosine triphosphate, ADP - Adenosine diphosphate synthesis), respiration, cell division and nucleic acid formation (11, 12). Phosphorus is required throughout the plants' life cycle, from seedling establishment to maturity. It influences seed quality, flowering uniformity, pod formation and plant strength, reducing susceptibility to lodging. Phosphorus deficiency leads to stunted growth, reduced root development and poor branching, ultimately affecting seed yield (13–15). Phosphorus availability to plants from soil is influenced by many factors, such as soil pH, organic matter content, etc. In general, phosphorus fertilisers have a use efficiency of 15 to 20 % with soil having a pH of 6.5 to 7.5. Remaining phosphorus applied as fertilisers is lost as fixation

with aluminium and iron in acidic soils, calcium in calcareous soil and sodium in sodic soils, adsorption in clay minerals and lost as leaching and surface runoff, making it unavailable to plant growth.

Biofertilisers, particularly phosphorus-solubilising bacteria (PSBs), play a crucial role in enhancing phosphorus availability (16–18). PSBs, including *Bacillus*, *Pseudomonas* and *Rhizobium*, employ mechanisms such as soil pH reduction, chelation and mineralisation to convert unavailable phosphorus into plant-accessible orthophosphate forms (19, 20). Inoculating soils with PSBs has been reported to improve phosphorus solubilization and mobilisation, leading to increased phosphorus uptake, improved plant growth and higher yields. Combining phosphorus fertiliser with phosphobacteria influences nutrient dynamics by synergistically increasing P solubility, root growth, microbial activity and nutrient uptake, ultimately enhancing P use.

Despite sesame being the most important oilseed crop their productivity is low due to cultivation in rainfed and nutrient-depleted regions where phosphorus availability becomes low. In most regions, applied phosphorus gets fixed in insoluble forms, resulting in poor nutrient uptake and inefficient utilisation by the crop. As sesame being shallow root crop and highly nutrient-demanding from early establishment to seed formation, it is necessary to optimise the phosphorus levels to improve the growth, seed setting, seed yield and oil yield of the crop. PSB have emerged as a sustainable option to enhance phosphorus by converting fixed phosphorus to available form through acidification, chelation and enzymatic solubilisation in both irrigated and rainfed regions. Despite the benefit of its effect on sesame on nutrient uptake, use efficiency is limited, especially in its combination with different phosphorus levels. Further, the phosphorus response to sesame varieties was scarce. Therefore, this study aims to evaluate the response of sesame varieties to phosphorus fertilisation and phosphobacteria inoculation, focusing on nutrient uptake, availability, phosphorus use efficiency and yield performance. By understanding the interactive effects of phosphorus application levels and PSBs, this research seeks to provide valuable insights into effective nutrient management strategies to enhance sesame productivity in phosphorus-limiting soils.

Materials and methods

Experimental location

The experiment was conducted at Korakottai Village of Vandavasi Taluk, Tiruvannamalai District, Tamil Nadu, during the *khari* season of 2024. The experimental site is geographically located at 12°23'56.7" N latitude and 79°30'24.6" E longitude and 104 m above mean sea level (MSL). During the experiment period, the mean maximum temperature varied between 34.4 and 38.5 °C, the mean minimum air temperature varied between 26.6 and 29.0

°C and rainfall varied between 12.00 and 80.0 mm. The field had a uniform topography with a gentle slope and good drainage conditions. Before sowing, a composite soil sample was collected using a "V"-shaped cut to a depth of 0–15 cm to analyse the physicochemical properties. The analysis method was presented in Table 1. The soil was sandy clay loam in texture with a pH of 7.7, EC of 0.33 dS m⁻¹, low in available nitrogen (190 kg ha⁻¹) and phosphorus (8.96 kg ha⁻¹) and medium in potassium (155 kg ha⁻¹).

Experimental details

The experiment comprises of six levels of phosphorus, viz., P₀-control, P₂₅- 25 % RDP (Recommended dose of phosphorus at 50 kg ha⁻¹), P₅₀- 50 % RDP, P₇₅- 75 % RDP, P₁₀₀- 100 % RDP and P₁₂₅- 125 % RDP and phosphobacteria, viz., Pb₀- control and Pb₁- Phosphobacteria at 2 kg ha⁻¹, laid in factorial randomized block design and replicated thrice. All the treatments were uniformly fertilised with the recommended dose of fertiliser, 25:75 Kg of N: K₂O ha⁻¹. Sesame varieties, namely TMV 3 (Black seed) and ASWIN 3 (White seed), were used as the test crop.

Observation recorded

Nutrient uptake, viz., nitrogen, phosphorus and potassium (flowering, capsule formation, seed and stalk) and availability, viz., nitrogen, phosphorus, potassium and phosphobacteria population in soil at harvest of sesame varieties were recorded. The plant samples were collected at flowering and capsule formation and seed and stalk at harvest from three tagged plants, shade dried and oven dried for 72 hr at 65 °C. The samples were weighed and powdered in willey mill. The powdered samples were analysed for N, P and K content. The methods involved in the plant analysis are presented in Table 1.

The nutrient uptake in flowering, capsule formation, seed and stalk was calculated as per the formula given in an Equation 1–3.

$$\text{Nutrient uptake by plant (kg ha}^{-1}\text{)} = \frac{\text{Percent nutrient content (\%)}}{100} \times \text{DMP} \quad (\text{Eqn. 1})$$

$$\text{Nutrient uptake by seed (kg ha}^{-1}\text{)} = \frac{\text{Percent nutrient content in seed (\%)}}{100} \times \text{seed yield} \quad (\text{Eqn. 2})$$

$$\text{Nutrient uptake by stalk (kg ha}^{-1}\text{)} = \frac{\text{Percent nutrient content in stalk (\%)}}{100} \times \text{stalk yield} \quad (\text{Eqn. 3})$$

Soil samples were collected after harvest to depth of 0-15cm by making "V" shape cut and analysed by the procedure presented in

Table 1. Methods of soil analysis

S. No.	Properties	Methodology	References
Plant analysis			
1	Nitrogen	Mikrokjeldhal (Diacid extraction H ₂ SO ₄ :HClO ₄ in the ratio of 4:1 method)	(21)
2	Phosphorus	Vanadomolybdate yellow colour method (Tri acid extraction (HNO ₃ :H ₂ SO ₄ :HClO ₄ in the ratio of 9:2:1)	(22)
3	Potassium	Flame photometry (Tri-acid extract)	(23)
Soil analysis			
4	Available nitrogen	Alkaline permanganate method	(24)
5	Available phosphorus	Colorimetric method	(25)
6	Available potassium	Flame photometric method	(26)
7	Phosphobacteria population	Serial dilution plate technique	(27)

the Table 1.

Response ratio =

$$\frac{\left[\begin{array}{l} \text{seed yield in fertilized plot - seed yield in control plot} \\ \text{(kg ha}^{-1}\text{)} \qquad \qquad \qquad \text{(kg ha}^{-1}\text{)} \end{array} \right]}{\text{Nutrients applied in fertilized plot (kg ha}^{-1}\text{)}}$$

(Eqn. 4)

Nutrient use efficiency

Response ratio and apparent nutrient recovery for nutrient use efficiency were calculated by

Apparent nutrients recovery (%) =

$$\frac{\left[\begin{array}{l} \text{Nutrient uptake in fertilized plot - Nutrients uptake in control plot} \\ \text{(kg ha}^{-1}\text{)} \qquad \qquad \qquad \text{(kg ha}^{-1}\text{)} \end{array} \right]}{\text{Nutrients applied in fertilized plot (kg ha}^{-1}\text{)}}$$

(Eqn. 5)

Statistical analysis

The data obtained from the field experiment were statistically analysed by using OP STAT software (28). For significant results, the critical difference was set at 5 % probability level. Principal component analysis was performed using the software R.

Results

Nutrient uptake

The nutrient uptake, viz., nitrogen, phosphorus and potassium, showed a significant effect on application of different levels of phosphorus, phosphobacteria inoculation and its combination (Table 2–7). Among phosphorus levels, application of 100 % RDP recorded the maximum nitrogen uptake of 23.35, 37.62, 39.91 and 34.67 kg ha⁻¹, phosphorus uptake of 3.74, 6.66, 6.17 and 8.65 kg ha⁻¹ and potassium uptake of 29.91, 42.87, 16.56 and 38.54 kg ha⁻¹ in TMV 3 and nitrogen uptake of 21.85, 36.08, 38.70 and 31.92 kg ha⁻¹, phosphorus uptake of 3.60, 5.95, 5.70 and 7.26 kg ha⁻¹ and potassium uptake of 29.13, 41.96, 14.81 and 36.96 kg ha⁻¹ at ASWIN 3 at flowering, capsule formation, by seed and stalk respectively and it was followed by 125 % RDP and 75 % RDP treatments.

The application of phosphobacteria alone significantly improved nutrient uptake at all growth stages of sesame varieties. In phosphobacteria-inoculated plots, nitrogen uptake was highest at 21.51 and 19.84 kg ha⁻¹ during the flowering stage, 33.50 and 32.51 kg ha⁻¹ at the capsule formation stage, 33.37 and 32.56 kg ha⁻¹ in seeds and 28.43 and 26.17 kg ha⁻¹ in stalks for TMV 3 and ASWIN 3, respectively. Phosphorus uptake was recorded at 3.34 and 3.27 kg ha⁻¹ during flowering, 6.08 and 5.36 kg ha⁻¹ at capsule formation, 5.35 and 4.99 kg ha⁻¹ in seeds and 7.51 and 6.48 kg ha⁻¹ in stalks. Similarly, potassium uptake reached 26.50 and 26.17 kg ha⁻¹ during flowering, 36.78 and 35.69 kg ha⁻¹ at capsule formation, 13.60 and 12.16 kg ha⁻¹ in seeds and 32.33 and 30.57 kg ha⁻¹ in stalks for TMV 3 and ASWIN 3 respectively.

The interaction effect showed that application of 100 % RDP along with phosphobacteria inoculation at 2 kg ha⁻¹ (P₁₀₀Pb₁) showed highly significant effect by registering nitrogen uptake (323.95 and 22.75 kg ha⁻¹ at flowering; 38.75 and 37.02 kg ha⁻¹ at capsule formation; 40.95 and 39.77 kg ha⁻¹ in seed; 35.62 and 33.26 kg ha⁻¹ in stalk),

phosphorus uptake (3.85 and 3.69 kg ha⁻¹ at flowering; 6.87 and 6.12 kg ha⁻¹ in capsule formation; 6.33 and 5.87 kg ha⁻¹ in seed; 8.87 and 7.46 kg ha⁻¹ in stalk) and potassium uptake (30.72 and 29.88 kg ha⁻¹ at flowering; 44.17 and 43.26 kg ha⁻¹ in capsule formation; 17.09 and 15.25 kg ha⁻¹ in seed; 40.44 and 38.29 kg ha⁻¹ in stalk) in TMV 3 and ASWIN 3 respectively.

Available nutrient status

The data about the available nutrients viz., nitrogen, phosphorus and potassium content of the soil at the post-harvest stage, was presented in the Table 8–10. It was found that there was a significant increase in the available phosphorus content in the soil with an increase in P levels up to 100 % RDP. The treatment P₁₀₀ recorded 280.97 kg ha⁻¹ of nitrogen, 14.54 kg ha⁻¹ of phosphorus and 246.70 kg ha⁻¹ of potassium in TMV 3 and 274.91 kg ha⁻¹ of nitrogen, 14.44 kg ha⁻¹ of phosphorus and 244.99 kg ha⁻¹ of potassium in ASWIN 3. The effect of phosphobacteria inoculation on soil available phosphorus indicated a significant effect with uninoculated plots, which recorded nitrogen of 256.30 and 252.76 kg ha⁻¹, phosphorus of 11.65 and 11.54 kg ha⁻¹ and potassium of 208.12 and 206.91 kg ha⁻¹ in TMV 3 and ASWIN 3 respectively.

The interaction effect shows that application of phosphorus and phosphobacteria inoculation significantly influences the soil available nutrients at harvest. Treatment combination P₁₀₀Pb₁ (100 % RDP with phosphobacteria at 2 kg ha⁻¹) registered the highest nitrogen content of 287.92 and 281.69 kg ha⁻¹, phosphorus content of 14.95 and 14.79 kg ha⁻¹ and potassium content of 253.27 and 251.01 kg ha⁻¹ in TMV 3 and ASWIN 3 varieties respectively.

Phosphobacteria population

The different levels of phosphorus, phosphobacteria inoculation and their combination caused a significant effect on the bacterial population in sesame on both varieties (Table 11). Among phosphorus application levels, the highest bacterial population was recorded in P₁₀₀ treatment (8.35 and 8.25 × 10⁶ g⁻¹ of oven-dry soil) in both TMV 3 and ASWIN 3 genotypes respectively. This was followed by P₁₂₅ and P₇₅. Phosphobacteria inoculation increased the bacterial population significantly more than uninoculated plots. The maximum bacterial population was recorded in Pb₁ treatment by registering 8.61 and 8.54 (× 10⁶ g⁻¹ of oven-dry soil) in TMV 3 and ASWIN 3 respectively. In the interaction effect highest phosphobacteria population was recorded with P₁₀₀Pb₁ by registering 9.73 and 9.69 (× 10⁶ g⁻¹ of oven dry soil) in TMV 3 and ASWIN 3 varieties, respectively.

Yield

Addition of different levels of phosphorus, phosphobacteria inoculation and their combination caused a significant effect on seed and stalk yield (Table 12–13). Among different levels of phosphorus, application of 100 % recommended dose of phosphorus registered the maximum seed yield of 1161.36 and 913.46 kg ha⁻¹ and stalk yield of 2436.52 and 1949.05 kg ha⁻¹ in TMV 3 and ASWIN 3 varieties, respectively. Regarding phosphobacteria inoculation, application of phosphobacteria at 2 kg ha⁻¹ (Pb₁) recorded the maximum seed yield (1030.67 and 817.83 kg ha⁻¹) and stalk yield (2126.96 and 1727.49 kg ha⁻¹) in both varieties, respectively. In the combined application, application of 100 % RDP along with phosphobacteria at 2 kg ha⁻¹ (P₁₀₀Pb₁) recorded the highest seed yield of 1192.32 kg ha⁻¹ and stalk yield of 2503.20 kg ha⁻¹ in TMV 3. The respective treatment highest seed and stalk yield (936.51 and 1994.76 kg ha⁻¹) in ASWIN 3 varieties, respectively.

Table 2. Effect of Phosphorus fertilization and phosphobacteria inoculation on nitrogen uptake (kg ha^{-1}) by TMV 3 sesame varieties.

P Levels	Pb Levels	FS			CFS			Seed			Stalk		
		Pb ₀	Pb ₁	Mean	Pb ₀	Pb ₁	Mean	Pb ₀	Pb ₁	Mean	Pb ₀	Pb ₁	Mean
P ₀		16.97	18.55	17.76	24.89	27.44	26.16	22.28	24.34	23.31	16.54	19.57	18.06
P ₂₅		18.67	19.89	19.28	28.12	30.29	29.21	26.41	28.49	27.45	20.71	23.41	22.06
P ₅₀		20.05	21.32	20.69	30.79	32.75	31.77	30.57	32.63	31.60	24.36	27.63	25.99
P ₇₅		21.43	22.66	22.04	33.62	35.76	34.69	34.71	36.79	35.75	29.97	31.89	30.99
P ₁₀₀		22.75	23.95	23.35	36.49	38.75	37.62	38.88	40.95	39.91	33.71	35.62	34.67
P ₁₂₅		21.55	22.70	22.13	34.21	36.03	35.12	35.82	37.06	36.44	31.55	32.47	32.01
Mean		20.24	21.51		31.35	33.50		31.44	33.37		26.14	28.43	
Factor		P	Pb	P × Pb	P	Pb	P × Pb	P	Pb	P × Pb	P	Pb	P × Pb
CD ($p = 0.05$)		1.03	1.01	1.15	1.88	1.67	1.93	1.59	1.55	2.01	1.23	1.16	1.23
SEd		0.50	0.49	0.56	0.91	0.81	0.93	0.77	0.75	0.97	0.60	0.56	0.59

P₀- control, P₂₅- 25 % RDP (Recommended dose of phosphorus at 50 kg ha^{-1}), P₅₀- 50 % RDP, P₇₅- 75 % RDP, P₁₀₀- 100 % RDP and P₁₂₅- 125 % RDP and phosphobacteria, Pb₀- control and Pb₁- Phosphobacteria at 2 kg ha^{-1}

Table 3. Effect of phosphorus fertilization and phosphobacteria inoculation on nitrogen uptake (kg ha^{-1}) by ASWIN 3 sesame genotype

P Levels	Pb Levels	FS			CFS			Seed			Stalk		
		Pb ₀	Pb ₁	Mean	Pb ₀	Pb ₁	Mean	Pb ₀	Pb ₁	Mean	Pb ₀	Pb ₁	Mean
P ₀		14.99	16.37	15.68	24.85	27.39	26.12	21.56	23.59	22.57	15.29	18.63	16.96
P ₂₅		16.57	18.09	17.33	27.66	29.63	28.64	25.61	27.64	26.62	19.57	21.86	20.72
P ₅₀		18.47	19.66	19.07	29.98	31.87	30.92	29.65	31.68	30.66	22.31	25.43	23.87
P ₇₅		19.69	20.86	20.28	32.05	34.16	33.10	33.74	35.76	34.75	26.84	28.72	27.78
P ₁₀₀		20.95	22.75	21.85	35.13	37.02	36.08	37.62	39.77	38.70	30.57	33.26	31.92
P ₁₂₅		19.77	21.34	20.56	33.21	34.99	34.10	35.42	36.92	36.17	27.80	29.12	28.46
Mean		18.40	19.84		30.48	32.51		30.60	32.56		23.73	26.17	
Factor		P	Pb	P × Pb	P	Pb	P × Pb	P	Pb	P × Pb	P	Pb	P × Pb
CD ($p = 0.05$)		0.95	0.92	1.14	1.57	1.51	1.83	1.51	1.49	1.96	1.23	1.16	1.64
SEd		0.46	0.44	0.55	0.76	0.73	0.88	0.73	0.72	0.95	0.59	0.56	0.79

P₀- control, P₂₅- 25 % RDP (Recommended dose of phosphorus at 50 kg ha^{-1}), P₅₀- 50 % RDP, P₇₅- 75 % RDP, P₁₀₀- 100 % RDP and P₁₂₅- 125 % RDP and phosphobacteria, Pb₀- control and Pb₁- Phosphobacteria at 2 kg ha^{-1}

Table 4. Effect of phosphorus fertilization and phosphobacteria inoculation on phosphorus uptake (kg ha^{-1}) by TMV 3 sesame genotype

P Levels	Pb Levels	FS			CFS			Seed			Stalk		
		Pb ₀	Pb ₁	Mean	Pb ₀	Pb ₁	Mean	Pb ₀	Pb ₁	Mean	Pb ₀	Pb ₁	Mean
P ₀		2.55	2.78	2.66	4.77	5.19	4.98	3.66	4.11	3.89	5.31	6.09	5.70
P ₂₅		2.82	3.03	2.92	5.20	5.55	5.38	4.22	4.67	4.44	6.12	6.57	6.35
P ₅₀		3.08	3.28	3.18	5.62	5.99	5.81	4.75	5.19	4.97	6.73	7.29	7.01
P ₇₅		3.31	3.51	3.41	6.05	6.40	6.23	5.42	5.87	5.65	7.38	7.87	7.63
P ₁₀₀		3.62	3.85	3.74	6.44	6.87	6.66	6.00	6.33	6.17	8.42	8.87	8.65
P ₁₂₅		3.39	3.60	3.50	6.25	6.49	6.37	5.71	5.95	5.83	7.77	8.39	8.08
Mean		3.13	3.34		5.72	6.08		4.96	5.35		6.96	7.51	
Factor		P	Pb	P × Pb	P	Pb	P × Pb	P	Pb	P × Pb	P	Pb	P × Pb
CD ($p = 0.05$)		0.16	0.13	0.19	0.28	0.25	0.34	0.25	0.23	0.30	0.33	0.31	0.41
SEd		0.08	0.06	0.09	0.14	0.12	0.16	0.12	0.11	0.14	0.16	0.15	0.20

P₀- control, P₂₅- 25 % RDP (Recommended dose of phosphorus at 50 kg ha^{-1}), P₅₀- 50 % RDP, P₇₅- 75 % RDP, P₁₀₀- 100 % RDP and P₁₂₅- 125 % RDP and phosphobacteria, Pb₀- control and Pb₁- Phosphobacteria at 2 kg ha^{-1}

Table 5. Effect of phosphorus fertilization and phosphobacteria inoculation on phosphorus uptake (kg ha^{-1}) by ASWIN 3 sesame genotype

P Levels	Pb Levels	FS			CFS			Seed			Stalk		
		Pb ₀	Pb ₁	Mean	Pb ₀	Pb ₁	Mean	Pb ₀	Pb ₁	Mean	Pb ₀	Pb ₁	Mean
P ₀		2.45	2.77	2.61	4.15	4.50	4.33	3.12	3.99	3.55	4.98	5.45	5.22
P ₂₅		2.82	2.99	2.90	4.53	4.87	4.70	4.15	4.47	4.31	5.47	5.88	5.68
P ₅₀		3.01	3.22	3.11	4.92	5.25	5.09	4.50	4.85	4.68	5.90	6.29	6.09
P ₇₅		3.26	3.45	3.35	5.30	5.64	5.47	5.01	5.31	5.16	6.35	6.79	6.57
P ₁₀₀		3.50	3.69	3.60	5.77	6.12	5.95	5.53	5.87	5.70	7.05	7.46	7.26
P ₁₂₅		3.31	3.47	3.39	5.49	5.77	5.63	5.24	5.42	5.34	6.69	6.99	6.84
Mean		3.06	3.27		5.03	5.36		4.59	4.99		6.07	6.48	
Factor		P	Pb	P × Pb	P	Pb	P × Pb	P	Pb	P × Pb	P	Pb	P × Pb
CD ($p = 0.05$)		0.14	0.12	0.17	0.23	0.21	0.31	0.23	0.19	0.28	0.29	0.27	0.35
SEd		0.07	0.06	0.08	0.11	0.10	0.15	0.11	0.09	0.14	0.14	0.13	0.17

P₀- control, P₂₅- 25 % RDP (Recommended dose of phosphorus at 50 kg ha^{-1}), P₅₀- 50 % RDP, P₇₅- 75 % RDP, P₁₀₀- 100 % RDP and P₁₂₅- 125 % RDP and phosphobacteria, Pb₀- control and Pb₁- Phosphobacteria at 2 kg ha^{-1}

Table 6. Effect of phosphorus fertilization and phosphobacteria inoculation on potassium uptake (kg ha^{-1}) by TMV 3 sesame genotype

P Levels	Pb Levels	FS			CFS			Seed			Stalk		
		Pb ₀	Pb ₁	Mean	Pb ₀	Pb ₁	Mean	Pb ₀	Pb ₁	Mean	Pb ₀	Pb ₁	Mean
P ₀		20.08	21.69	20.89	24.09	28.64	26.37	8.22	9.75	8.99	17.69	22.97	20.33
P ₂₅		21.77	24.11	22.94	29.02	31.56	30.29	10.13	11.09	10.61	23.66	27.36	25.51
P ₅₀		24.29	25.89	25.09	32.66	35.98	34.32	12.20	13.39	12.79	28.12	31.07	29.60
P ₇₅		26.27	28.05	27.16	37.62	40.03	38.83	13.86	14.82	14.34	32.83	35.72	34.29
P ₁₀₀		29.09	30.72	29.91	41.57	44.17	42.87	16.02	17.09	16.56	36.64	40.44	38.54
P ₁₂₅		27.09	28.55	27.82	38.23	40.27	39.25	14.46	15.45	14.96	34.03	36.39	35.21
Mean		24.77	26.50		33.86	36.78		12.48	13.60		28.83	32.33	
Factor		P	Pb	P × Pb	P	Pb	P × Pb	P	Pb	P × Pb	P	Pb	P × Pb
CD ($p = 0.05$)		1.25	1.23	1.51	1.72	1.66	2.21	0.63	0.60	0.82	1.47	1.23	2.57
SEd		0.60	0.60	0.73	0.83	0.80	1.07	0.30	0.29	0.40	0.71	0.60	1.24

P₀- control, P₂₅- 25 % RDP (Recommended dose of phosphorus at 50 kg ha^{-1}), P₅₀- 50 % RDP, P₇₅- 75 % RDP, P₁₀₀- 100 % RDP and P₁₂₅- 125 % RDP and phosphobacteria, Pb₀- control and Pb₁- Phosphobacteria at 2 kg ha^{-1}

Table 7. Effect of phosphorus fertilisation and phosphobacteria inoculation on potassium uptake (kg ha^{-1}) by ASWIN 3 sesame genotype

P Levels	Pb Levels	FS			CFS			Seed			Stalk		
		Pb ₀	Pb ₁	Mean	Pb ₀	Pb ₁	Mean	Pb ₀	Pb ₁	Mean	Pb ₀	Pb ₁	Mean
P ₀		19.54	21.55	20.55	23.62	26.52	25.07	7.67	8.66	8.17	16.55	19.57	18.06
P ₂₅		21.79	23.86	22.83	28.72	31.82	30.27	8.74	9.57	9.16	21.62	24.27	22.95
P ₅₀		24.07	25.76	24.92	32.05	34.40	33.23	10.33	11.65	10.99	28.01	30.89	29.45
P ₇₅		26.33	27.92	27.13	35.99	38.97	37.48	12.74	13.75	13.25	32.15	34.67	33.41
P ₁₀₀		28.37	29.88	29.13	40.66	43.26	41.96	14.36	15.25	14.81	35.62	38.29	36.96
P ₁₂₅		26.61	28.03	27.32	37.51	39.15	38.33	13.43	14.05	13.74	33.29	35.72	34.51
Mean		24.45	26.17		33.09	35.69		11.21	12.16		27.87	30.57	
Factor		P	Pb	P × Pb	P	Pb	P × Pb	P	Pb	P × Pb	P	Pb	P × Pb
CD ($p = 0.05$)		1.24	1.21	1.49	1.65	1.61	2.13	0.57	0.55	0.74	1.43	1.37	2.03
SEd		0.60	0.58	0.72	0.80	0.78	1.03	0.28	0.27	0.36	0.69	0.66	0.98

P₀- control, P₂₅- 25 % RDP (Recommended dose of phosphorus at 50 kg ha^{-1}), P₅₀- 50 % RDP, P₇₅- 75 % RDP, P₁₀₀- 100 % RDP and P₁₂₅- 125 % RDP and phosphobacteria, Pb₀- control and Pb₁- Phosphobacteria at 2 kg ha^{-1}

Table 8. Effect of phosphorus fertilization and phosphobacteria inoculation on available nitrogen (kg ha^{-1}) of sesame genotypes

P Levels	Pb Levels	TMV - 3			Aswin - 3		
		Pb ₀	Pb ₁	Mean	Pb ₀	Pb ₁	Mean
P ₀		203.75	220.06	211.91	201.07	218.91	209.99
P ₂₅		222.09	237.51	229.80	220.01	234.02	227.02
P ₅₀		238.72	252.67	245.70	235.47	249.61	242.54
P ₇₅		253.98	267.45	260.72	250.99	265.07	258.03
P ₁₀₀		274.01	287.92	280.97	268.12	281.69	274.91
P ₁₂₅		260.54	272.19	266.37	257.62	267.23	262.43
Mean		242.18	256.30		238.88	252.76	
Factor		P	Pb	P × Pb	P	Pb	P × Pb
CD ($p = 0.05$)		12.09	11.99	13.39	11.95	11.87	12.98
SEd		5.84	5.79	6.47	5.77	5.73	6.27

P₀- control, P₂₅- 25 % RDP (Recommended dose of phosphorus at 50 kg ha^{-1}), P₅₀- 50 % RDP, P₇₅- 75 % RDP, P₁₀₀- 100 % RDP and P₁₂₅- 125 % RDP and phosphobacteria, Pb₀- control and Pb₁- Phosphobacteria at 2 kg ha^{-1}

Table 9. Effect of phosphorus fertilization and phosphobacteria inoculation on available phosphorus (kg ha^{-1}) of sesame genotypes

P Levels	Pb Levels	TMV - 3			Aswin - 3		
		Pb ₀	Pb ₁	Mean	Pb ₀	Pb ₁	Mean
P ₀		8.99	9.75	9.37	8.59	9.41	9.00
P ₂₅		9.97	10.72	10.35	9.86	10.66	10.26
P ₅₀		11.18	11.91	11.55	11.08	11.87	11.48
P ₇₅		12.34	13.11	12.73	12.31	13.07	12.69
P ₁₀₀		14.13	14.95	14.54	14.09	14.79	14.44
P ₁₂₅		13.29	14.09	13.69	13.29	14.01	13.65
Mean		11.65	12.42		11.54	12.30	
Factor		P	Pb	P × Pb	P	Pb	P × Pb
CD ($p = 0.05$)		0.59	0.55	0.69	0.57	0.53	0.65
SEd		0.29	0.27	0.33	0.28	0.26	0.31

P₀- control, P₂₅- 25 % RDP (Recommended dose of phosphorus at 50 kg ha^{-1}), P₅₀- 50 % RDP, P₇₅- 75 % RDP, P₁₀₀- 100 % RDP and P₁₂₅- 125 % RDP and phosphobacteria, Pb₀- control and Pb₁- Phosphobacteria at 2 kg ha^{-1}

Table 10. Effect of phosphorus fertilization and phosphobacteria inoculation on available potassium (kg ha^{-1}) of sesame genotypes

P Levels	Pb Levels	TMV - 3			Aswin - 3		
		Pb ₀	Pb ₁	Mean	Pb ₀	Pb ₁	Mean
P ₀		171.62	185.54	178.58	169.87	184.31	177.09
P ₂₅		187.53	201.87	194.70	186.92	199.62	193.27
P ₅₀		203.07	216.73	209.90	202.13	214.82	208.48
P ₇₅		217.97	231.07	224.52	216.42	229.62	223.02
P ₁₀₀		240.13	253.27	246.70	238.97	251.01	244.99
P ₁₂₅		228.42	239.13	233.78	227.17	238.23	232.70
Mean		208.12	221.27		206.91	219.60	
Factor		P	Pb	P × Pb	P	Pb	P × Pb
CD ($p = 0.05$)		10.53	10.21	12.41	10.49	10.09	11.37
SEd		5.09	4.93	6.00	5.07	4.87	5.49

P₀- control, P₂₅- 25 % RDP (Recommended dose of phosphorus at 50 kg ha^{-1}), P₅₀- 50 % RDP, P₇₅- 75 % RDP, P₁₀₀- 100 % RDP and P₁₂₅- 125 % RDP and phosphobacteria, Pb₀- control and Pb₁- Phosphobacteria at 2 kg ha^{-1}

Table 11. Effect of phosphorus fertilization and phosphobacteria inoculation on phosphobacteria population of sesame varieties

P Levels	Pb Levels	TMV - 3			Aswin - 3		
		Pb ₀	Pb ₁	Mean	Pb ₀	Pb ₁	Mean
P ₀		4.51	7.44	5.98	4.41	7.31	5.86
P ₂₅		5.00	7.92	6.46	4.93	7.83	6.38
P ₅₀		5.51	8.41	6.96	5.41	8.32	6.87
P ₇₅		6.01	8.89	7.45	5.89	8.87	7.38
P ₁₀₀		6.97	9.73	8.35	6.81	9.69	8.25
P ₁₂₅		6.49	9.27	7.88	6.32	9.21	7.77
Mean		5.75	8.61		5.63	8.54	
Factor		P	Pb	P × Pb	P	Pb	P × Pb
CD ($p = 0.05$)		0.39	0.36	0.43	0.40	0.38	0.46
SEd		0.19	0.17	0.21	0.19	0.18	0.22

P₀- control, P₂₅- 25 % RDP (Recommended dose of phosphorus at 50 kg ha^{-1}), P₅₀- 50 % RDP, P₇₅- 75 % RDP, P₁₀₀- 100 % RDP and P₁₂₅- 125 % RDP and phosphobacteria, Pb₀- control and Pb₁- Phosphobacteria at 2 kg ha^{-1}

Table 12. Effect of phosphorus fertilization and phosphobacteria inoculation seed yield (kg ha^{-1}) of sesame varieties

P Levels	Pb Levels	TMV - 3			Aswin - 3		
		Pb ₀	Pb ₁	Mean	Pb ₀	Pb ₁	Mean
P ₀		750.22	840.15	795.19	600.27	686.23	643.25
P ₂₅		865.65	940.67	903.16	698.22	746.11	722.17
P ₅₀		942.33	1010.25	976.29	752.13	799.21	775.67
P ₇₅		1020.45	1080.22	1050.34	810.22	850.45	830.34
P ₁₀₀		1130.40	1192.32	1161.36	890.4	936.51	913.46
P ₁₂₅		1065.22	1120.42	1092.82	835.46	888.45	861.96
Mean		962.38	1030.67		764.45	817.83	
Factor		P	Pb	P × Pb	P	Pb	P × Pb
CD ($p = 0.05$)		48.87	39.84	59.62	34.39	31.52	40.08
SEd		23.61	19.25	28.80	16.61	15.23	19.36

P₀- control, P₂₅- 25 % RDP (Recommended dose of phosphorus at 50 kg ha^{-1}), P₅₀- 50 % RDP, P₇₅- 75 % RDP, P₁₀₀- 100 % RDP and P₁₂₅- 125 % RDP and phosphobacteria, Pb₀- control and Pb₁- Phosphobacteria at 2 kg ha^{-1}

Table 13. Effect of phosphorus fertilization and phosphobacteria inoculation stalk yield (kg ha^{-1}) of sesame varieties

P Levels	Pb Levels	TMV - 3			Aswin - 3		
		Pb ₀	Pb ₁	Mean	Pb ₀	Pb ₁	Mean
P ₀		1542.39	1701.66	1622.03	1309.36	1429.05	1369.21
P ₂₅		1668.49	1878.52	1773.51	1400.15	1577.68	1488.92
P ₅₀		1952.87	2092.54	2022.71	1598.48	1691.45	1644.97
P ₇₅		2140.75	2273.15	2206.95	1711.25	1817.39	1764.32
P ₁₀₀		2369.84	2503.20	2436.52	1903.33	1994.76	1949.05
P ₁₂₅		2216.35	2312.67	2264.51	1787.48	1854.62	1821.05
Mean		1981.78	2126.96		1618.34	1727.49	
Factor		P	Pb	P × Pb	P	Pb	P × Pb
CD ($p = 0.05$)		105.69	85.31	125.16	77.26	65.49	89.09
SEd		51.06	41.21	60.46	37.32	31.64	43.04

P₀- control, P₂₅- 25 % RDP (Recommended dose of phosphorus at 50 kg ha^{-1}), P₅₀- 50 % RDP, P₇₅- 75 % RDP, P₁₀₀- 100 % RDP and P₁₂₅- 125 % RDP and phosphobacteria, Pb₀- control and Pb₁- Phosphobacteria at 2 kg ha^{-1}

Table 14. Effect of phosphorus fertilization and phosphobacteria inoculation on NPK response ratio and apparent NPK recovery of sesame genotypes

Treatments	TMV - 3						ASWIN - 3					
	NPK Response ratio			Apparent NPK recovery percentage (%)			NPK Response ratio			Apparent NPK recovery percentage (%)		
	N	P	K	N	P	K	N	P	K	N	P	K
P ₀ Pb ₀	-	-	-	-	-	-	-	-	-	-	-	-
P ₀ Pb ₁	3.60	-	1.20	0.20	-	0.02	3.44	-	1.15	0.21	-	0.11
P ₂₅ Pb ₀	4.62	9.23	1.54	0.33	0.11	0.03	3.92	7.84	1.31	0.33	0.12	0.12
P ₂₅ Pb ₁	7.62	8.84	2.54	0.52	0.12	0.04	5.83	6.72	1.94	0.51	0.11	0.17
P ₅₀ Pb ₀	7.68	7.68	2.56	0.64	0.10	0.05	6.07	6.07	2.02	0.60	0.09	0.19
P ₅₀ Pb ₁	10.40	10.40	3.47	0.86	0.14	0.07	7.96	7.96	2.65	0.81	0.12	0.24
P ₇₅ Pb ₀	10.81	7.21	3.60	1.03	0.10	0.08	8.40	5.60	2.80	0.95	0.09	0.28
P ₇₅ Pb ₁	13.20	8.80	4.40	1.19	0.13	0.09	10.01	6.67	3.34	1.11	0.11	0.32
P ₁₀₀ Pb ₀	15.21	7.60	5.07	1.35	0.11	0.10	11.61	5.80	3.87	1.25	0.09	0.34
P ₁₀₀ Pb ₁	17.68	11.84	5.69	1.51	0.15	0.12	13.45	7.99	4.48	1.45	0.13	0.39
P ₁₂₅ Pb ₀	12.60	5.04	4.20	1.14	0.07	0.08	9.41	3.76	3.14	1.05	0.06	0.30
P ₁₂₅ Pb ₁	14.81	5.92	4.94	1.23	0.09	0.10	11.53	4.61	3.84	1.17	0.07	0.34

P₀- control, P₂₅- 25 % RDP (Recommended dose of phosphorus at 50 kg ha⁻¹), P₅₀- 50 % RDP, P₇₅- 75 % RDP, P₁₀₀- 100 % RDP and P₁₂₅- 125 % RDP and phosphobacteria, Pb₀- control and Pb₁- Phosphobacteria at 2 kg ha⁻¹

Nutrient use efficiency

The nutrient use efficiency parameters, viz., response ratio and apparent NPK recovery, were significantly influenced by phosphorus fertilisation and phosphobacteria inoculation (Table 14). Application of 100 % RDP and phosphobacteria inoculation at 2 kg ha⁻¹ (T₁₀) recorded the maximum NPK response ratio of 17.68, 11.84 and 5.69 in TMV 3 and 13.45, 7.99 and 4.48 in ASWIN 3 varieties. The highest NPK recovery recorded in the same treatment T₁₀ with values are 1.51, 0.15 and 0.12 % in TMV 3 and 1.45, 0.13 and 0.39 per cent in ASWIN 3, respectively. The lowest NPK recovery and response ratio was recorded in T₂ in both varieties of TMV 3 and ASWIN 3.

Principal component analysis

The biplots of principal component analysis (PCA) for TMV 3 and ASWIN -3 varieties are shown in Fig. 1–2, respectively. The PCA analysis indicated similar trends in both varieties. Dimension 1 of the PCA explained approximately 90.2 % of the variation in TMV 3 and 89.1 % in ASWIN -3, respectively, highlighting its significant role in understanding the factors influencing sesame growth. The variables associated with PC-1 included yield, nutrient uptake, availability and microbial population. Dimension 2 captured the remaining 5.8 and 4.5 % of the variation, having less influence. In the biplot, arrows pointing in the same direction signify positive correlations between variables, as they help to promote the seed yield.

Discussion

The uptake of major nutrients plays a crucial role in sesame crop growth and yield performance. In this study, nutrient uptake values progressively increased from the flowering to harvest stages. Higher nitrogen (N) uptake was observed in seeds compared to stalks in both TMV 3 and ASWIN 3 varieties. In contrast, maximum phosphorus and potassium uptake occurred in the stalks rather than the seeds of both genotypes. A significant difference in NPK uptake was noted across different phosphorus treatment levels. The highest NPK uptake in both seed and stalk was recorded under the 100 % recommended dose of fertiliser (RDF) treatment in both genotypes. This might be due to phosphorus application, which likely increased its concentration in soil solution, thereby improving nutrient availability and plant

uptake (29–31). Phosphorus application is essential role in root elongation and proliferation, which leads to a well-developed root system, increasing the plants' ability to absorb NPK from the soil (32). Phosphorus is a key component of ATP, which drives energy transfer within the plant, helping in improving chlorophyll synthesis and photosynthetic efficiency, leading to higher dry matter production and better utilisation of NPK for growth and yield (33). The application of phosphobacteria at 2 kg ha⁻¹ further enhanced nutrient uptake by solubilising phosphorus from unavailable to available forms. In saline soils, phosphorus exists in the form of hydroxyl apatite [Ca(PO₄)₂CaFe]. Phosphorus availability in saline soil and other soils is mainly concerned with mineralisation of organic phosphorus and solubilization of mineral phosphorus (34). Phosphorus-solubilising microorganisms play a significant role in making phosphorus available to sesame plants through solubilising (35).

Thereby, combining phosphorus and phosphobacteria enhances the microbial activity in the rhizosphere, where Phosphobacteria solubilize fixed phosphorus into available forms, increasing its uptake and improving overall nutrient absorption, including nitrogen and potassium. These findings are in line with (36, 37). However, an excessive phosphorus level along with phosphobacteria inoculation resulted in reduced NPK uptake, likely due to an inhibitory effect on dry matter production at different growth stages in both genotypes. In the present investigation as evidenced by positive correlation of seed yield with N uptake by seed ($r = 0.987^{**}$), P uptake by seed ($r = 0.994^{**}$) and K uptake by seed ($r = 0.977^{**}$) in TMV 3 and seed yield with N uptake by seed ($r = 0.987^{**}$), P uptake by seed ($r = 0.994^{**}$) and K uptake by seed ($r = 0.977^{**}$) in ASWIN 3 genotypes. Results of the present study were ably supported by a significant linear relationship between seed yield with N, P and K uptake in seed and stalk (Fig. 3–5).

The application of different levels of phosphorus, in combination with phosphobacteria inoculation, significantly influenced soil available nitrogen (N), phosphorus (P) and potassium (K) status. The highest NPK availability was recorded at the optimum phosphorus application level (P₁₀₀), while excessive phosphorus application (P₁₂₅) led to a reduction in nutrient availability. A progressive increase in phosphorus levels from 0 % to 100 % of the recommended dose significantly

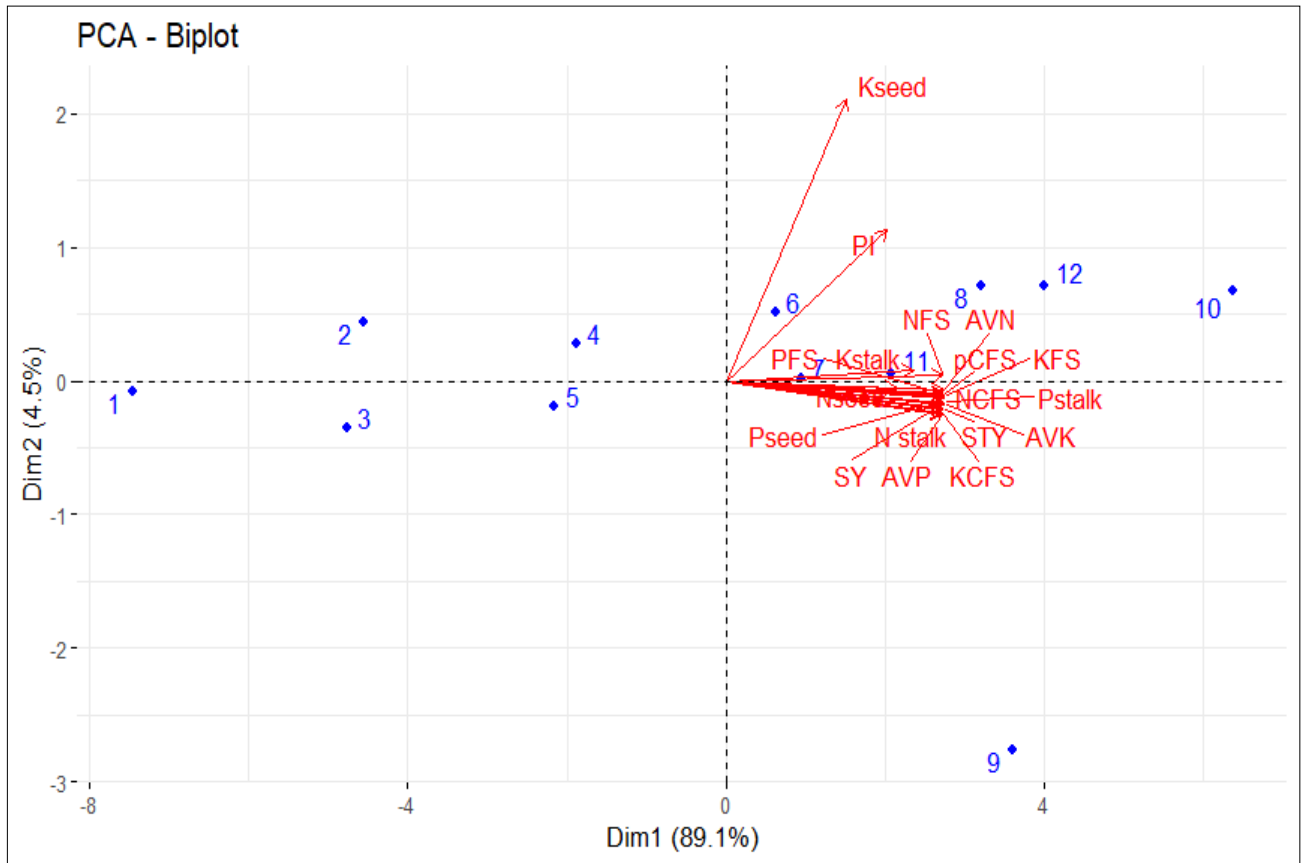


Fig. 1. Biplot for principal component analysis for TMV 3 (SY: Seed yield, STY: Stalk yield NFS: Nitrogen uptake at flowering stage, NCFS: Nitrogen uptake at capsule formation stage, N seed : Nitrogen by seed, N stalk: Nitrogen uptake by stalk, PFS: Phosphorus uptake at flowering stage, PCFS: Phosphorus uptake at capsule formation stage, P seed : Phosphorus by seed, P stalk: Phosphorus uptake by stalk, KFS: Potassium uptake at flowering stage, KCFS: Potassium uptake at capsule formation stage, K seed : Potassium by seed, K stalk: Potassium uptake by stalk AN: Available nitrogen, AP: Available phosphorus, AK: Available potassium, PI: Phosphorus inoculation).

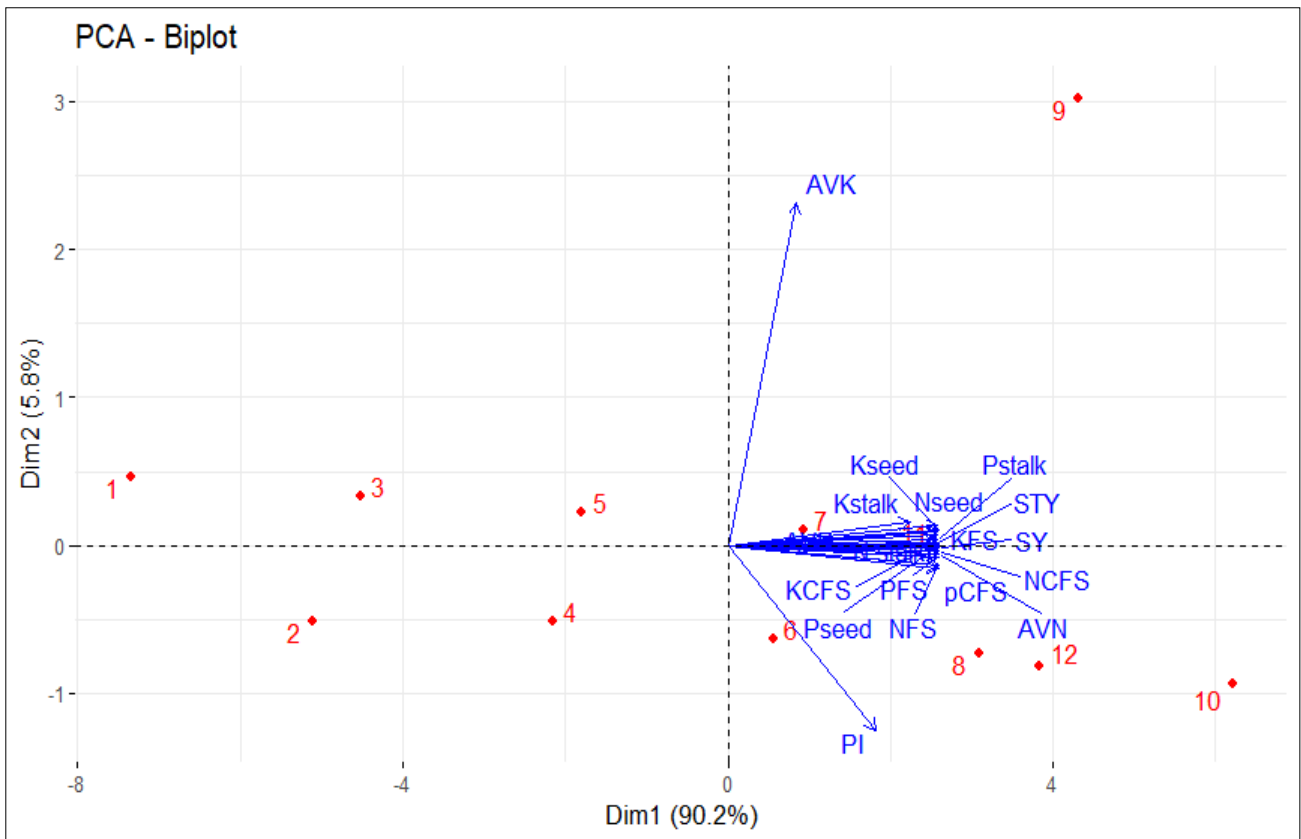


Fig. 2. Biplot for principal component analysis for ASWIN -3 (SY: Seed yield, STY: Stalk yield NFS: Nitrogen uptake at flowering stage, NCFS: Nitrogen uptake at capsule formation stage, N seed : Nitrogen by seed, N stalk: Nitrogen uptake by stalk, PFS: Phosphorus uptake at flowering stage, PCFS: Phosphorus uptake at capsule formation stage, P seed : Phosphorus by seed, P stalk: Phosphorus uptake by stalk, KFS: Potassium uptake at flowering stage, KCFS: Potassium uptake at capsule formation stage, K seed : Potassium by seed, K stalk: Potassium uptake by stalk AN: Available nitrogen, AP: Available phosphorus, AK: Available potassium, PI: Phosphorus inoculation).

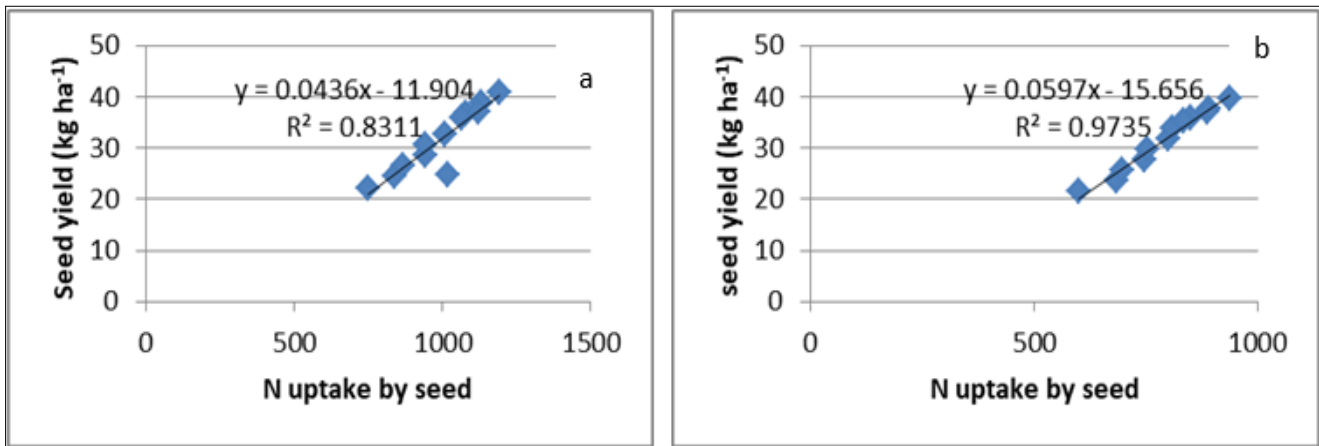


Fig. 3. Linear relationship between seed yield with N uptake (seed): a. TMV 3 b. ASWIN 3 varieties.

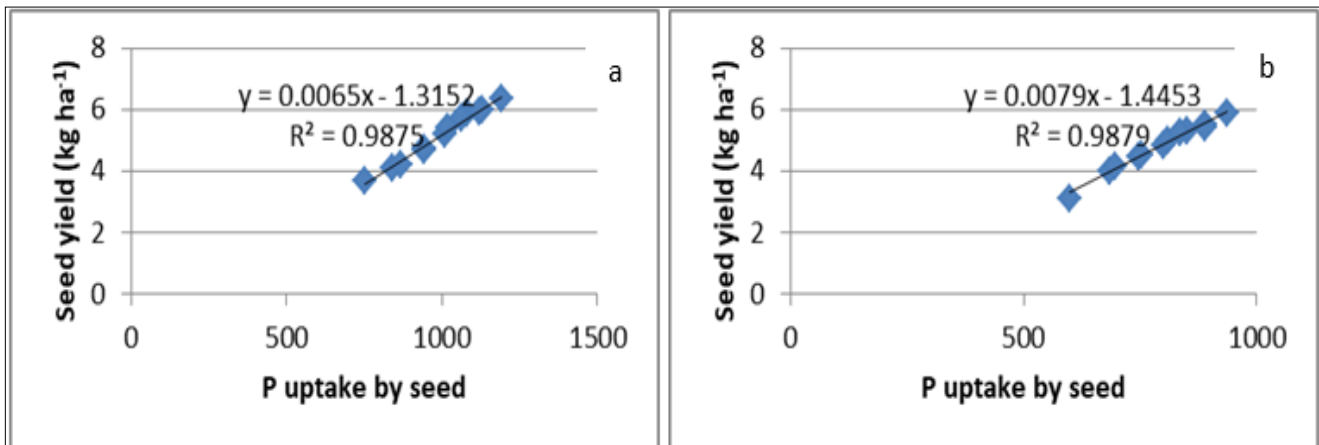


Fig. 4. Linear relationship between seed yield with P uptake (seed): a. TMV- 3 b. ASWIN 3 varieties.

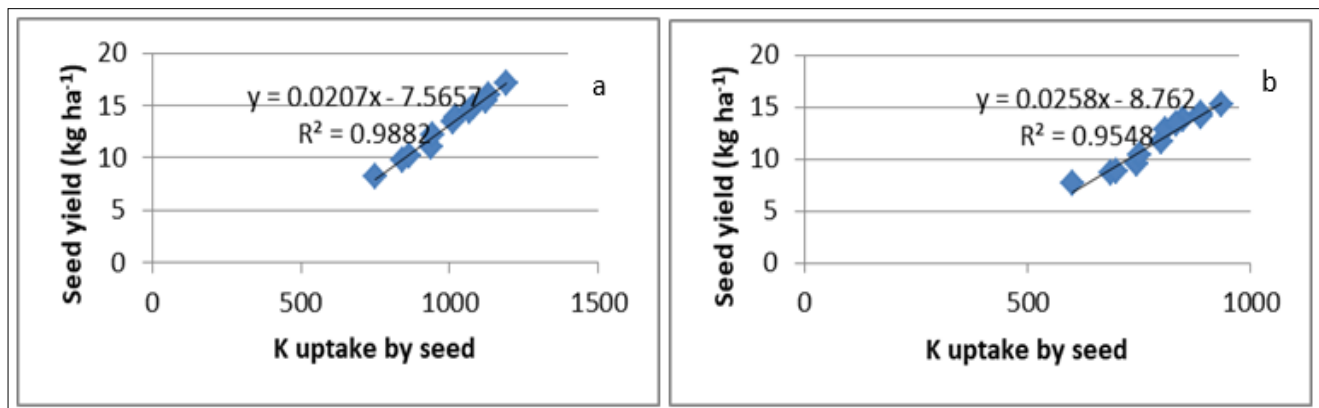


Fig. 5. Linear relationship between seed yield with K uptake (seed): a. TMV 3 b. ASWIN 3 varieties.

enhanced soil NPK availability over the control. Meanwhile, the application of 125 % of the recommended phosphorus dose was statistically at par with 75 % phosphorus application, indicating a 100 % RDP is a threshold level beyond which additional phosphorus does not further enhance soil nutrient availability to plants. Research has demonstrated the similar findings in their observations (31, 38, 39).

The available nitrogen content in the soil increased with nitrogen fertiliser application, primarily due to the direct addition of nitrogen, which helps plants to uptake the nutrient required for their growth. In addition to these, nitrogen is also involved in the nitrogen cycling process, promoting nitrogen-fixing microorganisms population, which fixes the atmospheric nitrogen either as free living or associative in soil, further improving nitrogen availability in soil (40). Phosphorus additions influence nitrogen availability by reducing nitrogen leaching losses and volatilisation by promoting rapid plant establishment and soil coverage, thereby

retaining more nutrients in the soil, particularly in sandy soils where leaching is a major concern (41–45). Phosphorus also promotes biological nitrogen fixation by forming symbiotic associations with nitrogen-fixing bacteria and stimulating microbial decomposition of organic matter, thereby increasing nitrogen input into the soil. This mechanism is supported by the studies of (46, 47).

Although potassium is abundant in soil, its availability is limited by various soil properties, environmental conditions and management practices. The cation exchange capacity and presence of clay minerals such as vermiculite and illite strongly fix potassium, making it less available for plant uptake (48). Furthermore, high concentrations of competing cations, such as calcium, magnesium and ammonium, also limit potassium uptake. From the results, it is clear that potassium availability is increased mainly by the application of potassium fertiliser. Further, the results show that application of phosphorus at 100 RDP enhanced the potassium availability by indirectly influencing

cation exchange capacity and stimulating root exudates that promote the activity of potassium-solubilising bacteria, which solubilise the fixed potassium to an available form. This interaction has been supported by the application of phosphorus, which promotes the mineralisation of potassium and improves its pool concentration for plant uptake (49, 50).

Phosphobacteria inoculation at 2 kg ha⁻¹ significantly improved soil available phosphorus levels in both TMV3 and ASWIN 3 genotypes compared to treatments without inoculation (Pb0). The increase in phosphorus availability with phosphobacteria application can be attributed to its ability to solubilise mineral phosphates and improve plant phosphate nutrition. These results are consistent with the previous work (35). The combination of phosphobacteria inoculation with varying phosphorus levels demonstrated a significant impact on soil available NPK throughout the growth stages to harvest. This suggests that phosphobacteria inoculation enhances phosphorus solubilization and nutrient availability, reinforcing its role in improving soil fertility and nutrient uptake efficiency.

The positive effect of phosphorus fertilisation on seed and stalk yield of sesame might be attributed to the low level of available phosphorus content of the experimental soil. This necessitated the high demand for phosphorus by the crop, as phosphorus is known to enhance the development of the root system, which in turn increases the efficiency of the roots in absorbing various nutrients. The application of phosphorus stimulates photosynthesis, carbohydrate metabolism and synthesis of protein, which increases the amount of metabolites synthesised by sesame plants. Also, it plays a role in enhancing the translocation of metabolites, which might be the reason for the increasing seed and stalk yield. These findings have also supported that application of phosphorus enhanced the seed and stalk yield of sesame (38, 39).

Various NPK efficiency parameters were significantly influenced by the application of 100 % RDF along with phosphobacteria inoculation. The highest NPK response ratio and apparent NPK recovery values were recorded in the T₁₀ treatment. The increased nutrient supply and improved plant response facilitated enhanced nutrient translocation, contributing to higher phosphorus availability and improved phosphorus use efficiency. These findings align with observations as phosphorus and phosphobacteria application enhanced the phosphorus use efficiency in sesame (39).

Conclusion

The study demonstrated that phosphorus fertilisation and phosphobacteria inoculation significantly influence nutrient uptake, availability, use efficiency and yield of sesame. Among the different treatments, the application of 100 % recommended phosphorus dose (RDP) along with phosphobacteria at 2 kg ha⁻¹ resulted in the highest nutrient uptake, improved soil nutrient status and enhanced seed and stalk yield in both TMV 3 and ASWIN 3 varieties. This combination also promoted greater microbial activity and phosphorus solubilization, leading to increased nutrient use efficiency. The findings highlight the importance of integrated nutrient management in optimising sesame productivity in phosphorus-limited soils. The synergistic effect of phosphorus application and phosphobacteria inoculation not only improved crop growth and yield but also contributed to sustainable soil

fertility management. Therefore, applying 100 % RDP with phosphobacteria inoculation at 2 kg ha⁻¹ is recommended for sesame cultivation in Tiruvannamalai District, Tamil Nadu, to achieve higher productivity and profitability while maintaining long-term soil health.

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Authors' contributions

KP, SK and AK carried out the field experiment and manuscript writing. LAR and SA contributed in statistical analysis and manuscript writing. 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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