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Effects of vermicompost and phosphatic fertilizers on soybean yield, phosphorus content, uptake, and post-harvest soil properties

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ABSTRACT

To boost phosphorus (P) availability in soils, adding organic matter like compost, manure, or vermicompost (VC) is a sustainable solution. A field experiment investigated how VC and phosphatic fertilizers affect P bioavailability, plant uptake, and yield response of BARI Soybean-5. Eight treatments i.e., T_1 = control (no P), T_2 = 100% recommended dose of P (RDP) from triple superphosphate (TSP), T_3 = 100% RDP from diammonium phosphate (DAP), T_4 = 100% RDP from VC, T_5 = 75% RDP from TSP + 25% from VC, T_6 = 75% RDP from DAP + 25% from VC, T_7 = 50% RDP from TSP + 50% from VC, and T_8 = 50% RDP from DAP + 50% from VC were replicated thrice on randomized complete block design (RCBD). T_2 treatment generated a maximum seed yield of soybean (1.66 t ha^{-1}), exceeding T_3, T_5, T_6, T_7, and T_8 treatments with 1.63, 1.54, 1.52, 1.50, and 1.50 t ha^{-1}, respectively. Additionally, T2 exhibited the highest P content in seed, root, and straw (1.27, 0.19, and 0.41%, respectively), as well as the total uptake of P (28.15 kg ha^{-1}) among the treatments. T_4 exhibited significantly higher levels of organic C, total N, available P, exchangeable K, and available S. Overall findings revealed that growing BARI Soybean-5 with 100% RDP from TSP (T_2) proved a good practice for yield response, but 100% RDP from VC (T_4) would be preferable for long-term soil health. This study would be helpful in choosing between organic and inorganic sources of P fertilizers for soybean production.

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1. INTRODUCTION

Soybean stands as a globally essential leguminous crop due to their widespread production and trade. As a leading oilseed crop, it is valued for its high protein content (approximately 40%) compared to other commonly cultivated crops (Chatterjee et al., 2018). It has become an industrially vital and viable oilseed crop, gaining increasing market demand and leading to expanded cultivation in many parts of the world. In 2023, worldwide soybean production totaled 371.86 million tons, cultivated over 136.9 million hectares. Conversely, soybean production at the same time in Bangladesh was 107,307 tons covering 58,940 hectares of land, yielding 1.82 t ha^{-1}, considerably below the global average of 2.71 t ha^{-1} (FAO, 2025). Soybeans, once overlooked, are increasingly recognized as a valuable cash crop in Bangladesh, particularly among farming families in the southern districts of Bhola, Lakshmipur, and Noakhali. The expansion of small-scale, soy-based food businesses producing items such as biscuits, bread, curd, flour, halwa, meat, milk, and snacks could significantly improve the economic standing of the people in those areas. Bangladesh has opportunities to expand soybean farming with short-maturing improved varieties and favorable agro-climatic conditions. Concurrently, better crop and soil management strategies and post-harvest processing are needed for higher production targets that could lead to an increase in farmer income from soybean cultivation (Miah & Mondal, 2017).

In Bangladesh, the crop was introduced around 1942; however, efforts to promote its cultivation and conduct research on it did not begin until 1960–61. In 1961, the Bangladesh Agricultural Research Institute's (BARI) pulses and oilseeds division selected two soybean varieties, Pelican and Barnali, to help expand fallow land cultivation during the kharif-2 season. However, by the following year, both varieties were found to be vulnerable to yellow mosaic virus, leading to the discontinuation of their cultivation (Islam et al., 2022). However, these were also afflicted by the yellow mosaic virus,

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making them unsuitable for cultivation. Additionally, the region of experimentation had low phosphorus (P) availability, which may be due to the fixation of P in either calcareous or acidic soil conditions, leading to a reduction in crop yields. P is often a limiting factor for soybean growth and yield, despite its abundance in many soils, primarily due to its low solubility and availability to plants (Begum et al., 2015; Bilal et al., 2021). Consequently, optimizing phosphorus (P) availability through sustainable management practices is crucial for maximizing soybean productivity and enhancing the efficacy of nutrient utilization (Grant et al., 2001). As economic and environmental costs are associated with the application of synthetic P fertilizers, the combined use of inorganic P inputs with vermicompost (VC) could be an alternative for managing P nutrition, as well as a feasible and cost-effective approach to sustainable farming for smallholders in Bangladesh.

Soil acidity and P nutrition are globally known as important factors to limit the soybean nodulation and overall yield (Hansel et al., 2019; Mathenge et al., 2019). P is a vital macronutrient in plant nutrition and exists in soils as insoluble P forms that cannot be utilized directly by crops. While inorganic P fertilization is the most common practice for this major limiting nutrient, the soil properties, like soil pH, cause the added P to become unavailable to plants through soil sorption or precipitation with iron, aluminum, and calcium ions (Asomaning, 2020). P fertilization rates in arable lands currently exceed the plant uptake capacity, leading to an increased risk of P losses into water sources and subsequent eutrophication. Therefore, appropriate P management strategies are crucial to optimize the P utilization by crops from applied P fertilizers (Akhtar et al., 2020; Hashmi et al., 2017). It has been suggested that integrating organic amendments with synthetic P fertilizers represents a promising strategy to ensure a consistent P supply, thereby enhancing crop uptake and use efficiency. To improve the usefulness and utilization of P in problematic soils, such as those with acidic or alkaline soil conditions, the addition of VC has been widely recognized as one of the best solutions for sustainable crop production. VC contributes to enhanced nutrient cycling and availability through its rich microbial diversity, which includes a variety of beneficial microorganisms capable of solubilizing P and other essential nutrients (Pereira et al., 2023).

Contemporary agricultural practices are increasingly focusing on substituting inorganic fertilizers with organic alternatives, such as VC. Research indicates that VC application enhances plant development and positively influences the growth and increased yield of crops, including cereals and legumes. Furthermore, the utilization of VC has been shown to significantly improve the physical and biochemical attributes of soil, while simultaneously reducing exchangeable acidity, thereby facilitating nutrient availability in acidic soil environments (Adisu et al., 2019). Using 50% of the recommended fertilizer doses combined with 2.5 t ha-1 of VC significantly enhanced the seed, straw, and biological yields of soybeans (22.62, 23.86, and 46.48 q ha^{-1}, respectively). Additionally, this treatment resulted in higher NPK content in both seeds and straw, as well as greater nutrient uptake by soybean (Tomar et al., 2018). The incorporation of rice husk ash at 3.75 t ha^{-1} resulted in an increment in seed weight, with a positive correlation observed between higher rice husk ash application rates and increased root nodule production (Perdanatika et al., 2018). Some studies have compared the effects of biochars, zeolites, cow or quail manure, biofertilizers, and/or other organic-inorganic soil amendments either individually or in combination in ameliorating problem soils and evaluating the performance of soybean (Bertham et al., 2025; Minardi et al., 2020; Rashad et al., 2022). However, there is inadequate information on the combined use of VC and inorganic P fertilizer on acidic or alkaline soil for crop production, particularly concerning soybeans. Furthermore, the yield benefits of combined VC and/or P fertilizer applications on grain legumes, and whether these arise from enhanced P use efficiency, are not well-documented. Considering the above circumstances, this study has been undertaken: (i) to study the effect of inorganic phosphatic fertilizers alone or in integration with VC on the growth and yield of soybean; (ii) to examine whether VC and inorganic P fertilizer would modify the plant-available P ions in the soil and consequently improve P uptake; and (iii) to investigate whether the combined use of VC with inorganic P fertilizer may change the post-harvest soil properties.

2. MATERIALS AND METHODS

2.1. Experimental design

The research was conducted in the experimental field under the Soil Science Department at Hajee Mohammad Danesh Science and Technology University (HSTU), Dinajpur, Bangladesh, which is situated at 25.130 N latitude and 88.23^0 E longitude. The soil is a sandy loam under the Inceptisol order. The experimental soil had a pH of 6.48, 0.70% organic C, 0.035% total N, 45.6 ppm available P, 0.012 m.e. 100^{-1} g soil of exchangeable K, and 22.4 ppm of available S. The land was plowed and leveled thoroughly by plowing and cross-plowing with a tractor by laddering. Each block was divided into eight units, and a unit plot size of 1 m^2 (1 m × 1 m) was maintained. The distances between the two blocks and plots were 50 cm and 25 cm, respectively. The experiment was consisted eight treatments i.e., T_1 = control (no P), T_2 = 100% recommended dose of P (RDP) from TSP, T_3 = 100% RDP from DAP, T_4 = 100% RDP from VC, T_5 = 75% RDP from TSP + 25% from VC, T_6 = 75% RDP from DAP + 25% from VC, T_7 = 50% RDP from TSP + 50% from VC and T_8 = 50% RDP from DAP + 50% from VC. A randomized complete block design was implemented, with three replications for each treatment.

2.2. Vermicompost and fertilizer application

The recommended doses of fertilizers, such as urea, TSP, MoP, gypsum, ZnSO4, and boric acid, were used at 65, 175, 100, 112, 11, and 8.6 kg ha^{-1}, respectively, for soybean cultivation (FRG, 2018). The treatment-specific RDP from VC was determined based on the P content in VC (P = 2.2%). N and K contents in the VC (N = 1.5% and K = 1.3%) and N contents in DAP (N = 18%) were also considered for adjusting the 100% recommended doses of fertilizers (RDF). Except for urea, the required amounts of other fertilizers, based on 100% RDF from organic and inorganic sources, were applied during the final land preparation, just two days before seed sowing. Urea was applied in three equal installments as top dressing: the first at 10 days after sowing (DAS), the second at 30 DAS, and the third at 45 DAS, prior to flowering.

2.3. Plant materials and cultural practices

The BARI Soybean-5 variety was planted. Seed-to-seed and row-to-row spacing were maintained at 5-6 cm and 30 cm, respectively. Intensive care was taken to manage weeding (three times at 15, 30, and 45 DAS), water management, and pest control during the growing season to support adequate crop growth and development. The pest aphid was attacked during the experimental period; hence, the insecticide Takat (cyhalothrin 10.5%) was applied with a 3:1 mixture of water to control the pest.

2.4. Data collection on the growth and yield of soybean

Five plants were randomly chosen and subsequently tagged within each plot for collecting several growth and yield-related data. Plant height, measured from ground level to the top of the leaves of five tagged plants of each plot, was recorded at 15, 30, 45, 60, 75, and 90 DAS, and the mean was calculated. Root length was recorded manually after harvesting. For measuring root length, selected plants were carefully dug up, their roots gently washed with a gentle flow of water, and then separated from the shoots. The taproot length was measured and averaged. The number of nodules and fresh weight of nodules, plant^{-1}, number of pods plant^{-1}, number of seeds plant^{-1}, and seed yield plant^{-1} were also measured from the specific tagged plants. Plot-wise seed and straw were collected, sun-dried to 15% moisture content, and weighed. The weights of seeds and straw of the selected five plants were also added to the respective unit plot to record the final seed and straw yield plot^{-1}, which was then converted to tons per hectare (t ha^{-1}) and averaged.

2.5. Determination of P from plant samples and calculation of P uptake

Seed, root, and straw samples were oven-dried at 60 °C for 24 hours and then ground. Subsequently, 0.5 g of each sample was placed in a 100 ml Kjeldahl flask and treated with 10 ml of a di-acid mixture (HNO3:HClO4 = 2:1). The flasks were slowly heated to 200 °C until the contents were clear and colorless. Following cooling, the sample digests were diluted to 50 ml using distilled water. P content was measured using the Olsen method for soil P analyses, using 1 ml of digest for seed and 2 ml of digests for straw and root from the 50 ml extract. P uptake was calculated using Equation 1.

$$\text{P uptake}(\text{kg ha}^{-1}) = \frac{\text{Yield (kg ha}^{-1}) \times \text{P content (\%)}}{100} \quad \text{.................[1]}$$

2.6. Chemical analysis of soil

Both initial and post-harvest soils were analyzed in the Soil Science Laboratory, HSTU, Dinajpur. Chemical analyses, like determination of soil pH, organic C, total N, available P, exchangeable K, and available S, were analyzed using standard protocols such as glass electrode pH meter, wet oxidation, semi-micro-Kjeldahl, Olsen, NH_4OAs extraction, and $CaCl_2$ extraction method, respectively (Black et al., 1965a, 1965b).

2.7. Statistical analysis

Statistical analyses were accomplished using IBM SPSS 22.0 for Windows. Data were shown as mean value ± standard deviation (*n* = 3). Significant variation between treatments was evaluated using one-way analysis of variance followed by Duncan's Multiple Range Test, with a *p*-value < 0.05 indicating statistical significance.

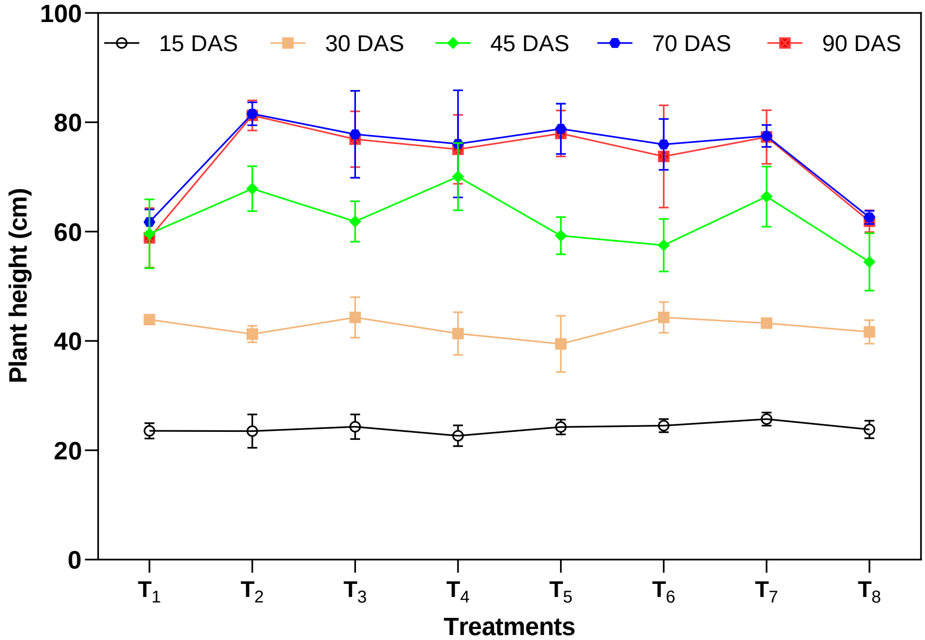

Figure 1. Effect of VC and phosphatic fertilizers on the plant height of soybean at different days after sowing (DAS). Data were shown as the mean value ± SD (*n = 3*).

Table 1. Effect of VC and phosphatic fertilizers on the root length, number of nodules plant^{-1}, fresh weight of nodules plant^{-1}, number of pods plant^{-1}, and number of seed plant^{-1} of soybean.

Treatment	Root length (cm)	No. of nodules plant^{-1}	Fresh wt. of nodules plant^{-1} (g)	No. of pods plant^{-1}	No. of seeds plant^{-1}
T_1	19.03±0.66 bc	8.00±6.50 c	0.26±0.24	34.87±2.30 c	75.33±4.16 c
T_2	19.50±4.30 b	9.67±5.50 bc	0.38±0.20	47.6±1.00 a	101.33±4.75 a
T_3	20.10±3.60 ab	10.67±4.61 ab	0.41±0.16	45.67±6.99 a	107.00±14.22 a
T_4	21.57±0.94 a	12.00±6.35 a	0.45±0.28	35.4±5.11 c	78.33±12.50 c
T_5	16.53±2.57 d	8.33±0.57 c	0.41±0.06	39.47±10.26 b	89.00±21.37 b
T_6	20.70±2.13 ab	9.67±8.08 bc	0.39±0.07	39.73±4.27 b	88.33±7.76 b
T_7	17.53±3.88 cd	8.33±2.00 c	0.36±0.20	35.27±3.63 c	80.33±6.42 bc
T_8	19.17±1.82 bc	9.67±7.37 bc	0.37±0.23	35.6±2.16 c	79.67±3.05 bc
Sx^-	0.6	0.61	0.06	1.15	2.9
LS	**	**	NS	**	**

Notes: NS, **, Sx^-, and LS denote nonsignificant, $p < 0.05$, standard error of mean, and level of significance, respectively. Data were shown as mean value ± SD (*n = 3*). In the column, figures having a similar letter(s) did not differ significantly ($p > 0.05$).

Table 2. Effect of VC and phosphatic fertilizers on the seed yield plant^{-1}, 1000-seed weight, seed yield, and straw yield of soybean.

Treatment	Seed yield plant^{-1} (g)	1000 seed weight (g)	Seed yield (t ha^{-1})	Straw yield (t ha^{-1})
T_1	6.10±0.26 c	80.67±21.73	1.24±0.34 c	1.39±0.32 c
T_2	8.30±0.45 a	99.67±6.64	1.66±0.26 a	1.68±0.21 a
T_3	7.83±1.32 ab	96.00±6.55	1.63±0.26 a	1.59±0.38 b
T_4	6.07±0.64 c	95.00±7.54	1.07±0.06 d	1.22±0.20 d
T_5	6.67±1.18 c	85.67±8.50	1.54±0.26 b	1.45±0.42 c
T_6	6.97±0.85 bc	95.00±5.29	1.52±0.05 b	1.57±0.18 b
T_7	6.50±1.57 c	99.33±12.50	1.50±0.28 b	1.54±0.48 b
T_8	6.80±0.65 c	93.33±17.89	1.50±0.44 b	1.56±0.47 b
Sx^-	0.3	7.42	0.03	0.02
LS	**	NS	**	**

Notes: NS, **, Sx^-, and LS denote nonsignificant, $p < 0.05$, standard error of mean, and level of significance, respectively. Data were shown as mean value ± SD (*n = 3*). In the column, figures having a similar letter(s) did not differ significantly ($p > 0.05$).

3. RESULTS

3.1. Growth and yield of soybean

This study evaluated the impact of VC and phosphatic fertilizers on various growth and yield attributes of soybean. Plant height showed insignificant variation at 15, 30, 45, and 90 DAS ($p > 0.05$), but at 70 DAS, significant differences were observed ($p < 0.01$), with the highest value (81.57 cm) in T_2 (100% RDP from TSP), which was statistically similar to T_3-T_7 (Fig. 1). Root length showed significant variation ($p < 0.01$), with T_4 (100% RDP from VC) showing the maximum (21.57 cm), comparable to T_3 and T_6 (Table 1). According to Table 1, the nodule number plant^{-1} also varied significantly ($p < 0.01$), peaking at 12.00 in T_4, similar to T_3. Nodule weight plant^{-1}**,** however, did not show significant variation among the treatments ($p > 0.05$). For yield components, the pod numbers plant^{-1} showed substantial variation ($p < 0.01$), with T_2 recording the highest (47.60), similar to T_3 (Table 1). The number of seeds plant^{-1} also differed significantly ($p < 0.01$), with T_3 achieving the highest (107.00), comparable to T_2. Seed yield plant^{-1} displayed significant variability ($p < 0.01$), with T_2 (8.30 g) and T_3 (7.8 g) exhibiting the highest yields (Table 2). From Table 2**,** thousand-seed weight did not show significant variation ($p > 0.05$), although T_2 had the highest value (99.67 g). Finally, it was also observed that both seed yield and straw yield (significant variation, $p < 0.01$) were highest in T_2 (1.62 and 1.68 t ha^{-1}, respectively), with T_3 showing a statistically similar seed yield (1.63 t ha^{-1}).

3.2. Phosphorus content and uptake in seed, root, and straw of soybean

P contents in different plant parts of BARI Soybean-5 were significantly affected by the utilization of VC and phosphatic fertilizers (Table 3). The initial soil of the experimental field contained 45.6 ppm available P. After soybean harvest, available P in different treatments of the postharvest soil ranged from 26.60 to 44.49 ppm. Seed P content varied significantly ($p < 0.05$), ranging from 0.61% to 1.27%, with the highest value recorded in the T_2 treatment (100% RDP from TSP) and the lowest in the control (T_1). Similarly, root P content of the different treatments was shown to vary significantly ($p < 0.01$), with the maximum value (0.19%) observed in T_2, closely followed by T_3 (0.18%), while the minimum (0.10%) was again noted in the control (Table 3). P content in straw also varied significantly among treatments ($p < 0.01$), ranging between 0.20% and 0.41%. The significantly highest concentration of P in straw was noted in T_2 (0.41%),

Table 3: Effect of VC and phosphatic fertilizers on P content in seed, root, and straw, and P uptake in seed and straw of soybean.

Treatments	Seed P (%)	Root P(%)	Straw P (%)	Total P uptake in seed and straw (kg ha^{-1})
T_1	0.61±.01 e	0.10±0.01 d	0.20±0.01e	10.49±0.41 f
T_2	1.27±0.02 a	0.19±0.01 a	0.41±0.01 a	28.15±0.87 a
T_3	1.05±0.01 b	0.18±0.01 a	0.40±0.02 ab	23.49±0.32 b
T_4	0.83±0.01 d	0.12±0.02 bc	0.33±0.01 d	13.02±0.28 e
T_5	0.90±0.02 c	0.15±0.01 b	0.38±0.02 abc	19.55±0.53 c
T_6	0.90±0.01 c	0.13±0.01 bc	0.36±0.03 cd	19.49±0.57 c
T_7	0.88±0.01 c	0.13±0.01 bc	0.34±0.02 cd	18.65±0.66 cd
T_8	0.84±0.02 d	0.12±0.01 c	0.32±0.01 d	17.86±0.23 d
$S\bar{x}$	0.04	0.01	0.01	1.08
LS	*	**	**	*

Notes: *, **, $S\bar{x}$, and LS denote $p < 0.01$, $p < 0.05$, standard error of mean, and level of significance, respectively. Data were shown as mean value ± SD ($n = 3$). In the column, figures having a similar letter(s) did not differ significantly ($p > 0.05$).

Table 4. Effect of VC and phosphatic fertilizers on the pH and OC of the post-harvest soil**.**

Treatments	pH	OC (%)
T_1	6.26±0.08	0.67±0.02 c
T_2	6.17±010	0.67±0.01 c
T_3	6.13±0.12	0.66±0.02 c
T_4	6.51±0.05	0.86±0.06 a
T_5	6.30±0.26	0.75±0.03 b
T_6	6.26±0.11	0.73±0.06 bc
T_7	6.35±0.13	0.80±0.03 b
T_8	6.31±0.12	0.78±0.03 b
Initial soil	6.48±0.14	0.70±0.11
$S\bar{x}$	0.03	0.01
LS	NS	**

Notes: NS, **, $S\bar{x}$, and LS denote nonsignificant, $p < 0.05$, standard error of mean, and level of significance, respectively. Data were shown as mean value ± SD ($n = 3$). In the column, figures having a similar letter(s) did not differ significantly ($p > 0.05$).

which was statistically similar to T_3 (0.40%) and T_5 (0.38%). Overall, the findings suggested that 100% RDP derived from TSP, either alone or in combination with VC, effectively enhanced P accumulation in seed and straw compared to the control. The total uptake of P (seed and straw) for different treatments ranged from 10.45 to 28.15 kg ha^{-1} (Table 3). The maximum total uptake of P (28.15 kg ha^{-1}) was documented in T_2, and the minimum total uptake of P (10.45 kg ha^{-1}) was manifested in T_1.

3.3. Chemical properties of post-harvest soil

The application of phosphatic fertilizers with VC had varying impacts on the post-harvest soil chemical characteristics (Table 4 & 5). Soil pH was not significantly affected ($p > 0.05$), with values ranging from 6.13 to 6.51. The highest pH (6.51) was observed in T_4 (100% RDP from VC), while the lowest (6.13) was in T_3 (100% RDP from DAP). The amount of organic C was significantly affected by the various treatments ($p < 0.01$), ranging from 0.66% to 0.86%, with the highest OC observed in T_4 and the lowest in T_3 (Table 5). Although total nitrogen (N) content did not vary significantly across treatments ($p > 0.05$), all treatments improved soil N content compared to the initial value (0.035%), with treatment T_4 showing the highest concentration (0.077%) and the control (T_1) exhibiting the lowest (0.057%). Available P content varied significantly ($p < 0.01$), ranging from 26.60 to 44.49 ppm. The highest value was observed in T_4, statistically comparable to T_3 and T_7, while the lowest was recorded in T_1 (Table 5). Exchangeable K content also showed significant differences ($p < 0.01$), ranging from 0.18 to 0.32 me 100^{-1} g soil, with all treatments increasing K levels compared to the initial value (0.12 me 100^{-1} g soil). The uppermost K content was found in T_4, closely followed by T_7 and T_8 (Table 5). Available S content showed no significant changes ($p > 0.05$), with values ranging from 14.01 to 22.42 ppm. Only T_4 exceeded the initial value, while all other treatments recorded lower S contents, with the lowest in T_8 (Table 5). Overall, T_4 (100% RDP from VC) consistently resulted in the best improvements in soil fertility indicators, highlighting the effectiveness of organic nutrient sources in enhancing soil health.

4. DISCUSSION

The various treatments employed in this study demonstrated a significant outcome on all growth and yield-attributed characteristics of soybean. The highest value of plant height, number of pods plant^{-1}, seed yield plant^{-1}, and seed and straw yield per hectare was documented in T_2. The highest number of seed plant^{-1} (101) was noted in treatment T_3. P contents in seed, root, and straw of BARI soybean-5 were varied significantly, and the treatment T_2 resulted in the maximum P contents in root (0.19%), shoot (0.41%), and seed (1.27%), while the least values were obtained in T_1. The highest P uptake in both seed and straw, together with total uptake (28.15 kg ha^{-1}), was observed in T_2, whereas the lowest uptake (10.49 kg ha^{-1}) was attained from control (T_1). The integration of P nutrition from VC also showed better performance in generating yield contributing components, as well as P content and uptake by soybean, compared to the control treatment. Application of VC as a source of P resulted in a substantial effect on the chemical characteristics of the post-harvest soils. The treatment T_4 (100% RDP from VC) exerted positive improvements of soil OC, total N, available P, exchangeable K and available S contents of the soil with the values 0.86%, 0.077%, 44.49 ppm, 0.32 me 100 g^{-1} soil and 22.42 ppm, respectively which were comparable to the initial soil as well as the sole inorganic fertilizer amended treatments (Fig. 1 and Table 1, 2, 3, 4, & 5).

The study revealed that while plant height showed insignificant variation at early stages, a significant increase was observed at 70 DAS in T_2 treatment, supporting findings by Aritonang and Sidauruk (2020) and Meena et al. (2023). Table 6 shows a positive correlation between plant height at 70 DAS and soybean seed yield plant^{-1} (r = 0.51). Root length was significantly improved by T_4 (100% RDP from VC), aligning with Khanam et al. (2016), indicating that VC enhances root development. The maximum quantity of nodules plant^{-1} was also documented in T_4, possibly due to improved soil conditions from VC, consistent with (Khanam et al., 2016), though nodule weight per plant remained statistically similar across treatments, echoing the conclusions of Aritonang and Sidauruk (2020) and Meena et al. (2023). A positive and statistically significant correlation (r = 0.82, p < 0.01) was identified among the root length of soybean plants and the number of nodules plant^{-1} (Table 6). Soybean needs a proper supply of P for proper growth and nitrogen fixation, and this situation complies with the treatment T_2 that can significantly impact improved growth. The pod number plant^{-1} was noticeably highest in T_2, with VC-amended treatments for 100% RDP showing comparable results, similar to observations elsewhere (Aritonang & Sidauruk, 2020). The quantity of seeds plant^{-1} peaked in T_3 (75% RDP from DAP), corroborating Begum et al. (2015), and seed yield plant^{-1} was also maximized in T_2 and T_3, as inorganic amendments positively influenced yield (Singh et al., 2013). Sufficient P bioavailability from T_2 enhanced uniform ripening and harvest quality, resulting in higher yields compared to treatments with less available P from organic or organic-inorganic sources. This optimized nutrient availability from T_2 also improved chlorophyll content, protein synthesis, and sugar accumulation in soybean plants, supporting robust physiological processes with improved growth performance and higher yields (Begum et al., 2015; Shahid et al., 2024). The weight of a thousand seeds showed no significant variation, consistent with other studies (Begum et al., 2015; Khanam et al., 2016). Finally, the highest seed and straw yields per hectare were obtained from T_2, followed by T_3, highlighting the benefit of both complete inorganic and combined organic-inorganic fertilization strategies, as suggested by other investigators (Begum et al., 2015; Khanam et al., 2016; Tomar et al., 2018). Based on Table 6, the greater number of pods plant^{-1} and seeds plant^{-1} positively influenced the seed yield plant^{-1} (r = 0.95 and r = 0.92, respectively; p < 0.01) and overall soybean seed yield per hectare.

The P content in seed, root, and straw of BARI Soybean-5 was significantly influenced by the addition of VC alone and/or together with phosphatic fertilizers. The highest seed P content (1.27%) was observed in T_2 (100% RDP from TSP), followed by T_3 (100% RDP from DAP) with the value of 1.05%, indicating the greater availability of P in soil from inorganic sources. While P is essential for soybean growth and yield, excessive application can be detrimental. However, the optimal rate in T_2 achieves a proper balance among the nutrient ions, thereby enhancing the efficiency of plants in absorbing nutrients from the soil and higher contents of P in the plants. Treatments combining VC with TSP or DAP also showed improved seed P content compared to sole VC application as a P source. Root P content was generally lower than in seeds and straw, but treatments with VC and reduced mineral P doses enhanced root P content over the control.

Table 5. Effect of VC and phosphatic fertilizers on total N, available P, exchangeable K, and available S in the post-harvest soils.

Treatments	Total N (%)	Available P (ppm)	Exchangeable K (m.e. 100^{-1} g soil)	Available S (ppm)
T_1	0.057±0.01	26.60±3.06 d	0.18±0.02 e	14.01±1.66
T_2	0.068±0.01	36.77±3.69 bc	0.23±0.01 cd	17.01±1.39
T_3	0.066±0.01	40.02±2.12 ab	0.21±0.01 de	15.01±1.02
T_4	0.077±0.01	44.49±3.72 a	0.32±0.01 a	22.42±1.31
T_5	0.071±0.01	35.41±5.99 bc	0.24±0.02 cd	18.54±13.87
T_6	0.069±0.01	32.48±2.53 c	0.27±0.03 bc	17.43±2.57
T_7	0.071±0.01	38.83±1.35 ab	0.29±0.02 ab	19.19±2.65
T_8	0.072±0.01	36.21±0.46 bc	0.29±0.01 ab	19.05±1.40
Initial soil	0.035±0.01	45.61±2.5	0.012±0.02	22.4±1.82
Sx$^-$	0.01	1.17	0.01	1.03
LS	NS	**	**	NS

Notes: NS, **, Sx$^-$, and LS denote nonsignificant, p < 0.05, standard error of mean, and level of significance, respectively. Data were shown as mean value ± SD (n = 3). In the column, figures having a similar letter(s) did not differ significantly (p > 0.05).

Table 6. Pearson's correlation matrix between different parameters.

Parameters	Plant height	No. of pods plant^{-1}	No. of seeds plant^{-1}	Seed yield plant^{-1}	Seed yield (t ha^{-1})	Straw yield (t ha^{-1})	Seed P (%)	Straw P (%)	Total P uptake (kg ha^{-1})	OC in soil	Total N in soil
Plant height	1										
No. of pods plant^{-1}	0.62	1									
No. of seeds plant^{-1}	0.64	0.97**	1								
Seed yield plant^{-1} (g)	0.50	0.95**	0.92**	1							
Seed yield (t ha^{-1})	0.39	0.71	0.74*	0.81*	1						
Straw yield (t ha^{-1})	0.24	0.66	0.64	0.82*	0.94**	1					
Seed P (%)	0.74*	0.89**	0.84**	0.91**	0.70	0.67	1				
Straw P (%)	0.83*	0.72*	0.77*	0.72*	0.67	0.52	0.87**	1			
Total P uptake (kg ha^{-1})	0.67	0.89**	0.87**	0.95**	0.88**	0.83*	0.96**	0.86**	1		
OC in soil	0.01	-0.66	-0.61	-0.63	-0.56	-0.61	-0.32	-0.04	-0.44	1	
Total N in soil	0.44	-0.09	-0.05	-0.06	-0.09	-0.19	0.28	0.55	0.16	0.78*	1

Notes: Correlation significance is indicated by '*' and '**' at the 0.05 and 0.01 levels, respectively.

Similarly, straw P content was highest in T_2, T_3, and T_5, while the lowest was found in control and treatments with sole VC or reduced mineral P (Table 3). These results confirm that integrating VC with phosphatic fertilizers improves P uptake and distribution in soybean, consistent with previous findings by Tomar et al. (2018). According to Table 6, P content in seed and straw exhibited a positive and significant association with the total P uptake by soybean (r = 0.96 and r = 0.87, respectively; p < 0.05). The application of supplemented P from VC, along with reduced recommended doses of phosphatic fertilizers, improved total P uptake by soybean seed and straw compared to sole VC application and the control. This improvement might have resulted from the better accessibility of P due to the interaction between VC and phosphatic fertilizers, as supported by Sikka et al. (2013), Savita and Girijesh (2019), (Singh et al., 2013), and Rachna and Badiyala (2001). Also, this synergistic effect is likely attributed to the capacity of VC to enhance soil microbial activity and organic matter content, which in turn improves the solubility and plant availability of P from applied fertilizers (Verma et al., 2014).

The observed improvement in soil properties following the application of VC and phosphatic fertilizers can be explained by the interaction between organic and inorganic nutrient sources. The slight increase in soil pH in the 100% VC treatment (T_4) is likely due to the buffering effect of organic acids released during VC decomposition, which helps neutralize soil acidity. This contrasts with the lower pH in T_3 (100% DAP), where chemical fertilizers contributed to acidification, as commonly reported (Rosolem et al., 2022). VC application has been shown to increase soil pH and the activity of crucial enzymes like urease, phosphatase, and catalase, which are indicative of enhanced microbial activity and nutrient cycling (Tian et al., 2024). The significant rise in organic carbon in VC-amended treatments is directly linked to the input of organic matter from VC, which enhances microbial biomass and soil structure, thereby increasing carbon accumulation in soil (Rosolem et al., 2022; Syamsiyah et al., 2023). This organic matter also aids in nitrogen retention and mineralization, contributing to the improved total N content seen across the treatments, especially in T_4. In Table 6, a notable and significant positive relationship was noted between soil OC and total N in post-harvest soils (r = 78, p < 0.05). The increase in N content may also result from the addition of soybean residues (fallen leaves) during later growth stages. Similar positive effects of VC and phosphatic fertilizers on soil N have been reported by Verma et al. (2014). The higher availability of P in post-harvest soils under VC amended treatments is connected to enhanced activities of microbes and the release of organic acids, which solubilize fixed soil P, making it plant-available (Muktamar et al., 2020; Rosolem et al., 2022). The same mechanism explains the improved P levels in combined VC and fertilizer treatments ($T_{5\text{-}8}$). The increase in exchangeable K in VC-applied treatments is due to the mineralization of organic inputs and the better nutrient-holding capacity of soils with higher organic matter content. This aligns with the results of Xiang et al. (2012), who claimed improved K availability following VC and integrated nutrient application. Although the available S content did not change significantly, the slightly higher value in T_4 suggests that VC may contribute some S addition to the soil. However, the lower S in other treatments indicates possible losses through leaching or insufficient retention in the absence of stable organic matter. This trend did not consistent with Xiang et al. (2012), who had previously reported more consistent improvements in S content with organic inputs.

5. CONCLUSION

The different treatments in this study significantly affected soybean seed yields, P contents, and uptake. The utilization of 100% RDP from TSP (T_2) led to higher seed yields, P content, and uptake in plant tissues of soybean. Omitting inorganic P via sole VC application (T_4) or no P availability in the control (T_1) treatment decreased seed and straw yields, in addition to P content and accumulation in plant tissues. The treatment T_4 (100% RDP from VC) showed better performance with respect to post-harvest fertility status. In VC-amended treatments, especially T_5, T_6, T_7, and T_8 (integrating 25-50% RDP from VC with 50-75% RDP from TSP/DAP), BARI soybean-5 produced comparatively less yield than the sole application of 100% RDP from TSP/DAP-treated treatments; but these treatments positively improved soil health for the next crops. Overall, this experiment suggests that BARI soybean-5 can be cultivated in the studied soil using 100% RDP from inorganic TSP/DAP along with other inorganic nutrients (T_2) if short-term profitability is the main goal. However, the treatments T_4, T_5, T_6, T_7, and T_8 should not be overlooked when considering sustainable and long-term soil health.

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Declaration of Competing Interest

The authors declare that no competing financial or personal interests may appear to influence the work reported in this paper.

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