



RESEARCH ARTICLE

Exploring the effect of graded nitrogen, phosphorus and potassium (NPK) levels on soybean (*Glycine max* L.) growth, yield and soil fertility responses

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Abstract

A field experiment was conducted during the kharif seasons of 2023 and 2024 at the Soil Test Crop Response (STCR) farm, Department of Soil Science, Mahatma Phule Krishi Vidyapeeth (MPKV), Rahuri, India, to evaluate the effect of graded nitrogen, phosphorus and potassium (NPK) levels on the growth, yield, nutrient uptake and soil fertility status of soybean (*Glycine max* L.). The experiment involved 12 treatments comprising the application of NPK in various combinations and a control, arranged in a randomised block design (RBD) with three replications. The soil of the experimental site was silty clay loam in texture, low in available N and P, but very high in available K. Results revealed that application of 50:75:45 N:P₂O₅:K₂O kg ha⁻¹ + 10 t ha⁻¹ farmyard manure (FYM) (T₁₂) significantly improved chlorophyll content at 30 (36.28), 45 (37.89), 60 (40.01) and 90 (37.80) days after sowing (DAS), as well as grain (33.07 q ha⁻¹) and straw yield (41.67 q ha⁻¹) of soybean on a pooled basis. It also enhanced the number of pods plant⁻¹ (88.17), number of seeds plant⁻¹ (184.00) and weight of seeds plant⁻¹ (35.92 g) of soybean on a pooled basis. The T₁₂ recorded the highest N, P and K uptake in the grain and straw of soybean, while improving soil organic carbon (SOC) (0.72 %) and the available nutrient status after the harvest of soybean compared with nutrient omission and unfertilised treatments. In contrast, nutrient omission treatments markedly reduced crop performance and nutrient uptake, indicating the importance of a balanced nutrient supply. The principal component analysis (PCA) clearly demonstrated the differential response of soybean treatments to graded NPK levels. The study concluded that the integrated application of inorganic fertilisers with FYM (50:75:45 N:P₂O₅:K₂O kg ha⁻¹ + 10 t ha⁻¹ FYM) enhances soybean productivity, nutrient use efficiency and soil fertility sustainability.

Keywords: balanced fertilisation; grain yield; NPK levels; nutrient uptake; soil fertility; soybean

Introduction

Soybean (*Glycine max* L.) plays a crucial role in addressing food security and contributing to agricultural systems, being one of the most vital leguminous crops globally (1). Soybean is valued for its high protein and oil contents and is widely used in human nutrition, livestock feed and industrial products such as biodiesel (2, 3). Originating in China, soybean has become one of the most extensively cultivated oilseed crop worldwide. As a versatile legume, it possesses a diverse range of applications. Moreover, soybean is an important component in processed feed for poultry and fish, as well as a valuable commodity for food manufacturers, the pharmaceutical industry and various other industrial applications. Hence, there is a growing need to increase soybean production to meet this demand efficiently while also maintaining environmental sustainability and soil health.

During the past four decades, soybean cultivation in India has expanded substantially in both area and production. Soybean

has emerged as a promising monsoon-season crop in the rainfed agro-ecosystems of Central and Peninsular India, contributing substantially to crop intensity and productivity per unit area (4). At the global level, soybean is cultivated over an area exceeding 136.19 million hectares worldwide. Among the major soybean-producing countries, Brazil and the United States contribute the largest share of global production, while India ranks fifth in soybean production (5). In India, soybean occupies approximately 13 million hectares and contributes substantially to national oilseed production, with Maharashtra being the leading producer state.

Generally, crop growth and development, which essentially determine the economic value of a crop are affected by climate and soil conditions. Soybean cultivation is highly dependent on nutrient availability. Efficient nutrient management is important for optimising soybean productivity and ensuring better plant health. Being a legume, half of the nitrogen (N) requirement of soybean is fulfilled through symbiotic nitrogen fixation, whereas remaining N requirement is sourced from the soil (6). Hence, it is necessary to

apply N fertiliser judiciously to augment soybean yield and efficiency. Adequate phosphorus (P) nutrition is vital for soybean growth, especially during the initial crop growth stages and throughout pod and seed production. For proper nodule development, adequate P absorption and utilisation in soybean are critical. Potassium (K) is involved in maintaining plant water balance, activating enzymes for various physiological processes, preventing necrosis and reducing the risk of insect-pest attacks. Many high-yielding varieties of soybean require relatively higher amounts of K (7). Hence, the prerequisite condition for sustainable and enhanced crop production is the thoughtful management of different nutrient resources.

Declining soil fertility due to nutrient removal by previous crops can intensify competition for available nutrients and constrain crop productivity. Achieving optimum biomass accumulation and higher yields therefore requires an adequate and balanced nutrient input. During its reproductive stage, when soybean has substantial nutrient requirements, chemical fertilisers are frequently applied in excess, to maximise yield production. However, excessive and imbalanced fertiliser application can adversely affect both crop productivity and soil health. Due to such imbalanced nutrient application, a decline in the use efficiency of applied nutrients becomes a major concern for crop productivity. Considering this situation, enhancing the nutrient use efficiency in production systems becomes more relevant. The use efficiency of fertiliser nutrients is a measure which helps in understanding how effectively applied fertilisers are utilised by crops under a given soil, climate and management conditions to achieve optimum yield. Although various nutrient management strategies have been developed to improve fertiliser-use efficiency, an assessment of these nutrient application strategies is necessary to identify an efficient nutrient management approach for improving crop productivity while sustaining soil fertility (8). Balanced nutrient application is expected to improve crop growth, nutrient uptake and yield while maintaining soil fertility compared with imbalanced nutrient application. Therefore, the present study was undertaken to evaluate the effects of graded nitrogen, phosphorus and potassium (NPK) levels and nutrient omission treatments on soybean growth, chlorophyll content, yield attributes, nutrient uptake and soil fertility status.

Materials and Methods

Experimental details

The field experiments were conducted on soybean during the kharif seasons of 2023 and 2024 at the STCR farm, Department of Soil Science, Mahatma Phule Krishi Vidyapeeth, Rahuri (19°21'29" N latitude and 74°39'4" E longitude), India. The location of the field experiment had a semi-arid and sub-tropical climate characterised by dry, hot summers and cold winters. The mean monthly meteorological data of the experimental site during 2023 and 2024 were recorded at Mahatma Phule Krishi Vidyapeeth's meteorological observatory at Rahuri and are presented in Fig. 1. The experimental site had silty clay loam-textured soil classified under the Inceptisol order with uniformly levelled topography. Prior to sowing, the soil was assessed for its chemical properties (Table 1). The pH and electrical conductivity of the soil samples were determined in a 1:2.5 soil–water suspension using potentiometric and conductometric methods, respectively (9). The organic carbon content was estimated by wet oxidation method (10), while available N was determined using the alkaline permanganate method (11). Available P was extracted with 0.5 M sodium bicarbonate (pH 8.5) by the Olsen method (12) and available K was extracted with 1 N ammonium acetate (pH 7.0) and quantified using a flame photometer (13). The experiment comprised 12 treatments (Table 2, Fig. 2) arranged in randomised block design with 3 replications. Basal application of N, P₂O₅ and K₂O as per the treatment details, using urea, single super phosphate (SSP) and muriate of potash (MOP) respectively, was followed in all treatment plots except treatment T₁ (control). The recommended dose of fertilisers (RDF) for soybean was 50:75:45 kg ha⁻¹ of N, P₂O₅ and K₂O respectively + 10 t ha⁻¹ farmyard manure (FYM), which was given to treatment T₁₂ through urea, SSP, MOP and FYM, respectively. The FYM was applied 15 days before sowing. Before application, the FYM was analysed for its chemical properties (Table 3). The pH and electrical conductivity of the FYM were determined in a 1:10 organic manure–water suspension using potentiometric and conductometric methods, respectively (9). Total organic carbon content was measured by the loss on ignition method (14), while

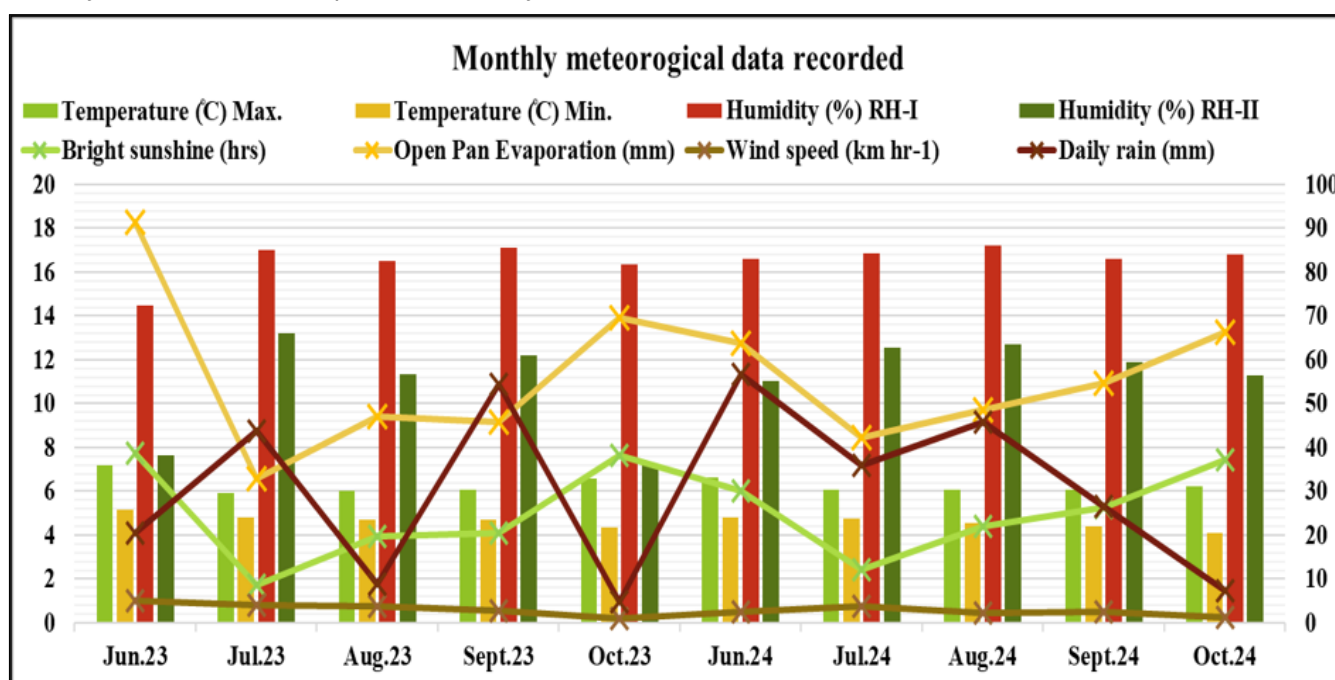


Fig. 1. Mean monthly meteorological data of experimental site during 2023 and 2024.

Table 1. Soil chemical analysis

Sl. No.	Parameter	Value	Interpretation
1.	pH (1:2.5)	8.01	Slightly alkaline
2.	Electrical conductivity (1:2.5) (dS m ⁻¹)	0.15	Normal
3.	Organic carbon (%)	0.66	*
4.	Available nitrogen (kg ha ⁻¹)	168	Low
5.	Available phosphorus (kg ha ⁻¹)	14.33	Low
6.	Available potassium (kg ha ⁻¹)	434	Very high

*No interpretation.

Table 2. Treatments details

Treatment No.	Treatment details
T ₁	0:0:0 N:P ₂ O ₅ :K ₂ O kg ha ⁻¹ (Absolute control)
T ₂	25:0:0 N:P ₂ O ₅ :K ₂ O kg ha ⁻¹
T ₃	50:0:0 N:P ₂ O ₅ :K ₂ O kg ha ⁻¹
T ₄	0:50:0 N:P ₂ O ₅ :K ₂ O kg ha ⁻¹
T ₅	0:75:0 N:P ₂ O ₅ :K ₂ O kg ha ⁻¹
T ₆	0:0:30 N:P ₂ O ₅ :K ₂ O kg ha ⁻¹
T ₇	0:0:45 N:P ₂ O ₅ :K ₂ O kg ha ⁻¹
T ₈	25:75:0 N:P ₂ O ₅ :K ₂ O kg ha ⁻¹
T ₉	50:50:0 N:P ₂ O ₅ :K ₂ O kg ha ⁻¹
T ₁₀	50:75:0 N:P ₂ O ₅ :K ₂ O kg ha ⁻¹
T ₁₁	25:75:45 N:P ₂ O ₅ :K ₂ O kg ha ⁻¹
T ₁₂	50:75:45 N:P ₂ O ₅ :K ₂ O kg ha ⁻¹ + 10 t ha ⁻¹ FYM

Note: N:P₂O₅:K₂O: nitrogen, phosphorus and potassium; FYM: farmyard manure.

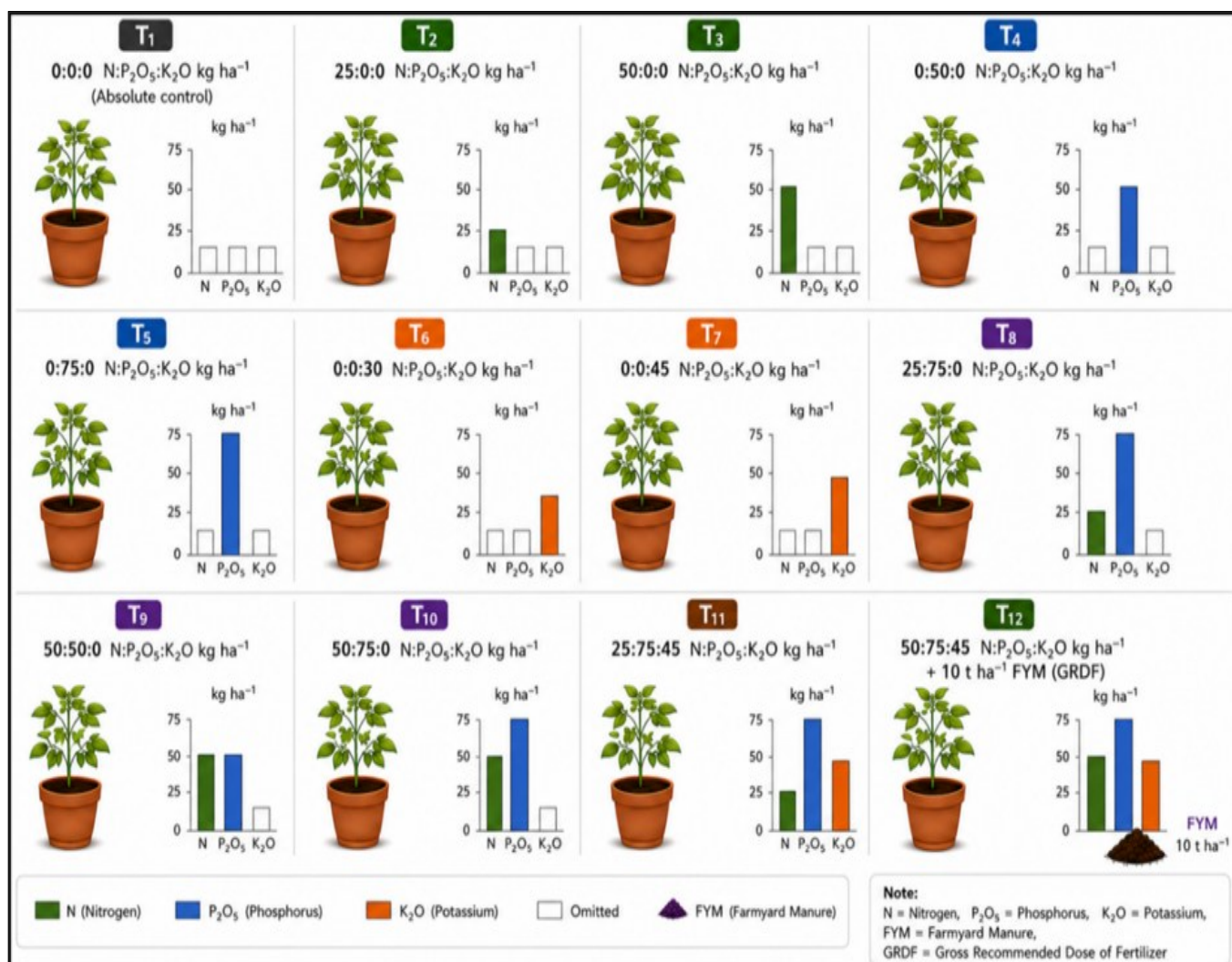
**Fig. 2.** Overview of nutrient management treatments utilised in this study.

Table 3. Characterisation of FYM

Sl. No.	Particulars	Value	
		2023	2024
1.	pH (1:10)	8.03	7.98
2.	EC (1:10) (dS m ⁻¹)	2.10	2.13
3.	Organic carbon (%)	23.32	21.35
4.	Organic matter (%)	40.20	36.80
5.	Total nitrogen (%)	1.23	1.26
6.	Total phosphorus (%)	0.36	0.31
7.	Total potassium (%)	0.75	0.80
8.	C:N ratio	18.95	16.94
9.	Ash (%)	59.80	63.20

Note: EC: electrical conductivity; C:N: carbon:nitrogen.

total N was determined using the micro-Kjeldahl method (15). Total P was analysed using a spectrophotometer with vanadomolybdate reagent (9) and total K was estimated using a flame photometer (16). The experimental details, including the sowing of soybean variety 'Phule Durva' at the recommended spacing of 45 × 5 cm for both years of the study, are presented in Table 4. All the cultural operations were performed in accordance with the recommended package of practices for the crop.

Table 4. Experiment details

Crop	:	Soybean (<i>Glycine max</i> L.)
Variety	:	KDS 992 (Phule Durva)
Season	:	Kharif (2023 and 2024)
Location	:	STCR farm, MPKV., Rahuri
Soil type	:	Inceptisol
Design	:	Randomised block design
No. of treatments	:	12 (Twelve)
No. of replications	:	03 (Three)
Plot size	:	Gross plot - 3.50 × 2.70 m Net plot - 3.10 × 1.80 m
Sowing method	:	Dibbling
Spacing	:	45 × 5 cm

Collection of data

The representative soil samples were collected from each treatment plot at a depth of 0–15 cm before the beginning of the experiment and after the harvest of the soybean crop. The samples were dried in the shade, ground, sieved and analysed for their chemical properties. For plant analysis, representative plant samples were collected from each treatment plot, cleaned, dried in the shade and subsequently oven-dried at 65 ± 2 °C until a constant dry weight was achieved. The dried samples were then finely ground, processed, digested and used for further chemical analysis following standard analytical methods. Total N was determined by the micro-Kjeldahl method (15), total P was estimated using the vanadomolybdate reagent with a spectrophotometer (9) and total K was determined using a flame photometer (16). Leaf chlorophyll content was measured using a soil plant analysis development (SPAD) chlorophyll meter (Minolta, Japan) at 30, 45, 60 and 90 days after sowing (DAS) of the soybean crop (17). The SPAD readings were recorded from five labelled observation plants in each treatment plot and their average values were used for further statistical analysis. The NPK uptake by the crop was measured by multiplying dry matter accumulation with the corresponding concentrations of N, P and K in plant tissue at harvest. Soybean grain and straw yield, along with the yield attributes, which included number of pods plant⁻¹, number of seeds plant⁻¹ and weight of seeds plant⁻¹ of soybean were recorded at harvest for further statistical analysis.

Statistical analysis

Data were subjected to analysis of variance (ANOVA), appropriate for a randomised block design, following standard statistical procedures (18). Treatment means were compared using the critical difference (CD) test at the 5 % level of significance. Principal component analysis (PCA) was performed using the generalised and robust analysis of principal component explorations and statistics (GRAPES) software platform to evaluate the relationships among treatments and measured variables.

Results and Discussion

Chlorophyll content

In 2023 and 2024, the chlorophyll content of soybean as measured by SPAD at 30, 45, 60 and 90 DAS, differed significantly among treatments, with T₁₂ recording the highest values. The pooled data for chlorophyll content of soybean were significantly higher in T₁₂ at 30 (36.28), 45 (37.89), 60 (40.01) and 90 (37.80) DAS. Among the sole N, P and K fertiliser application treatments, the pooled chlorophyll content was consistently higher for T₃ at 30 (30.35), 45 (31.61), 60 (33.43) and 90 DAS (31.72) (Table 5). However, T₁(control) consistently recorded the lowest chlorophyll content in 2023 and 2024. On a pooled basis, T₁ exhibited the lowest chlorophyll content at 30 (23.17), 45 (24.43), 60 (26.25) and 90 (24.54) DAS.

Results from the present study reported increased chlorophyll content in soybean plants supplied with RDF compared with nutrient-stressed plants. In plants, the synthesis of chlorophyll is a biochemical process which is directly related to N, as N is a major constituent of the chlorophyll molecule. However, P supports chlorophyll formation indirectly by facilitating energy transfer (ATP synthesis), root development and nutrient uptake, while K enhances photosynthetic efficiency through stomatal regulation, enzyme activation and efficient translocation of photosynthates (19). In the absence of these essential nutrients in the growing medium, it is likely that plant health is compromised due to decreased chlorophyll synthesis. In the present study, T₁₂ ensured a steady nutrient supply through inorganic NPK fertilisers, while FYM enhanced soil physical structure, stimulated microbial activity and nutrient mineralisation, which supported improved nutrient availability and uptake throughout the soybean crop growth period. Comparable findings were reported in studies conducted in soybean under the integrated application of inorganic NPK with FYM (20, 21). It was indicated from the results that chlorophyll content was lower initially and increased gradually towards the pod development stage, reaching the highest level due to maximum nitrogen fixation. Thereafter, chlorophyll content gradually declined as the crop approached maturity due to

Table 5. Effect of graded NPK levels on periodical chlorophyll (SPAD) content of soybean

Treatment. No.	SPAD value at 30 DAS			SPAD value at 45 DAS			SPAD value at 60 DAS			SPAD value at 90 DAS		
	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled
T ₁	22.97	23.37	23.17	24.24	24.62	24.43	25.50	27.00	26.25	23.37	25.71	24.54
T ₂	27.59	32.19	29.89	28.86	33.44	31.15	30.12	35.82	32.97	27.99	34.53	31.26
T ₃	28.23	32.48	30.35	29.50	33.73	31.61	30.76	36.11	33.43	28.63	34.82	31.72
T ₄	26.70	28.85	27.77	27.97	30.10	29.03	29.23	32.48	30.85	27.10	31.19	29.14
T ₅	27.12	31.14	29.13	28.39	32.39	30.39	29.65	34.77	32.21	27.52	33.48	30.50
T ₆	25.62	25.24	25.43	26.89	26.49	26.69	28.15	28.87	28.51	26.02	27.58	26.80
T ₇	26.28	28.63	27.46	27.55	29.88	28.72	28.81	32.26	30.54	26.68	30.97	28.83
T ₈	29.77	33.42	31.59	31.04	35.33	33.19	32.46	37.71	35.09	30.33	35.42	32.88
T ₉	31.45	34.56	33.01	32.72	36.48	34.60	34.32	38.52	36.42	32.19	36.90	34.54
T ₁₀	32.10	35.21	33.65	33.37	37.46	35.41	34.96	39.17	37.06	32.83	37.55	35.19
T ₁₁	33.87	36.17	35.02	35.14	38.42	36.78	36.40	39.80	38.10	34.27	38.51	36.39
T ₁₂	34.35	38.22	36.28	35.62	40.16	37.89	37.42	42.61	40.01	35.29	40.32	37.80
Sem (±)	1.64	1.85	1.24	1.64	2.17	1.36	1.77	1.87	1.29	1.75	1.84	1.27
CD at 5 %	4.81	5.43	3.52	4.81	6.36	3.87	5.18	5.47	3.66	5.13	5.41	3.62

Note: T1-0:0:0 N:P₂O₅:K₂O kg ha⁻¹ (absolute control); T2-25:0:0 N:P₂O₅:K₂O kg ha⁻¹; T3-50:0:0 N:P₂O₅:K₂O kg ha⁻¹; T4-0:50:0 N:P₂O₅:K₂O kg ha⁻¹; T5-0:75:0 N:P₂O₅:K₂O kg ha⁻¹; T6-0:0:30 N:P₂O₅:K₂O kg ha⁻¹; T7-0:0:45 N:P₂O₅:K₂O kg ha⁻¹; T8-25:75:0 N:P₂O₅:K₂O kg ha⁻¹; T9-50:50:0 N:P₂O₅:K₂O kg ha⁻¹; T10-50:75:0 N:P₂O₅:K₂O kg ha⁻¹; T11-25:75:45 N:P₂O₅:K₂O kg ha⁻¹; T12-50:75:45 N:P₂O₅:K₂O kg ha⁻¹ + 10 t ha⁻¹ farmyard manure.

senescence-induced degradation of green pigments in leaves. These results are in accordance with the study conducted in soybean at various growth stages (22).

Yield of soybean

The number of pods plant⁻¹ was significantly highest under T₁₂ in 2023 (87.33) and 2024 (89.00). The number of seeds plant⁻¹ of soybean was found to be significantly highest under T₁₂ in 2023 (177.67) and 2024 (190.33). The weight of seeds plant⁻¹ was significantly highest in T₁₂ in 2023 (34.68 g) and 2024 (37.15 g) (Table 6). Pooled data for 2023 and 2024 indicated that treatment T₃, among the sole applications of N, P and K resulted in higher number of pods plant⁻¹ (74.00), number of seeds plant⁻¹ (147.83) and weight of seeds plant⁻¹ (28.86 g) of soybean (Table 6). Conversely, the lowest number of pods plant⁻¹, number of seeds plant⁻¹ and weight of seeds plant⁻¹ of soybean were recorded in T₁ during 2023, 2024 and on a pooled basis.

The superior yield attributes under T₁₂ could be attributed to the integrated application of FYM with balanced NPK, which improved nutrient availability throughout the crop growth period.

Balanced N and P application led to enhanced leaf area development, with increased photosynthetic activity and efficient energy transfer through ATP, which led to improved flowering and pod initiation, respectively. Balanced K application facilitated enzyme activation, carbohydrate synthesis and translocation of assimilates to developing pods and seeds of the plant (23). Further, the addition of FYM improved soil nutrient availability, resulting in greater nutrient efficiency and sustained nutrient supply during the critical reproductive stages of soybean (24). Consequently, enhanced assimilate production and partitioning improved seed filling and ultimately increased the number of pods and seeds in the plant (25).

The grain yield of soybean (Table 7, Fig. 3) was significantly highest under T₁₂ in 2023 (32.12 q ha⁻¹) and 2024 (34.02 q ha⁻¹). Pooled grain yield of soybean was significantly highest under T₁₂ (33.07 q ha⁻¹), while treatments T₁₁ and T₁₀ were statistically at par with T₁₂. In contrast, the control (T₁) recorded the lowest grain yield in 2023 (14.31 q ha⁻¹), 2024 (16.21 q ha⁻¹) and on a pooled basis (15.26 q ha⁻¹). Straw yield of soybean (Table 7, Fig. 3) was highest under treatment T₁₂ in 2023 (40.48 q ha⁻¹) and 2024 (42.87 q ha⁻¹). Pooled straw yield of

Table 6. Effect of graded NPK levels on yield attributing characters in soybean

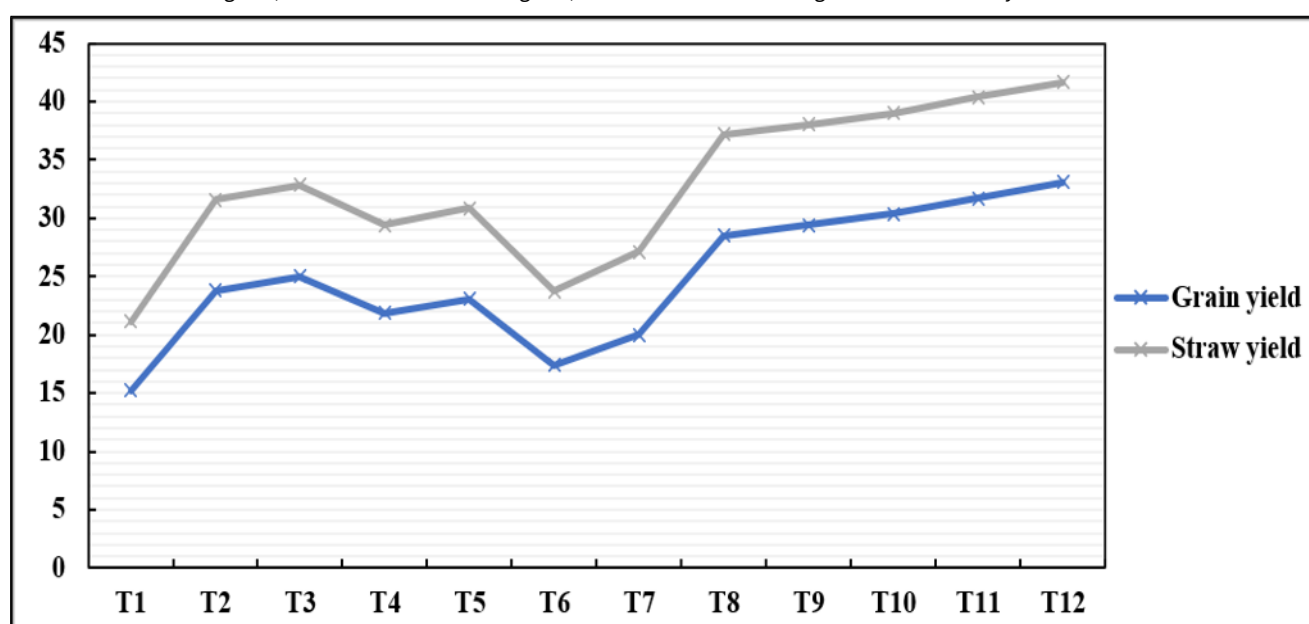
Treatment No.	Number of pods plant ⁻¹			Number of seeds plant ⁻¹			Seed weight plant ⁻¹ (g)		
	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled
T ₁	49.67	52.67	51.17	96.33	104.67	100.50	18.80	20.43	19.62
T ₂	73.00	72.67	72.83	133.00	142.00	137.50	25.96	27.72	26.84
T ₃	74.33	73.67	74.00	146.33	149.33	147.83	28.56	29.15	28.86
T ₄	67.33	69.33	68.33	126.00	129.00	127.50	24.60	25.18	24.89
T ₅	68.67	70.67	69.67	129.33	131.00	130.17	25.25	25.57	25.41
T ₆	56.00	61.00	58.50	103.67	113.33	108.50	20.24	22.12	21.18
T ₇	64.67	67.00	65.83	120.67	125.00	122.83	23.55	24.40	23.98
T ₈	76.33	80.67	78.50	153.00	166.33	159.67	29.87	32.47	31.17
T ₉	78.67	82.67	80.67	159.67	171.33	165.50	31.17	33.44	32.31
T ₁₀	80.67	84.00	82.33	162.00	176.33	169.17	31.62	34.42	33.02
T ₁₁	83.67	85.33	84.50	166.00	185.33	175.67	32.40	36.18	34.29
T ₁₂	87.33	89.00	88.17	177.67	190.33	184.00	34.68	37.15	35.92
Sem (±)	4.28	5.13	3.34	8.44	8.46	5.98	1.65	1.58	1.14
CD at 5 %	12.55	15.05	9.52	24.75	24.82	17.03	4.83	4.64	3.26

Note: T1-0:0:0 N:P₂O₅:K₂O kg ha⁻¹ (absolute control); T2-25:0:0 N:P₂O₅:K₂O kg ha⁻¹; T3-50:0:0 N:P₂O₅:K₂O kg ha⁻¹; T4-0:50:0 N:P₂O₅:K₂O kg ha⁻¹; T5-0:75:0 N:P₂O₅:K₂O kg ha⁻¹; T6-0:0:30 N:P₂O₅:K₂O kg ha⁻¹; T7-0:0:45 N:P₂O₅:K₂O kg ha⁻¹; T8-25:75:0 N:P₂O₅:K₂O kg ha⁻¹; T9-50:50:0 N:P₂O₅:K₂O kg ha⁻¹; T10-50:75:0 N:P₂O₅:K₂O kg ha⁻¹; T11-25:75:45 N:P₂O₅:K₂O kg ha⁻¹; T12-50:75:45 N:P₂O₅:K₂O kg ha⁻¹ + 10 t ha⁻¹ farmyard manure.

Table 7. Effect of graded NPK levels on grain and straw yield of soybean

Treatment No.	Grain yield (q ha ⁻¹)			Straw yield (q ha ⁻¹)		
	2023	2024	Pooled	2023	2024	Pooled
T ₁	14.31	16.21	15.26	19.73	22.51	21.12
T ₂	22.88	24.78	23.83	30.21	32.96	31.58
T ₃	24.03	25.93	24.98	31.49	34.23	32.86
T ₄	20.92	22.82	21.87	28.04	30.81	29.43
T ₅	22.14	24.04	23.09	29.46	32.22	30.84
T ₆	16.45	18.35	17.40	22.38	25.14	23.76
T ₇	19.07	20.97	20.02	25.75	28.52	27.13
T ₈	27.57	29.47	28.52	35.84	38.61	37.22
T ₉	28.44	30.34	29.39	36.69	39.44	38.07
T ₁₀	29.40	31.30	30.35	37.64	40.38	39.01
T ₁₁	30.75	32.65	31.70	39.05	41.79	40.42
T ₁₂	32.12	34.02	33.07	40.48	42.87	41.67
Sem (±)	1.56	1.57	1.11	2.10	2.11	1.49
CD at 5 %	4.58	4.59	3.15	6.15	6.19	4.24

Note: T₁-0:0:0 N:P₂O₅:K₂O kg ha⁻¹ (absolute control); T₂-25:0:0 N:P₂O₅:K₂O kg ha⁻¹; T₃-50:0:0 N:P₂O₅:K₂O kg ha⁻¹; T₄-0:50:0 N:P₂O₅:K₂O kg ha⁻¹; T₅-0:75:0 N:P₂O₅:K₂O kg ha⁻¹; T₆-0:0:30 N:P₂O₅:K₂O kg ha⁻¹; T₇-0:0:45 N:P₂O₅:K₂O kg ha⁻¹; T₈-25:75:0 N:P₂O₅:K₂O kg ha⁻¹; T₉-50:50:0 N:P₂O₅:K₂O kg ha⁻¹; T₁₀-50:75:0 N:P₂O₅:K₂O kg ha⁻¹; T₁₁-25:75:45 N:P₂O₅:K₂O kg ha⁻¹; T₁₂-50:75:45 N:P₂O₅:K₂O kg ha⁻¹ + 10 t ha⁻¹ farmyard manure.

**Fig. 3.** Effect of different nutrient levels on grain and straw yield of soybean (pooled).

Note: T₁-0:0:0 N:P₂O₅:K₂O kg ha⁻¹ (absolute control); T₂-25:0:0 N:P₂O₅:K₂O kg ha⁻¹; T₃-50:0:0 N:P₂O₅:K₂O kg ha⁻¹; T₄-0:50:0 N:P₂O₅:K₂O kg ha⁻¹; T₅-0:75:0 N:P₂O₅:K₂O kg ha⁻¹; T₆-0:0:30 N:P₂O₅:K₂O kg ha⁻¹; T₇-0:0:45 N:P₂O₅:K₂O kg ha⁻¹; T₈-25:75:0 N:P₂O₅:K₂O kg ha⁻¹; T₉-50:50:0 N:P₂O₅:K₂O kg ha⁻¹; T₁₀-50:75:0 N:P₂O₅:K₂O kg ha⁻¹; T₁₁-25:75:45 N:P₂O₅:K₂O kg ha⁻¹; T₁₂-50:75:45 N:P₂O₅:K₂O kg ha⁻¹ + 10 t ha⁻¹ farmyard manure.

soybean was found to be significantly highest for T₁₂ (41.67 q ha⁻¹). However, T₁ recorded the lowest straw yield in 2023 (19.73 q ha⁻¹), 2024 (22.51 q ha⁻¹) and on a pooled basis (21.12 q ha⁻¹). Among the sole applications of N, P and K, pooled analysis indicated that treatment T₃ resulted in higher grain (24.98 q ha⁻¹) and straw yield of soybean (32.86 q ha⁻¹). The higher grain and straw yield under T₁₂ indicated a positive response of soybean to the integrated application of balanced NPK with FYM. This combined application ensured improved NPK availability through continuous and synchronised nutrient supply and promoted nutrient mobilisation and influx into plant tissues. Consequently, this balanced nutrition led to better root growth and increased nodulation, photosynthetic efficiency and nutrient uptake, thereby promoting greater biomass accumulation and efficient translocation of assimilates towards reproductive organs. This ultimately increased dry matter production and its partitioning into grains, leading to higher yields in soybean. Similar outcomes have been reported in various studies on soybean (25–27). In contrast, the lowest grain and straw yield of soybean was obtained in plants supplied with no fertilisers (T₁),

followed by plants supplied with incomplete nutrient application. The absence or limited supply of nutrients to plants, adversely affected vegetative growth, chlorophyll formation and photosynthetic activity, causing reduced dry matter accumulation and reproductive efficiency. These findings are similar to the results obtained in a study which reported that application of integrated nutrient supply of inorganic NPK fertiliser with FYM significantly elevated grain and straw yield parameters (28).

Nitrogen, phosphorus and potassium (NPK) uptake in soybean

Data indicated that NPK uptake in grain and straw (Table 8–10, Fig. 4) was significantly highest under treatment T₁₂ in 2023 and 2024. The pooled N, P and K uptake in grain and straw of soybean was significantly highest for T₁₂ i.e. 167.27 kg ha⁻¹ and 26.95 kg ha⁻¹ for N uptake in grain and straw, respectively; 22.13 kg ha⁻¹ and 9.44 kg ha⁻¹ for P uptake in grain and straw, respectively; and 20.40 kg ha⁻¹ and 58.12 kg ha⁻¹ for K uptake in grain and straw, respectively. Based on pooled data, among the sole applications of N, P and K, treatment T₃ recorded comparatively higher N, P and K uptake in grain and straw.

Table 8. Effect of graded NPK levels on nitrogen uptake in grain and straw of soybean

Treatment No.	N uptake (kg ha ⁻¹)					
	Grain uptake			Straw uptake		
	2023	2024	Pooled	2023	2024	Pooled
T ₁	68.70	79.71	74.21	11.35	14.73	13.04
T ₂	111.62	123.85	117.74	17.75	21.86	19.80
T ₃	117.46	129.85	123.65	18.53	22.73	20.63
T ₄	101.49	113.44	107.46	16.31	20.25	18.28
T ₅	107.62	119.73	113.67	17.22	21.27	19.24
T ₆	79.31	90.64	84.97	12.95	16.46	14.70
T ₇	92.15	103.77	97.96	15.01	18.78	16.89
T ₈	135.61	148.48	142.05	21.14	25.70	23.42
T ₉	140.14	153.14	146.64	21.76	26.38	24.07
T ₁₀	145.14	158.27	151.70	22.40	27.09	24.74
T ₁₁	152.29	165.61	158.95	23.29	28.09	25.69
T ₁₂	160.49	174.05	167.27	24.34	29.56	26.95
SEm(±)	7.43	7.59	5.31	1.19	1.38	0.91
CD at 5 %	21.79	22.27	15.14	3.50	4.05	2.60

Note: T₁-0:0:0 N:P₂O₅:K₂O kg ha⁻¹ (absolute control); T₂-25:0:0 N:P₂O₅:K₂O kg ha⁻¹; T₃-50:0:0 N:P₂O₅:K₂O kg ha⁻¹; T₄-0:50:0 N:P₂O₅:K₂O kg ha⁻¹; T₅-0:75:0 N:P₂O₅:K₂O kg ha⁻¹; T₆-0:0:30 N:P₂O₅:K₂O kg ha⁻¹; T₇-0:0:45 N:P₂O₅:K₂O kg ha⁻¹; T₈-25:75:0 N:P₂O₅:K₂O kg ha⁻¹; T₉-50:50:0 N:P₂O₅:K₂O kg ha⁻¹; T₁₀-50:75:0 N:P₂O₅:K₂O kg ha⁻¹; T₁₁-25:75:45 N:P₂O₅:K₂O kg ha⁻¹; T₁₂-50:75:45 N:P₂O₅:K₂O kg ha⁻¹ + 10 t ha⁻¹ farmyard manure; NPK: nitrogen, phosphorus and potassium.

Table 9. Effect of graded NPK levels on phosphorus uptake in grain and straw of soybean

Treatment No.	P uptake (kg ha ⁻¹)					
	Grain uptake			Straw uptake		
	2023	2024	Pooled	2023	2024	Pooled
T ₁	8.28	10.54	9.41	4.14	4.96	4.55
T ₂	13.53	16.44	14.98	6.44	7.37	6.91
T ₃	14.27	17.34	15.80	6.72	7.67	7.19
T ₄	12.46	15.35	13.91	5.99	6.90	6.45
T ₅	13.30	16.30	14.80	6.31	7.24	6.77
T ₆	9.58	12.03	10.81	4.72	5.56	5.14
T ₇	11.17	13.83	12.50	5.44	6.33	5.89
T ₈	16.69	20.11	18.40	7.68	8.68	8.18
T ₉	17.34	20.84	19.09	7.86	8.87	8.37
T ₁₀	18.04	21.62	19.83	8.07	9.08	8.58
T ₁₁	19.00	22.69	20.85	8.54	9.58	9.06
T ₁₂	20.22	24.04	22.13	8.98	9.89	9.44
SEm(±)	0.94	1.05	0.71	0.46	0.49	0.34
CD at 5 %	2.77	3.09	2.02	1.35	1.43	0.96

Note: T₁-0:0:0 N:P₂O₅:K₂O kg ha⁻¹ (absolute control); T₂-25:0:0 N:P₂O₅:K₂O kg ha⁻¹; T₃-50:0:0 N:P₂O₅:K₂O kg ha⁻¹; T₄-0:50:0 N:P₂O₅:K₂O kg ha⁻¹; T₅-0:75:0 N:P₂O₅:K₂O kg ha⁻¹; T₆-0:0:30 N:P₂O₅:K₂O kg ha⁻¹; T₇-0:0:45 N:P₂O₅:K₂O kg ha⁻¹; T₈-25:75:0 N:P₂O₅:K₂O kg ha⁻¹; T₉-50:50:0 N:P₂O₅:K₂O kg ha⁻¹; T₁₀-50:75:0 N:P₂O₅:K₂O kg ha⁻¹; T₁₁-25:75:45 N:P₂O₅:K₂O kg ha⁻¹; T₁₂-50:75:45 N:P₂O₅:K₂O kg ha⁻¹ + 10 t ha⁻¹ farmyard manure.

Table 10. Effect of graded NPK levels on potassium uptake in grain and straw of soybean

Treatment No.	K uptake (kg ha ⁻¹)					
	Grain uptake			Straw uptake		
	2023	2024	Pooled	2023	2024	Pooled
T ₁	7.51	8.82	8.16	26.12	30.51	28.31
T ₂	12.39	13.76	13.08	40.36	44.93	42.64
T ₃	13.15	14.54	13.85	42.15	46.76	44.45
T ₄	11.15	12.90	12.03	37.43	41.93	39.68
T ₅	11.93	13.72	12.83	39.35	43.92	41.63
T ₆	9.08	10.06	9.57	30.02	34.43	32.23
T ₇	10.63	11.57	11.10	34.57	39.06	36.81
T ₈	15.45	16.91	16.18	48.48	53.28	50.88
T ₉	16.22	17.54	16.88	50.06	54.91	52.49
T ₁₀	17.01	18.85	17.93	51.54	56.31	53.93
T ₁₁	18.12	19.83	18.97	53.93	58.51	56.22
T ₁₂	19.29	21.50	20.40	56.08	60.16	58.12
Sem (±)	0.83	1.04	0.67	2.63	2.87	1.95
CD at 5 %	2.43	3.06	1.90	7.70	8.43	5.55

Note: T₁-0:0:0 N:P₂O₅:K₂O kg ha⁻¹ (absolute control); T₂-25:0:0 N:P₂O₅:K₂O kg ha⁻¹; T₃-50:0:0 N:P₂O₅:K₂O kg ha⁻¹; T₄-0:50:0 N:P₂O₅:K₂O kg ha⁻¹; T₅-0:75:0 N:P₂O₅:K₂O kg ha⁻¹; T₆-0:0:30 N:P₂O₅:K₂O kg ha⁻¹; T₇-0:0:45 N:P₂O₅:K₂O kg ha⁻¹; T₈-25:75:0 N:P₂O₅:K₂O kg ha⁻¹; T₉-50:50:0 N:P₂O₅:K₂O kg ha⁻¹; T₁₀-50:75:0 N:P₂O₅:K₂O kg ha⁻¹; T₁₁-25:75:45 N:P₂O₅:K₂O kg ha⁻¹; T₁₂-50:75:45 N:P₂O₅:K₂O kg ha⁻¹ + 10 t ha⁻¹ farmyard manure.

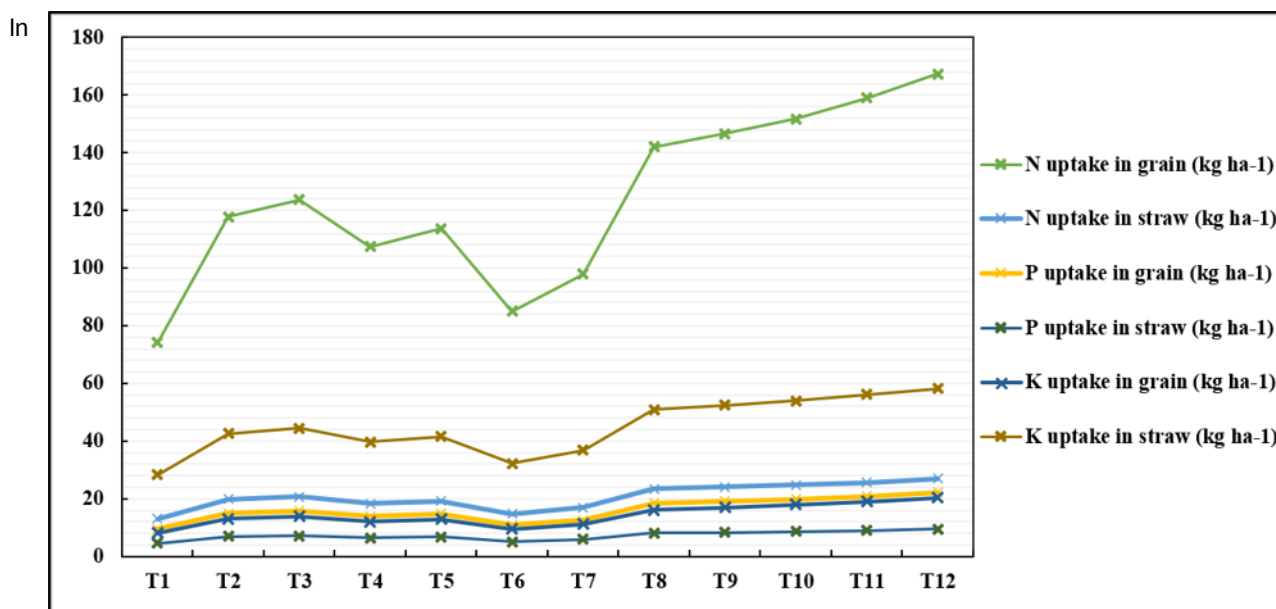


Fig. 4. Effect of different nutrient levels on nitrogen, phosphorus and potassium uptake in grain and straw of soybean (pooled).

Note: T1-0:0:0 N:P₂O₅:K₂O kg ha⁻¹ (absolute control); T2-25:0:0 N:P₂O₅:K₂O kg ha⁻¹; T3-50:0:0 N:P₂O₅:K₂O kg ha⁻¹; T4-0:50:0 N:P₂O₅:K₂O kg ha⁻¹; T5-0:75:0 N:P₂O₅:K₂O kg ha⁻¹; T6-0:0:30 N:P₂O₅:K₂O kg ha⁻¹; T7-0:0:45 N:P₂O₅:K₂O kg ha⁻¹; T8-25:75:0 N:P₂O₅:K₂O kg ha⁻¹; T9-50:50:0 N:P₂O₅:K₂O kg ha⁻¹; T10-50:75:0 N:P₂O₅:K₂O kg ha⁻¹; T11-25:75:45 N:P₂O₅:K₂O kg ha⁻¹; T12-50:75:45 N:P₂O₅:K₂O kg ha⁻¹ + 10 t ha⁻¹ farmyard manure.

contrast, T₁ exhibited the lowest N (74.21 kg ha⁻¹ and 13.04 kg ha⁻¹), P (9.41 kg ha⁻¹ and 4.55 kg ha⁻¹) and K (8.16 kg ha⁻¹ and 28.31 kg ha⁻¹) uptake in grain and straw respectively, on a pooled basis.

The significantly higher macronutrient uptake under T₁₂ may be attributed to the integrated application of balanced NPK with FYM, which improved nutrient availability, retention and synchronisation of nutrient release with crop demands at various growth stages. The FYM addition promoted aggregation and microbial activity in the soil thereby improving soil organic carbon, which led to enhanced root proliferation and increase the efficiency of nutrient acquisition. Balanced and complete fertilisation ensured an adequate supply of available nutrients to plants throughout the crop growth period. This caused high accumulation of NPK in the dry matter of soybean plants, leading to increased yield of grain and straw, consequently increasing NPK uptake in grain and straw of soybean plants. Similar findings were reported in various studies (29–31). Results also indicated that the exclusion of any one of the primary nutrients led to imbalance in nutrient supply to plants causing a decline in NPK uptake and yield of soybean. In this context, P uptake was found to be lower in plants not supplied with N fertiliser than in plants not supplied with P fertiliser. This could be attributed to lower biomass production by these plants resulting in lower P uptake. Adequate N application promotes vigorous root growth and nodulation, which facilitates P acquisition, while sufficient P improves energy transfer and biological N fixation. Such outcomes are consistent with the results of various studies (32, 33). It was also reported from the results that omission of N and P from supplied fertiliser treatments had a greater impact on reducing the K uptake by plants than omission of K itself, showing a synergistic effect of balanced fertilisation on the plants. Similar findings were reported in various studies (34–36).

Chemical properties of soil

In 2023 and 2024, the treatment effects on soil pH and electrical conductivity (EC) were found to be non-significant (Table 11). The soil organic carbon (SOC) was significantly highest under treatment T₁₂ in 2023 (0.71 %) and 2024 (0.73 %). Results indicated small

changes in soil pH and EC due to application of inorganic NPK fertilisers at different levels and in combination with FYM. These findings were supported by studies conducted in various crops (34, 35).

The pooled SOC following the harvest of the soybean crop was found to be significantly highest for T₁₂ (0.72 %) while treatments T₁₁, T₁₀, T₉, T₈ and T₃ were at par with T₁₂. Results from the pooled data indicated that T₃ recorded higher SOC (0.69 %) among sole N, P and K fertiliser application treatments. Results indicated that after harvest, SOC increased significantly in soil supplied with inorganic NPK fertilisers in combination with FYM, which might be due to addition of a large amount of leaf biomass and ground biomass of soybean in the soil. Such outcomes are consistent with findings reported in various investigations (37, 38). Soil from the unfertilised plot had the lowest SOC followed by soil supplied with K and P fertilisers alone. This decrease might be ascribed to a reduction in the biomass of plants not supplied with an ample quantity of integrated nutrients. Integrated nutrient supply to plants resulted in an improvement in root and shoot biomass of soybean plants. This, in turn, enhanced SOC content after decomposition of these materials. Similar results were reported by studies conducted in maize, soybean and cotton (28, 31).

Results in Table 12 indicated that available N, P and K were significantly highest for T₁₂ in 2023 and 2024. Pooled available N, P and K were found to be significantly highest for T₁₂ (187 kg ha⁻¹, 19.99 kg ha⁻¹, 470 kg ha⁻¹ respectively). Results from the pooled data indicated that after soybean harvest, higher available N, P and K were observed for treatments T₃ (177 kg ha⁻¹), T₅ (18.77 kg ha⁻¹) and T₇ (437 kg ha⁻¹), respectively, among the sole N, P and K fertiliser application treatments.

Highest N availability could be attributed to enhanced N fixation by soybean root nodules, as well as improved biomass production, resulting in greater incorporation of organic matter as leaves and roots leading to an increase in N status of soil. Lower N availability was observed in soil not supplied with N fertiliser (21, 29). The highest available P and K were recorded in soil receiving

Table 11. Effect of graded NPK levels on chemical properties of soil after harvest of soybean (2023 and 2024)

Treatment No.	pH			EC (dS m ⁻¹)			Organic Carbon (%)		
	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled
T ₁	8.02	8.04	8.03	0.14	0.15	0.15	0.62	0.64	0.63
T ₂	7.97	7.92	7.94	0.15	0.17	0.16	0.67	0.69	0.68
T ₃	7.96	7.92	7.94	0.15	0.16	0.15	0.68	0.70	0.69
T ₄	7.97	7.94	7.96	0.15	0.16	0.15	0.64	0.65	0.65
T ₅	7.97	7.93	7.95	0.16	0.17	0.16	0.64	0.66	0.65
T ₆	7.98	7.95	7.97	0.16	0.17	0.16	0.63	0.65	0.64
T ₇	7.98	7.94	7.96	0.15	0.16	0.15	0.63	0.65	0.64
T ₈	7.96	7.92	7.94	0.16	0.16	0.16	0.69	0.70	0.69
T ₉	7.96	7.91	7.93	0.16	0.16	0.16	0.69	0.71	0.70
T ₁₀	7.95	7.90	7.93	0.16	0.17	0.16	0.70	0.71	0.71
T ₁₁	7.94	7.90	7.92	0.16	0.17	0.16	0.69	0.72	0.71
T ₁₂	7.93	7.89	7.91	0.16	0.17	0.16	0.71	0.73	0.72
Sem (±)	0.02	0.03	0.02	0.004	0.004	0.003	0.02	0.02	0.01
CD at 5 %	NS	NS	NS	NS	NS	NS	0.05	0.06	0.04

Note: T1-0:0:0 N:P₂O₅:K₂O kg ha⁻¹ (absolute control); T2-25:0:0 N:P₂O₅:K₂O kg ha⁻¹; T3-50:0:0 N:P₂O₅:K₂O kg ha⁻¹; T4-0:50:0 N:P₂O₅:K₂O kg ha⁻¹; T5-0:75:0 N:P₂O₅:K₂O kg ha⁻¹; T6-0:0:30 N:P₂O₅:K₂O kg ha⁻¹; T7-0:0:45 N:P₂O₅:K₂O kg ha⁻¹; T8-25:75:0 N:P₂O₅:K₂O kg ha⁻¹; T9-50:50:0 N:P₂O₅:K₂O kg ha⁻¹; T10-50:75:0 N:P₂O₅:K₂O kg ha⁻¹; T11-25:75:45 N:P₂O₅:K₂O kg ha⁻¹; T12-50:75:45 N:P₂O₅:K₂O kg ha⁻¹ + 10 t ha⁻¹ farmyard manure.

Table 12. Effect of graded NPK levels on available nitrogen, phosphorus and potassium in soil after harvest of soybean

Treatment No.	Available nitrogen (kg ha ⁻¹)			Available phosphorus (kg ha ⁻¹)			Available potassium (kg ha ⁻¹)		
	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled
T ₁	147	154	150	9.34	11.46	10.40	418	420	419
T ₂	169	182	176	12.32	14.32	13.32	426	429	427
T ₃	170	185	177	12.58	14.45	13.51	428	431	430
T ₄	155	171	163	16.83	18.56	17.69	421	424	422
T ₅	160	176	168	17.71	19.84	18.77	424	427	425
T ₆	149	161	155	11.83	13.96	12.90	431	435	433
T ₇	152	168	160	12.20	13.71	12.95	435	438	437
T ₈	171	186	179	17.86	19.95	18.90	438	441	440
T ₉	175	191	183	17.44	18.98	18.21	442	445	444
T ₁₀	177	193	185	18.53	20.75	19.64	449	453	451
T ₁₁	173	188	181	18.40	20.22	19.31	461	466	464
T ₁₂	178	195	187	18.94	21.03	19.99	468	472	470
Sem (±)	4.42	5.20	3.41	0.42	0.47	0.32	2.12	2.15	1.51
CD at 5 %	12.96	15.25	9.72	1.23	1.39	0.90	6.23	6.32	4.31

Note: T1-0:0:0 N:P₂O₅:K₂O kg ha⁻¹ (absolute control); T2-25:0:0 N:P₂O₅:K₂O kg ha⁻¹; T3-50:0:0 N:P₂O₅:K₂O kg ha⁻¹; T4-0:50:0 N:P₂O₅:K₂O kg ha⁻¹; T5-0:75:0 N:P₂O₅:K₂O kg ha⁻¹; T6-0:0:30 N:P₂O₅:K₂O kg ha⁻¹; T7-0:0:45 N:P₂O₅:K₂O kg ha⁻¹; T8-25:75:0 N:P₂O₅:K₂O kg ha⁻¹; T9-50:50:0 N:P₂O₅:K₂O kg ha⁻¹; T10-50:75:0 N:P₂O₅:K₂O kg ha⁻¹; T11-25:75:45 N:P₂O₅:K₂O kg ha⁻¹; T12-50:75:45 N:P₂O₅:K₂O kg ha⁻¹ + 10 t ha⁻¹ farmyard manure.

balanced application of NPK with FYM. Being a legume crop, enhanced soil P availability under soybean may result from increased rhizospheric activity of P-solubilising microorganisms. These findings align with the study conducted in leguminous crops (39). Likewise, improvement in available K status may be a combined response to direct K supplementation by inorganic fertilisers and beneficial residual effects of FYM, which help to maintain K availability in soil. The results corroborated the findings of studies conducted in maize, soybean and cotton (40).

Principal component analysis (PCA)

In Fig. 5 showing the individual PCA plot, treatments were found to be distinctly separated across the axes of PCA, which indicated substantial variability among these graded NPK level treatments for chlorophyll content, NPK uptake and yield attributes. The PCA analysis in Figs. 5 and 6 showed that T₁₁ and T₁₂ were observed on the positive side of PC1 and were closely associated with NPK uptake of soybean and yield attributes, which indicated their superior

performance. This suggested that balanced fertilisation enhanced biomass production and nutrient acquisition. However, T₁ was located in the negative quadrant of PC1, indicating poor performance due to nutrient deficiency. In the PCA biplot (Fig. 7), a stronger positive relationship was observed between chlorophyll content, yield attributes and nutrient uptake traits, suggesting strong positive correlations among physiological efficiency, photosynthetic activity and yield formation in soybean. The vectors of chlorophyll content were oriented towards significant treatments, which implied that higher chlorophyll concentration contributed to improved photosynthetic efficiency and biomass accumulation. The vectors of NPK uptake by grain and straw of soybean were also clustered together, which confirmed synergistic nutrient accumulation patterns under balanced fertilisation. Similar outcomes have been observed in a study conducted on soybean in which PCA effectively separated soybean treatments based on yield and nutrient-related traits under zinc (Zn) and iron (Fe) fertilisation (41).

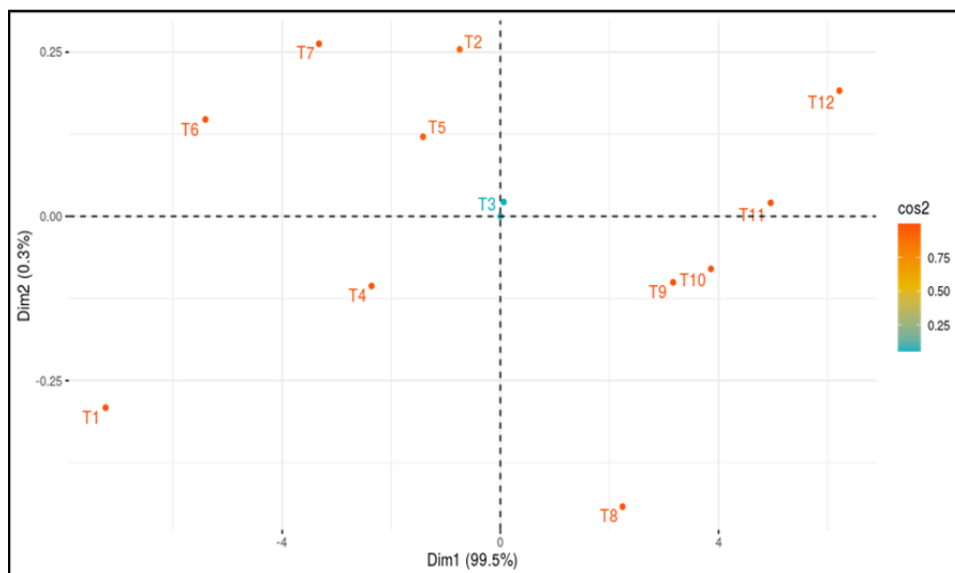


Fig. 5. Principal component analysis (PCA) score plot of soybean treatments under graded nutrient levels.

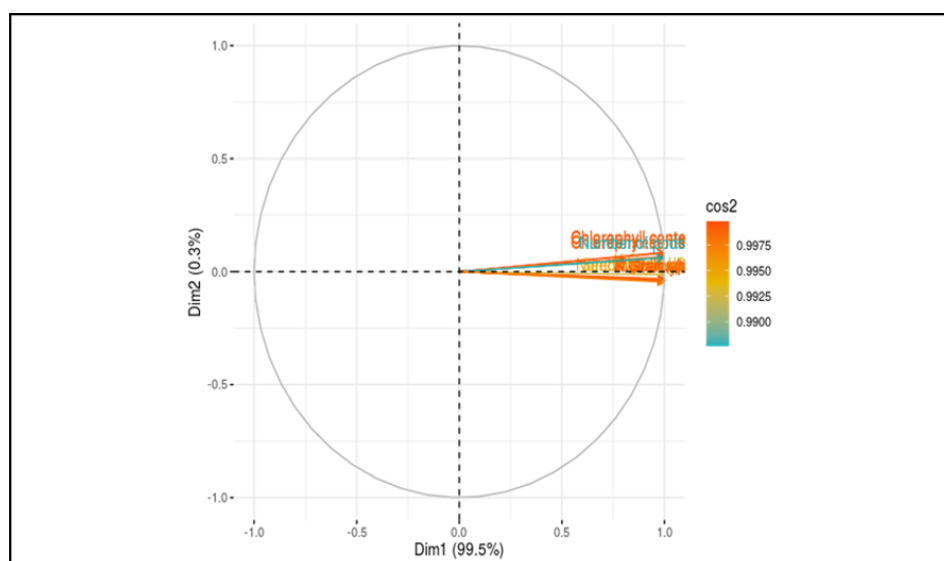


Fig. 6. Principal component analysis (PCA) correlation circle showing relationships among soybean chlorophyll content, nutrient uptake and yield attributes.

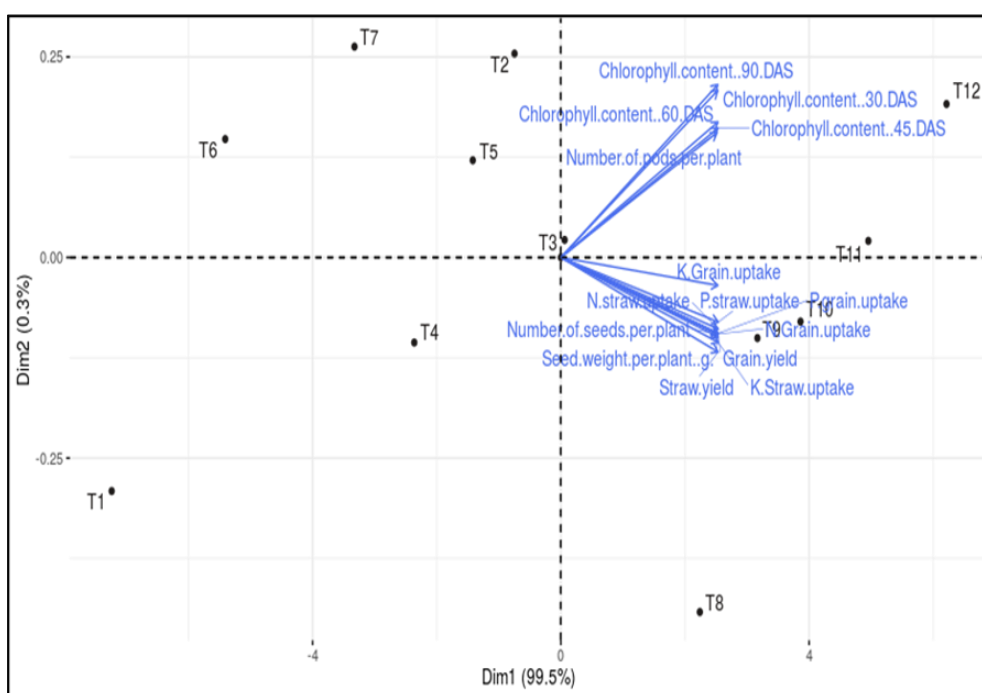


Fig. 7. Principal component analysis (PCA) biplot of soybean chlorophyll content, nutrient uptake and yield attributes.

Conclusion

The two-year field study demonstrated that soybean growth, yield, nutrient uptake and soil fertility were strongly influenced by the level and balance of nutrient application. Application of 50:75:45 N:P₂O₅:K₂O kg ha⁻¹ + 10 t ha⁻¹ farmyard manure (FYM) was found to improve crop growth and increase yield as well as nitrogen, phosphorus and potassium (NPK) uptake in soybean and maintain soil fertility status. The principal component analysis (PCA) effectively summarised the multidimensional relationships among soybean chlorophyll dynamics, nutrient uptake and yield traits by demonstrating the differential response of the soybean crop under graded NPK levels. Under the soil and climatic conditions of Rahuri, Maharashtra, application of 50:75:45 N:P₂O₅:K₂O kg ha⁻¹ + 10 t ha⁻¹ FYM may be recommended for achieving higher soybean productivity while maintaining soil fertility. The integrated nutrient management approach contributed to sustainable nutrient use and improved soil health, supporting long-term soybean production.

Future research directions:

Future research should focus on validating these findings across diverse soil types, agro-climatic regions and soybean cultivars to enhance their wider adaptability.

Further studies integrating precision nutrient management tools and long-term assessment of soil health and nutrient use efficiency are also recommended to support sustainable soybean production.

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Authors' contributions

SGA executed the research work, analysed the data and drafted the initial manuscript. VSP supervised the research work and reviewed the manuscript. RST, SAK, SRS, MRP, BMK, MMJ, NGB and RBZ reviewed the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

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

Ethical issues: None

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