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RESEARCH

Improving soybean yield and oil productivity: an integrated nutrient management approach for sustainable soybean production

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Abstract

The increasing demand for oilseed crops like soybeans requires sustainable cultivation practices that not only boost productivity but also maintain the long-term health of soil and the environment. This research aimed to investigate the impact of an integrated nutrient management strategy, which includes organic sources (compost types), phosphorus management, and inoculation with phosphate-solubilizing bacteria (PSB), on soybean productivity and profitability. Furthermore, the study examined the response of soybeans to varying potassium levels and different types of compost under both irrigated and dryland conditions. Two separate field experiments were conducted, with and without PSB seed inoculation, to evaluate various parameters including yield components, seed quality, protein and oil contents, grain yield, and growers' income. The results demonstrated that the application of sole poultry manure compost significantly improved yield components, grain yield (3064 kg ha^{-1}), protein yield (771 kg ha^{-1}), and oil yield (546 kg ha^{-1}). Application of the highest P level (90 kg P ha^{-1}) produced the maximum grain yield (3222 kg ha^{-1}), protein yield (823 kg ha^{-1}), and oil yield (588 kg ha^{-1}). Furthermore, plots treated with PSB exhibited higher yield components, grain yield (3051 kg ha^{-1}), protein yield (769 kg ha^{-1}) and oil yield (550 kg ha^{-1}). Moreover, increasing phosphorus levels in conjunction with poultry manure compost or a combination of poultry + cattle manure composts resulted in improved yield components, protein and oil yields, and grain yield. In another aspect of the study, the response of soybean to potassium levels and different compost types under irrigated and dryland conditions was assessed. The findings revealed that higher potassium level (90 kg K ha^{-1}) significantly increased yield components and produced the maximum grain yield (3189 kg ha^{-1}), protein yield (725 kg ha^{-1}), and oil yield (574 kg ha^{-1}). Additionally, the application of sole poultry manure compost increased all yield components, grain yield (3160 kg ha^{-1}), protein yield (719 kg ha^{-1}), and oil yield (569 kg ha^{-1}). Moreover, the irrigated plots demonstrated higher yield components, grain yield (2981 kg ha^{-1}), protein yield (680 kg ha^{-1}) and oil yield (536 kg ha^{-1}). In conclusion, this research emphasizes the significance of an integrated nutrient management approach, incorporating compost, potassium, phosphorus, and phosphate solubilizing bacteria in enhancing soybean productivity and profitability.

Keywords Compost, Phosphorus, Potassium, Phosphate solubilizing bacteria (PSB), Water stress, Grain yield, Oil yield, Protein yield

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Introduction

The escalating global demand for oilseed crops such as soybeans underscores the need for advanced agricultural practices that enhance yield and profitability. However, these practices must also ensure the sustainable management of soil nutrients to preserve soil health and protect environmental quality. The primary aim of this research was to assess the effectiveness of an integrated nutrient management strategy on soybean productivity and profitability.

Soybean (*Glycine max* L. Merrill) is a widely cultivated oilseed crop known for its high protein content and edible oil. It serves as a valuable source of food and feed, contributing to food security and nutrition worldwide [1]. Additionally, soybean is recognized for its ability to improve soil health and reduce the need for nitrogen fertilizers through nitrogen fixation and biomass addition [2]. The crop's importance extends beyond its nutritional value, as it also plays a crucial role in addressing global challenges such as climate change and biofuel production.

Composting is a biodegradable process that converts undecomposed organic materials into decomposed organic matter, facilitating nutrient release. It is widely used to improve crop yield, soil fertility, and productivity [3]. Compost offers numerous benefits in crop production, such as increased water holding capacity, improved soil water infiltration, enhanced water conservation, reduced soil bulk density, and increased microbial activity, thereby improving plant nutrient availability [4]. Recent studies have shown that the application of compost to soybean fields significantly improves nutrient availability and enhances crop growth and yield.

Phosphorus is a vital nutrient that plays a crucial role in root development, plant maturation, and disease resistance. However, it is estimated that only 15–20% of the applied phosphorus is effectively utilized by crops, with the rest being retained in forms that are not readily available to plants [5]. The response of soybean to phosphorus application varies, particularly in soils with low to medium phosphorus availability, as a significant portion of applied phosphorus may become fixed in the soil. Nevertheless, phosphorus application to leguminous crops has shown promising effects, including improved crop quality and increased nitrogen uptake and protein content [6]. Enhancing phosphorus availability through the use of phosphorus-solubilizing bacteria (PSB) can further promote organic phosphorus mineralization and nutrient uptake [7, 8].

Potassium is a critical macronutrient for plant growth, ranking third after nitrogen and phosphorus. It plays a vital role in protein synthesis, enzyme activation, photosynthesis, and resistance to pests and diseases [8]. Although Pakistani soils contain a relatively high concentration of potassium, only a small amount is available to plants. Applying optimal doses of potassium during vegetative growth enhances plant growth, maintains tissue pressure (turgor), improves protein production, increases water use efficiency, and enhances plant resistance to diseases, insects, and stalk lodging [9]. Regular potassium fertilization is necessary to prevent nutrient deficiencies in the soil, as soil alone often cannot supply sufficient potassium for high-yielding crops [10].

Organic materials serve as valuable sources of plant nutrients, promoting sustainable crop production [11, 12]. Compared to inorganic fertilization, the use of organic waste and compost is not only economically viable but also environmentally sustainable [13]. Utilizing organic manures, including poultry manure, farm waste, and crop residues, as alternatives to chemical fertilizers can further enhance crop growth and yield [14]. When combined with biofertilizers such as PSB, organic manures can significantly improve crop yield and growth [15].

Drought stress is one of the most significant environmental factors affecting soybean productivity, causing yield reductions [16]. Drought stress occurs due to factors such as high temperature, low humidity, and water deficiency [17]. The response of soybean to drought varies among crop species and involves biochemical, molecular, and physiological changes [18]. Drought stress affects various aspects of plant growth, including root and shoot dry and fresh weight, root length, cell division, and differentiation [19]. It also negatively impacts nitrogenase activity and photosynthesis, further affecting soybean yield [20].

Soybean serves as a vital legume and restorative crop, enhancing soil health, reducing nitrogen requirements, and providing numerous benefits such as food, feed, and fuel sources. Its cultivation contributes to food security, mitigates global warming and climate change, and promotes the production of biofuels, oils, and proteins. Recent publications have emphasized the importance of composts, phosphorus, potassium, irrigation/drought stress, and biofertilizers/PSB for improving soybean growth, yield, protein, and oil content, which are important for food security for humans, livestock, poultry, biodiesel, and climate change [21]. The study focused on the combined use of organic sources (various compost types), phosphorus management, and phosphate-solubilizing bacteria (PSB). Additionally, the research explored the response of soybeans to different potassium levels and compost types under both irrigated and dryland conditions. By understanding the optimal nutrient management practices and their impact on soybean production, we can enhance crop productivity, soil fertility, and overall agricultural sustainability.

Materials and methods

Site description

The research was conducted at the Agriculture Research Institute Tarnab (ARI) during the spring of 2016. ARI is located at 340 15 20" North, 71o 36 6" East, with an altitude of 358 m above sea level in the Peshawar valley. The climate in Peshawar is semiarid, and the region is situated on the northern side of the Indian Ocean. The soil texture at the research site is clay loam, alkaline (pH 8.2), and calcareous, with low organic matter (0.87%), extractable phosphorus (6.57 mg kg − 1), and exchangeable potassium (121 mg kg^{-1}). Irrigation water is sourced from the Kabal River. The region experiences 60–70% of its annual rainfall in summer, while the remaining 30–40% occurs in winter, with an average of 300 to 500 mm [8].

Experiment #01

The experiment was conducted using a split-plot design with three replications. The primary treatment, PSB (phosphate-solubilizing bacteria), was assigned to the main plots with two levels: PSB + ve (with PSB) and PSB-ve (without PSB). The sub-plot factor comprised 10 treatments, which included the combination of three compost types and three phosphorus (P) levels, along with a control plot (3 compost types × 3 P levels + 1 control = 10 treatments). Each replication contained these 10 treatments, allowing for the evaluation of interactions between compost type and phosphorus level.

The plot size was 3 m by 3 m, containing six rows that were 3 m long and spaced 50 cm apart. The compost types were applied and incorporated into their respective plots five days before sowing. The two pure compost types, animal manure compost and poultry manure compost, were applied at a rate of 6 t ha-1 each. In the combined animal + poultry manures compost treatment (mixed compost), both organic sources were applied at a rate of 3 t ha^{-1} each. The required P levels (30, 60 and 90 kg P ha^{-1}) in the form of single superphosphate (SSP, 18% P_2O_5) were applied at seedbed preparation just before sowing (seedbed preparation). The soybean variety NARC-2 was used as the test crop and sown at a rate of 100 kg ha^{-1} on April 11, 2016, and harvested in the last week of October 2016.

Experiment #02

This experiment also followed a split-plot design with three replications. The primary treatment, irrigation regimes was assigned to the main plots with two levels: six irrigations (no water stress) and two irrigations (water stress). The sub-plot factor comprised 10 treatments, which included the combination of three compost types and three potassium (K) levels, along with a control plot (3 compost types × 3 K levels + 1 control = 10 treatments). Each replication contained these 10 treatments, allowing for the evaluation of interactions between compost type and potassium level.

The plot size was 3 m by 3 m, containing six rows that were 3 m long and spaced 50 cm apart.

The two pure compost types, animal manure compost and poultry manure compost, were applied alone at a rate of 6 t ha^{-1} each. In case of mixed compost, animal + poultry manures compost treatment, both organic sources were applied at a rate of 3 t ha^{-1} each one week before sowing. The required K levels (30, 60 and 90 kg K ha^{-1}) in the form of muriate of potash (MOP, 60% K_2O) were applied at seedbed preparation just before sowing (seedbed preparation). The experiment included six irrigations for the fully irrigated plots: two during vegetative growth, two around flowering (before and at flowering), one at pod initiation, and one at pod development. For the moisture-stress plots, three irrigations were applied: one during vegetative growth, one at flowering, and one at pod development. Soybean variety NARC-2 was sown at a seed rate of 100 kg ha^{-1} in the second week of April 2016 and harvested in the last week of October 2016.

To protect against defoliating insects, the crop was sprayed with Stomp 330 emulsifiable concentrate (EC) in both experiments. The nozzle size was adjusted to deliver the appropriate rate and ensure uniform distribution. Standard agronomic practices were applied uniformly throughout the growing season.

Data were recorded on yield components (pods per plant, seeds per pod, pod length, thousand grains weight), grain yield, protein yield and oil yield. Pods per plant were counted in ten randomly selected plants from two central rows at physiological maturity, and the mean was recorded. From the above count of pods per plant, ten pods were randomly selected from ten plants, threshed, and the number of seeds was counted. The average number of seeds per pod was calculated. Pod length (cm) was measured for ten randomly selected pods from five plants in each plot, and the average was calculated. Thousand grains weight (g) was calculated by weighing a thousand grains from the seed lot of each sub-plot using an electronic balance.

The total dried material from the three central rows was threshed, seeds were cleaned, weighed, and converted to grain yield (kg ha^{-1}) using a formula:

$$\text{Grain yield (kg ha}^{-1}) = \frac{\text{Grain weight of three rows (kg)}}{\text{No of rows} \times \text{Row length} \times \text{R - R distance}} \times 10,000\text{m}^2$$

Seed oil content (%) and protein contents (%) in soybean grains were determined with near infra-red reflectance spectroscopy system. Oil and protein yields (kg ha^{-1}) were determined using the following formulae:

$$Oil\ yield\ (kg\ ha^{-1}) = Grain\ Yield \times Oil\ Content \quad (1)$$

$$Protein\ yield\ (kg\ ha^{-1}) = Grain\ yield \times Protein\ Content \quad (2)$$

Statistical analysis

The collected data on various parameters were subjected to an analysis of variance using a split-plot design according to Steel & Torrie [22] combined over the two PSB levels in experiment one and combined over the two irrigation regimes in experiment two. Means between treatments were compared using the least significant difference (LSD) test at a 5% level of probability ($P < 0.05$).

Results

Soybean response to composts types, phosphorus levels and PSB

Yield components

The number of pods plant-1 was significantly influenced by phosphorus levels, compost types, PSB inoculation, and control vs. treated plots (Table 1). Among the different phosphorus levels, the highest number of pods plant-1 (65.3) was observed at 90 kg P ha-1, while the lowest number (61.2) was recorded at 30 kg P ha-1. Poultry manure compost resulted in the highest number of pods plant-1 (66.9), followed by the combined application of poultry and animal manure compost (62.9). The lowest number of pods plant-1 (59.2) was observed with the application of animal manure compost. Plots inoculated with PSB showed a higher number of pods plant-1 (66.0), while plots without PSB had the lowest number (60.1 cm). Treated plots overall had a significantly higher number of pods plant-1 (63.4) compared to the control (54.7). The interaction between compost types and phosphorus levels showed an increase in the number of pods plant-1 in soybean, regardless of the compost type used (CT x P).

The number of seeds pod-1 was significantly affected by phosphorus levels, compost types, PSB inoculation, and control vs. treated plots, while the interactions had no significant effect (Table 2). The highest number of seeds pod-1 (2.8) was observed at the highest phosphorus level of 90 kg P ha-1. Plots treated with the lowest phosphorus level of 30 kg P ha-1 had the lowest number of seeds pod-1 (2.3). Poultry manure compost resulted

Table 1 Number of pods plant^{-1} of soybean as affected by phosphorus levels (kg ha^{-1}) and compost types with and without PSB

PSB	P levels (kg ha^{-1})	AMC	PMC	AMC + PMC	PSB x P
With PSB (+)	30	60.0	67.3	65.0	64.1
	60	63.3	68.3	65.0	65.6
	90	66.0	72.7	66.0	68.2
Without PSB (-)	30	52.7	61.3	61.0	58.3
	60	55.0	63.3	60.3	59.6
	90	58.3	68.7	60.3	62.4
With PSB (+)		63.1	69.4	65.3	66.0
Without PSB (-)		55.3	64.4	60.6	60.1
	30	56.3	64.3	63.0	61.2 b
	60	59.2	65.8	62.7	62.6 b
	90	62.2	70.7	63.2	65.3 a
Mean		59.2 c	66.9 a	62.9 b	
		Planned mean comparison		*P* value	
Control	54.7	Control vs. rest		0.0000	
Rest	63.4				
LSD for compost types		1.24			
LSD for phosphorus		1.24			
CT x P		*			
PSB x CT		ns			
PSB x P		ns			
PSB x CT x P		ns			

Means of the same category followed by different letters are significantly different from each other using LSD test ($P \leq 0.05$)

Where: ns stands for non-significant data, while * indicates significant at 5% level of probability using LSD test ($P \leq 0.05$)

AMC stands for animal manures compost (6 t ha^{-1}), *PMC* stands for poultry manure compost (6 t ha^{-1}), and *AMC + PMC* stands for combined use of animal manure and poultry manure compost (3 tha^{-1} each)

Table 2 Number of seeds pod^{-1} of soybean as affected by phosphorus levels (kg ha^{-1}) and compost types with and without PSB

PSB	Phosphorus (kg P ha^{-1})	AMC	PMC	AMC + PMC	PSB x P
With PSB (+)	30	2.3	2.7	2.3	2.4
	60	2.3	3.0	2.3	2.6
	90	2.7	3.5	3.0	3.1
Without PSB (-)	30	1.8	2.3	2.2	2.1
	60	2.0	2.7	2.5	2.4
	90	2.2	2.5	2.7	2.4
With PSB (+)		2.4	3.1	2.6	2.7
Without PSB (-)		2.0	2.5	2.4	2.3
	30	2.1	2.5	2.3	2.3 b
	60	2.2	2.8	2.4	2.5 b
	90	2.4	3.0	2.8	2.8 a
Mean		2.2 c	2.8 a	2.5 b	
		Planned mean comparison		*P* value	
Control	1.9	Control vs. rest		0.0007	
Rest	2.5				
LSD for compost types		0.25			
LSD for phosphorus		0.25			
CT x P		ns			
PSB x CT		ns			
PSB x P		ns			
PSB x CT x P		ns			

Means of the same category followed by different letters are significantly different from each other using LSD test ($P \leq 0.05$)

Where ns stands for non-significant data ($P \leq 0.05$)

AMC stands for animal manures compost (6 t ha^{-1}), *PMC* stands for poultry manure compost (6 t ha^{-1}), and *AMC + PMC* stands for combined use of animal manure and poultry manure compost (3 tha^{-1} each)

in the highest number of seeds pod-1 (2.8), followed by the combined application of poultry and animal manure compost (2.5). The lowest number of seeds pod-1 (2.2) was recorded with the application of sole animal manure compost. Plots inoculated with PSB had a higher number of seeds pod-1 (2.7), while plots without PSB showed the lowest number of pods plant-1 (2.3). Treated plots overall had a significantly higher number of seeds pod-1 (2.5) compared to the control (1.9).

Pod length was significantly influenced by phosphorus levels, compost types, PSB inoculation, and control vs. treated plots, while the interactions had no significant effect (Table 3). The application of phosphorus at the rate of 90 kg P ha-1 resulted in the longest pod length (4.4 cm), while 30 kg P ha-1 led to the shortest pod length (4.0 cm). The sole application of poultry manure compost produced the longest pod length (4.4 cm), followed by the combined application of poultry and animal manure compost (4.2 cm). The shortest pod length (3.9 cm) was recorded with the application of sole animal manure compost. Plots inoculated with PSB showed a longer pod length (4.3 cm), while plots without PSB had a shorter pod length (4.0 cm). Treated plots overall had a significantly higher pod length (4.2 cm) compared to the control (3.6 cm).

Thousand grains weight (g) was significantly influenced by phosphorus levels, compost types, PSB inoculation, and control vs. treated plots, while the interactions had no significant effect (Table 4). The application of phosphorus at the rate of 90 kg P ha-1 resulted in the highest thousand grains weight (152.8 g), while the lowest weight (137.0 g) was recorded at 30 kg P ha-1. Among the compost types, poultry manure compost produced the highest thousand grains weight (148.9 g), followed by the combined application of poultry and animal manure compost (144.4 g). The lowest thousand grains weight (137.6 g) was recorded with the application of sole animal manure compost. Plots inoculated with PSB had heavier grains (151.7 g) compared to plots without PSB (135.6 g). Treated plots overall had a significantly higher thousand grains weight (144.6 g) compared to the control (125.5 g).

Yield

The grain yield of soybean was significantly influenced by phosphorus levels, compost types, PSB inoculation,

Table 3 Pod length (cm) of soybean as affected by phosphorus (kg ha^{-1}) and compost types with and without PSB

PSB	Phosphorus (kg P ha^{-1})	AMC	PMC	AMC + PMC	PSB x P
With PSB (+)	30	4.1	4.3	4.3	4.2
	60	4.0	4.5	4.5	4.4
	90	4.1	4.7	4.3	4.4
Without PSB (-)	30	3.3	4.1	3.9	3.8
	60	3.9	4.2	4.0	4.0
	90	4.0	4.5	4.5	4.3
With PSB (+)		4.1	4.5	4.4	4.3
Without PSB (-)		3.7	4.3	4.1	4.0
	30	3.7	4.2	4.1	4.0 c
	60	4.0	4.4	4.2	4.2 b
	90	4.1	4.6	4.4	4.4 a
Mean		3.9 c	4.4 a	4.2 b	
		Planned mean comparison		*P* value	
Control	3.6	Control vs. rest		0.0000	
Rest	4.2				
LSD for compost types		0.11			
LSD for phosphorus		0.11			
CT x P		ns			
PSB x CT		ns			
PSB x P		ns			
PSB x CT x P		ns			

Means of the same category followed by different letters are significantly different from each other using LSD test ($P \leq 0.05$)

Where ns stands for non-significant data ($P \leq 0.05$)

AMC stands for animal manures compost (6 t ha^{-1}), *PMC* stands for poultry manure compost (6 t ha^{-1}), and *AMC + PMC* stands for combined use of animal manure and poultry manure compost (3 tha^{-1} each)

and control vs. treated plots (Table 5). The application of the highest phosphorus level (90 kg P ha-1) resulted in a higher grain yield (3222 kg ha-1) compared to the lowest phosphorus level (30 kg P ha-1), which produced the minimum grain yield (2597 kg ha-1). Among the compost types, the sole application of poultry manure compost produced the highest grain yield (3064 kg ha-1), followed by the combined application of poultry and animal manure compost (2947 kg ha-1). The lowest grain yield (2756 kg ha-1) was recorded for the sole application of animal manure compost. Plots inoculated with PSB showed a higher grain yield (3051 kg ha-1) compared to plots without PSB (2794 kg ha-1). Treated plots overall had a significantly higher grain yield (2976 kg ha-1) compared to the control (2266 kg ha-1).

Protein yield of soybean was significantly influenced by phosphorus levels, compost types, PSB inoculation, and control vs. treated plots, while the interactions had no significant effect (Table 6). The highest protein yield (823 kg ha-1) was recorded at the highest phosphorus level (90 kg P ha-1), while the lowest protein yield (624 kg ha-1) was noted at the lowest phosphorus level (30 kg P ha-1). The sole application of poultry manure compost resulted in higher protein yield (771 kg ha-1), followed by the combined application of poultry and animal manure compost (729 kg ha-1). The lowest protein yield (683 kg ha-1) was produced by animal manure compost. Plots sown with PSB inoculation showed higher protein yield (769 kg ha-1) compared to plots without PSB (687 kg ha-1). Treated plots overall had a significantly higher protein yield (743 kg ha-1) compared to the control (537 kg ha-1).

Oil yield of soybean was significantly influenced by phosphorus levels, compost types, PSB inoculation, control vs. treated plots, and the interactions between compost types and phosphorus levels (CT x P) and PSB inoculation and phosphorus levels (PSB x P) (Table 7). The highest oil yield (588 kg ha-1) was recorded at the highest phosphorus level (90 kg P ha-1), while the lowest oil yield (429 kg ha-1) was noted at the lowest phosphorus level (30 kg P ha-1). The sole application of poultry manure compost resulted in higher oil yield (546 kg ha-1), followed by the combined application of poultry and animal manure compost (510 kg ha-1). The lowest oil yield (470 kg ha-1) was produced by animal manure compost. Seeds sown with PSB inoculation

Table 4 Thousand grains weight (g) of soybean as affected by phosphorus levels (kg ha^{-1}) and compost types with and without PSB

PSB	Phosphorus (kg P ha^{-1})	AMC	PMC	AMC+PMC	PSB x P
With PSB (+)	30	141.7	145.0	145.0	143.9
	60	148.3	155.0	145.0	149.4
	90	158.3	168.3	158.3	161.7
Without PSB (-)	30	123.7	135.0	131.7	130.1
	60	121.7	138.3	138.3	132.8
	90	131.7	151.7	148.3	143.9
With PSB (+)		149.4	156.1	149.4	151.7
Without PSB (-)		125.7	141.7	139.4	135.6
	30	132.7	140.0	138.3	137.0 c
	60	135.0	146.7	141.7	141.1 b
	90	145.0	160.0	153.3	152.8 a
Mean		137.6 c	148.9 a	144.4 b	
		Planned mean comparison		*P* value	
Control	125.5	Control vs. rest		0.0000	
Rest	144.6				
LSD for compost types		3.4			
LSD for phosphorus		3.4			
CT x P		ns			
PSB x CT		ns			
PSB x P		ns			
PSB x CT x P		ns			

Means of the same category followed by different letters are significantly different from each other using LSD test ($P \leq 0.05$)

Where ns stands for non-significant data ($P \leq 0.05$)

AMC stands for animal manures compost (6 t ha^{-1}), *PMC* stands for poultry manure compost (6 t ha^{-1}), and *AMC+PMC* stands for combined use of animal manure and poultry manure compost (3 tha^{-1} each)

showed a higher oil yield (550 kg ha-1) compared to plots without PSB (467 kg ha-1). Treated plots overall had a significantly higher oil yield (506 kg ha-1) compared to the control (354 kg ha-1).

Soybean response to composts types, potassium levels and irrigation

Yield components

The number of pods per plant was significantly influenced by potassium levels, compost types, irrigation, and control vs. treated plots, while the interactions had a non-significant effect (Table 8). The highest number of pods (62.7) was recorded at the highest potassium level of 90 kg K ha-1. Plots treated with the lowest potassium level of 30 kg K ha-1 produced the lowest number of pods (56.9). Among the compost types, poultry manure resulted in a higher number of pods (62.0), followed by the combined application of poultry and animal manure (59.3), while the lowest number of pods (57.4) was recorded with the application of animal manure. Plots with irrigation showed a higher number of pods (60.4) compared to plots without irrigation (58.8). Treated plots overall had a significantly higher number of pods (60) compared to the control (54).

The number of seeds per pod was significantly affected by potassium levels, compost types, irrigation, and control vs. treated plots, while the interactions had a non-significant effect (Table 9). The highest number of seeds per pod (3.8) was recorded at the highest potassium level of 90 kg K ha-1. Plots treated with the lowest potassium level of 30 kg K ha-1 produced a lower number of seeds per pod (3.3). Among the compost types, poultry manure resulted in a higher number of seeds per pod (4.1), followed by the combined application of poultry and animal manure (3.6), while the lowest number of seeds per pod (3.1) was recorded with the application of animal manure. Plots with irrigation showed a higher number of seeds per pod (3.9) compared to plots without irrigation (3.3). Treated plots overall had a significantly higher number of seeds per pod (4) compared to the control (3).

Pod length was significantly affected by potassium levels, compost types, irrigation, and control vs. treated plots, while the interactions had a non-significant effect (Table 10). The highest pod length (4.4 cm) was recorded at the highest potassium level of 90 kg K ha-1. Plots

Table 5 Grain yield (kg ha −1) of soybean as affected by phosphorus levels (kg ha −1) and compost types with and without PSB

PSB	Phosphorus (kg P ha^{-1})	AMC	PMC	AMC + PMC	PSB x P
With PSB (+)	30	2644	2821	2700	2722
	60	3063	3142	3032	3079
	90	3268	3478	3307	3351
Without PSB (-)	30	2167	2660	2591	2473
	60	2503	3033	2918	2818
	90	2889	3253	3137	3093
With PSB (+)		2992	3147	3013	3051
Without PSB (-)		2520	2982	2882	2794
	30	2405	2741	2646	2597 c
	60	2783	3087	2975	2948 b
	90	3079	3365	3222	3222 a
Mean		2756 c	3064 a	2947 b	
		Planned mean comparison		*P* value	
Control	2266	Control vs. rest		0.000	
Rest	2976				
LSD for compost types		76.05			
LSD for phosphorus		76.05			
CT x P		ns			
PSB x CT		ns			
PSB x P		ns			
PSB x CT x P		ns			

Means of the same category followed by different letters are significantly different from each other using LSD test ($P \leq 0.05$)

Where ns stands for non-significant data ($P \leq 0.05$)

AMC stands for animal manures compost (6 t ha^{-1}), *PMC* stands for poultry manure compost (6 t ha^{-1}), and *AMC+PMC* stands for combined use of animal manure and poultry manure compost (3 tha^{-1} each)

treated with the lowest potassium level of 30 kg K ha-1 produced the lowest pod length (3.9 cm). Among the compost types, poultry manure resulted in the highest pod length (4.5 cm), followed by the combined application of poultry and animal manure (4.3 cm), while the lowest pod length (3.7 cm) was recorded with the application of animal manure. Plots with irrigation showed the highest pod length (4.2 cm) compared to plots without irrigation (4.0 cm). Treated plots overall had a significantly higher pod length (4 cm) compared to the control (3 cm).

Thousand grains weight (g) was significantly affected by potassium levels, compost types, irrigation, and control vs. treated plots, while the interactions had a non-significant effect (Table 11). The highest thousand grain weight (155 g) was recorded at the highest potassium level of 90 kg K ha-1. Plots treated with the lowest potassium level of 30 kg K ha-1 produced the lowest thousand grain weight (139 g). Among the compost types, poultry manure resulted in the highest grain weight (156 g), followed by the combined application of poultry and animal manure (151 g), while the lowest thousand grain weight (132 g) was recorded with the application of animal manure. Plots with irrigation showed a higher thousand grain weight (149 g) compared to plots without irrigation (143 g). Treated plots overall had a significantly higher thousand grain weight (148 g) compared to the control (122 g).

Yield

Grain yield was significantly affected by potassium levels, compost types, irrigation, and control vs. treated plots, while the interactions had a non-significant effect (Table 12). The highest grain yield (3189 kg ha-1) was recorded at the highest potassium level of 90 kg K ha-1. Plots treated with the lowest potassium level of 30 kg K ha-1 produced the lowest grain yield (2629 kg ha-1). Among the compost types, poultry manure resulted in the highest grain yield (3160 kg ha-1), followed by the combined application of poultry and animal manure (3070 kg ha-1), while the lowest grain yield (2533 kg ha-1) was recorded with the application of animal manure. Plots with irrigation showed the highest grain yield (2981 kg ha-1) compared to plots without irrigation (2861 kg ha-1). Treated plots overall had a significantly higher

Table 6 Protein yield (kg ha^{-1}) of soybean as affected by phosphorus levels (kg ha^{-1}) and compost types with and without PSB

PSB	Phosphorus (kg P ha^{-1})	AMC	PMC	AMC + PMC	PSB x P
With PSB (+)	30	627	698	648	658
	60	769	815	772	785
	90	871	892	828	864
Without PSB (-)	30	518	636	618	591
	60	601	746	716	688
	90	715	838	792	781
With PSB (+)		756	802	749	769
Without PSB (-)		611	740	709	687
	30	573	667	633	624 c
	60	685	781	744	737 b
	90	793	865	810	823 a
Mean		683 c	771 a	729 b	
		Planned means comparison		*P* value	
Control	537	Control vs. rest		0.000	
Rest	743				
LSD for compost types		17.73			
LSD for phosphorus		17.73			
CT x P		ns			
PSB x CT		ns			
PSB x P		ns			
PSB x CT x P		ns			

Means of the same category followed by different letters are significantly different from each other using *LSD* test($P \leq 0.05$) Where ns stands for non-significant data ($P \leq 0.05$) *AMC* stands for animal/cattle manures compost (6 t ha^{-1}), *PMC* stands for poultry manure compost (6 t ha^{-1}), and *AMC + PMC* stands for combined use of animal manure and poultry manure compost (3 t ha^{-1} each)

grain yield (2974 kg ha-1) compared to the control (2078 kg ha-1).

Both protein yield (Table 13) and oil yield (Table 14) showed a positive relationship with an increase in grain yield. Increasing the potassium rate resulted in increased grain yield, oil yield, and protein yield in soybean. The application of poultry manure compost or a combination of poultry and animal manure compost had a positive impact on both oil and protein yields compared to the sole application of animal manure compost. Full irrigation conditions without moisture stress increased both grain and oil yields and showed a positive relationship with grain yield. On the other hand, grain yield reduced under moisture stress conditions, which also had a negative impact on oil and protein yields compared to conditions without moisture stress.

Discussion

The results of experiment one demonstrated significant improvements in yield components, grain yield, oil and protein yields in soybean with the application of phosphorus, compost types, and phosphate-solubilizing bacteria (PSB).The application of phosphorus at a rate of 90 kg P ha^{-1}, sole poultry manure compost, and PSB treatment showed positive effects on yield components in soybean. The number of pods per plant, number of seeds per pod, pod length, and thousand grain weight were significantly increased with these treatments. The number of pods per plant is a crucial yield component as it directly contributes to overall yield. The adequate nutrition of soybean plants is essential for enhancing pod set and nutrient availability. Similar findings have been reported by Bekere et al. [23], who observed improved yield components with higher phosphorus application in soybean. Integrated application of compost at a rate of 1 t ha-1 and PSB treatment also significantly influenced the number of pods per plant and seeds per pod [24]. Suppadit et al. [25] reported a positive correlation between organic and mineral fertilizer use and the number of pods per plant. Additionally, inoculation with PSB and different levels of phosphorus application resulted in significant differences in the number of seeds per pod. PSB inoculations have been shown to increase pod number, thousand seed weight, seed yield, and total biomass yield [26].

Table 7 Oil yield (kg ha^{-1}) of soybean as affected by phosphorus levels (kg ha^{-1}) and compost types with and without PSB

PSB	Phosphorus (kg P ha^{-1})	AMC	PMC	AMC + PMC	PSB x P
With PSB (+)	30	442	486	452	460
	60	536	589	523	549
	90	624	646	653	641
Without PSB (-)	30	341	434	420	398
	60	407	523	473	468
	90	469	596	541	535
With PSB (+)		534	574	542	550
Without PSB (-)		405	518	478	467
	30	391	460	436	429 c
	60	471	556	498	508 b
	90	546	621	597	588 a
Mean		470 b	546 a	510 a	
	Planned means comparison			*P* value	
Control	354	Control vs. rest		0.0000	
Rest	506				
LSD for compost types	42.26				
LSD for phosphorus	42.26				
CT x P	*				
PSB x CT	ns				
PSB x P	**				
PSB x CT x P	ns				

AMC stands for animal/cattle manures compost (6 t ha^{-1}), *PMC* stands for poultry manure compost (6 t ha^{-1}), and *AMC + PMC* stands for combined use of animal manure and poultry manure compost (3 t ha^{-1} each)

Where ns stands for non-significant data, while ** and * indicates significant at 1 and 5% level of probability, respectively using LSD test ($P \leq 0.05$)

Yield components and grain yield were also significantly improved with phosphorus application, compost types, and PSB treatment. Adequate soil fertilization and plant nutrition play a vital role in enhancing agricultural production [27]. Phosphorus has important effects on various physiological processes in plants, such as photosynthesis, nitrogen fixation, root development, flowering, seed formation, fruiting, and crop quality improvement. Soybean has a high phosphorus requirement, and applying phosphorus fertilizer to phosphorus-deficient soils can enhance yield. However, excessive or insufficient phosphorus levels can negatively affect soybean growth and development [28].

The sole application of poultry manure compost resulted in higher grain yield compared to combined and sole animal manure compost applications. Similar findings have been reported for increased grain yield with poultry litter use in soybean [29, 30]. The combined use of mineral fertilizers and organic amendments, such as compost46. The combined use of mineral fertilizers and organic amendments, such as compost, has been shown to synergistically increase soybean grain productivity [31]. Increases in yield with vermicompost applications have been observed in various crops, including okra, strawberry, eggplant, potato, cucumber, peppers, lettuce, and Amaranthus species [32–34].

Phosphate-solubilizing bacteria (PSB) had a positive impact on phosphorus availability to plants by mineralizing organic phosphorus in the soil and solubilizing precipitated phosphate [35]. Co-inoculation with PSB has been reported to significantly increase grain yield in soybean. PSB can solubilize fixed soil phosphorus and applied phosphates, leading to higher crop yields Co-inoculation of Rhizobium with PSB resulted in the highest grain yield compared to Rhizobium inoculation alone [36]. PSB can enhance nutrient uptake, root system development, and crop yield through increased phosphorus availability, solubility of phosphate, and production of plant hormones affecting nutrient uptake and photosynthesis. Harvest index, which is highly correlated with grain yield in soybean, was also positively influenced by PSB treatment.

In experiment two, the effects of potassium levels, compost types, and irrigation regimes on yield components of soybean were investigated. The results demonstrated that the application of potassium at a rate of 90 kg K ha^{-1}, along with poultry manure and adequate irrigation, led to significant improvements in yield components compared

Table 8 Number of pods per plant of soybean as affected by potassium levels, compost types under full irrigated and limited irrigated conditions

Moisture (M)	K levels (kg ha^{-1})	AMC	PMC	AMC + PMC	M x K
No stress	30	57.2	60.0	57.0	58.1
	60	59.1	63.0	57.7	59.9
	90	62.8	64.0	63.0	63.3
With stress	30	53.7	57.7	55.7	55.7
	60	54.6	62.3	58.7	58.5
	90	57.3	65.0	64.0	62.1
No stress		59.7	62.3	59.2	60.4
with stress		55.2	61.7	59.4	58.8
	30	55.4	58.8	56.3	56.9 c
	60	56.8	62.7	58.2	59.2 b
	90	60.1	64.5	63.5	62.7 a
Mean		57.4 c	62.0 a	59.3 b	
		Planned mean comparison		*P* value	
Control	54	Control vs. rest		0.0000	
Rest	60				
LSD for organic sources	1.36				
LSD for K levels	1.36				
M x K	ns				
I x OS	ns				
M x K	ns				
I x OS x K	ns				

Means of the same category followed by different letters are significantly different from each other using LSD test ($P \leq 0.05$)

Where ns stands for non-significant data ($P \leq 0.05$)

AMC stands for animal manures compost (6 t ha^{-1}), *PMC* stands for poultry manure compost (6 t ha^{-1}), and *AMC + PMC* stands for combined use of animal manure compost and poultry manure compost (3 t ha^{-1} each)

to lower potassium rates of 30 kg K ha^{-1} and limited irrigation.

Yield components, such as the number of pods per plant, number of seeds per pod, pod length, and thousand grain weight, are important factors that contribute to overall soybean yield. Adequate plant nutrition, including potassium, is essential for enhancing pod set and the availability of nutrients and assimilates in soybean plants [37]. Yield components, such as the number of pods per plant, number of seeds per pod, pod length, and thousand grains weight, have been found to be significantly improved with the application of potassium, organic sources, and irrigation regimes [38–40]. Studies have shown that potassium application at a rate of 90 kg K ha-1, along with poultry manure and adequate irrigation, can lead to increased yield components compared to lower potassium rates (30 kg K ha-1) and limited irrigation [28]. The number of pods per plant is a crucial yield component for soybean, as it directly influences yield performance.Adequate plant nutrition, including potassium availability, is essential for enhancing pod set in soybean plants [37]. The maximum number of pods per plant has been observed with potassium application by Xiang et al. [28].

Potassium levels have also been found to significantly influence pod length in soybean [41]. The highest pod length has been recorded with the application of 90 kg K ha-1. Furthermore, the number of seeds per pod has been positively affected by various levels of potassium fertilizer, with the maximum number of seeds per pod observed at 90 kg K ha-1 [28]. The application of potassium not only enhances the availability of other nutrients but also increases the transportation of photosynthates, leading to an increase in the number of seeds [28]. Similar results have been reported by previous studies, indicating that the weight of 1000 seeds significantly increases with potassium fertilizer application [28].

Grain yield has also shown significant improvements with the application of potassium, organic sources, and irrigation regimes. Studies have reported that the highest soybean seed yield was obtained with potassium fertilization. Additionally, the combination of inorganic and organic fertilizers, such as poultry manure, has shown positive effects on grain yield and biological

Table 9 Number of seeds per pod of soybean as affected by potassium levels, compost types under full irrigated and limited irrigated conditions

Moisture (M)	K levels (kg ha^{-1})	AMC	PMC	AMC + PMC	M x K
No stress	30	3.1	4.0	3.9	3.7
	60	3.2	4.7	4.1	4.0
	90	3.3	4.8	4.3	4.1
With stress	30	2.9	3.2	3.0	3.0
	60	3.2	3.5	3.1	3.3
	90	3.1	4.3	3.3	3.6
No stress		3.2	4.5	4.1	3.9
with stress		3.1	3.7	3.1	3.3
	30	3.0	3.6	3.5	3.3 b
	60	3.2	4.1	3.6	3.6 a
	90	3.2	4.5	3.8	3.8 a
Mean		3.1 c	4.1 a	3.6 b	
		Planned mean comparison		*P* value	
Control	3	Control vs. rest		0.0000	
Rest	4				
LSD for organic sources	0.22				
LSD for K levels	0.22				
M x K	*				
I x OS	ns				
M x K	ns				
I x OS x K	ns				

Means of the same category followed by different letters are significantly different from each other using LSD test ($P \leq 0.05$)

Where ns stands for non-significant data, while * indicates significant at 5% level of probability using LSD test ($P \leq 0.05$)

AMC stands for animal manures compost (6 t ha^{-1}), *PMC* stands for poultry manure compost (6 t ha^{-1}), and *AMC + PMC* stands for combined use of animal manure compost and poultry manure compost (3 t ha^{-1} each)

yield [42]. Harvest index, which reflects the crop's ability to convert dry matter into economic yield, has been positively influenced by potassium application at different levels. The seed yield of soybean has been significantly affected by different irrigation levels, with maximum seed yield observed in well-irrigated conditions compared to water-st-stressed conditions.

Oil and protein yields have also shown a positive relationship with increased grain yield, which can be achieved through potassium and compost management [43]. In conclusion, the application of potassium, organic sources, and appropriate irrigation regimes have a significant impact on various yield components, grain yield, and harvest index in soybean. The specific effects depend on the level of potassium application, type of organic sources used, and irrigation practices employed. These findings highlight the importance of proper nutrient management and irrigation strategies to maximize soybean yield potential.

Among compost types, poultry manure compost increased oil and protein contents and yield in soybean compared to combined and sole application of animal manure compost. Manivannan et al. [44] indicated that the application of vermi-compost with inorganic fertilizers improved the yield and protein content of Phaseolus vulgaris seeds. These results are similar to those of Khaliq [45], who reported an increase in grain protein content with the application of organic sources. Rana et al. [36] also reported that the application of animal manure compost and vermi compost significantly improved protein content (39.4%) and oil content (18.9%). Enhancement in oil and protein concentration might be due to the balanced nutrition supply by organic and inorganic fertilizers, which enhanced primary metabolites conversion to fatty acids, resulting in an increase in oil and protein content in seeds.

The oil and protein contents and yield in soybean seeds were significantly improved with the application of phosphorus. Oil content of soybean seeds increases with an increase in levels of phosphorus fertilizer. Similarly, oil yield also increases in the same trend. Similar findings were reported by Tomar and Khajanji (2009) [46], who

Table 10 Pods length (cm) of soybean as affected by potassium levels, compost types under full irrigated and limited irrigated conditions

Moisture (M)	K levels (kg ha^{-1})	AMC	PMC	AMC + PMC	M x K
No stress	30	3.7	4.5	4.0	4.0
	60	3.7	4.6	4.2	4.2
	90	3.8	5.0	4.6	4.5
With stress	30	3.3	4.0	3.9	3.7
	60	3.7	4.2	4.4	4.1
	90	3.9	4.6	4.4	4.3
No stress		3.7	4.7	4.3	4.2
with stress		3.6	4.3	4.2	4.0
	30	3.5	4.2	4.0	3.9 c
	60	3.7	4.4	4.3	4.2 b
	90	3.9	4.8	4.5	4.4 a
Mean		3.7 c	4.5 a	4.3 b	
		Planned mean comparison		*P* value	
Control	3	Control vs. rest		0.0000	
Rest	4				
LSD for organic sources	0.10				
LSD for K levels	0.10				
M x K	ns				
I x OS	ns				
M x K	ns				
I x OS x K	ns				

Means of the same category followed by different letters are significantly different from each other using LSD test ($P \leq 0.05$)

Where ns stands for non-significant data ($P \leq 0.05$)

AMC stands for animal manures compost (6 t ha^{-1}), *PMC* stands for poultry manure compost (6 t ha^{-1}), and *AMC + PMC* stands for combined use of animal manure compost and poultry manure compost (3 t ha^{-1} each)

observed that inoculation and higher doses of phosphorus increased the oil content of soybean. Protein content concentration is a major quality parameter, and most legumes have a high percentage of protein in their seeds. Phosphorus is a major plant essential nutrient, and it is very important for soybean growth and development. Significant effects on oil and protein content were noted at different levels of phosphorus and seed inoculation. Phosphorus application is necessary for high protein and oil yields of soybean seeds. Phosphorus application improves soybean yield qualitatively and quantitatively, especially protein and oil contents in seeds. Yadav et al. [47] also reported that the application of phosphorus at 60 kg/ha produced higher oil and protein contents in soybean. Likewise, Tiwari et al. [48] and Mahmoodi et al. [49], reported that the application of phosphorus significantly increased the oil and protein contents in soybean.

The oil and protein contents in soybean seed were significantly influenced by potassium application. Similar reports were given by Bellaloui et al. [50], who reported that application potassium application increase protein content in soybean with an increase in potassium level. It might be due to the importance of potassium in plant metabolism [51], the most important is the plant protein synthesis. Potassium is essential for increasing the transport rate of essential amino acids during seed development [51]. Application potassium increases oil and protein contents in seed. Application of potassium at the rate of 70 kg ha-1 increases protein content in soybean [52]. Krueger et al. [53] also reported that application of P and K increases quality, i.e., oil and protein content of soybean.

The oil and protein contents in soybean seed were significantly influenced by phosphate-solubilizing bacteria. The plots sown with PSB increased oil and protein contents and yield in soybean as compared to plots sown without PSB. Phosphate-solubilizing bacteria are capable of transforming soil phosphorus into forms available to plants. Similarly, oil and protein yield were also maximum with the treatment SSP + PSB. It was due to higher oil and protein content of seed as well as higher grain yield per unit area. Phosphate-solubilizing bacteria caused the gradual and balanced supply of phosphorus, part of the energy needed for nitrogen fixation (by

Table 11 Thousand grains weight (g) of soybean as affected by potassium levels, compost types under full irrigated and limited irrigated conditions

Moisture (M)	K levels (kg ha^{-1})	AMC	PMC	AMC + PMC	M x K
No stress	30	129	150	149	143
	60	133	157	151	147
	90	144	173	155	157
With stress	30	119	140	147	136
	60	127	147	151	142
	90	136	169	154	153
No stress		135	160	152	149
with stress		128	152	151	143
	30	124	145	148	139 c
	60	130	152	151	144 b
	90	140	171	155	155 a
Mean		132 c	156 a	151 b	
		Planned mean comparison		*P* value	
Control	122	Control vs. rest		0.0000	
Rest	148				
LSD for organic sources	2.45				
LSD for K levels	2.45				
M x K	**				
I x OS	ns				
M x K	ns				
I x OS x K	ns				

Means of the same category followed by different letters are significantly different from each other using LSD test ($P \leq 0.05$)

Where ns stands for non-significant data, while ** indicates significant at 1% level of probability using LSD test ($P \leq 0.05$)

AMC stands for animal manures compost (6 t ha^{-1}), *PMC* stands for poultry manure compost (6 t ha^{-1}), and *AMC + PMC* stands for combined use of animal manure compost and poultry manure compost (3 t ha^{-1} each)

stabilizer bacteria) provided [54]. Seed protein content was increased in response to biofertilizer application to soybean These results are also in agreement with those obtained by who found that using Azotobacter chroococcum as a biofertilizer could enhance the oil yield, as compared to the control [11–15]. Oil and protein yields showed a positive relationship with an increase in grain yield.

The oil and protein contents in soybean seed were significantly influenced by water regimes. Water-deficient conditions decrease oil and protein contents in soybean. Soybean plants under water stress conditions produce drought-tolerant compounds such as chaperones, whereas the decrease in protein might be due to hydrolysis and degradation [55]. Mertz-Henning et al. [56] also reported similar results that water stress decreases oil and protein contents of soybean. Water stress decreases oil and protein contents of the soybean seed, which might be due to the lesser uptake of essential nutrients and a low rate of photosynthesis [57]. Drought stress negatively affects oil and protein content of the soybean; it might be due to shorter grain filling duration due to a lack of sufficient water. The decrease in protein in soybean might be attributed to the prevention of NO3, which has a leading role in protein synthesis [57]. The reduction in the oil content under drought stress could be due to the oxidation of some of the polyunsaturated fatty acids [58].

The oil and protein contents in soybean seeds were significantly influenced by the application of compost and phosphorus (P). The combined use of organic compost and P increased oil and protein content, corroborating the findings of [36] and [59], who reported enhancements in oil (19.97%) and protein contents (40.33%) in soybean with compost and P application. Similarly, integrated use of compost and potassium (K) showed greater improvements in protein content compared to sole applications, aligning with [60] who observed increased protein content in cluster bean. The results are consistent with [61], who noted that nutrient management enhances oil and protein yields in sunflower. Combined application of compost and phosphate-solubilizing bacteria (PSB) also increased soybean oil and protein yields, as reported by Singh and Rai [58], who found that FYM at 5 t/ha plus biofertilizers maximized protein and oil content (20.07%).

Table 12 Grain yield (kg ha^{-1}) of soybean as affected by potassium levels, compost types full irrigated and limited irrigated conditions

Moisture (M)	K levels (kg ha^{-1})	AMC	PMC	AMC + PMC	M x K
No stress	30	2343	2920	2933	2732
	60	2617	3223	3063	2968
	90	2734	3790	3201	3242
With stress	30	2112	2660	2803	2525
	60	2503	3033	3235	2924
	90	2889	3334	3183	3135
No stress		2565	3311	3066	2981
with stress		2501	3009	3074	2861
	30	2228	2790	2868	2629 c
	60	2560	3128	3149	2946 b
	90	2812	3562	3192	3189 a
Mean		2533 c	3160 a	3070 b	
		Planned mean comparison		*P* value	
Control	2078	Control vs. rest		0.0000	
Rest	2974				
LSD for organic sources	86				
LSD for K levels	86				
M x K	**				
I x OS	ns				
M x K	ns				
I x OS x K	ns				

Means of the same category followed by different letters are significantly different from each other using LSD test ($P \leq 0.05$)

Where ns stands for non-significant data, while ** indicates significant at 1% level of probability using LSD test ($P \leq 0.05$)

AMC stands for animal manures compost (6 t ha^{-1}), *PMC* stands for poultry manure compost (6 t ha^{-1}), and *AMC + PMC* stands for combined use of animal manure compost and poultry manure compost (3 t ha^{-1} each)

According to [24], the combination of compost and PSB significantly improved oil and protein content in soybean, supported by Waghmare et al. [62], who recorded the highest percentages of oil and protein contents with compost and PSB.

Application of P with PSB significantly improved protein and oil contents in soybean. Malik et al. [63] highlighted the essential role of P for soybean growth and yield, noting that P combined with PSB enhances protein and oil content. P alone or with PSB significantly increased soybean oil and protein content, and PSB application alone also improved these metrics [61]. Kanojia and Sharma [64] concluded that P application at 60–90 kg/ha increased the quality and quantity of soybean oil and protein. Integrated use of organic compost, P, and PSB significantly enhanced soybean oil and protein content due to the ready availability of essential nutrients [65]. Similar findings were reported in cluster bean [66]. Increasing K levels enhanced oil and protein yields under both fully irrigated and limited irrigation conditions. Potassium increases crop tolerance to drought stress by promoting deeper rooting, greater water absorption, and water-holding capacity in plant tissues [67]. Adequate potassium improves dry matter accumulation under drought conditions due to its role in stomatal regulation and higher photosynthesis rates [68]. Additionally, potassium is crucial for photoassimilate transport to roots, promoting root growth and increasing water absorption under water deficit conditions [69, 70].

The combined application of compost, P, and PSB significantly influenced soybean seed oil and protein content. Similar improvements were reported by [58, 59], who noted enhanced protein and oil contents with the application of P, organic carbon, and biofertilizers. According to [71], the highest seed oil content (18.18%) and protein content (38.86%) were achieved with 100% P, PSB, compost, and biofertilizers. Water regimes also significantly influenced oil and protein contents, with water deficiency reducing these metrics. Patel [72] found that potassium combined with organic compost increased soybean oil and protein contents. Potassium is essential for the transport of amino acids during seed development [51]. Compost application, particularly poultry manure compost, increases protein and oil contents and yields [73]. Phosphorus and potassium fertilizers also enhance protein and oil contents in soybean seeds [74], and PSB

Table 13 Protein yield (kg ha^{-1}) of soybean as affected by potassium levels, compost types under full irrigated and limited irrigated conditions

Moisture (M)	K levels (kg ha^{-1})	AMC	PMC	AMC + PMC	M x K
No stress	30	539	672	675	628
	60	602	741	704	683
	90	629	822	736	729
With stress	30	486	612	645	581
	60	576	698	744	672
	90	664	767	732	721
No stress		590	745	705	680a
with stress		575	692	707	658b
	30	512	642	660	605 c
	60	589	719	724	678 b
	90	647	794	734	725 a
Mean		583 c	719 a	706 b	
		Planned means comparison		*P* value	
Control	478	Control vs. rest		0.0000	
Rest	681				
LSD for compost types	18.46				
LSD for K levels	18.46				
M x K	**				
I x OS	ns				
M x K	ns				
I x OS x K	ns				

Means of the same category followed by different letters are significantly different from each other using LSD test (P ≤ 0.05) Where ns stands for non-significant data, while ** indicates significant at 1% level of probability using LSD test (*P* ≤ 0.05) *AMC* stands for animal/cattle manures compost (6 t ha^{-1}), *PMC* stands for poultry manure compost (6 t ha^{-1}), and *AMC + PMC* stands for combined use of animal manure and poultry manure compost (3 t ha^{-1} each)

Table 14 Oil yield (kg ha^{-1}) of soybean as affected by potassium levels, compost types under full irrigated and limited irrigated conditions

Moisture (M)	K levels (kg ha^{-1})	AMC	PMC	AMC + PMC	M x K
No stress	30	422	526	528	492
	60	471	580	551	534
	90	492	682	576	584
With stress	30	380	479	505	455
	60	451	546	582	526
	90	520	600	573	564
No stress		462	596	552	536
with stress		450	542	553	515
	30	401	502	516	473 c
	60	461	563	567	530 b
	90	506	641	575	574 a
Mean		456 c	569 a	553 b	
		Planned means comparison		*P* value	
Control	374	Control vs. rest		0.0000	
Rest	535				
LSD for organic sources	15.48				
LSD for K levels	15.48				
M x K	**				
I x OS	ns				
M x K	ns				
I x OS x K	ns				

Means of the same category followed by different letters are significantly different from each other using LSD test (*P* ≤ 0.05) Where ns stands for non-significant data, while ** indicates significant at 1% level of probability using LSD test (P ≤ 0.05) *AMC* stands for animal/cattle manures compost (6 t ha^{-1}), *PMC* stands for poultry manure compost (6 t ha^{-1}), and *AMC + PMC* stands for combined use of animal manure and poultry manure compost (3 t ha^{-1} each) presence further improves these metrics by enhancing nutrient availability and uptake [75]. However, the specific effects may vary depending on soil conditions, environmental factors, and management practices.

Conclusions

Integrated nutrient management is vital for sustainable soybean production. By incorporating phosphorus, potassium, compost, irrigation, and phosphate-solubilizing bacteria, this approach significantly enhances soybean growth, yield, oil and protein content, soil fertility, and health. Additionally, integrated nutrient management helps mitigate climate change impacts by reducing greenhouse gas emissions and enhancing carbon sequestration. Future research should focus on optimizing nutrient management based on specific soil and environmental conditions, exploring innovative technologies, and assessing long-term effects on soil health and ecosystem services. In summary, integrated nutrient management is essential for sustainable soybean production, enhancing yield, quality, and soil health while addressing food security and climate change challenges.

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Authors' contributions
Amanullah designed and supervised the research project, drafted and revised the manuscript, and Junaid Ali Khan and Muhammad Yasir carried out two separate and independent field studies. Both students took data, analyzed data, made tables, and wrote their internship reports to get their degree. All authors have read and agreed to the published version of the manuscript in the esteemed BMC journal.

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Data availability
All related data is presented as mean tables and figures.

Declarations

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Not Applicable.

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The authors declare no competing interests.

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