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Research Paper

Growth response of soybean (*Glycine max* L.) to integrated use of vermicompost and phosphorus fertilizer

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ABSTRACT

In the present study, the impact of four levels of vermicompost (0, 2.5, 5 and 7.5 t ha^{-1}) and four dosages of phosphorus (0, 10, 20 and 30 kg ha^{-1}) fertilizer was evaluated on soybean growth parameters over two years. Results showed significant differences in growth parameters of the crop, including the number of leaves per plant, leaf area, leaf area index, plant height and the number of branches per plant over the years and across sites. On average, over the two years, the application of 20 kg ha^{-1} phosphorus and 7.5 t ha^{-1} vermicompost increased the number of leaves per plant, leaf area and plant height by 58.6 %, 32.3 % and 67.3 %, respectively compared to the control, with statistical similarity to 10 kg ha^{-1} phosphorus combined with 7.5 t ha^{-1} vermicompost. The study indicates that combining 10 kg ha^{-1} of phosphorus with 7.5 t ha^{-1} of vermicompost can enhance soybean growth without affecting the measured parameters when compared to higher phosphorus application rates. This integrated approach reduces the necessity for the standard 20 kg ha^{-1} phosphorus fertilizer and is therefore suggested for maximizing crop growth outcomes.

***Key words*: Leaf area, Leaf area index, Number of branches, Plant height**

INTRODUCTION

Soybean (*Glycine max* L.) is an important and cultivated food legume, currently grown worldwide under various climatic conditions (Siamabele 2021). It plays a crucial role in global food security (Dilawari *et al*. 2022) and agricultural sustainability due to its high seed protein and oil concentration (Guo *et al.* 2022), as well as its low reliance on nitrogen fertilization (Schipanski, Drinkwater and Russelle 2010). Soybean enhances soil health through biological nitrogen fixation (Gelfand and Philip Robertson 2015). An economically important leguminous crop, soybean is recognized as a nutrient store crop as it contains significant levels of all the essential amino acids, oil, minerals and vitamins (Anderson *et al*. 2019).

Soybean, despite being a versatile crop, faces challenges in growth and development due to various factors. Poor soil fertility leads to reduced crop growth in tropical regions (Siamabele 2021). In Ethiopia, the soils are highly weathered and infertile due to low organic matter content and inefficient nutrient cycling systems (Bedadi *et al*. 2023). Soil fertility depletion is primarily caused by insufficient fertilizer use, removal of crop residues, continuous cropping, climate change, soil conditions, and soil erosion (Tan *et al*. 2005).

Effective soil fertility management practices are crucial for maintaining healthy soil conditions and promoting optimal crop growth. Integrating organic and inorganic fertilizers is an important soil fertility management approach that can enhance soil fertility and crop growth. Optimizing plant growth is essential for maximizing resource utilization, such as water, nutrients and sunlight, resulting in higher yields and improved harvest quality. When crops realize their optimal growth potential, they produce more biomass, which could probably result in higher yields, but excess biomass could reduce grain yield. Combined use of vermicompost and phosphorus fertilizer can improve crop growth performance by enhancing soil fertility status. However, there is limited information available regarding the effects of the combined use of vermicompost and phosphorus fertilizer on the growth performance of soybean. Furthermore, the ideal combination rates of vermicompost and phosphorus fertilizers for optimal soybean crop growth have not been determined. Therefore, research focusing on identifying the best combination to improve soybean growth performance is needed, especially in regions with soil fertility challenges. This study evaluated the effects of integrating vermicompost and phosphorus fertilizer to determine the best-performing combination for improved soybean growth parameters.

MATERIALS AND METHODS

Description of the study area

The study was conducted at two sites: Boricha district, Aldada Fulasa 'Kebele' (6°59′ 34.872′′N, 38°17′ 29.382′′E and 1952 meters above sea level) and Wondo Genet Agricultural Research Center (7°5′ 40.332′′N, 38°37′ 30.726′′E and 1781 meters above sea level). Both areas experience a bimodal rainfall pattern with a short rain season from March to May and a main rain season from June to October. The soil types in Boricha and Wondo Genet are loam and sandy loam, respectively.

Experimental materials and design

The soybean variety, Nyala, released in 2014 by the Hawassa Agricultural Research Institute, was used in this study. Vermicompost was produced from a mixture of 50% common bean straw and 50% coffee husk combined with cow dung in a 2:1 ratio using *Eisenia fetida* earthworms at the vermiculture center, College of Agriculture, Hawassa University. The vermicompost selected had favorable physicochemical properties and high nutrient content (Dugassa and Worku 2025). Triple Super Phosphate was used as the phosphorus source. The experiment was set up using a randomized complete block design (RCBD).

Experimental treatments and procedures

The experiment included four levels of vermicompost (0, 2.5, 5 and 7.5 t ha^{-1}) and four levels of phosphorus (0, 10, 20 and 30 kg ha^{-1}) in a factorial design with 16 treatment combinations and 3 replications. Vermicompost was applied 14 days before sowing at the designated rate and mixed in~~to~~ the top 15-20 cm of soil. Seeds were sown at a rate of 80 kg ha^{-1} and Triple Super Phosphate (TSP) was applied at sowing according to the assigned amount. Crop management practices, including weeding and inter-cultivation, were carried out uniformly to support optimal crop growth.

Table 1. Experimental treatments

Treatments	Treatment details
1	0VC + 0P ha^{-1}
2	2.5 t ha^{-1} VC + 0kg P ha^{-1}
3	5 t ha^{-1} VC + 0kg P ha^{-1}
4	7.5 t ha^{-1} VC + 0kg P ha^{-1}
5	0 VC + 10 kg P ha^{-1}
6	2.5 t ha^{-1} VC + 10 kg P ha^{-1}
7	5 t ha^{-1} VC + 10 kg P ha^{-1}
8	7.5 t ha^{-1} VC + 10 kg P ha^{-1}
9	0 VC + 20 kg P ha^{-1}
10	2.5 t ha^{-1} VC + 20 kg P ha^{-1}
11	5 t ha^{-1} VC + 20 kg P ha^{-1}
12	7.5 t ha^{-1} VC + 20 kg P ha^{-1}
13	0 VC + 30 kg P ha^{-1}
14	2.5 t ha^{-1} VC + 30 kg P ha^{-1}
15	5 t ha^{-1} VC + 30 kg P ha^{-1}
16	7.5 t ha^{-1} VC + 30 kg P ha^{-1}

VC= vermicompost, P= phosphorous, ha^{-1} = per hectare

Data and data collection

Observations on growth parameters, including the number of leaves per plant, leaf area, leaf area index, plant height and number of branches per plant, were collected from five randomly selected plants from each plot. The data were collected at the late flowering stage and the average values for each treatment were recorded. The number of leaves per plant was determined by counting at late flowering stages from five randomly selected plants per plot and the average was calculated. The leaf area per plot was measured by sampling five plants per plot using a portable area meter model LI-3000A (LI-COR, USA). The average leaf area was then recorded for each plot. The leaf area index was measured during early flowering growth stages using the formula proposed by Williams (1946) .

$$\text{LAI} = \frac{\text{Total leaf area of a plant}}{\text{Ground area occupied by the plant}}$$

Plant height was measured by selecting five random plants per plot and using a graduated scale to measure from ground level to the top of the shoot. The number of branches on the main stem was determined by counting branches on five randomly selected sampled plants in each plot that were used for the other parameters.

Data analysis

Analysis of various growth parameters of this study was conducted using the General Linear Model procedure in SAS software (SAS 2000) with fixed effects. The normality of the data was assessed using the Shapiro-Wilk test and the homogeneity of variance was tested with Levene's test.

RESULTS AND DISCUSSION

Main effects of phosphorus and vermicompost on growth parameters

The study results indicate that soybean growth parameters, such as leaf area per plot, leaf area index, plant height and number of branches per plant were significantly influenced by phosphorus, vermicompost and site factors ($p<0.001$) (Supplementary 1 to 5). In 2023, the application of 30 kg ha^{-1} phosphorus resulted in the highest leaf number (53.4), which was not significantly different from the 20 kg ha^{-1} phosphorus application. Compared to the control, the 30 kg ha^{-1} phosphorus application in 2023 increased the number of leaves per plant by 29%. In 2024, the 20 kg ha^{-1} phosphorus application showed a similar increase of 30% compared to the control. The application of 7.5 t ha^{-1} vermicompost improved the number of leaves per plant in 2023, with similar results to the 5 t ha^{-1} vermicompost application, while in 2024, it was significantly different from the control only.

Regarding leaf area in 2023 the 30 kg ha^{-1}, phosphorus application significantly increased leaf area compared to the control with no statistical difference from other phosphorus levels. In 2024, the 30 kg ha^{-1} phosphorus application was comparable to the 20 kg ha^{-1} application, outperforming the 10 kg ha^{-1} phosphorus and the control. The 7.5 t ha^{-1} vermicompost application in 2023 significantly, increased leaf area and leaf area index compared to other levels with an 11% and 12% increase respectively, compared to the control. In 2024 it was on par with the 5 t ha^{-1} vermicompost application, showing an 8% increase in both parameters. Site effects were significant, with the Boricha site showing higher values for the number of leaves per plant, leaf area and leaf area index in both years compared to the Wondo Genet site (Table 2).

Plant height and the number of branches per plant were significantly ($p < 0.001$) influenced by the main effect of phosphorus fertilizer, vermicompost and site (Supplementary 4). In both years, phosphorus levels significantly affected plant height, with statistically similar results for the 20 kg ha^{-1} and 30 kg ha^{-1} treatments (Figure 1A). The effect of vermicompost rates was significant, with the highest values observed with the 7.5 t ha^{-1} vermicompost treatment in both years (Figure 1B). Boricha site exhibited better performance in plant height compared to Wondo Genet sites in both years (Figure 1C). The application of 30 kg ha^{-1} of phosphorus led to a significant increase in plant height and the number of branches per plant, showing statistical similarity with the 20 kg ha^{-1} phosphorus in both years. On average over the two years, the application of 30 kg ha^{-1} of phosphorus resulted in a nearly 24% increase in plant height compared to the control. On average over two years, the application of 7.5 t ha^{-1} of vermicompost led to a nearly 62% increase in plant height compared to the control.

Table 2. Main effects of phosphorus, vermicompost and site on number of leaves per plant, leaf area and leaf area index at late flowering stage

Factors	Levels	Means of the parameters					
		NLPP		LA plot^{-1} (cm^2)		LAI	
		2023	2024	2023	2024	2023	2024
P	0	41.4c	38.8c	874b	875c	2.9b	2.6c
	10 kg ha^{-1}	48.3b	45.5b	950a	923b	3.2a	2.9b
	20 kg ha^{-1}	52.7a	50.5a	955a	939a	3.2a	3.1a
	30 kg ha^{-1}	53.4a	49.7a	968a	951a	3.3a	3.2a
	LSD (p=0.05)	1.8	1.7	22	23	0.2	0.2
	P value	<.0001	0.001	<.0001	<.0001	<.0001	<.0001
VC	0	46.5c	43.7b	891d	887b	2.9d	2.9c
	2.5 t ha^{-1}	48.7b	45.9a	917c	906b	3.1c	3.0b
	5.0 t ha^{-1}	50.0ab	47.1a	950b	938a	3.2b	3.1a
	7.5 t ha^{-1}	50.6a	47.6a	989a	957a	3.3a	3.2a
	LSD (p=0.05)	1.8	1.7	22	23	0.08	0.08
	P value	<.0001	0.001	<.0001	0.001	<.0001	<.0001
S	Boricha	53.5a	50.8a	998a	984a	3.3a	3.3a
	W/G	44.4b	41.4b	876b	681b	2.9b	2.9b
	LSD (p=0.05)	1.3	1.2	15	16	0.1	0.1
	P value	<.0001	0.01	<.0001	0.001	<.0001	<.0001
CV (%)		6.4	6.6	4.1	4.4	4.3	4.7

NLPP = number of leaf per plant, LAPP = leaf area, LAI= leaf area index, P=phosphorus, VC=vermicompost, S=site, W/G=Wondo Genet, LSD=least significant difference, CV = coefficient of variation. Means in each column for similar factors followed by similar letter are not significantly different (p=0.05), ns=not significant.

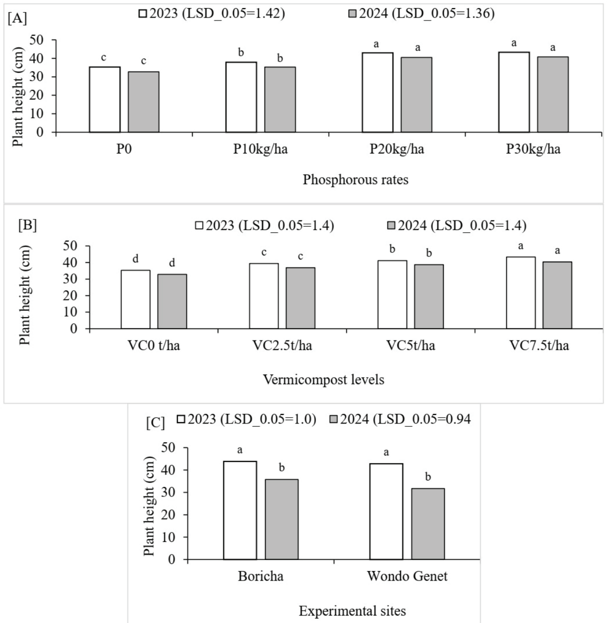

Figure 1. Main effects of phosphorous [A], vermicompost [B] and sites [C] on plant height

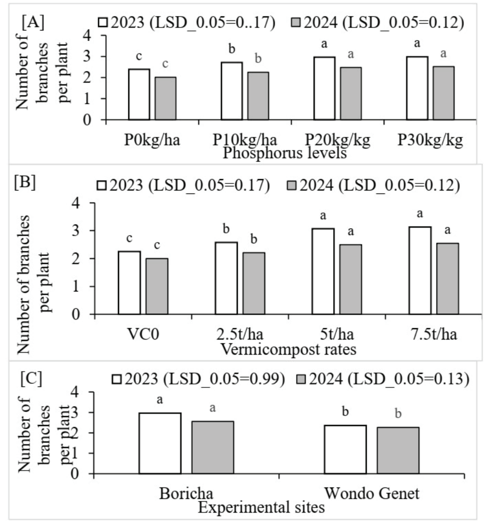

Figure 2. Main effects of phosphorous [A], vermicompost [B] and sites [C] on number of branches

Phosphorus levels, vermicompost rates and site conditions significantly influenced the number of branches per plant (Supplementary 5). The application of 20 kg ha^{-1} and 30 kg ha^{-1} phosphorus resulted in statistically similar results for the number of branches per plant, while the control resulted in a significantly lower results (Figure 1A). The highest values were observed with the application of 20 and 30 kg ha^{-1} of phosphorus, while the control had the lowest values in both years. Similarly, the application of 5 t ha^{-1} and 7.5 t ha^{-1} of vermicompost led to significantly higher values (Figure 2B). The Boricha site consistently showed higher values for the number of branches per plant in both years compared to Wondo Genet (Figure 2C).

Interaction effects of phosphorus and vermicompost on growth parameters

The interaction effects of phosphorus and vermicompost significantly influenced growth parameters (Supplementary 1 to 5). The highest number of leaves per plant was observed with the combined application of 20 kg ha^{-1} P + 7.5 t ha^{-1} VC, with 57 leaves in 2023 and 54 leaves in 2024. Additionally, the combination of 30 kg ha^{-1} P + 7.5 t ha^{-1} VC showed comparable results to other combinations, such as 10 kg ha^{-1} P + 7.5 t ha^{-1} VC, 20 kg ha^{-1} P + 5 t ha^{-1} VC, 30 kg ha^{-1} P + 5 t ha^{-1} VC, 30 kg ha^{-1} P + 2.5 t ha^{-1} VC, and 20 kg ha^{-1} P + 2.5 t ha^{-1} VC in both years. In contrast, the control group had the lowest number of leaves per plant, with 36 leaves in 2023 and 34 leaves in 2024. Overall, the combined application of 20 kg ha^{-1} P +7.5 t ha^{-1} VC led to a 64% increase in the number of leaves per plant compared to the control group over the two years.

In 2023, the application of 10 kg ha^{-1} P +7.5 t ha^{-1} VC resulted in a higher leaf area per plot of 1026.74 cm^2, which was not significantly different from other treatment combinations. These included 30 kg ha^{-1} P + 7.5 t ha^{-1} of VC, 30 kg ha^{-1} P +5 t ha^{-1} VC, 7.5 t ha^{-1} VC alone, 30 kg ha^{-1} P + 2.5 t ha^{-1} VC, 20 kg ha^{-1} P + 7.5 t ha^{-1} VC, 20 kg ha^{-1} P + 5 t ha^{-1} VC, 10 kg ha^{-1} P + 5 t ha^{-1} VC, and 30 kg ha^{-1} P alone (Table 2). In 2024, the highest leaf area per plant of 979 cm^2 was achieved by combining 20 kg ha^{-1} P + 7.5 t ha^{-1} VC. This result was statistically similar to most combinations except for 10 kg ha^{-1} P + 5 t ha^{-1} of VC, 5 t ha^{-1} VC alone, 10 kg ha^{-1} P +2.5 t ha^{-1} VC, 2.5 t ha^{-1} VC alone, 10 kg ha^{-1} VC alone, and the control group (Table 3).

In 2023, applying 20 kg ha^{-1} P + 7.5 t ha^{-1} VC resulted in a leaf area index of 3.5, which was not significantly different from other treatments, including 30 kg ha^{-1} P + 7.5 t ha^{-1} VC, 10 kg ha-1 P + 7.5 t ha^{-1} VC, 7.5 t ha^{-1} VC alone, 30 kg ha^{-1} P + 5 t ha^{-1} VC, 20 kg ha^{-1} P + 5 t ha^{-1} VC, and 10 kg ha^{-1} P + 5 t ha^{-1} VC. In 2024, the highest leaf area index (3.4) was achieved with 20 kg ha^{-1} P+7.5 t ha^{-1} VC, which was statistically similar to most combinations except for 30 kg ha^{-1} P alone, 20 kg ha^{-1} P alone, 10 kg ha^{-1} P alone, 5 t ha^{-1} P alone, 2.5 t ha^{-1} VC alone, and the control group. The control group had a minimum leaf area index of 2.5 in 2023 and 2.6 in 2024 (Table 3).

Table 3. Interaction effects of phosphorus and vermicompost levels on soybean number of leaves per plant, leaf area and leaf index at late flowering stage

Factors & levels (t ha^{-1})		Means of the parameters					
		NLPP		LA (plot^{-1}) (cm^2)		LAI m^2/m^2	
P	VC	2023	2024	2023	2024	2023	2024
0	0	36.1f	33.7g	741.0e	775.4e	2.5f	2.6e
	2.5	43.2e	40.2fg	877.7d	872.4de	2.9e	2.9cd
	5.0	43.2e	40.7f	888.0cd	880.2cd	3.0de	2.9cd
	7.5	46.5d	40.7f	989.4ab	973.0ab	3.3abc	3.1abcd
10	0	46.5d	43.8ef	882.5cd	866.9d	2.9e	2.93cd
	2.5	47.8bcde	44.8cdef	929.3abcd	902.9bcd	3.1cde	3.1abcd
	5.0	49.5bcde	45.7bcdef	968.3a	909bcd	3.2abcde	3.1abcd
	7.5	50.5abcd	47.5abcde	1021.7a	943.3abcd	3.5a	3.2ab
20	0	47.2de	44.3def	918.7bcd	913.4abcd	3.0cde	3.0bcd
	2.5	54.1ab	51.2abc	929.3bcd	939.1abcd	3.1cde	3.2abcd
	5.0	55.2a	52.1ab	968.3abcd	952.6abcd	3.2abcd	3.2abcd
	7.5	56.8a	53.8a	968.3abcd	979.2a	3.4ab	3.4a
30	0	47.5cde	44.7cdef	929.7abcd	920.7abcd	3.1cde	3.0bcd
	2.5	53.8abc	50.8abcd	974.4abc	958.1abcd	3.1cde	3.2abcd
	5.0	53.8abc	50.8abcd	990.7ab	968.6abc	3.3abc	3.2abcd
	7.5	55.8a	52.8a	1021.7a	974.4ab	3.3abc	3.2abcd
LSD (p=0.05)		2.5	2.5	69.3	72.7	0.3	0.2
SE		1.3	1.2	15.9	16.4	0.7	0.1

P=phosphorus, VC=vermicompost, LA=leaf area, LAI=leaf area index, Means in the same column sharing at least one similar letter are not significantly different at p=0.05

The interaction effects of phosphorus (P) and vermicompost (VC) levels significantly influenced plant height and the number of branches per plant (Supplementary 4 and 5). The combination of 20 kg ha^{-1} P + 7.5 t ha^{-1} VC resulted in the highest plant height of 46 cm in 2023. This combination was statistically similar to 20 kg ha^{-1} P + 5 t ha^{-1} VC, 20 kg ha^{-1} P + 2.5 t ha^{-1} VC, and 10 kg ha^{-1} P + 7.5 t ha^{-1} VC (Figure 3A). Similarly, it was statistically similar to 7.5 t/ha VC alone, 30 kg ha^{-1} P + 7.5 t ha^{-1} VC, 30 kg ha^{-1} P + 5 t ha^{-1} VC, and 30 kg ha^{-1} P + 2.5 t ha^{-1} VC. In 2024, the maximum plant height of 43 cm was recorded from the combination of 20 kg ha^{-1} P + 7.5 t ha^{-1} VC, which was statistically similar to most combinations except the control, 2.5 t ha^{-1}VC alone, 5 t ha^{-1} vermicompost alone, 10 kg ha^{-1} P alone, and 10 kg ha^{-1} P + 2.5 t ha^{-1} VC (Figure 3B).

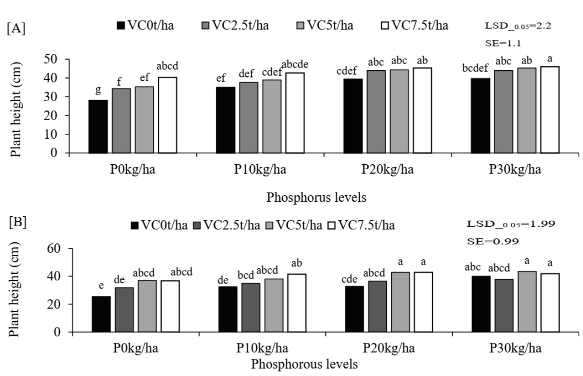

Figure 3. Interaction effects of vermicompost and phosphorous levels on plant height [A] 2023, [B] 2024. VC0=no vermicompost, VC2.5=vermicompost 2.5 tons/ha, VC5=vermicompost 5tons/ha, VC7.5=vermicompost 7.5 tons/ha, P0=no phosphorous, P10=10 kg/ha phosphorous, P20=20 kg/ha phosphorous, P30=30 kg/ha phosphorous. LSD=least significant difference, SE=standard error. Bars with similar color in similar rows sharing at least one similar letter are not significantly different

In 2023, the combination of 30 kg ha^{-1} P + 5 t ha^{-1} VC and 10 kg ha^{-1} P + 7.5 t ha^{-1} VC resulted in the highest number of branches per plant, with 3.4 branches. This combination was statistically similar to 30 kg ha^{-1} P + 7.5 t ha^{-1} VC and 10 kg ha^{-1} P + 5 t ha^{-1} VC (Figure 4A). In 2024, the maximum number of branches per plant, 2.8, was observed with the application of 30 kg ha^{-1} P + 5 t ha^{-1} VC. This combination was statistically similar to several other combinations but significantly different from the control, 2.5 t ha^{-1} VC alone, 5 t ha^{-1} vermicompost alone, 10 kg ha^{-1} P alone, and 10 kg ha^{-1} P combined with 2.5 t ha^{-1} VC (Figure 4B). The control group had the minimum number of branches per plant, with 2 in 2023 and 1.7 in 2024.

Correlation analysis

Pearson correlation analysis was conducted to evaluate the relationship between the crop growth parameters. The results indicated highly significant ($p<0.0001$) relationships between the parameters evaluated (Table 4). The maximum correlation coefficient of 0.97717 was observed between leaf

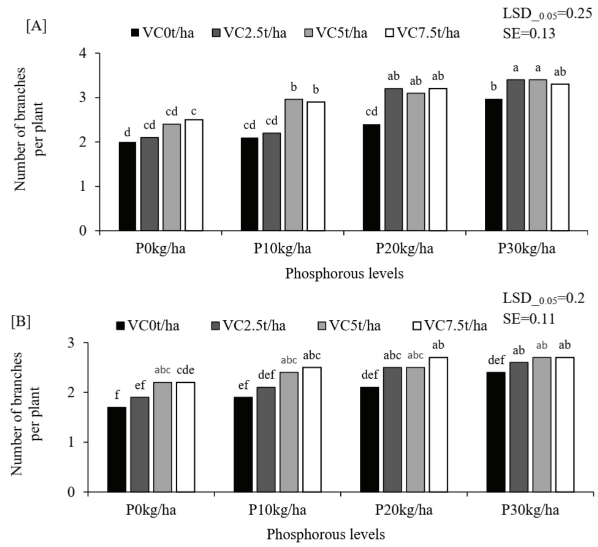

Figure 4. Interaction effects of vermicompost and phosphorous levels on number of branches per plant [A] 2023, [B] 2024. VC0=vermicompost 0, VC2.5=vermicompost 2.5 tons/ha , VC5=vermicompost 5 tons/ha, VC7.5=vermicompost 7.5 tons/ha, P0=no phosphorous, P10=10 kg/ha phosphorous, P20=20 kg/ha phosphorous, P30=30 kg/ha phosphorous. LSD=least significant difference, SE=standard error. Bars with similar color in similar rows sharing at least one similar letter are not significantly different

area and leaf area index, followed by the correlation between plant height to leaf area and leaf area index that exhibited 0.77620 and 0.76139 correlation coefficients, respectively.

Table 4. Pearson correlation coefficient between growth parameters of soybean

	NLPP	LA	LAI	PH	NBPP
NLPP	1	0.64570***	0.62260***	0.77815***	0.47673***
LA		1	0.97717***	0.77620***	0.47061***
LAI			1	0.76139***	0.48072***
PH				1	0.54831***
NBPP					1

NLPP=number of leaves per plant, LA=leaf area, LAI=leaf area index, PH=plant height, NBPP=number of branches per plant. ***=significant at $p<0.0001$

The study found that applying phosphorus, vermicompost, or a combination of both positively impacted soybean growth. Different levels of phosphorus significantly improved soybean growth, likely due to its essential role in cellular processes such as membrane maintenance, biomolecule synthesis, and energy production (Malhotra *et al.* 2018). Phosphorus is crucial for deoxyribonucleic acid (DNA), ribonucleic acid (RNA), adenosine triphosphate (ATP), which are vital for energy transfer in cells (Razaq *et al*. 2017). Increasing phosphorus levels from zero to 10 kg ha^{-1} and 20 kg ha^{-1} significantly enhanced crop growth parameters. This is because phosphorus application supports essential physiological processes like root development, nutrient uptake and photosynthesis, leading to improved plant growth (Malhotra *et al.* 2018). Increasing phosphorus application from 20 kg ha^{-1} to 30 kg ha^{-1} did not result in significant improvement, suggesting that 20 kg ha^{-1} may be the optimal level for crop growth.

The use of vermicompost improved plant growth by enhancing soil structure, providing nutrients, boosting microbial activity and supporting root development. This led to better overall plant health and increased stand vigor (Chatterjee *et al*. 2020). Vermicompost contains growth-promoting substances and beneficial microorganisms that enhance seed germination and support strong root development in young plants, resulting in healthier and more robust plants. The study found that vermicompost application led to a significant increase in plant growth parameters such as number of leaves, leaf area, branches and plant height. This is likely due to the nutrient-rich and microbe-filled nature of vermicompost, which provides plants with optimal conditions for growth (Manzoor *et al.* 2024).

The combination of phosphorus and vermicompost resulted in increased plant growth compared to using them separately. This synergistic effect enhances soil fertility and nutrient availability, particularly phosphorus, essential for plant growth (Malhotra *et al*. 2018). The combination of 10 kg ha^{-1} phosphorus and 7.5 t ha^{-1} vermicompost led to significantly better growth parameters, making it the best choice for improving crop growth. This aligns with previous research showing enhanced crop growth when phosphorus and vermicompost are used together (Sande *et al*. 2024).

The study found that combining phosphorus fertilizer and vermicompost increased the number of leaves per plant. Increasing the application of phosphorus and vermicompost from zero to 10 kg ha^{-1} phosphorus and 7.5 t ha^{-1} vermicompost led to a 40% increase in the number of leaves and a 29% increase in leaf area. The increased number of leaves also resulted in a proportional increase in leaf area, indicating a positive relationship between these two parameters. The synergy between phosphorus and vermicompost likely promotes plant growth and enriches soil nutrients, leading to improved leaf initiation and growth (Chatterjee *et al*. 2020, Manzoor *et al.* 2024). A study showed that combining phosphorus and vermicompost led to a higher leaf count in chickpea (*Cicer arietinum* L.) plants (Kaunda *et al*. 2023).

A study showed that combining phosphorus

Supplementary 1. Analysis of variance for effects of phosphorus and vermicompost on number of leaves per plant of soybean

Source of variation	df	Number of leaves per plant					
		MS		F Value		Pr> F	
		2023	2024	2023	2024	2023	2024
S	1	1962.03166	2090.666667	202.04	225.16	<.0001	<.0001
P	3	727.16666	686.708333	74.88	73.96	<.0001	<.0001
VC	3	78.50000	71.458333	8.08	7.70	0.0001	0.0002
S*P	3	0.04166	0.944444	0.00	0.10	0.9996	0.9587
S*VC	3	0.04126	0.083333	0.00	0.01	0.9792	0.9988
P*VC	9	66.09259	64.162037	6.81	6.91	<.0001	<.0001
S*P*VC	9	0.04136	0.064815	0.00	0.01	1.0000	1.0000

df=degrees of freedom, MS=mean of squares, S=site, P=phosphorous, VC=vermicompost

Supplementary 2. Analysis of variance for effects of phosphorus and vermicompost on leaf area of soybean

Source of variation	df	**Leaf area**					
		MS		**F Value**		**Pr> F**	
		2023	**2024**	**2023**	**2024**	**2023**	**2024**
S	1	357216.000	361744.2604	244.99	223.08	<.0001	<.0001
P	3	43321.664	26808.1147	29.71	16.53	<.0001	<.0001
VC	3	43295.979	23593.1675	27.69	14.55	<.0001	<.0001
S*P	3	5667.580	5269.7663	3.89	3.25	0.0132	0.0279
S*VC	3	5667.580	656.8035	3.68	0.41	0.0112	0.7499
P*VC	9	18833.002	14434.9098	12.92	8.90	<.0001	<.0001
S*P*VC	9	3778.386	4068.0363	2.59	2.51	0.0136	0.0165

df=degrees of freedom, MS=mean of squares, S=site, P=phosphorous, VC=vermicompost

Supplementary 3. Analysis of variance for effects of phosphorus and vermicompost on leaf area index of soybean

Source of variation	df	**Leaf area index**					
		MS		**F Value**		**Pr> F**	
		2023	**2024**	**2023**	**2024**	**2023**	**2024**
S	1	3.33760417	3.80010417	180.01	182.22	<.0001	<.0001
P	3	0.52788194	0.25788194	28.47	12.37	<.0001	<.0001
VC	3	0.53093750	0.28982639	28.63	13.90	<.0001	<.0001
S*P	3	0.02149306	0.09427083	1.16	4.52	0.3328	0.0063
S*VC	3	0.03788194	0.00454861	2.04	0.22	0.1174	0.8835
P*VC	9	0.24501157	0.16991898	13.21	8.15	<.0001	<.0001
S*P*VC	9	0.03843750	0.04019676	2.07	1.93	0.0463	0.0649

df=degrees of freedom, MS=mean of squares, S=site, P=phosphorous, VC=vermicompost

Supplementary 4. Analysis of variance for effects of phosphorus and vermicompost on plant height of soybean

Source of variation	df	**Plant height**					
		MS		**F Value**		**Pr> F**	
		2023	**2024**	**2023**	**2024**	**2023**	**2024**
S	1	1552.04166	2915.010417	257.84	494.30	<.0001	<.0001
P	3	369.48611	375.204861	61.38	63.62	<.0001	<.0001
VC	3	275.59722	273.815972	45.78	46.43	<.0001	<.0001
S*P	3	0.04368	0.010297	0.01	0.00	0.9989	0.9999
S*VC	3	0.04166	0.010317	0.01	0.00	0.9992	0.9999
P*VC	9	28.07870	27.167824	4.66	4.61	0.0001	0.0001
S*P*VC	9	0.04166	0.010437	0.01	0.00	1.0000	1.0000

df=degrees of freedom, MS=mean of squares, S=site, P=phosphorous, VC=vermicompost

Supplementary 5. Analysis of variance for effects of phosphorus and vermicompost on number of branches per plant of soybean

Source of variation	df	Number of branches per plant					
		MS		F Value		Pr> F	
		2023	2024	2023	2024	2023	2024
S	1	3.84000000	0.15843750	39.63	2.64	<.0001	0.1093
P	3	1.79111111	1.33399306	18.48	22.24	<.0001	<.0001
VC	3	4.26333333	1.60260417	44.00	26.72	<.0001	<.0001
S*P	3	0.00000000	0.05677083	0.00	0.95	1.0000	0.4239
S*VC	3	0.00000000	0.62315972	0.00	10.39	1.0000	<.0001
P*VC	9	0.49222222	0.09908565	5.08	1.65	<.0001	0.1211
S*P*VC	9	0.00000000	0.18593750	0.00	3.10	1.0000	0.0040

df=degrees of freedom, MS=mean of squares, S=site, P=phosphorous, VC=vermicompost

fertilizer and vermicompost increased plant leaf area by improving nutrient availability, supporting plant growth and resulting in larger leaves. Previous studies on legume crops like groundnut (*Arachis hypogaea* L.) (Das *et al*. 2015), and hyacinth bean (*Lablab purpureus* L.) (Walia and Kaur 2024) reported increased leaf area when vermicompost is combined with chemical fertilizers. Our study found that combining phosphorus and vermicompost increased the number of branches per plant, likely due to enhanced plant growth. Previous research also supports this finding in French bean plants (Singh *et al*. 2011).

The combination of phosphorus and vermicompost increased plant height, suggesting enhanced effectiveness of inorganic phosphorus with vermicompost. Organic fertilizers improve soil quality by increasing organic matter and reducing bulk density and compaction (Celik *et al*. 2010). Increasing phosphorus and vermicompost application from zero to 10 kg ha^{-1} and 7.5 t h^{-1}, respectively, resulted in a 55% increase in plant height. This combination has been shown to enhance plant growth in mung beans (Aslam *et al*. 2024). It was discovered that the combination of organic and inorganic fertilizers resulted in better green gram growth compared to using only inorganic fertilizers (Rajkhowa *et al*. 2002). A previous study found that the combined application of phosphorus and vermicompost increased the height of chickpea plants (Kumar *et al*. 2014).

The correlation analysis revealed a strong relationship between growth parameters, possibly indicating that one parameter contributes to the enhancement of another. An increase in the number of leaves showed a significant correlation with leaf area, suggesting that individual leaves contribute to overall leaf area. The strong correlation between leaf area and leaf area index may be due to an increase in leaf area. Similarly, the strong correlation between plant height and the number of leaves may be attributed to the increased area available for producing more leaves.

CONCLUSION

Applying phosphorus and vermicompost, either separately or in integration, significantly enhanced soybean growth parameters. Increasing vermicompost rates from 2.5 t ha^{-1} to 5 and 7.5 t ha^{-1} further increased the growth of the crop. However, applying phosphorus beyond 20 kg ha^{-1} did not show substantial benefits. The study confirmed that combining phosphorus and vermicompost enhances soybean growth parameters synergistically. A combination of 10 kg ha^{-1} phosphorus and 7.5 t ha^{-1} vermicompost optimized soybean growth without the need for the recommended 20 kg ha^{-1} phosphorus. Therefore, the study recommends using 10 kg ha^{-1} phosphorus and 7.5 t ha^{-1} vermicompost for optimal soybean crop growth in the study area and similar agro-ecological conditions.

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