frontiers | Frontiers in Agronomy

TYPE Systematic Review
PUBLISHED 06 August 2024
DOI 10.3389/fagro.2024.1422876

OPEN ACCESS

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RECEIVED 24 April 2024
ACCEPTED 17 July 2024
PUBLISHED 06 August 2024

CITATION
Sande TJ, Tindwa HJ, Alovisi AMT, Shitindi MJ and Semoka JM (2024) Enhancing sustainable crop production through integrated nutrient management: a focus on vermicompost, bio-enriched rock phosphate, and inorganic fertilisers – a systematic review.
Front. Agron. 6:1422876.
doi: 10.3389/fagro.2024.1422876

Enhancing sustainable crop production through integrated nutrient management: a focus on vermicompost, bio-enriched rock phosphate, and inorganic fertilisers – a systematic review

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Securing a consistent food supply remains a pressing global challenge, particularly for small-scale farmers grappling with obstacles in enhancing agricultural yields, especially in tropical soils. Integrated Nutrient Management (INM) techniques, employing organic manures like vermicompost and bio-enriched rock phosphate, emerge as recommended solutions. Vermicompost is lauded for its nutrient richness and positive soil health impacts. At the same time, bio-enriched rock phosphate serves as a sustainable alternative to conventional phosphorus fertilisers, specifically tailored for tropical soil conditions. Despite individual studies assessing the effects of vermicompost, bio-enriched rock phosphate, and soluble fertilisers on plant growth, a comprehensive overview of their combined application is noticeably lacking. To fill this gap, this study employs the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) method to explore the synergies of combining these elements and their impacts on crop production and the environment. This review is among the first to comprehensively summarize the complexities of combining vermicompost, bio-enriched rock phosphate, and chemical fertilisers on various crops. It thoroughly examines potential advantages, disadvantages, effects on agricultural systems, socio-economic implications, and existing policies governing their usage. Our findings reveal that the combined application of vermicompost, bio-enriched rock phosphate, and soluble fertilisers leads to significant improvements in plant growth, yield, and soil properties. The optimal impact is observed when vermicompost constitutes 25% and soluble fertiliser comprises 75 or 100% of the recommended fertiliser dosage. Moreover, incorporating a mixture of phosphate-solubilizing bacteria (PSB) strains in rock phosphate further enhances its positive effects. Despite these positive findings, we identified gaps in comprehensive approaches addressing socio-cultural dimensions and the lack of literature on prevailing policies regarding vermicompost use in agricultural systems highlighting the need for a more holistic understanding of vermicompost incorporation and a better grasp of the institutional frameworks guiding these practices. However, to secure sustainable crop production, farmers need to integrate vermicompost and biofertilisers with chemical fertilisers. In fostering the adoption of sustainable and inclusive agricultural practices on small rural properties, it is advisable to incorporate agricultural education into farmer training programs.

KEYWORDS

sustainable agriculture, organic manures, mineral fertilizers, crop yield, soil health

1 Introduction

Food security remains a critical global concern, particularly for smallholder farmers facing numerous challenges in increasing crop output. To address these issues, contemporary agricultural practices incorporate Integrated Nutrient Management (INM) techniques, emphasizing the importance of balancing soil nutrient supply, crop absorption, yield quality, and soil health (Shabani et al., 2015; Leoni et al., 2019). As agricultural technology advances, there's a concerning trend of neglecting natural supplements (Mondal et al., 2017) in favor of synthetic options, leading to diminished soil fertility and reduced crop quantity and quality (Mondal et al., 2017).

The excessive and indiscriminate use of chemical fertilisers poses significant challenges to soil health (Ahmed et al., 2022), water quality, and the environment (Yu et al., 2014). To achieve sustainable crop production, alternative strategies must be explored. Judicious use of organic manures, such as vermicompost and bio-enriched RP, has garnered attention (Wahid et al., 2020) due to their consistent positive effects on various crops (Parween et al., 2019; Mazylyte et al., 2022). These organic amendments offer benefits such as increased nutrient availability, improved soil structure, aeration, water holding capacity, and enhanced microbial populations (Pezeshkpour et al., 2014; Desai et al., 2019; Ahmed et al., 2022), contributing to a healthier nutrient cycle and improved plant growth and yield (Gaddi et al., 2020). Vermicompost, produced through the symbiotic interaction between earthworms and microorganisms, outperforms conventional compost.

Phosphorus is crucial for plant development, with natural RP serving as a source, but its low solubility limits plant access. (Biswas and Shivaprakash, 2020; Munda et al., 2016; Venu et al., 2023). To overcome this limitation, phosphate-solubilizing microorganisms (PSM) are introduced in bio-enrichment procedures (Venu et al., 2023), transforming phosphorus into a more usable form. Alternatively, RP can be added to the vermicomposting process, enhancing plant nutrition, and elevating agricultural yields (Tahir et al., 2018; Babulu et al., 2022). Bio-enriched RP emerges as a sustainable alternative to traditional phosphorus fertilisers (Ditta et al., 2018), mitigating negative environmental effects, particularly in tropical soils characterized by high phosphate sorption, low soil organic matter, low pH, nutrient imbalances, and diminishing agricultural production and quality (Giro et al., 2015).

While the efficacy of organic amendments in addressing nutrient deficiencies, improving soil health, and boosting crop output in African tropical soils is undisputed (Ajibade et al., 2022), concerns arise regarding the biological and chemical characteristics of the soil and the application efficacy of bio-enriched RP (Boubekri et al., 2023) drawing attention to the need for careful consideration of specific soil conditions, pH ranges, organic phosphorus levels, and the types of phosphate-solubilizing microorganisms (PSMs), emphasizing that the performance of PSMs from bio-enriched RP products may be less effective under unfavorable conditions. Vermicompost and bio-enriched RP emerge as pivotal techniques for sustainable agriculture (Ditta et al., 2018; Changkiri et al., 2023), not only due to their impact on plant growth but also for their role in enhancing the biological and physical qualities of the soil (Zhang et al., 2023). The combination of inorganic fertilisers with organic manures such as vermicompost and bio-enriched RP presents a holistic approach to sustainable agricultural production, addressing a spectrum of nutrient deficiencies and contributing to increased crop yields (Ahmed et al., 2022).

Research has demonstrated the positive impacts of vermicompost and bio-enriched RP on diverse crops such as soybean, rice, potato, and beans (Desai et al., 2019; Ghosh et al., 2020b; Lallawmkima et al., 2018; Rady et al., 2020; Hoque et al., 2022). These impacts manifest in increased yields and improved plant health, whether applied independently or as part of integrated nutrient management strategies. Yet, despite these promising findings, the combined effects of employing these amendments on various crops remain largely unexplored. By minimizing environmental impacts, especially in the context of tropical soils, bio-enriched RP, and vermicompost present themselves as sustainable alternatives to traditional inorganic fertilisers (Holeckova et al., 2018).

The study systematically examines the effects of vermicompost, bio-enriched RP, and synthetic fertiliser application methods on crop yield, offering a pragmatic and cost-efficient choice for resource-constrained farmers. In addition to exploring their impacts on soil health and socio-economic implications, the research extends to the existing policies governing vermicompost. This multifaceted approach seeks to furnish precise information on the management practices associated with these organic amendments, thereby fostering improved agricultural outcomes and productivity. The conceptual framework that serves as the guiding structure for this study is visually represented (see Figure 1), delineating the intricate relationship between law enforcement and the utilization of organic and inorganic fertilisers.

The combined application of these inputs yields a synergistic effect, reinforcing the soil's physical, chemical, and biological properties. This comprehensive approach fosters robust crop growth and higher yields, illustrating the interconnectedness of these elements in optimizing agricultural outcomes. Each component, whether applied individually or in combination, carries implications for crop performance, soil health, social economics, and the overarching sustainability of the agricultural system. This intricate web of relationships underscores the need for a holistic understanding of the multifaceted factors influencing fertiliser practices within the agricultural landscape. The thought process encapsulated in this logical framework enabled us to establish key terms, and delineating the study's boundaries, however, it is noteworthy that the socio-economic factors related to the utilization of bio-enriched rock and chemical fertilisers were not explicitly discussed.

2 Methods deployed in literature research

To improve food security on small farms as part of a broader strategy for sustainable crop production, this article uses the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) method to explore the best agronomically and environmentally viable options for applying vermicompost, bio-enriched rock phosphate (RP), and inorganic fertilisers (NPK) in agriculture (Caione et al., 2018; Page et al., 2021). The PRISMA technique makes sure that the literature is adequately covered and offers checklists of crucial topics to address (see Figure 2) (Page et al., 2021).

To find out pertinent publications that fit the study's scope, data was gathered on vermicompost, rock-phosphate, PSB, and NPK on crop production from five (05) sources, including Web of Science, Science Direct, Research Gate, Google Scholar, and Pubmed Central. The search terms "Vermicompost", "Rock-phosphate" AND, "Phosphate solubilizing bacteria" on "crop production" were combined and used to search in "title", "abstract", and "keywords" of the articles to retrieve a substantial amount of research from the databases. Research articles authored in English, Spanish, and Portuguese were found in the database, covering a period from 2013 to 2023. The search performed resulted in 1075 papers published being Web of Science 837 articles, Science Direct 92 articles, Research Gate 11 articles, Google Scholar 111 articles, and Pubmed Central 67 articles. Papers were reviewed, and duplicates were ignored, to preserve the honest evaluation process. A focus on the search keyword was examined, along with appropriate experimental design and statistical analysis, in the titles, abstracts, and conclusions of the included publications.

The findings from these sources have been arranged and presented in subchapters that discuss how the use of these additives in agriculture affects crop growth, soil health, agricultural productivity, and the environment. These subchapters highlight the importance of these factors in determining the widespread adoption of these additives by mainstream producers as well as the effectiveness of their use. Vermicompost, bio-enriched RP, phosphate-solubilizing bacteria, and inorganic fertilisers (e.g., NPK) were considered concerning the combined application of at least one of these substances when examining their effects on crop production and soil health.

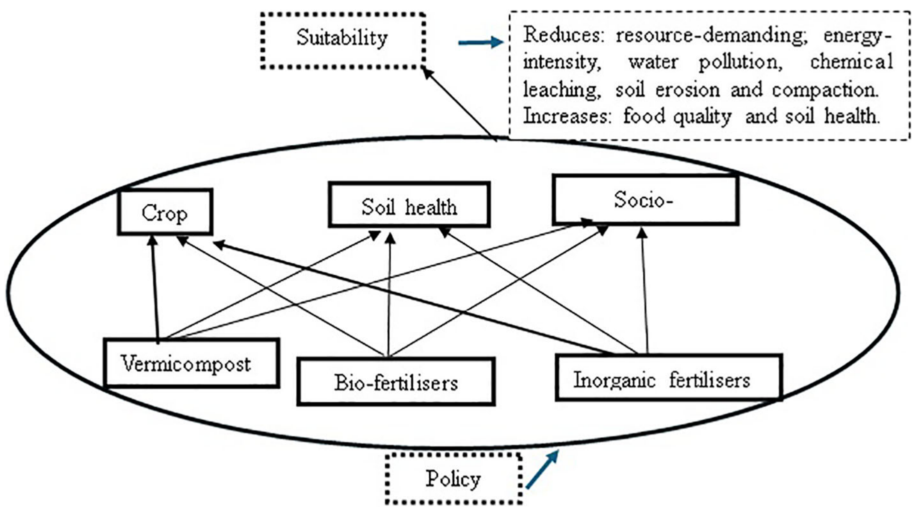

FIGURE 1
The intricate network of relationships between vermicompost, bio-enriched RP, and inorganic fertilisers for agricultural outcomes optimization.

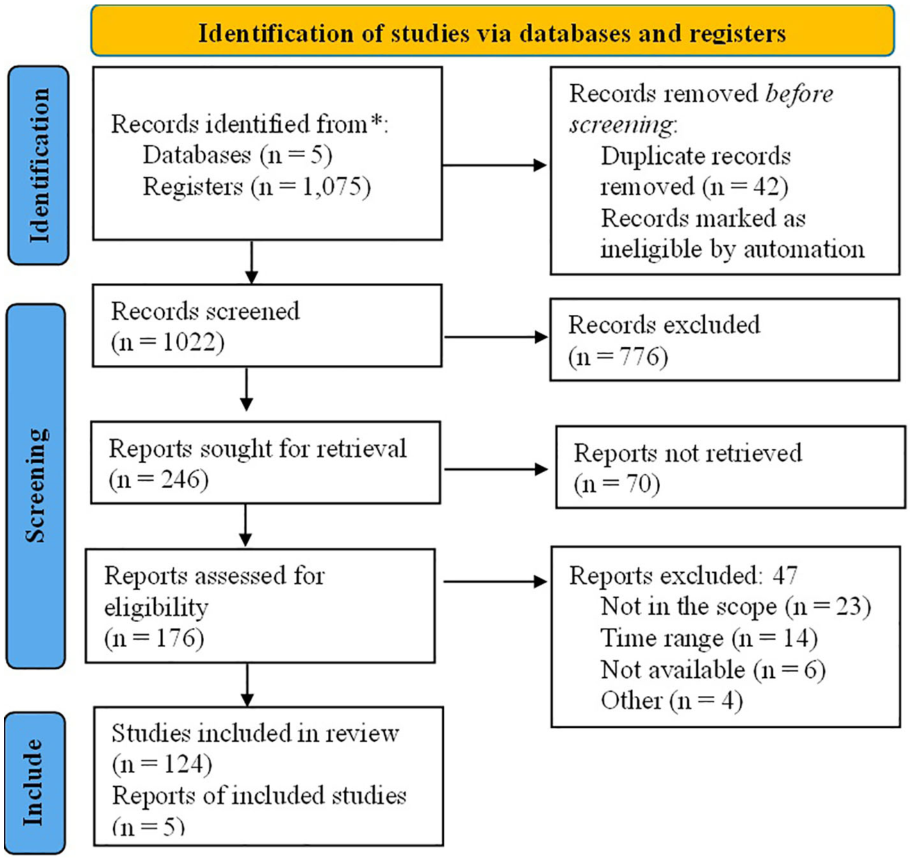

FIGURE 2
The PRISMA flow chart deployed in the review.

3 Findings of the review

The findings of the review are presented and discussed under Section 3.1. The socio-economic implications and existing policies regarding the use of vermicompost are presented and discussed under Sections 3.2 and 3.3.

3.1 Effect of combined application of vermicompost on crop performance and biochemical Attributes

3.1.1 Vermicompost production process

Vermicompost, or worm castings, is a nutrient-rich organic fertiliser produced through the process of vermicomposting, which involves the decomposition of organic materials by earthworms and microorganisms mostly found in the worms' guts and released in the casts (Jha et al., 2021; Vyas et al., 2022). The production process of vermicompost typically involves the selection of earthworm species and organic materials like kitchen scraps yard waste, livestock manure, shredded paper, and cardboard (Atteya et al., 2021), which are chopped into small pieces to facilitate decomposition (Aslam et al., 2019). Earthworm species and organic matter are placed in vermicomposting bins with appropriate drainage to prevent waterlogging and allow excess moisture to escape (see Figure 3). Before adding the worms, bedding materials such as shredded newspaper, cardboard, or coconut coir, moistened to a sponge-like consistency, are added to create a favorable habitat (Kaur, 2020). After that, worms and organic waste are introduced. Although microorganisms play a key role in biochemically breaking down organic waste (Keniya et al., 2023), earthworms are the catalysts for this process, as they condition the substrate through their systems digestion and conversion of complex organic compounds into simpler ones, releasing nutrients along the way. They also change the microorganism's biological activity by aerating the substrate as they burrow through it, creating an environment that encourages microbial growth and activity (Vyas et al., 2022). During vermicomposting, earthworms and mesophilic microorganisms work together to break down organic matter (Rehman et al., 2023), resulting in the production of vermicompost enriched with various enzymes such as lipase, amylase, cellulase, chitinase (Aslam et al., 2019; Oyege and Balaji Bhaskar, 2023) and plant growth hormones, such as auxins, cytokinin, gibberellic acid which further accelerates the decomposition process (Huang and Xia, 2018). As the decomposition process progresses, the substrate's levels of potassium, phosphorus, and nitrogen gradually increase (Aslam et al., 2019; Haiba et al., 2014). Several factors contribute to this enhancement. First, the decay of dead worm tissue releases nutrients (Robatjazi, 2023), while the continual secretion of

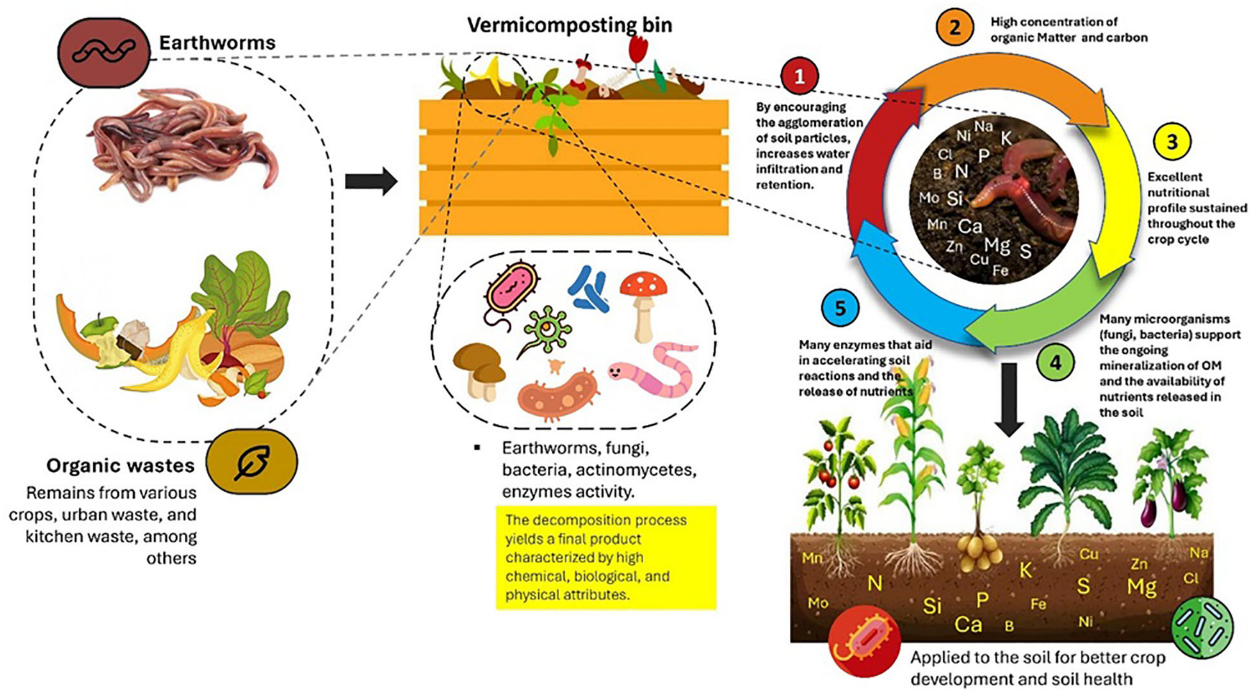

FIGURE 3
Vermicomposting production process and their effects on crop growth, soil health and environment.

nitrogen-rich mucus by earthworms supports microbial growth and nitrogen mineralization within the earthworm gut (Anbazhagan et al., 2024). Additionally, phosphorus mineralization during vermicomposting results in higher levels of accessible phosphorus in the finished vermicompost. This occurs due to the action of phosphatases and phosphorus-solubilizing bacteria within the earthworm's digestive system (Keniya et al., 2023). Similarly, the combined effects of enzymatic activity and mechanical grinding as the substrate moves through the worm's intestine further boost the available potassium in the resulting vermicompost (Aslam et al., 2019; Oyege and Balaji Bhaskar, 2023). To ensure a successful vermicomposting process, it's important to maintain ideal conditions for the earthworms. This involves checking moisture levels and pH, maintaining a temperature range of 18-26°C, and regularly turning or mixing the compost to ensure adequate aeration (Kaur, 2020). Managing these variables encourages effective organic matter decomposition and guarantees the production of high-quality vermicompost.

The nutrient composition of vermicompost varies based on source materials and the vermicomposting process intricacies (see Table 1) (Hoque et al., 2022), but generally it contains essential plant (nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur) (Bekele et al., 2022). Trace amounts of micronutrients including iron, manganese, zinc, copper, and boron are also present (Atteya et al., 2021). Aside from adding beneficial microorganisms and nutrients into the soil, vermicompost contributes to maintain a low carbon-to-nitrogen ratio (Anbazhagan et al., 2024), enhance soil structure by loosening compacted material, and allows better air and water penetration in the soil (Pezeshkpour et al., 2014; Qasim et al., 2018). It also improves soil porosity and water-holding capacity (Rajkhowa et al., 2017; Rehman et al., 2023), overall leading to improved moisture retention, which is crucial for plant growth. These combined benefits positively impact crop yield and quality, making vermicompost a valuable amendment for organic gardening, farming, and landscaping (Aslam et al., 2019).

3.1.2 Effect of combined application of vermicompost and chemical fertilizer on crop yield

Soil, being a finite resource, demands prudent conservation and sustainable management. Intensive chemical fertiliser use, and organic waste neglect degrade soil health, compromising agricultural sustainability (Sangeeth, 2016; Koireng et al., 2022; Raj et al., 2022). Employing organic fertilisers can ameliorate these issues by enhancing soil composition and reducing pollution (Khodaei-Joghan et al., 2018; Bezabeh et al., 2021; Sefaoglu et al., 2021), as well as lessening reliance on inorganic fertilisers (Safari et al., 2020; Sefaoglu et al., 2021; Uddin and Jeong, 2021). Studies advocate for an integrated approach combining chemical and organic fertilisers for sustainable agriculture (Ahmed et al., 2022; Esmaeilian et al., 2022; Kumar and Dubey, 2020), emphasizing the need to optimize nutrient sources for each production system (Bezabeh et al., 2021; Changkiri et al., 2023).

In crops such as rice, cowpea, wheat, pepper, tomato, lentil, and sunflower, a significant increase in production is observed when vermicompost is combined with inorganic fertiliser, compared to the use of only inorganic fertilisers, as indicated by 17 reviewed studies (see Table 2). These studies analyzed the yield differences (Kumar and Pandita, 2016; Rajkhowa et al., 2017; Qasim et al., 2018;

TABLE 1 Some studies reporting different physic-chemical characteristics of Vermicompost.

VC substrate	pH	EC (mS cm^{-1})	Moisture (%)	OC (%)	OM (%)	TN (%)	AvP (%)	AvK (%)	References
–	–	–	20	23.9	–	1.01	0.29	0.79	(Mukherjee et al., 2019)
Cow dung,	8.0	5.95	–	–	2.37	0.30	0.001	0.034	(Aslam et al., 2019)
Paper waste,	8.0	6.12	–	–	2.58	0.24	0.023	0.142	(Aslam et al., 2019)
Rice straw	7.9	2.98	–	–	2.30	0.07	0.006	0.012	(Aslam et al., 2019)
–	7.2	1.78	–	44.57	–	1.82	0.46	0.19	Atteya et al. (2021)
	–	–	68.0	34.0	–	1.68	0.41	1.3	(Hoque et al., 2022)
Cow manure	8.31	–	–	30.75	–	2.15	0.048	0.22	(Zhang et al., 2023)
Fish silage	–	–	–	–	–	1.38	0.37	0.9	(Tanuja et al., 2019)
–	–	–	–	–	–	1.1	0.15	0.26	(Tanuja et al., 2019)
Cow manure	7.74	3.56	–	18.13	–	1.85	0.68	0.93	(Qasim et al., 2023)
–	8.07	4.26	–	16.70	–	1.75	0.81	0.83	(Qasim et al., 2023)
Rice straw	7.09	2.61	–	–		0.99	0.62	0.26	(Ahmad et al., 2022)
Rice straw and microbial strains	6.51	2.56	–	–		1.25	0.92	0.94	(Ahmad et al., 2022)
Cow dung sheep and goat manures	7.5	5.2	–	14.3	–	1.95	0.53	1.0	(Bekele et al., 2018)

EC, electrical conductivity; OC, Organic carbon; OM, Organic matter; TN, Total Nitrogen; AvP, available phosphorus; AvK, available potassium; TP (%), total phodphorus; TK (%), total potassium; VCs, fish silage enriched vermicompost.

Aslam et al., 2019; Tanuja et al., 2019; Ghosh et al., 2020b; Rani et al., 2020; Atteya et al., 2021; Sefaoglu et al., 2021; Ghosh et al., 2022; Hoque et al., 2022; Koireng et al., 2022; Patra et al., 2022; Gonzalez-Cortes et al., 2023; Kumar et al., 2023; Zhang et al., 2023), highlighting the importance of integrated nutrient management strategies for enhancing crop productivity and sustainability. Bezabeh et al. (2021) reported that, in treatments applying vermicompost at 7 t ha^{-1} rate combined with 100 kg ha^{-1} of diammonium phosphate (DAP) (as 50% of RDN each), applied at sowing, yielded approximately 3.40 t ha^{-1}, statistically at par to mineral fertilizers yielding 3.81 t ha^{-1} on faba bean. Similar additions of vermicompost led to higher residual nitrogen (3.6 g kg^{-1}), number of nodules per plant (368), and uptake of nitrogen (102 kg ha^{-1}), phosphorus (3.6 kg ha^{-1}), and sulfur (19.5 kg ha^{-1}) into straw compared to mineral fertilizer, which showed lower uptake and lower residual nitrogen (3.3 g kg^{-1}), number of nodules per plant (337).

Similarly, under saline conditions, Rani et al. (2020), noted a significant improvement in the yield of pearl millet (3.54 t ha^{-1}) and wheat (4.98 t ha^{-1}) with the integrated application of vermicompost (VC) at the rate of 2.5 t ha^{-1}, 100% recommended dose of mineral fertilizer (RDF NP) at 150 and 60 kg ha^{-1}, and microbial inoculants (Azotobacter, Azospirillum, and PSB), compared to untreated control (1.71 t ha^{-1} and 2.03 t ha^{-1}) and RDF treatments (3.12 t ha^{-1} and 4.44 t ha^{-1}), respectively. The higher yield was attributed to a decrease in soil EC by 18.5% and pH by 1.2%, an increase in organic carbon by 0.31%, and a marked improvement in the availability of nitrogen, phosphorus, potassium, calcium, and magnesium in the soil, along with a reduction in sodium content in the integrated application treatment. Additionally, Atteya et al. (2021), investigated the impact of vermicompost and NPK fertilizers on Moringa oleifera seed and fixed oil production in calcareous soil conditions. They found that increasing the application rate of vermicompost (from 10 to 20 t ha^{-1}) in conjunction with 100% NPK fertilization significantly enhanced all parameters measured, resulting in higher yields of pods (4356 kg ha^{-1}), seeds (1588 kg ha^{-1}), and fixed oil (53.6 ml plant^{-1}) compared to the control, which yielded 256 kg ha^{-1} of pods, 10 kg ha^{-1} of seeds, and 0.4 ml plant^{-1} of fixed oil. Similar findings were also reported by Sefaoglu et al. (2021), who observed the highest sunflower seed yield (4854 kg ha^{-1}) and oil yield (2114 kg ha^{-1}) with the combination of 100 kg ha^{-1} of inorganic nitrogen (100% RDN) and 1.5 t ha^{-1} of vermicompost. In general, results of all the reported experiments show that the yields are 12% - 140% higher when vermicompost is combined with chemical fertiliser than when 100% of mineral recommended dose fertilizer (RDF) is applied alone. The increase in crop yield is largely due to the natural growth hormones present in vermicompost, which help regulate plant growth, improve soil pH, and increase the availability and uptake of nutrients by the roots. This increase was observed both when vermicompost was applied along with 100% of the mineral RDF, and when it was combined with 50% of the nitrogen requirement from vermicompost. In other studiedies, Ghosh et al., 2020b and Patra et al. (2022) documented yield increases of 13.8% and 24% in maize and ginger, respectively, when vermicompost was applied before planting. Further research by Tanuja et al. (2019); Atteya et al. (2021)), and

Zhang et al. (2023) on moringa, cowpea, and pepper reported yields increases of 14.8%, 188%, and 15.5%, respectively, with vermicompost applied 10 days before planting.

Similarly, Aslam et al. (2019) evaluated the efficiency of vermicompost (10 t ha-^{1}) derived from different biowastes on wheat plant growth and soil health. They found that applying 100% RDF N:P:K (100:50:50 kg ha^{-1}) along with 10 t ha^{-1} cow dung vermicompost, with a full dose of P and K and one-third of urea at sowing, followed by the remaining urea at critical growth stages (tillering and spikelet initiation), resulted in the maximum grain yield (5.37 t ha^{-1}) and harvest index (41.32%) which was 11.64% and 1.16% higher over the control (100% RDF). This was followed by the treatment where 100% mineral RDF N:P:K (100:50:50 kg ha^{-1}) and 10 t ha^{-1} paper waste vermicompost were applied. In contrast, the lowest grain yield (3.22 t ha^{-1}) and harvest index (26.67%) were observed with 50% mineral RDF N:P:K (50:25:25 kg ha^{-1}) and 10 t ha^{-1} paper waste vermicompost. Amanullah and Khan (2015) investigated the effects of inorganic phosphorus levels, compost application timing (2 t ha^{-1}), and phosphate-solubilizing bacteria (PSB) as seed inoculation on maize yields. Their study revealed significantly higher maize yields (up to 5.9% and 2.5%) when vermicompost was applied at sowing time compared to applications 30 and 15 days before sowing, respectively. Similarly, Kumar et al. (2023) observed a 50.4% higher lentil yield over the control when 50% RDN was applied with vermicompost (1 t ha^{-1}) as basal in the semi-arid region of northern India. Other studies reveal that, combining vermicompost in a rate between 1 t ha^{-1} to 2.5 t ha^{-1} with lime (4 t ha^{-1}), and 75% mineral NPK enhances nitrogen availability by 45% and 18,8% in nutrient-deficient soils, leading to improved plant growth throughout the cycle (Bekele et al., 2018; Rani et al., 2020), while the gradual mineralization of organic matter and staggered chemical fertiliser applications further boost nutrient availability, resulting in higher yields, enhanced soil quality, and increased productivity (Ghosh et al., 2022; Hoque et al., 2022; Koireng et al., 2022; Kumar and Pandita, 2016; Kumar et al., 2023; Thakur et al., 2023).

The inconsistent results observed in these studies indicate that the effectiveness of vermicompost when combined with chemical fertilizers can vary widely based on several factors. These factors include crop type, soil conditions, nutrient content in the vermicompost (Ghosh et al., 2020a; Hoque et al., 2022), the amount, source, and type of both vermicompost and chemical fertilizers (Kumar and Pandita, 2016; Tanuja et al., 2019; Atteya et al., 2021; Gonzalez-Cortes et al., 2023; Zhang et al., 2023), the timing and method of application, and overall management practices. This variability suggests that there is no universal formula for using vermicompost in conjunction with chemical fertilizers, and growers need to tailor their fertilization strategies to their specific circumstances. Applying vermicompost at rates ranging from 1 t ha^{-1} to 10 t ha^{-1} combined with reduced doses of chemical fertilizers (25% to 50%) has been shown to be effective in reducing reliance on synthetic inputs. Optimal results require precise combinations of vermicompost and inorganic fertilizers, based on the vermicompost's nitrogen content and the crop's specific nutritional needs. Chemical yields are observed when chemical fertilizers are applied with vermicompost at sowing, due to the immediate availability of nutrients provided by both sources. Alternatively, applying vermicompost 10 to 15 days before planting allows for mineralization of the organic matter, gradually releasing nutrients throughout the crop growth stage. Using methods such as broadcasting, banding, or incorporation into the soil can help optimize nutrient availability.

Gradually mineralizing organic manures, splitting chemical fertilizer applications and intercropping is an effective strategy to boost nutrient availability during critical crop growth stages, leading to higher grain yields. Studies by Koireng et al. (2022) on intercropping oats with chickpeas demonstrated that combining 50% of the recommended dose of nitrogen (RDN) with 50% nitrogen from vermicompost resulted in the highest chickpea grain yield (5.22%) and the highest harvest index (4.26%) over three consecutive growing seasons, outperforming the full RDF application of inorganic NPK fertilizers. Similarly, the combined application of 100% mineral fertilizers NPK, with urea applied in three split doses as a top-dressing fertilizer, and vermicompost (10 t ha^{-1}) significantly increased rice grain yield by 25% and the harvest index by 9.36%, compared to the control treatment (Hoque et al., 2022). Kumar and Pandita (2016)'s research further supports these findings, showing that the integrated use of 75% RD NPK mineral fertilizers and vermicompost (2.5 t ha^{-1}) was the most effective combination over two years of experimentation, resulting in higher seed yield (43% and 49%), germination rates (6.0% and 8.5%), and vigor index I (25% and 9.36%) compared to the control (100% RDF) in cowpea. Thakur et al. (2023)'s research further supported these findings, showing that an integrated combination of 75% NP fertilizers, vermicompost (VC), and enriched compost (EC) at 2.5 t/ha, along with plant growth-promoting rhizobacteria (PGPR) reduced NP fertilizer use by 25% while improving growth and yield by 29.3%, 39.3%, and 31.1%, respectively. This approach also resulted in higher annual net returns (17.5%) compared to the control (100% mineral fertilizer + FYM) in a cabbage, capsicum, and radish cropping sequence. Kumar et al. (2023) demonstrated that lentils could be successfully cultivated by substituting 50% of the recommended dose of nitrogen (RDN) with vermicompost. The treatment combining 50% RDN, 100% RDP, and vermicompost at 1 t ha^{-1} recorded significantly higher seed yield (1.61 Mg ha^{-1}) and nitrogen uptake (67.6 kg ha^{-1}) over the control which recorded 1.07 Mg ha^{-1} and 37.04 kg ha^{-1} respectively. For Mondal et al. (2017), balanced approach might involve 75% RDF as inorganic fertiliser and 25% RDF as organic sources like vermicompost.

These studies collectively underscore the benefits of integrating organic amendments like vermicompost with reduced doses of chemical fertilizers, by combining the application of 75% to 100% of RDF NPK with additional N (25% to 50%) coming from vermicompost for enhancing crop yields and improving soil health while reducing dependency on inorganic inputs. However, a focus on the balance is crucial, as overreliance on organic sources could lead to lower yields, whereas too much inorganic fertiliser might harm soil health. To maximize these benefits, in combining applications of vermicompost and chemical fertilisers, applying full dose of recommended dose fertilizer NPK alongside 2 to 10 t ha^{-1} of vermicompost enriched with appropriate microbial inoculants may potentially contribute to higher crop yields compared to imbalanced ratios (less than 50% NPK RDF) alongside vermicompost. Timing and method of fertilizer application are critical. Applying vermicompost at sowing or shortly before sowing (10 to 15 days), either broadcast, in a band, or incorporated into the soil, combined with full recommended dose of NPK fertilizers, ensuring phosphorus and potassium are applied at planting or just before and, nitrogen split into two or three applications during critical growth stages, ensures continuous nutrient availability throughout the crop growth stages, promoting optimal plant development and yield.

3.1.3 Role of co-application of vermicompost and chemical fertiliser on crops biochemical attributes

Several factors impact the nutritional composition of crops, including crop type, postharvest processing, fertiliser application, climate variations, and soil characteristics. Vermicompost, rich in readily accessible nutrients, plays a beneficial role in enhancing crop yield (Rajkhowa et al., 2017; Aslam et al., 2019; Zhang et al., 2023). Its integration with chemical fertilisers not only boosts nutrient availability but also promotes soil microorganism growth, leading to the release of substances beneficial to plant growth (Ahmed et al., 2022; Zhang et al., 2023). Efficient NPK application is crucial for synthesizing phospholipids and nucleic acids, fundamental to crop chemical characteristics and fruit quality (Desai et al., 2019; Ahmed et al., 2022; Zhang et al., 2023).

Vermicompost's benefits include improved fruit quality, with notable examples such as increased vitamin C and shelf life in guava, higher essential oil content in ginger, and reduced sugar in peppers (Atteya et al., 2021; Patra et al., 2022; Gonzalez-Cortes et al., 2023; Sourabh et al., 2023). Additionally, combining vermicompost with chemical fertilisers can increase protein levels in crops like wheat, tomato, cabbage, and lentils as demonstrated by (Qasim et al., 2018; Aslam et al., 2019; Kumar et al., 2023; Thakur et al., 2023). Integrated Nutrient Management (INM) experiments show the positive impact of combining organic and inorganic fertilisers. Kumar and Pandita (2016) observed a significant better cowpea seed yield (476 kg ha^{-1}) compared to the control (332 kg ha^{-1}), as well as seed quality parameters such as seedling dry weigh and seedling length with 27.5% and 34% higher than control, when using a combination of 100% inorganic fertilisers and vermicompost compared to a control treatment. Mamnabi et al. (2020) found that integrated fertiliser management improved various plant antioxidant enzyme activity like polyphenol oxidase by 55.9%, proline by 1.7%, and chlorophyll content by by 18%, even under water-deficit conditions.

The key to this success is the slow release of nitrogen and phosphorus from vermicompost combined with the immediate availability of nutrients from chemical fertilisers (Arfan-ul-Haq et al., 2021; Ahmed et al., 2022). This synergy ensures a steady supply of essential nutrients, promoting high protein synthesis in crops. However, solely using vermicompost may not meet crops' nutritional demands throughout their growth cycle. Therefore, using 75% chemical fertiliser with vermicompost can maintain crop production and soil fertility (Jahanban et al., 2018). This balance not only supports agricultural productivity but also contributes to soil, human, and environmental health by reducing reliance on inorganic fertilisers and incorporating organic sources (Thakur et al., 2023).

3.1.4 The role of vermicompost as bio-alleviator of abiotic and biotic stresses

Vermicompost has proven effective in mitigating various plant stresses due to its high levels of organic matter, essential nutrients, and beneficial microorganisms. These attributes make vermicompost a powerful ally in addressing issues like soil salinity, drought, pests, and plant diseases (Oyege and Balaji Bhaskar, 2023; Rehman et al., 2023). Vermicompost also improves soil structure by enhancing aggregation and porosity, which facilitates water drainage and reduces the accumulation of soluble salts in the soil (Rivier et al., 2022). The organic matter in vermicompost acts as a buffer, moderating the impact of salinity on plant roots (Rehman et al., 2023). Additionally, beneficial microorganisms in vermicompost help decompose salts and improve soil health, allowing plants to thrive even under saline conditions (Suhani et al., 2023).

Qasim et al. (2018) reported a significant increase in membrane stability index of tomato plants by 16% due to the combined applications of vermicompost at a dose of 1.5 t ha^{-1} and reduced doses of mineral fertilizer NPK (50:25:25) compared to the control treatment (NPK 100:50:0), highlighting the vermicompost's ability to alleviate adverse effects on cell membranes under stress conditions. Vermicompost prolongs moisture availability, reducing the need for frequent irrigation and strengthening crop resilience in drought-prone areas (Robin et al., 2018; Rivier et al., 2022). Fortified roots can penetrate deeper soil layers to access water during dry periods (Oyege and Balaji Bhaskar, 2023). Rivier et al. (2022) observed that, even small amounts and short incubation times, organic amendments (i.e. vermicompost 20 t ha^{-1}) improved soil water retention capacity by 29% and water use efficiency over the mineral fertilizer treatment in wheat cultivated in sandy soils. Robin et al. (2018) noted that increasing the dose of organic matter from vermicompost elevated soil organic carbon, improved porosity, and structural stability, thereby decreasing compaction.

In addition to combating salinity and drought effects, vermicompost suppresses diseases caused by various phytopathogens such as fungi, bacteria, and viruses (Oyege and Balaji Bhaskar, 2023; Rehman et al., 2023). Its rich microbial diversity introduces beneficial organisms into the soil that can compete with or inhibit harmful pathogens (Tikoria et al., 2022; Zhang et al., 2022; Rehman et al., 2023; Robatjazi, 2023). Tikoria et al. (2022) reported that vermicompost acts as an insecticide due to the toxic substances released during decomposition, which can eliminate crop pests. Aslam et al. (2019) observed a 21.7% reduction in aphid population when applying a combination of N:P:K (100:50:50) with 10 t ha^{-1} of cow dung vermicompost. This underscores the importance of maintaining a balanced level of mineral nutrients to optimize the effectiveness of vermicompost in chemical fertilizer combinations. Additionally, the presence of antibiotics and actinomycetes in vermicompost increases crops' biological resistance against pests (Rehman et al., 2023; Vyas et al., 2022), and phenolic substances released during decomposition help in the plants' defense mechanisms under abiotic and oxidative stresses (Qasim et al., 2018; Tikoria et al., 2022; Suhani et al., 2023). Ghosh et al. (2022) reported that adding 75% of the recommended dose of NPK fertilizer and 25% of the recommended nitrogen from vermicompost reduced weed density and biomass by 6.79% compared to 100% NPK.

In other study, Suhani et al. (2023) reported that adding vermicompost in different proportions significantly reduced stress levels in okra under high salinity irrigation. Compared to high salinity levels (NaCl 150 mM) without vermicompost, the combined application of 6 t ha^{-1} of vermicompost reduced proline production by 66.6%, phenol by 64.14%, ascorbic acid, and lipid peroxidation by 56.12% in okra leaves, indicating a reduced response to extreme stress. Ahmad et al. (2022) also found that vermicompost significantly increased the morphological, physiological, and biochemical parameters of two wheat varieties (Faislabad-08 and Galaxy-13) under both drought and non-drought conditions. Under severe drought, the application of 6 t ha^{-1} of vermicompost increased seedling length by 14.02-26.14%, fresh weight by 15.16-22.91%, and dry weight by 0.37-28.20% in the studied cultivars compared to the control. Additionally, vermicompost treatment at 6 t ha^{-1} reduced leaf water potential by 6.36% and 3.36%, leaf osmotic potential by 1.74% and 1.68%, while increasing turgor potential by 4.83% and 3.36% and photosynthetic rate by 18.59% and 26.42% respectively. Vermicompost not only increases microbial diversity and reduces the risk of disease but also boosts microbial activity and mineral nutrient release, leading to a more balanced and resilient soil ecosystem (Haiba et al., 2014; Robatjazi, 2023). Healthy plants are more resilient and can recover more quickly from pest damage, and vermicompost promotes healthier plant growth, helping them better withstand pest attacks.

Earthworms, with their robust metabolic processes, dense gut microbial populations, and innate capacity for metal bioaccumulation, enable the detoxification of heavy metals present in organic matter during the vermicomposting process (Usmani and Kumar, 2015; Zhang et al., 2022; Robatjazi, 2023). The detoxification mechanism occurs through the microflora in the earthworm's gut, which facilitates the formation of metal-humus complexes with extractable chemical properties (Huang and Xia, 2018; Tikoria et al., 2022). Landorfa-Svalbe et al. (2022) reported that soil amendment with vermicompost at a rate of 10 and 20% reduced Pb concentration in plant leaves and roots by 65% and increased plant biomass five times compared to the control, accelerating flowering and showing the potential of vermicompost in reducing heavy metal uptake and accumulation in crop plants while improving soil health. Sengupta et al. (2023) reported that applying zinc and iron-enriched vermicompost to soil at 3 t ha^{-1} resulted in the lowest levels of available soil arsenic (As) at 2.525 mg kg^{-1}, while the highest levels of available As (2.982 mg kg^{-1}) were observed when enriched vermicompost was applied at a lower quantity, i.e., 1.5 t ha^{-1}. The application of both enriched and non-enriched vermicompost significantly reduced arsenic levels in grain by 58.14% and 31.40%, respectively, compared to the control without vermicompost.

Vermicompost enhances soil structure and water retention capacity, suppresses diseases and pests, and aids in the removal of heavy metals from the soil. For optimal use as a stress bio-alleviator, it is recommended to apply vermicompost at rates of 1.5 to 6 t ha^{-1} based on crop requirements, integrating it into the soil before planting to improve structure, water retention, and nutrient supply, and top-dressing during growth for sustained benefits. Combining vermicompost with reduced chemical fertilizers can further enhance plant immunity and suppress pathogens. Additionally, the use of vermicompost, whether enriched with microorganisms or standard, shows promise in reducing heavy metal uptake in plants.

3.1.5 Potential challenges or limitations of using vermicompost in agriculture

While vermicompost offers numerous benefits for sustainable agriculture, it is important to consider its quality variations, nutrient content balance, slow release of nutrients, availability and scalability, and cost considerations. Depending on factors such as the feedstock used, species of earthworms involved, and processing conditions vermicomposting process can result in differences in nutrient content, maturity, and stability of the vermicompost (Kaur, 2020; Jakubus and Michalak-Oparowska, 2022) (see Table 1). It is crucial to guarantee consistent quality through appropriate management practices because this variability may influence the product's efficacy as a fertiliser. Due to the above-mentioned factors, the nutritional content of vermicompost may not always match the needs of crops, resulting in unbalanced nutrient ratios for some crops (Raj et al., 2022). However, to get the best nutritional balance for crop cultivation, vermicompost may need to be supplemented with extra fertilisers or amendments (Zhao et al., 2017).

The same advice may be used to prevent nutritional deficiencies in crops during the early stages of development since this organic substance releases nutrients gradually as it passes through microbial degradation and mineralization. The use of vermicompost always consists of considerable amounts due to its lower concentration of macro and micronutrients, which presents a huge logistical problem for the consistent supply of organic waste, suitable vermiculture infrastructures, and adequate management practices. Due to this circumstance, vermicompost's manufacturing and application costs are comparatively greater than those of traditional fertilisers (Chatterjee, 2015), although accessibility of organic waste and the local market might influence the availability of affordable vermicomposting alternatives.

To maximize the benefits of vermicompost and mitigate these limitations, it is recommended to consider factors such as feedstock selection, composting process optimization, proper nutrient management, and complementary use of other fertilisers or amendments as needed. However, conducting site-specific trials and monitoring crop responses can help identify the best practices and adjustments required to maximize the effectiveness of vermicompost in each farming system.

3.1.6 Production process, and potential benefits of bio enriched rock phosphate in agricultural systems

Phosphorus (P) is crucial for agriculture, playing a pivotal role in the growth and development plants (Caione et al., 2018). However, maintaining optimal phosphorus levels in soil is challenging due to its tendency to form insoluble compounds that are not readily available to plants. Integrated Nutrient Management (INM) strategies, such as the bio-enrichment of rock phosphate (RP) with phosphate-solubilizing bacteria (PSB), offer a sustainable solution by enhancing P bioavailability (Tahir et al., 2018; Ni et al., 2023), reduce chemical fertilizer use, and promote sustainable plant growth and yield (Shabani et al., 2015). This is especially beneficial in acidic and alkaline soils, where low P availability limits agricultural productivity (Shirmohammadi et al., 2020; Changkiri et al., 2023). The bio-enrichment process typically involves incorporating an organic base enriched with essential nutrients like carbon and nitrogen (Kwaslema et al., 2022; Ajibade et al., 2023). These nutrients are critical as they support the growth and metabolic functions of PSBs, enabling them to effectively solubilize phosphorus from RP (Shirmohammadi et al., 2020; Jha et al., 2021; Ajibade et al., 2022). However, its effectiveness can be influenced by agroclimatic conditions, RP reactivity, bio-enrichment process efficiency, P level and the competition with other soil microorganisms (Ribeiro et al., 2020; Alam et al., 2022).

Understanding the function of bioinoculants, their versatility, and performance across diverse conditions is key to effectively implementing this technology in agriculture. The use of phosphate-solubilizing bacteria (PSB) involves isolating them from soil samples (Nacoon et al., 2022), identifying and characterizing their traits (Kwaslema et al., 2022), and culturing them in a suitable medium with insoluble phosphate as the sole phosphorus source (Giro et al., 2015; Abawari et al., 2021; Venu et al., 2023). PSBs solubilize phosphate through organic acid secretion, enzyme production, and siderophore excretion, thereby making P available for plant uptake (Stephen et al., 2015; Khourchi et al., 2022; Kwaslema et al., 2022; Hajira et al., 2023).

Bio-enrichment of RP not only involves incorporating PSB to enhance P solubilization but can also occur through composting or vermicomposting of organic materials, with or without PSB (Jha et al., 2021; Ajibade et al., 2023). This process results in increased phosphorus availability, microbial density (Yu et al., 2014), and enzymatic activity (Tahir et al., 2018; Jha et al., 2021). Studies by Masrahi et al. (2023) demonstrate that the application of arbuscular mycorrhizal fungi (AMF) combined with 100% chemical fertilizer increased barley yield by 9.6%. Similarly, the use of phosphate-solubilizing bacteria (PSB) with 100% chemical fertilizer improved barley yield by 2.94% compared to the recommended dose of chemical fertilizer in saline soil. In another study, Datta et al. (2018) reported a significantly higher ginger fresh yield of 20.68 t ha^{-1} with the application of rock phosphate as 100% recommended P and multiple biofertilizers, compared to the control yield of 16.67 t/ha.

Co-inoculating PSB strains with other microorganisms has also been shown to increase crop yields. A study by Alam et al. (2022) observed that combining a single strain of PSB with 100% of the recommended mineral phosphorus in alkaline soil resulted in higher wheat yields, with increases of 14.2% and 28.4% over the sole application of 100% mineral P fertilizers or PSB, respectively. Additionally, research by Shirmohammadi et al. (2020) demonstrated positive outcomes when phosphate fertilizer and PSB were applied together to improve wheat yields, specifically, the application of 20 kg P ha^{-1} in rainfed farming combined with two PSB strains increased grain yield by 58%. Conversely, M. H. S. Leite et al. (2022) found the highest soybean grain yield in plants receiving co-inoculation of Bradyrhizobium spp. with Bacillus strains (4787 kg ha^{-1}) and with arbuscular mycorrhiza (5013 kg ha^{-1}), compared to standard inoculation (4379 kg ha^{-1}), regardless of phosphate fertilization. Further, El-Morshedy et al. (2020) found that balanced applications of 50% (1.5 kg plant^{-1}) Nitrogen Fixing Bacteria (NFB), 50% (1.5 kg plant^{-1}) Phosphate Solubilizing Bacteria (PSB) after mixed with suitable amount of sandy soil, and 50% Rock Phosphate (RDP) significantly improved the yield of banana plants by 0.4 t ha^{-1} and reducing sugar by 1.4% over mineral fertilizers, showing that organic elements can reduce nutrient losses from deep percolation and volatilization. These findings highlight the diverse effects of different combinations of biofertilizers, chemical fertilizers, and rock phosphate on crop performance. Incorporating organic manures can significantly enhance nutrient use efficiency and improve soil health.

Phosphate solubilizing bacteria (PSB) based bioinoculants either alone or combined with rock phosphates and mineral fertilizers, have multiple benefits such as promoting plant growth, mobilizing and solubilizing phosphorus, detoxifying soil, and enhancing enzyme activity. In their research, Javeed et al. (2019) demonstrated positive effects on crop perfomance and soil properties by improving the soil characteristics of sandy loam soil and grain yield of spring maize. They observed a yield improvement by 22.54% over the control when rock phosphate (RP) was combined with PSB, however, with 100% mineral fertilizer and biofertilizer, the yield was even greater (36.6%; 39.6%; 12.4%) compared to PSB alone, rock phosphate (RP) alone, or PSB together with rock phosphate. Additionally, there was an increase of 118% in phosphomonoesterase activity, 70.25% in acid phosphate and 9.7% reduction in soil pH in treatments comprising RP and PSB, while in the mineral fertilizer and PSB the phosphomonoesterase activity increased by 152%, acid phosphate by 117% and pH reduction by 13.5% over the control. Yu et al. (2014) found that a mixture of three phosphate-solubilizing bacteria (PSB) strains (P. aurantiaca, P. fluorescens, and B. cereus) with RP significantly increased plant height (by 36.9%), shoot dry weight (by 41.5%) and root dry weight (by 53.1%) in walnut, compared to using these organisms individually. Significantly decreased soil pH values (7.29 to 6.68), and increased concentration of soil available P (10.25 to 10.60 mg kg^{-1}) was also reported in the application of PSB with RP compared to the application of PSB without RP respectively. Abawari et al. (2021), in their study on the effect of phosphate-solubilizing bio-inoculants and vermicompost application on mineral uptake and growth of coffee seedlings under greenhouse conditions, observed significant improvements. They noted that combining phosphate-solubilizing bacteria with vermicompost and chemical fertilizer resulted in a 20% increase in mineral uptake and a 32.2% increase in growth compared to the sole application of vermicompost in coffee seedlings. These

TABLE 2 Description of some studies reporting the effect of co-applied vermicompost and chemical fertilisers on crop performance.

Type of Crop	location	Input	Application rate	Effect on yield	Yield difference over the control	Effect on crop quality	Application mode	References
Pepper	China	VC, CF	N P K 1.2 t ha^{-1} VC 3.75 t ha^{-1}	Significant increase fresh yield 18.3 t ha^{-1}	188%	Compared to CF, VC increased the reducing sugar by 45%	VC before transplanting (15 days)	(Zhang et al., 2023)
Rice	Bangladesh	VC, CF	NPK 130, 24, 60 Kg ha^{-1} VC 10 t ha^{-1}	Significantly highest yield 4.28 t ha^{-1}	71%	Nitrogen uptake significantly superior (110.6 kg ha^{-1}) over control (51.7 kg ha^{-1})	Full doses of CF Organic manures during final land preparation	(Hoque et al., 2022)
Cowpea	India	VC, CF	SSP 300 kg ha^{-1} + Enriched VC 3.33 t ha^{-1}	Not significant, VC treatment had highest yield (209.27 g fruits plant^{-1})	17.96%	Not significant, CF had higher carotenoid (1.497 mg g^{-1}) compared to VC (1.19 mg g^{-1})	CF aa day before sowing, VC 10 days before sowing	(Tanuja et al., 2019)
Tomato	Pakistan	VC, CF	50% RDF NPK (50:25:25 kg ha^{-1}) + VC 1.5 t ha^{-1}	Significantly highest yield 13,778 kg ha^{-1}	88%	Maximum tomato fruit protein contents found in CF + VC with a 43.47% increase over the control	–	(Qasim et al., 2018)
Green gram	India	VC, CF	50% RDF (NPK 20-60-40 kg ha) + VC 2.5 t ha^{-1} + lime 4 q ha^{-1}	Significantly higher yield of green gram (100 kg ha^{-1})	8%	–	VC in rows before sowing	(Rajkhowa et al., 2017)
Wheat	Pakistan	VC, CF	NPK 100:50:50 kg ha–1 + 10 t ha^{-1} cow dung VC	Significantly improved wheat yield (5.37 t ha^{-1})	11.6%	Significantly increased grain protein (15.97%) over CF (15.03%)	VC at sowing time, PK full dose, N 1/3rd at sowing	(Aslam et al., 2019)
Wheat	India	VC, CF, biofertiliser	NP: 150:60 VC 2.5 t ha^{-1}	Significantly outyielded (4.98 t ha^{-1})	145%	–	Biofertilisers by soaking seeds;	(Rani et al., 2020)
Chickpea	India	RDF, VC	NPK: 60:40:40 VC	Highest seed yield (1.62 t ha^{-1})	5%	–	–	(Koireng et al., 2022)
Papper	Mexico	Liquid VC, VC, CF	NPK: 240-200-120 + 50% of K from vermicompost	CF with highest yield (39 t ha^{-1}), was statistically at par with liquid VC and VC treatment (34.5 t ha^{-1}, 34.2 t ha^{-1})	–	VC High VitC 200 mg 100g), at par with CF (198 mg 100g and liquid VC (199 mg 100 g)	VC applied three times according to the phenological stage	(Gonzalez-Cortes et al., 2023)
Cabbage	India	VC, compost, CF, Biofertilisers	NP + VC + EC +PGPR (75% + 2.5 t ha^{-1} and 2.5 t ha^{-1} + 5 kg ha^{-1})	Significantly outperformed the yield (4.72 t ha^{-1})	–	Significantly higher protein (17.39%) when compared with NP + VC (75% +2.5 t/ha) (15.59%) and to control –RDF + FYA (16.44%)	Seed inoculation, 1/3 N, full dose PK as basal, manures during the soil preparation stage	(Thakur et al., 2023)
Lentil	India	VC, CF	50% RDN + 100% RDP + VC at 1 t ha^{-1} + 0.5% $ZnSO_4$ + 0.5% $FeSO_4$	Highest seed (1.65 Mg ha^{-1})	60.4%	Highest protein content (28.9%), statistically at par to 50% RDN + 100% RDP + VC at 1 t ha-1 (28.6%)	VC and CF into the soil at the seeding time	(Kumar et al., 2023)
Sunflower	Turkey	VC, CF	N 21:0:0 + VC 1.5 t ha^{-1}	Significantly highest seed yield (4854 kg ha^{-1})	58%	Protein content (10.5%), statistically at par to control (10.6%). Nitrogen with leonardite recorded	VC and CF into the soil before planting	(Sefaoglu et al., 2021)

(Continued)

TABLE 2 Continued

Type of Crop	location	Input	Application rate	Effect on yield	Yield difference over the control	Effect on crop quality	Application mode	References
						significantly high protein (13%)		
Rice	India	VC, CF	75% NPK: (60:30:30) and 25% VC	High grain yield (5.16 t ha^{-1})	15%	–	PK along with VC (25% N) as basal doses before transplanting, N split 3 times	(Ghosh et al., 2022)
Ginger	India	VC, CF	NPK: 75:50:50 kg·ha−1 and VC 25% as RDF 0.25 t ha^{-1}	Significantly highest yield (10.62 t ha^{-1})	24%	Significantly highest content of essential oil (0.45%) when compared to 100% CF (0.40%)	VC during the final land preparation, 1/3 N, PK as basal	(Patra et al., 2022)
Maize	India	RDF, VC	NPK: 200-60-60 kg ha^{-1} + VC 25% of RDN	Yielded 6.82 t ha^{-1}	13.8%	–	PK along with VC (25% N) as basal doses before transplanting, N split 3 times	(Ghosh et al., 2020b)
Cowpea	India	RDF, VC	75% RDF NPK: 20-60-50+VC 2.5 t ha^{-1}	Significantly higher yield (1.4 t ha^{-1})	40%	Significantly higher seed germination 93.8%) compared to control (85.3%) and 100% CF (90%)	VC as band application in the soil	(Kumar and Pandita (2016))
Moringa oleifera	Egypt	VC, CF	50 t ha^{-1} VC + 2gL^{-1} Nano-NPK	Significantly higher yield (14.8 t ha^{-1}) compared to control (10 t ha^{-1}) and all other treatments	14.8%	Significantly improved fixed oil content (299.1 mL $Plant^{-1}$) compared to control (0.4 mL $Plant^{-1}$) and all other treatments	VC 10 days before planting, NPK as a ground dose and 2 gL^{-1} Nano-NPK as foliar application	(Atteya et al., 2021)

VC, vermicompos; EC, Enriched compost; PGPR, Plant growth promoting rhizobacteria; RDF, Recommended dose fertiliser; FYM, Farm yard manure; RDN, Recommended dose of nitrogen; RDP, Recommended dose of phosphorus; CF, Chemical fertiliser; NC, Neem cake.

benefits likely arose from using phosphate-solubilizing bacteria (PSB) and vermicompost, which increased the solubility of phosphorus from rock phosphate and soil organic phosphorus reserves. Wahid et al. (2020) reported improved production performance on Maize, noting significantly higher maize grain yields (3387 kg ha^{-1}) compared to the control (1668 kg ha^{-1}), and increased phosphorus uptake by plants (18 kg ha^{-1} compared to 3.0 kg ha^{-1} in the control) in treatments combining rock phosphate (RP), arbuscular mycorrhizal fungi (AMF), and Bacillus sp. These outcomes were comparable to those achieved with single superphosphate application. Furthermore, the combination of phosphate-solubilizing bacteria (PSB) and AMF effectively increased available phosphorus release (8.05 mg kg^{-1}) compared to the control (1.11 mg kg^{-1}), resulting in significant improvements in plant growth and yield. Similarly, Liu et al. (2020) reported significantly higher aboveground biomass in alfalfa (27.03 g pot^{-1}) compared to the control (13.13 g pot^{-1}) due to the combined application of arbuscular mycorrhizal fungi (AMF), phosphate-solubilizing bacteria (PSB), and inorganic phosphorus at a rate of 50 mg kg^{-1}. These results surpassed those from the single application of inorganic phosphorus alone (18.98 g pot^{-1}).

These studies underscore that when rock phosphate (RP) or mineral phosphorus (P) is present, not only do phosphate-solubilizing bacteria (PSB) strains play a crucial role in enhancing plant growth and productivity, but other microorganisms such as arbuscular mycorrhizal fungi (AMF) also contribute significantly (Wahid et al., 2020; Nacoon et al., 2022) (see Table 3). For instance, in a saline soil experiment, Masrahi et al. (2023) reported that barley performed best when AMF and 100% of the mineral recommended dose of phosphorus (RDP) were applied, yielding 11.69 t ha^{-1}, compared to 11.02 t ha^{-1} when PSB and 100% of the recommended dose of fertilizer (RDF) were used. Similarly, Datta et al. (2018) observed that ginger produced the highest fresh yield (20.68 t ha^{-1}) and dry yield (4.52 t ha^{-1}) when a combination of green leaf manure, RP, wood ash, Azospirillum, and PSB was applied. This was followed by yields of 18.59 t ha^{-1} (fresh) and 4.06 t ha^{-1} (dry) with vermicompost, Azospirillum, and PSB, compared to the control yields of 13.08 t ha^{-1} (fresh) and 2.94 t ha^{-1} (dry). Widodo et al. (2015) observed a 27% increase in soybean yield with the application of PSB, full dose of triple superphosphate (TSP) (100 kg ha^{-1}) and lime. In soybeans, Leite et al. (2022) recorded

TABLE 3 Various literatures discussing the impact of combined application of rock- phosphate and PSB on soil P availability, crop productivity, and enzyme activity.

Type of Crop	Input	Mode of application	Yield difference (%) over the control	Available P difference (%) over the control	Phospho-monoesterase difference (%) over the control	References
Kikuyu Grass	PSB and RP (11.4% P)	PSB 2000 mL ha^{-1} after each productive cutting RP (134.5 kg ha^{-1}),	6.7	4.3	29,4	(Torres-Cuesta et al., 2023)
Peanut	Mixture of PSB and RP (15-20% P)	PSB and RP mixed to the soil; RP: 20 g kg RP; PSB 15 mL at 10^{8}CFU/mL	- 1.4	13	51,6	(Jiang et al., 2021)
Walnut	PSB and RP (72% P)	PSB and RP mixed to the soil; RP 20 g kg RP; PSB 50 mL at 10^{9} CFU/ml	4.1	3.9	28,9	(Yu et al., 2014)
Sunchoke	PSB, AMF and RP (25% P)	10 mL of PSB inoculum (1x10^{9} CFU mL^{-1} seedling-^{1}; Before planting, 27 g of AMF soil inoculum, 6 g RP pot-^{1}	12.0	–	95,6	(Nacoon et al., 2022)
Wheat	PSB, AMF and RP (20% P)	PSB inoculated to the seeds, 6 kg of AMF mixed to the soil before planting	10.3	38.0	–	(Wahid et al., 2020)
Maize	PSB, NERP	PSB 50 250 mL seeds kg^{-1}, RP 1140 P kg ha-^{1} mixed to soil before planting	8.2	30.1	–	(Yasmeen et al., 2022)
Rice	RP, PSB	PSB applied to the seeds and pothole after transplanting (5mL 8 × 10^{9} CFU ml^{-1}), RP basal dose 10 kg pot^{-1}	18.3	24.8	74,9	(Stephen et al., 2015)
wheat	PSB consortium, RP	PSB (5mL 7 × 10^{9} CFU ml^{-1}) after 7 days of emergence on rhizosphere, RP 130 kg ha-^{1} P_2O_5	12.4	51.4	–	(Boubekri et al., 2023)
Maize	PSB, RP	PSB applied to each planting hole (5mL × 10^{9} CFU ml^{-1}), RP 20 kg P ha^{-1}	11.2	19.9	–	(Kwaslema et al., 2022)
Green gram	PSB, RP, Lime	PSB deepening pineapple slips on 10 mL, RP as basal dose	18.9	14.8	–	(Venu et al., 2023)
Chickpea	RP, PSB, Compost	RP and compost (50:50 W/W), were applied 7 days before sowing. PSB inoculated to the seeds	10.9	–	–	(Ditta et al., 2018)
Wheat	RP, PSB, Compost	–	15	–	–	(Jamil et al., 2018)
Wheat	RP, PSB, FYM	RP incubated with PSB and FYM for 21 days and after, applied at sowing	14		–	(Vyas et al., 2013)
Mungbean	PROM, PSB, VAM, PF	RP as basal dose 40 kg ha^{-1}, VAM 5 kg ha^{-1}, PSB 2 ml kg seed all at sowing time	123	–	–	(Khangarot et al., 2022)

PROM, Phosphate Rich Organic Manure; PSB, Phosphate solubilizing bacteria; VAM, vascular arbuscular mycorrhiza; PF, Pseudomonas fluorescens; RP, Rock phosphate; NERP, non encapsulated rock phosphate; PL, poultry manure; CF, Chemical fertiliser; FYM, Farmyard manure.

increases in the number of pods by 14.8%, and number of grains by 10.8%, higher than standard inoculation under the plants co-inoculated with arbuscular mycorrhiza and Bradyrhizobium spp + 100% mineral fertilizer, however profitability index in soybeans under the co-inoculation with Bacillus strains and Bradyrhizobium spp. + 100% mineral fertilizer was greater by 28.3% and 2.7% over the standard inoculation and co-inoculation with arbuscular mycorrhiza respectively. Diverse groups of microorganisms, when combined, may provide various enzymatic functionalities and growth-promoting traits, resulting in efficient phosphorus bioconversion and enhanced plant growth.

Madeeha (2023) recommends a 25:75 ratio of rock phosphate (RP) to single superphosphate (SSP), combined with phosphate-solubilizing bacteria (PSB) and Rhizobium, to increase chickpea yield in calcareous soils. This combination significantly improved phenology, nodulation by 46.6%, yield-contributing traits, total phosphorus uptake by 36.6%, and increased seed yield by 53% compared to a 100:0 rock phosphate (RP) to single superphosphate ratio. Conversely, Arfan-ul-Haq et al. (2021) suggest a 50:50 ratio of bio activated RP (prepared by group of three bacterial strains i.e., Pseudomonas sp., Bacillus sp. and Enterobacter sp. aided with molasses (5%) and urea (10%), to diammonium phosphate

(DAP), which enhanced shoot biomass by 25%, total phosphorus uptake by 67%, and recovery efficiency of P by 75% on wheat. Furthermore, Abbasi et al. (2015) observed that the combined use of 50% P from RP, 50% P from poultry manure, and PSB in greenhouse experiments achieved similar growth, yield (10.4 g plant^{-1}), and phosphorus uptake (30.1 mg plant^{-1}) in chili as with 100% DAP which yielded 10 g plant^{-1} and 31.3 mg plant^{-1} respectively. However, conflicting results were noted by Holeckova et al. (2018) in field experiments with silage maize regarding application of Pseudomonas sp. in combination with phosphorus from rock phosphate (RP) or triple superphosphate (TSP) and nitrogen fertilizers, indicating that outcomes might vary depending on crop and soil conditions. Holeckova et al. (2018) found that the combination PSB with nitrogen and 100% RP as phosphorus fertiliser did not increase maize dry matter yields (19.5 t ha^{-1}), instead, the treatment containing inorganic phosphorus fertilisers as single super phosphate (STP) and PSB showed greater dry matter yields (20.8 t ha^{-1}). In contrast, Stephen et al. (2015) observed the highest rice yield in treatment combining two PSB's isolates (Gluconacetobacter sp. and Burkholderia sp.) and 100% RP at rate of 60 kg P_2O_5 ha^{-1}, achieving 18.2% increase over sole single superphosphate at a rate of 40 kg P_2O_5 ha^{-1}. The single application of PSB resulted in lower rice yields (4.72 g plant^{-1}) compared to the use of RP alone (5.71 g plant^{-1}), while the combination of RP and PSB increased yield to 6.37 g plant^{-1}. An even greater yield increase was observed when different PSB's isolates were combined with RP, resulting in yields of 7.01 g plant^{-1}. This confirms that different PSB species have varying performance when applied to soil. The phosphorus level in the soil, the application rate of both RP and mineral fertilizer, the RP grade and the competition between the introduced microorganisms and other existing microorganisms may all impact on the PSB effectiveness (Ribeiro et al., 2020; Nacoon et al., 2022).

In addition to the positive impacts observed in the yield of various studied crops, researchers also emphasize the beneficial effects on soil properties when Phosphate Solubilizing Bacteria (PSB) and mineral fertilisers are applied in the soil. Khan et al. (2022) demonstrated that inoculating soil with PSB alongside 100% mineral phosphate (SSP) improved post-harvest soil fertility by increasing soil organic matter from 0.61% to 0.70%, reducing pH from 7.74 to 7.68, and boosting soil total nitrogen from 0.04% to 0.09% in mungbean. Significant increases were also observed in extractable phosphorus, rising from 2.07 to 3.44 mg kg–1, and potassium concentrations, increasing from 100.27 to 129.45 mg kg^{-1}. Moreover, their study highlighted that 100% rock phosphate (RP) generally outperformed SSP when applied with PSB in alkaline-calcareous soils. Supporting these findings (Javeed et al., 2019), conducted experiments showing substantial improvements in various soil enzymes- phosphomonoesterase (63% increase), urease (43% increase), catalase (71% increase), APH (52% increase), dehydrogenase (67% increase), and β-glucosidase (46% increase) -with PSB combined with the full recommended dose of NPK fertilizers (RNPK) on spring maize experiment. These improvements were significantly greater compared to treatments using RNPK alone, PSB alone, or PSB combined with RP. PSB's play a crucial role as driving factors for increased productivity. Additionally, findings by Stephen et al. (2015) demonstrated significantly higher phosphatase and dehydrogenase activities in all inoculated treatments in rice. Phosphatase activity ranged from 24.18 to 291.11 µg PNP g^{-1} soil and dehydrogenase activity ranged from 10.24 to 40.20 µg TPF g^{-1} soil, averaging 6.5% and 56.1% higher, respectively, than in treatments with single super phosphate (SSP), regardless of the presence of rock phosphate (RP). The increased enzymatic activity led to higher phosphorus solubilization in plots inoculated with PSB combining Gluconacetobacter sp., Burkholderia sp., and RP at a rate of 60 kg ha^{-1} (RP60). This treatment achieved an available phosphorus content of 43.13 kg ha^{-1} in the soil, comparable to the application of 40 kg ha^{-1} of SSP (SP40). Consequently, phosphorus uptake in plants increased by 71%, leading to an 18.2% improvement in the growth and yield of rice crops compared to the SP40 treatment. Similar findings were reported by (Yu et al., 2014), who observed the most pronounced beneficial effects on walnut and alfalfa growth and soil enzyme activities when two or three PSB strains were co-inoculated with MAP (mono ammonium phosphate) or RP. Yu et al. (2014) reported that each PSB strain (Pseudomonas aurantiaca and P. fluorescens) improved soil quality, as indicated by increased activities of dehydrogenase by 10.5%, neutral phosphatase by 128%, and urease by 70.2% compared to the sole application of RP. These increases were even higher when the PSB strains were combined and applied together with RP, resulting in dehydrogenase activity increasing by 28.9%, neutral phosphatase by 384.6%, and urease by 144.6%. Research by An et al. (2022), and Boubekri et al. (2023) supports the findings of Stephen et al. (2015). Boubekri et al. (2021) observed a significant improvement in wheat yield biomass by up to 19.7% when a PSB strain was combined with high-grade rock phosphate (32.81% P_2O_5) which was comparable to full dose of single superphosphate (STP). An et al. (2022), demonstrated that double inoculations with Funneliformis mosseae and Bacillus megaterium, combined with mineral fertilizer (MAP), were more effective than single inoculations or uninoculated plots in alfalfa. Improved soil fertility was reported with double bacterial inoculation and the application of full RDP mineral phosphorus at a rate of 100 mg kg^{-1}. This combination increased soil organic matter and organic acids in the rhizosphere by 29.5% and 273%, respectively, and phosphatase activity by 391%, while decreasing soil pH by 5.6% compared to the control without inoculation and phosphorus application. These changes enhanced soil fertility and promoted phosphorus absorption by plants. Kwaslema et al. (2022) reported similar findings, observing that inoculating soils with two PSB isolates significantly increased available phosphorus (P) levels. Regardless of the phosphate source and application rate, the available P in the soil was 275% higher compared to the control. The effects were particularly pronounced when rock phosphate (RP) was used in soils with low P absorption maxima. They observed that, at any phosphate source and rate inoculated with two PSB isolates, there were numerically higher amounts of available P which was 275% higher over the control, having greater effects when the source of P was RP in soils with low P absorption maxima.

Divergent findings underscore the complexity of soil microbial interactions, with outcomes varying based on soil conditions and experimental setups. Nevertheless, most studies reviewed support the notion that the combined use of PSB with rock phosphate (RP) or mineral fertilizers can significantly improve crop performance and soil properties. The positive outcomes reported across diverse crops and soil conditions underscore the importance of considering microbial co-inoculation and interactions in developing effective soil management strategies. To maximize the benefits of combined applications of phosphate-solubilizing bacteria (PSB), rock phosphate (RP), and mineral fertilizers, integrating various microorganism-based biofertilizers into bio-fertilization plans is essential. This includes incorporating PSB, arbuscular mycorrhizal fungi (AMF), and Bradyrhizobium spp. By doing so, the availability of phosphorus from both the organic P present in the soil and additional P sources, such as mineral fertilizers or RP, can be significantly enhanced as has been shown that PSB are most effective when used in combination with different strains or alongside AMF. However, the integrated application of mineral phosphorus and RP with PSB could involve combining 50% to 100% of the recommended dose of phosphorus (RDP) as RP, with the other 50% of P coming from mineral fertilizers. This approach can significantly improve crop performance and soil properties. Additionally, combining PSB with 100% mineral fertilizer can lead to even greater yield improvements, depending on soil and crop requirements. This approach not only enhances crop growth but also mitigates the adverse effects of excessive chemical fertilizer application. The use of biofertilizers facilitates the mobilization and uptake of essential nutrients, reduces dependency on chemical inputs, and contributes to sustainable agricultural practices. Despite this, it is crucial to acknowledge the variability in results and the need for site-specific considerations in implementing these approaches. Further research is warranted to explore the underlying mechanisms of microbial interactions and optimize their application for enhanced agricultural productivity.

3.1.7 Challenges associated by the usage bio enriched rock phosphate in agricultural systems

Several factors influence the inconsistent performance of PSBs in field settings whether for its exclusive application or for RP enrichment. Direct effect linked to bio-enriched RP include variations in soil pH (Dasila et al., 2023; Ni et al., 2023), temperature, humidity, crop type and other environmental variables (Arabi et al., 2018), soil P availability (Chaves et al., 2013; Javeed et al., 2019; Liu et al., 2020) and RP grades (Boubekri et al., 2023). The pivotal role of soil pH is evident in its influence on microorganism activity (Ribeiro et al., 2020) and nutrient solubility, thereby shaping the growth and yields of plants (Boubekri et al., 2023). To enhance nutrient release, the application of specific bio-enriched rock phosphate products in soils with a targeted pH may be imperative (Ribeiro et al., 2020). Deviation from the appropriate soil environment to discharge the bio-enriched RP could compromise the effectiveness of the product, highlighting the significance of maintaining optimal soil conditions for maximizing the benefits of bio-enriched rock phosphate (Boubekri et al., 2023).

Venu et al. (2023) documented a noteworthy increase in economic yield, supported by statistical analysis, in soil subjected to a comprehensive treatment involving the combination of PSB, lime, and Rock Phosphate (RP) which contrasts with outcomes observed in soils treated solely with individual applications of PSB, lime, and RP. Intriguingly, when both PSB and RP were administered, the yield from the soil treated with lime and RP surpassed statistically the productivity of other untreated control soils. Adjusting soil acidity to a targeted pH may be crucial for maximizing the benefits of specific bio-enriched RP products to enhance nutrient release. Phosphorus uptake and nutritional needs vary among crops, emphasizing the importance of understanding specific crop requirements. Assessing whether bio-enriched rock phosphate can meet these needs is crucial. Despite its application, high-phosphorus-demanding crops may still require additional phosphorus for optimal growth. This underscores the necessity for a tailored and sophisticated nutrient management strategy to address the unique needs of each crop.

Despite the effectiveness of PSBs, their potential may be affected by the presence of other microorganisms in the soil that compete for the same nutrients and resources necessary for the development of PSBs (Sangeeth, 2016; Ribeiro et al., 2020). The nutrient content of bio-enriched rock phosphate may also differ depending on the specific processing method and properties of the RP, which may not provide the same immediate availability or concentrated levels of phosphorus as synthetic fertilisers (Ribeiro et al., 2020). Boubekri et al. (2023), demonstrated on their experiment that the agronomic performances of the PSB combined with RPs were greatly influenced by RP grades, soil characteristics and soil pH (see Table 3). He observed that loam-clay texture, acidic soils and the finer the particles containing the highest P_2O_5 content (32.81% and 31.12% respectively) the better agronomic performance of wheat plant were observed which positively correlated to the solubilization capacity of microorganisms.

An additional concern arises from the fact that bio-enriched rock phosphate might not be as readily accessible or cost-effective as traditional phosphate fertilisers. The intricate production and processing methods involved in bio-enriching rock phosphate can position it as a relatively specialized product, potentially leading to limited availability and higher costs compared to synthetic alternatives (Sangeeth, 2016). The lack of standardization in the manufacturing and formulation of PSB-based biofertilisers may impact their efficacy and shelf life (Ditta et al., 2018).

Furthermore, the necessity for in-depth studies aimed at understanding the long-term effects on microbial activity and soil health, coupled with the requirement for a substantial production infrastructure for the widespread use of PSBs as biofertilisers, renders the technology time-consuming, expensive, and impractical for small-scale farmers (Sangeeth, 2016). When rock phosphate (RP) is blended with phosphate-solubilizing bacteria (PSB), it functions as a slow-release fertiliser, minimizing phosphorus fixation in the soil particles and consistently supplying nutrients to plants. Nevertheless, evaluating the overall life cycle impacts of bio-enriched rock phosphate is necessary to ensure its sustainability credentials.

However, in situations where phosphorus (P) is abundantly available, as is the case with soluble Triple Super Phosphate (TSP), it becomes susceptible to leaching and complexation (Boubekri et al., 2023), particularly with calcium or aluminum in tropical soils (Khan et al., 2022). To mitigate the environmental impact of chemical fertilisers, adopting a holistic approach that integrates the use of bio-enriched rock phosphate with sustainable practices is advisable. Incorporating organic amendments like vermicompost, implementing cover cropping, and employing effective soil management techniques can serve as a strategic solution to address these limitations. This approach has the potential to optimize the benefits of bio-enriched rock phosphate while simultaneously minimizing adverse environmental effects. While bio-enriched rock phosphate is acknowledged for its environmental friendliness (Munda et al., 2016) compared to conventional phosphate fertilisers (Madeeha, 2023), conducting a comprehensive environmental impact assessment remains crucial. This holistic evaluation is essential to weigh the environmental benefits against the potential challenges and limitations associated with its production and application.

3.1.8 Inorganic fertiliser, bio-enriched rock phosphate, and vermicompost co-application methods and their effects on soil health and crop yield

According to recent studies (Pezeshkpour et al., 2014; Aslam et al., 2019), maintaining soil fertility requires mixing organic and inorganic resources in a balanced manner. To enhance both nutrient retention and microbial activity, vermicompost, bio-enriched rock phosphate (RP), and inorganic fertilisers can be strategically applied to match the unique requirements of various crops (Giro et al., 2015; Mukherjee et al., 2019) as topdressing, incorporated into the soil during planting, utilized as basal dressing (Giro et al., 2015), side dressing, or foliar application (Rady et al., 2020), depending on the specific nutrient requirements of the crop.

Tailoring co-application strategies based on soil testing and the specific nutrient requirements of crops is crucial for achieving a balanced and sustainable nutrient supply. The combination of vermicompost with bio-enriched rock phosphate and inorganic NPK has the potential to enhance nutrient retention, availability, and microbial activity throughout the crop cycle. However, implementing a split application of nutrients, especially for inorganic fertilisers, is advisable to optimize nutrient use efficiency. This targeted approach, particularly recommended for nitrogen (N) to mitigate leaching-related nutrient loss (Ghosh et al., 2022), ensures enhanced nutrient utilization. Additionally, applying phosphorus (P) and potassium (K) as a full dose during sowing, either individually or in combination with vermicompost and bio-enriched rock phosphate, proves to be a beneficial practice. The combined application of vermicompost, bio-enriched rock phosphate, and inorganic NPK demonstrates the potential to enhance soil fertility and structure by introducing organic matter (Mukherjee et al., 2019). This approach supplies phosphorus as a slow-release source crucial for plant growth and provides readily available NPK macronutrients, promoting both crop growth and soil health. Numerous studies have highlighted the positive effects of combining organic and inorganic fertilisers on crop yields, yield components, and soil properties, emphasizing the technique's potential to meet the growing nutrient demands of modern agriculture sustainably. Directly applying of 100% of the recommended dose of NPK to various crops significantly resulted in higher outputs, comparable to co-applications of chemical fertilisers and organic sources according to (Munda et al., 2016).

Research by Billah et al. (2020) and Gaddi et al. (2020) indicates that the application of organic fertilisers, alone or in combination with inorganic fertilisers, significantly increases available nitrogen, enzyme activities, and organic carbon in the soil. In the study by Billah et al. (2020), the combination of rock phosphate, poultry litter, and Pseudomonas sp. increased nitrogen levels by 36% and enzymatic activities, such as alkaline phosphatase, by 10.5%. However, Gaddi et al. (2020) observed significantly lower mean grain yields for rice (32.2%) and sesame (31.7%) compared to the 100% RDF treatment when using 50% of the recommended dose of nitrogen (RDN) through FYM combined with bio-fertilizers for N, and the recommended dose of phosphorus (RDP) through rock phosphate and phosphorus solubilizing bacteria (PSB).

Conversely, the use of inorganic fertilisers alone tends to result in lower levels of organic carbon and has minimal impact on biochemical and biological activities. Incorporating organic manure enhanced the organic carbon status of the soil by 46.2% and stimulates the activity of soil microorganisms, particularly through the production of humic acid according to Abafita et al., (2 021). The combination of vermicompost with biofertiliser contributes to maintaining higher organic carbon levels and recycling organic materials from crop residues. Research by Khourchi et al. (2022), and Elekhtyar et al. (2022) illustrates the positive impact of Phosphate Solubilizing Bacteria (PSB) on wheat and rice growth and nutrient acquisition. The concurrent use of PSB and polyphosphate yielded notable improvements in wheat's aboveground performance, characterized by increased shoot nutrient contents (P by 300%, K by 65%), high dry weight (54%), and enhanced spike numbers (50%) over the control. These enhancements were attributed to the augmented soil availability of phosphorus (by 55%) and the stimulated activities of acid phosphatase and pyrophosphatase (by 120%), as documented by Khourchi et al. (2022). Similarly, Rady et al. (2020) observed significant increases in soluble sugars by 185%, indol acetic acid by 113% and nitrogen and phosphorus content by 185% and 331%, respectively, in common beans grown under calcareous soil conditions with soil PSB application and foliar application of MAP or nano Phosphate.

Findings from Mukherjee et al. (2019) reveal significantly higher amounts of organic carbon (16.1%), water-soluble carbon (19.6%), and microbial biomass carbon (48.4%) in treatments with concurrent application of various organic sources and biofertilisers (vermicompost 2 t ha^{-1}) with PSB, Azotobacter, 50% RDF, and foliar spray Urea (2%) compared to treatments using only the recommended dosage of chemical fertilisers. In (Table 4) can be seen the various methods for co-applying organic and inorganic fertilisers, emphasizing the need for sustainable management practices to maintain soil fertility and achieve profitable crop yields. The integration of both organic and inorganic fertilisers emerges as a promising approach to enhance crop yield and soil fertility.

Improved wheat shoot biomass (25% more than 100% chemical fertiliser) and yield increase by 21.2% and 189.3% over sole applications of chemical fertilizer and RP was reported by Arfan-

TABLE 4 Description of some studies reporting different methods of combining the application of vermicompost, Inorganic fertiliser, bio-enriched RP, and their effects on soil health.

Crop	Input	Application method	Effect on crop yield	Effect on soil health	References
Wheat	PSB consortium, PolyP	PSB seed inoculation, PolyP to soil at sowing	Significant increased shoot PK contents (300%, 65%), dry weight (54%), number of spikes (50%)	Increased P soil availability in 170%, MBP, APH (10 and 3 times) higher compared to uninoculated	(Khourchi et al., 2022)
Comon bean	PSB, MAP, NP	Soil PSB application and foliar MAP or nano Phosphate	significant increase in plant growth, yields, photosynthetic efficiency	increase in 158% for phosphatase activity, and 143% for phytase	(Rady et al., 2020)
Maize	PSB, RNPK, RP	RNPK and RP to soil at sowing; PSB seed inoculation	PSB and RNPK fertilization, increased physiological parameters - shoot length (34%), root length (62%), cob diameter (29%), fresh biomass (32%), dry biomass (54%)	Significantly increased PHE (63%), UE (43%), CL (71%), APH (52%), DHG (67%) and βGS (46%) over the control, improved pH (14) and OM (64%)	(Javeed et al., 2019)
Potato	Azotobacter, VAM, PSB and RDF	Azotobacter, VAM, PSB and RDF soil application at sowing time; RDF as basal	50% RDF + PSB+ Azotobacter+ VAM + Mustard cake and 50% RDF + PSB+ VAM + Azotobacter promoted better survival (98.44% and 97.91%, respectively), plant growth (181.31% and 179.18%, respectively), Leaf Area Index (7.04 and 7.06, respectively), Harvesting Index (0.828 and 0.775, respectively) and marketable yield (30.63 t ha^{-1} and 30.21 t ha^{-1} respectively).	–	(Lallawmkima et al., 2018)
Wheat	B-RP, DAP,	B-RP and DAP at sowing time.	50% B-RP, 50% DAP improved shoot biomass (25%), total P-uptake (67%), recovery efficiency of P (75%), dry matter (29%), crude protein (29%), and other yield, physiological and nutritional quality parameters	–	(Arfan-ul-Haq et al., 2021)
Wheat	PM, FYM, SSP, RP, PSB	P sources and PSB seed inoculation.	PSB inoculation improved wheat yield in all inoculated treatments (15-20%) regardless of lime levels	PSB inoculation improved P availability in 3.54%, stimulated soil acidification in 9.78% over control regardless of P sources and lime levels	(Adnan et al., 2022)
Maize	RP, SSP, PSB	RP and FYM a month before sowing, SSP and PSB at sowing time. PSB seed inoculation	50% RP, 50% SSP and PSB application improved maize yield in 35,2% and 1000 grain weight in 25.8% over the control	50% RP, 50% SSP and PSB improved P availability in 32.6% over the control, and did not change the soil OM	(Hajira et al., 2023)
Potato	AMF, PSB, NN, Mineral NP.	Dipping tubers in PSB broth media and NN. AMF during planting	Significantly higher number of tubers $plant^{-1}$ (10.80), tubers weight (122.22g) as compared to control (4.60) and (74.77 g) respectively	–	(Saini et al., 2021)
Potato	RDP, RP, PSB and AMF	–	100% P as RP (19.1 kg P ha-1) + preceding bio fertilized soybean gave higher Potato yield (20.1 t ha^{-1})	–	(Munda et al., 2016)
Rice	1/3 RDN(FYM) + 1/3 RDN (VC) + 1/3 RDN (Neem cake) + NP carriers	–	1/3 RDN(FYM) + 1/3 RDN (VC) + 1/3 RDN (Neem cake) + NP carriers showed higher mean grain yield of paddy (3834 kg/ha^{-1}), 19% less than 100 CF	1/3 RDN(FYM) + 1/3 RDN (VC) + 1/3 RDN (Neem cake) + NP carriers improved P availability in 6.12% and OC in 44.08%. High available P and OC (14.28%, 64.4%) was recorded in 100% organic treatment - 1/3 RDN(FYM) + 1/3 RDN (VC) + 1/3 RDN (Neem cake)	(Gaddi et al., 2020)
Paddy	50% RDP-SSP +50% RDP- RP + PSB,	RP and SSP mixed to the soil, PSB seed inoculation	Highest dry mass (36.3% and 56.5% %) more than 100% CF and control respectively, higher P concentration on rice ((55.2%) more than 100% CF)	–	(Babulu et al., 2022)

(Continued)

TABLE 4 Continued

Crop	Input	Application method	Effect on crop yield	Effect on soil health	References
French bean	75% RDF + 25% (N) Vermicompost + Biofertiliser (Rhizobium+PSB)	Biofertiliser seed inoculation, VC soil incorporation, NPK as basal	Better yield (97.93 q/ha^{-1}) as compared to other treatments	–	(Parween et al., 2019)

B-RP, bio activated rock phosphate; PHE, Phosphomonoestarase; UE, Urease; CL, Catalase; APH, Acid Phosphate; DHG, Dehydrogenase; Bgs, β-glucosidase; VAM, Vesicular Arbuscular Mycorrhiza; Phosphate Solubilizing Bacteria (PSB); MBP, Microbe biomass phosphorus; OM, Organic Matter; RDF, recommended dose fertiliser; NP, Nitrogen and Phosphorus; NN, Nitrosomonas + Nitrobacter; AMF, Arbuscular Mycorrhizal Fungi; NP, Nano Phosphate; MAP, Monoammonium Phosphate; MBP, Microbial biomass Phosphorus; PolyP, Polyphosphate.

ul-Haq et al. (2021) through the application of bio-activated RP and DAP (B-RP 50% P + DAP 50% P). The results suggest that the conditions imposed by the treatment might have improved organic matter content, soil porosity, water, and nutrient holding capacity which in turn, assured continuous and uninterrupted nutrient supply to the wheat crop to meet its nutritional requirements resulting in improved wheat uptake and yield comparatively to sole application of DAP (100% P). Due to the activation of native phosphorus by the increased PSB activity in the rhizosphere following PSB application, which results in greater phosphorus solubilization and consequently increased plant growth and yield, several authors highlight the benefits of combining the use of vermicompost, bio-enriched rock phosphate, and chemical fertilizer.

Research conducted by Li et al. (2018); Javeed et al. (2019); An et al. (2022); Babulu et al. (2022) demonstrates significant improvements in the nutrition and yield of alfalfa, rice, sweet potatoes, and maize, with increases of 56.3%, 82.1%, and 15%, respectively. This improvement was positively correlated with increased enzyme activity (20.6%), total organic acid (233.3%), phosphorus uptake (69.6%), and microbial biomass carbon (182.7%) over chemical fertilizer treatments. These benefits were observed in treatments combining organic manures, chemical fertilizers as basal application, and phosphate-solubilizing bacteria (PSB) as seed inoculation, which led to reduced soil pH, increased phosphorus solubilization (by 95%), and enhanced phosphorus availability for plant uptake. PSB applied in conjunction with recommended mineral NPK or rock phosphate (RP), or in mixed inoculation with arbuscular mycorrhizal fungi (AMF) at sowing time, outperformed single inoculation or non-inoculated treatments. However, a study by Adnan et al. (2022) found that the application of 100% RP with PSB at sowing time was as effective as sole single super phosphate (SSP) in alkaline soils, recording statistically similar wheat yields (33.8 grains spike^{-1} and 34.5 grains spike^{-1}). Additionally, organic carbon contents and soil phosphorus levels were comparable to those observed with SSP (0.81% OC, 5.5 mg kg^{-1}, and 5.07 mg kg^{-1}, respectively).

In a study on the residual effect of phosphorus (P) in the soybean-potato cropping system with and without biofertilisers (PSB, AMF) as seed inoculation, Munda et al. (2016) observed that, at the recommended dose, tuber yield (19.1 t ha^{-1}) from the residual effect of RP and biofertilisers was comparable to DAP treatments (20.1 t ha^{-1} and 19.0 t ha^{-1}) with and without biofertilisers, respectively. This suggests that the beneficial residual effect of PSB in soils contributed to the prolonged existence of bacterial and fungal strains in the soybean-potato cropping system. Hajira et al. (2023) conducted research to assess the impacts of integrating SSP with FYM or RP and PSB in maize. The results indicated that 50% RP, 50% SSP, and PSB as seed inoculation were the most suitable combinations for enhancing P availability by 39.2% over the control under calcareous soils and for boosting maize production by 42.1% and yield components. The findings align with those of Abbasi et al. (2015); Lallawmkima et al. (2018); Demir et al. (2023), and Saini et al. (2021). These researchers similarly observed enhanced yields across various crops: chili yields increased by 44% under a treatment of 50% rock phosphate (RP) + 50% diammonium phosphate (DAP) + phosphate-solubilizing bacteria (PSB); lettuce and broccoli yields improved by 20% and 8.57%, respectively, under 100% chemical fertilizer (CF) + biofertilizer (BF); potato marketable tuber yields reached 30.63 t ha^{-1} under a treatment of 50% recommended dose of fertilizer (RDF) + PSB + Azotobacter + vesicular-arbuscular mycorrhizae (VAM) + mustard cake; and broccoli yields increased to 1319.9 kg plant^{-1} under a treatment of arbuscular mycorrhizal fungi (AMF) + PSB + Nitrosomonas and Nitrobacter (NN) + 75% urea + superphosphate. The increased microbial activity resulting from these inoculations likely contributed to improved soil quality, thereby stabilizing the soil's biophysical and chemical composition while reducing polyphenol activity in oxidative stress environments.

Furthermore, the addition of organic matter and litter to the field through bioturbation and/or leaching, combined with microbial inoculants and agrochemicals, stimulates the production of phytohormones such as gibberellin and auxin, among others, which encourage crop growth and reduces the need for inorganic fertilisers as reported by Ahmed et al. (2022). Co-applications of organic and inorganic sources are advised for better crop performances because PSB in RP or vermicompost can enhance P-solubilization and availability of the RP or inorganic phosphate complexes and decrease P-fixation by the bacterial secretion of the organic acids (Javeed et al., 2019; Khourchi et al., 2022; Demir et al., 2023). When used in conjunction with chemical fertilisers, vermicompost - which is generally rich in organic matter, advantageous microorganisms, and vital plant nutrients - has a very favorable effect (Zhao et al., 2017; Ajibade et al., 2022). This is because the nitrogen (N) in the fertiliser is readily absorbed by the plants, but the N in the vermicompost ensures nutrition throughout the crop cycle (Rajkhowa et al., 2017) and enhances the physical characteristics of the soil, such as moisture retention (Aslam et al., 2019). These effects have an impact on biomass production, growth, and crop yields. Contrarily, Chaves et al. (2013) asserted that the application of phosphorus sources and phosphate-solubilizing bacteria (PSB) as inoculation, specifically under 100% triple superphosphate (TSP applied at sowing furrow), 100% rock phosphate (RP applied as a surface broadcast application without incorporation), or a combination of 50% TSP and 50% RP, did not impact maize yield. These treatments yielded 7296.28 t ha^{-1}, 6428.19 t ha^{-1}, and 6665.16 t ha^{-1} respectively, with no statistically significant differences observed, likely due to the medium level of P on the experimented soil (6,61 mg dm^{-3}) which met the plant's phosphorus requirement in the absence of available phosphorus from rock phosphate (RP). This aligns with the results of Irungbam et al. (2018), whose experiment demonstrated markedly enhanced growth and yield characteristics by 8.38% in potatoes with the 100% mineral RDF (NPK) treatment over the organic treatments (all applied at final land preparation). Notably, the organic treatment containing one-third of the recommended nitrogen (N) each from farmyard manure, vermicompost, and neem cake, along with rock phosphate, phosphorus-solubilizing bacteria, and Azotobacter, exhibited significantly higher organic carbon (OC) by 30%, total nitrogen (TN) by 10.29%, available phosphorus by 11.3%, and available potassium by 4.58% over the 100% RDF. In another study, Gaddi et al. (2020) also noted significantly least mean in grain yield of rice (32.2%) and sesame (31.7%) over 100% RDF on treatment comprising 50% recommended dose of nitrogen (RDN) through FYM + bio-fertilisers for N + Recommended dose of phosphorus (RDP) through rock phosphate + phosphorus solubilizing bacteria (PSB). However, similar to Irungbam et al. (2018), 100% organic treatment improved major and micronutrients and soil fertility status. These findings underscore that the success of co-application strategies hinges on several variables, including crop type, climate, soil type, and effective management practices. Therefore, evaluating the impact of co-application and adjusting nitrogen management strategies through routine soil testing and crop performance monitoring are essential steps. Moreover, when applying vermicompost, bio-enriched rock phosphate (RP), and inorganic NPK fertilizers in combination, it is crucial to consider the specific crop requirements and soil conditions. Methods of application may include inoculating phosphate-solubilizing bacteria (PSB) at seeding or thoroughly incorporating them with soil at sowing time; broadcasting rock phosphate (RP) on the soil surface without incorporation or as a basal application during final land preparation; applying vermicompost as a basal dressing at final land preparation and incorporating it into the soil; and applying mineral fertilizers as a basal application in the furrow at sowing time, particularly splitting nitrogen (N) into two or three applications. The combination of vermicompost, RP, PSB, and chemical fertilizers can vary, such as using 2 to 10 t ha-1 of vermicompost with a full dose of RDF NPK or 25% of RP, and biofertilizers. A precise blend may include incorporating 25% of the recommended nitrogen from vermicompost, 25% of the recommended phosphorus as RP, and 75% of the recommended NP dose from mineral fertilizers. Utilizing different strains of PSB or various biofertilizers can optimize nitrogen and phosphorus efficiency and enhance mineralization and solubilization effects. With proper management, applying organic manures, including biofertilizers alone or in combination with inorganic fertilizers, has the potential to increase crop yields, improve soil health, and mitigate agriculture's adverse environmental impacts.

3.1.9 Synergies of vermicompost, fertilizers, and bio-enriched rock phosphate in nutrient management

Vermicompost, as an organic manure rich in organic matter, mineral nutrients, and beneficial microorganisms, has the potential to enhance soil health and nutrient availability (Sangeeth, 2016). Likewise, bio-enriched rock phosphate is the process of composting or vermicomposting organic materials, adding RP to the process with or without PSB which provides a slow-release source of phosphors (Ajibade et al., 2023). Due to its high nutrient profile, microbial density, diversity, and enzymatic activity, vermicompost (Rajkhowa et al., 2017) and bio-enriched RP (Arfan-ul-Haq et al., 2021) application combined with inorganic fertilisers are considered by many researchers to have positive effects and to be relevant as a method for ensuring a more balanced and sustainable nutrient supply to plants and quality (Babulu et al., 2022; Nadia et al., 2023).

The use of vermicompost, bio-enriched phosphate rock, and inorganic fertilisers in combination can decrease reliance on chemical fertilisers (Mpanga et al., 2018) while simultaneously increasing crop output and improving soil health, according to many authors. The results of the Mamnabi et al. (2020) experiment showed that the application of combined fertilisers (1/3 CF + 1/3 VC + PGPR inoculation) on rapeseed significantly improved all growth parameters, biochemical attributes (reducing proline content by 18% and leaf temperature 16.09%, increasing the activities of antioxidant enzymes, soluble sugars by 35.11%, chlorophyll content by 72.3%, leaf water content by 12.7%, membrane stability index by 7.9%, and stomatal conductance 40.9%), and grain yield (124.17 g m^{-1}), compared to CF (89.23 g m^{-1}), under different irrigation intervals. It was then concluded that the application of combined fertilisers reduced chemical fertilization by approximately 67% and mitigated the negative effects of water limitation on rapeseed performance in the field (see Table 4).

Similarly, Abawari et al. (2021) assessed the effectiveness of the best-performing bacterial and fungal isolates for phosphate solubilization in combination with vermicompost (VC) for improved coffee yield attributes. When VC was used 20.70 g shoot fresh weight was recorded which was compared favorably to chemical fertiliser (10.59 g shoot fresh weight), whose approach was advisable as a bio-inoculant for solubilizing inorganic phosphate and to obtain vigor and healthier coffee seedlings in the southwest soil of Ethiopia for the cultivation of Arabica coffee. In (Table 5) is possible to see how authors Ahmed et al. (2022) and Devi et al. (2013) agree with Abawari et al. (2021) in the experiments on tomatoes and soybeans, respectively. According to their research, the application of PSB and vermicompost significantly lowers production costs without affecting yield and using these materials with a lower rate of chemical fertiliser (75%) improved soil and plant nutrients status and improved the growth and yield traits of tomatoes and soybeans. In other studies, Irungbam and Pramanick, (2016) and Kant et al. (2021) reported identical above-mentioned effects on groundnut and marigold, respectively, combining (VC, PSB, Azospirillum, and RP) and (VC, PSB, RP, and CF). With Irungbam and Pramanick, (2016) maximum pod yield of 2501.23 kg ha^{-1} was observed in 50% recommended NPK (inorganic) + 50% N as FYM which was statistically at par with organic-based nutrient management (1/3 of recommended N each from FYM, VC and NC along with Rhizobium, RP and PSB) 2426.67 kg ha^{-1}. The improved crop performance under integrated fertiliser application may be attributed to a steady supply of nitrogen, phosphorus, and potassium from inorganic sources in the early stages of the crop's growth, as well as slow-release nutrients and an improvement in the physical properties of the soil using organic manure in later stages of the crop's growth. The highest seed yield of soybean (1760 kg ha^{-1}, 1809 kg ha^{-1}, and 1843 kg ha^{-1}) was achieved with the application of vermicompost at 2.5 t ha^{-1}, 60 kg P_2O_5, and seed treatment with Rhizobium + PSB, as reported by Desai et al. (2019). This increase in yield is likely due to improved soil physical properties, including enhanced water holding capacity, and a greater increase in soil organic carbon and plant nutrients. In treatment comprising a combination of rock phosphate treated with Pseudomonas striata, vermicompost 12 t ha^{-1}, PSB and mycorrhiza Pezeshkpour et al. (2014) reported an increase in yield of chickpea by 27.43% and 159.7% over the application of RP and mycorrhiza, or with PSB, respectively. However, under water stress conditions, the combination of 1/3 CF + 1/3 VC + PGPR on rapeseed significantly improved grain yield by 39.15% and increasing the activities of polyphenol oxidase enzymes, by 99.5% compared to CF as reported by Mamnabi et al. (2020). The chemical fertilization treatment produced higher yields under normal irrigation water supplies (263.11 g m^{-1}). However, under stress, the same treatment produced lower yields (89.23 g m^{-1}) than biofertiliser (133.03 g m^{-1}), vermicompost (124.17 g m^{-1}), or combination treatments (156.82 g m^{-1}). These results were likely caused by the reduction of water stress damages through the application of biofertiliser, as well as the increased beneficial effects of PGPR resulting from soil nutrient supply and microbial biomass from vermicompost.

The synergy of organic and inorganic inputs not only reduces dependence on chemical fertilisers but also yields positive impacts on both crop production and soil quality. While the results have been encouraging, it's imperative to address challenges associated with production costs, ecological implications, and potential constraints linked when considering combined applications (Pezeshkpour et al., 2014). Despite these hurdles, extensive research across various crops - ranging from tomatoes and soybeans to groundnut, marigold, and rapeseed - consistently underscores the economic and agronomic advantages of integrating organic and inorganic fertilisers. However, the effectiveness of this integrated strategy hinges on meticulous considerations of factors such as soil pH, microbial activity, and the specific requirements of each crop.

The slow-release properties of bio-enriched phosphate rock and the organic matter from vermicompost (Arfan-ul-Haq et al., 2021) help lessen the problem of nutrients seeping into groundwater (Abawari et al., 2021) that is frequently associated with chemical fertilisers (Gaddi et al., 2020). By doing this, the danger of eutrophication and water contamination is reduced. Because of the helpful bacteria and organic matter found in vermicompost, which can improve soil structure, moisture retention, and nutrient cycling, less often application of chemical fertilisers is necessary to maintain healthy soil (Sangeeth, 2016; Ajibade et al., 2023). Vermicompost, which is rich in nutrients, and slow-release phosphorus from bio-enriched rock phosphate can be combined to improve crop quality and perhaps boost yields (Arfan-ul-Haq et al., 2021). This is especially advantageous for crops that require a lot of nutrients. Although vermicompost and bio-enriched rock phosphate may have upfront costs, the long-term advantages include a decreased need for and overreliance on chemical fertilisers (Pezeshkpour et al., 2014), which saves farmers money while also promoting environmental sustainability through sustainable soil management and farming practices (Ahmed et al., 2022). However, the site-specific consideration of parameters (such

TABLE 5 Integrated application of vermicompost, bio-enriched rock phosphate, and inorganic fertilisers effect on crop production.

Crop	Effect on crop growth and yield				Reference
	Sole PSB	Sole CF	Sole VC	Integrated approach	
Coffee	8.88 g shoot fresh weight	10.59 g shoot fresh weight	10.35 g shoot fresh weight	PSB + VC: 20.70 g shoot fresh weight	(Abafita et al., 2021)
Soybean	–	1261 Kg ha^{-1}	1288 Kg ha^{-1}	75% RDF + VC+ PSB: 2035 Kg ha^{-1}	(Devi et al., 2013)
Tomato	–	1.26 t ha^{-1}	–	VC+PSB+75%RD: 1.39 t ha^{-1}	(Ahmed et al., 2022)
Groundnut	–	2107.47 kg ha^{-1}	–	1/3VC+RP+PSB + Azospirillum: 2426.67 kg ha $^{-1}$	(Irungbam and Pramanick, 2016)
Marigold	–	19.61 cm	–	50%VC+RP+PSB + Rhizobium + 50% CF: 31.80 cm plant height	(Kant et al., 2021)
Soybean	PSB + Rhizobium: 1843 kg ha^{-1}	1809 kg ha^{-1}	1760 kg ha^{-1}	–	(Desai et al., 2019)
Rapeseed	221.25 g m^{-1}	263.11 g m^{-1}	224.66 g m^{-1}	1/3 CF + 1/3 VC + inoculation PGPR: 249.48 g m^{-1}	(Mamnabi et al., 2020)

PGPR, plant growth promoter rhizobacteria; VC, vermicompost; CF, chemical fertiliser.

as crop needs and soil conditions) (Pezeshkpour et al., 2014) is necessary for the integrated approach to be implemented successfully (Javeed et al., 2019). The importance of farmer education, training, and extension services in fostering the adoption of sustainable practices and maximizing the use of these production elements should also be emphasized.

3.1.10 Potential synergy between vermicompost, inorganic fertilizers, and bio-enriched rock phosphate as bio-alleviators of several abiotic and biotic stresses

Combining vermicompost, inorganic fertilizers, and bio-enriched rock phosphate can create a synergistic approach to addressing various abiotic and biotic stresses in agriculture. Each component brings unique attributes, and together they offer a more holistic and sustainable method for enhancing plant growth, health, and resilience.

Vermicompost, with its high organic matter content and beneficial microorganisms, improves soil structure and promotes microbial diversity (Anbazhagan et al., 2024; Rivier et al., 2022). It helps enhance soil aggregation and water retention, which can be crucial in managing stresses like soil salinity and drought (Robin et al., 2018; Rehman et al., 2023). By fostering a diverse microbial ecosystem, vermicompost can also protect plants from diseases and pests through natural competition and antagonism against harmful organisms (Tikoria et al., 2022; Robatjazi, 2023). Inorganic fertilizers, on the other hand, provide a rapid source of essential nutrients (Koireng et al., 2022), which can be crucial in high-intensity agricultural systems where quick plant growth is desired. They offer a concentrated and controlled supply of nutrients like nitrogen, phosphorus, and potassium, which can boost plant growth and productivity. However, the challenge with inorganic fertilizers is that they can lead to soil degradation, nutrient leaching, and reduced microbial activity if used excessively (Sangeeth, 2016; Bezabeh et al., 2021; Ghosh et al., 2022). Bio-enriched rock phosphate adds another layer of sustainability to this combination. Rock phosphate, a natural source of phosphorus, is bio-enriched with beneficial microbes that can enhance phosphorus availability to plants (Jha et al., 2021; Ajibade et al., 2023). Phosphorus is a critical nutrient for root development, energy transfer, and overall plant health (Caione et al., 2018). The bio-enrichment process helps solubilize phosphorus (Yu et al., 2014), making it more accessible to plants, while also contributing to a balanced soil microbiome (Tahir et al., 2018; Jha et al., 2021).

When these three components are combined, they can complement each other to address abiotic and biotic stresses effectively. Vermicompost's ability to improve soil structure (Caione et al., 2018) and increase organic matter content creates a conducive environment for the beneficial microbes in bio-enriched rock phosphate (Pezeshkpour et al., 2014; Rajkhowa et al., 2017; Qasim et al., 2018; Rehman et al., 2023). This combination enhances phosphorus uptake and promotes healthier root development, which can improve plant resilience to drought and salinity. Under salinity stress, Masrahi et al. (2023) reported that the use of bio-fertilizers increased plant tolerance. Barley exhibited high growth and yield with the combination of AMF + 100% RDP resulting in a 10.3% and 10.1% increase, respectively, followed by the combination of PSB + 100% RDP, which led to 4% and 8.7% increases in growth and yield, respectively, compared to the use of 100% mineral P fertilizer. In another study, Hoque et al. (2022) reported that the combined application of a full dose of mineral nutrients and vermicompost (10 t ha^{-1}) significantly increased grain yield by 25% and 5.67% compared to the 100% mineral fertilizer and control treatments respectively. This increase was attributed to improved nutrient supply and uptake, particularly of nitrogen and phosphorus, in rice. This highlights the importance of vermicompost in enhancing soil health, while soluble fertilizers readily feed plants. Additionally, Munda et al. (2016) reported a maximum yield of 1.56 t ha^{-1} with the application of rock phosphate at the recommended dose along with biofertilizers. Additionally, the soil application of biofertilizers resulted in the highest protein content in soybean seeds (38.89%), indicating that qualitative improvement in crops is possible with the combined use of fertilizers and biofertilizers. The synergy between these components can also mitigate the downsides of inorganic fertilizers (Robin et al., 2018; Tahir et al., 2018; Ni et al., 2023). Due to their contribution to soil organic matter and microbial diversity (Yu et al., 2014; An et al., 2022), vermicompost and bio-enriched rock phosphate can reduce nutrient leaching and soil degradation often associated with inorganic fertilizers. Furthermore, the enhanced microbial activity resulting from the application of vermicompost and bio-enriched rock phosphate (Zhang et al., 2022; Rehman et al., 2023) can lead to increased natural disease resistance and pest control. Beneficial microbes can outcompete or inhibit the growth of pathogens, reducing the risk of plant diseases. This natural form of disease resistance can be especially valuable in reducing reliance on chemical pesticides, contributing to a more sustainable agricultural practice. The combination of vermicompost, inorganic fertilizers, and bio-enriched rock phosphate provides a synergistic approach to managing abiotic and biotic stresses by offering a balanced nutrient profile and supporting a healthy soil ecosystem. This integrated method can reduce the need for excessive inorganic fertilizers while maintaining high crop productivity. By leveraging the unique benefits of each component, this approach has the potential to improve soil health, enhance nutrient availability, boost plant resilience, and reduce environmental impacts, contributing to a more sustainable and productive agricultural system.

3.2 Socio-economic analysis and existing policies of vermicompost application in agriculture

The integration of vermicompost, enriched rock phosphate (RP), and chemical fertilisers in crop production offers a holistic approach for sustainable soil fertility and enhanced productivity (Kant et al., 2021). This integrated approach strives to reduce production costs by minimizing reliance on more expensive chemical fertilisers and maximizing the use of locally produced organic amendments, thereby reducing transportation needs (Billah et al., 2020; Boubekri et al., 2023). Economic analysis serves as a pivotal tool to gauge the performance of improved management practices in agricultural systems. In contrast to the use of solely chemical methods, existing research consistently links higher cultivation costs to organic fertilisers within integrated nutrient management (INM) (Zubair et al., 2019; Koireng et al., 2022; Thakur et al., 2023; Zhang et al., 2023). Despite these increased costs, the INM treatments yield higher net returns compared to relying solely on chemical fertilisers (Kumar and Pandita, 2016; Bezabeh et al., 2021; Ghosh et al., 2022), and the opposite is wounded by K. G. Vyas et al. (2013) who reported the optimal net return, with a benefit-cost (B:C) ratio of 2.45, achieved through the application of DAP followed by RP incubated with FYM and PSB. In the soybean-potato cropping system, Munda et al. (2016) reported a higher benefit-cost (B:C) ratio (1.77) and higher net return (15.9) in the treatment comprising 50% P as rock phosphate (RP), phosphorus-solubilizing bacteria (PSB), and vesicular arbuscular mycorrhizae (VAM) compared to 100% recommended dose of phosphorus (RDP) as diammonium phosphate (B:C ratio of 1.55 and net return of 14.9, respectively). This was comparable to the treatment with 50% RDP as diammonium phosphate combined with biofertilizers (B:C ratio of 1.74 and net return of 15.9, respectively).

Studies by Ghosh et al. (2022) highlight that while the use of organic manures, such as vermicompost, may be associated with higher cultivation costs, INM treatments, when compared to exclusive chemical use, demonstrate superior net returns. However, it is observed that the benefit-cost ratio for treatments involving sole vermicompost tends to be lower, potentially due to the higher cost associated with vermicompost in comparison to farmyard manure (Changkiri et al., 2023). Conversely, insights from Zargar's et al. (2022) show that employing vermicompost in agricultural treatments may result in higher cultivation costs, consequently influencing the benefit-cost ratios in comparison to treatments utilizing farmyard manure. Specific treatment combinations, such as the one involving 75% inorganic nitrogen, vermicompost, Azotobacter, and phosphate-solubilizing bacteria, have been identified as yielding the maximum benefit-cost ratios. Further, Zargar et al. (2022) emphasized his observation that the inclusion of vermicompost in treatment combinations leads to an increase in cultivation expenses, subsequently diminishing the benefit-cost (B:C) ratios when compared to treatments incorporating farmyard manure (FYM). Notably, the treatment with the highest B:C ratio (1:2.55) involved 75% inorganic nitrogen, vermicompost, Azotobacter, and phosphate-solubilizing bacteria, contrasting with the control treatment (100% NPK + FYM) which exhibits a B:C ratio of 1.96 (Koireng et al., 2022; Zargar et al., 2022). Conversely, Khangarot et al. (2022) reported a noteworthy improvement in the B:C ratio of mungbean when treated with RP-enriched compost and microbial inoculants, in stark contrast to the control group. Importantly, these treatments exhibited superior economic returns compared to the individual application of PROM (RP-enriched compost), VAM, PSB, and PF. The primary incentive for farmers to cultivate crops stems from the prospect of greater economic benefits (Zhang et al., 2023). The role of chemical fertilisers in providing direct nutrients to plants, thereby influencing crop growth and productivity, is crucial for understanding the cost-benefit dynamics (Koireng et al., 2022). Notably, the economic advantages of chemical fertilisers become apparent when considering gross productivity, emphasizing the significance of balancing cost considerations with the preservation or enhancement of soil health (Irungbam et al., 2018). By improving soil health and nutrient availability, vermicompost and enriched rock phosphate contribute to crop resilience, resulting in more reliable yields and economic benefits. However, it is essential to recognize that the economic advantages may vary based on several variables, including the specific crop, soil characteristics, climate, and management techniques employed. Consequently, site-specific economic analyses are crucial for a more accurate evaluation of these benefits. Studies by Hajira et al. (2023) emphasize the significance of phosphorus management, reporting maximum yield returns and the highest value-cost ratios for plots amended with combinations of farmyard manure, single superphosphate, and phosphate-solubilizing bacteria. They observed the highest value cost ratio (VCR) of 3.08 on plots amended with 100 kg P_2O_5 ha^{-1}, sourced equally from farmyard manure (FYM) and SSP along with PSB, outperforming all other treatments studied. However, a high yield return and a VCR of 2.7 on plots amended with 100 kg P_2O_5 ha^{-1}, sourced equally from rock phosphate (RP) and single superphosphate (SSP) along with PSB, compared to mineral fertilizer alone was also reported. Integrated approaches, particularly those involving organic manures and biofertilisers, are deemed more economical than solely applied mineral fertilisers. Nevertheless, Lallawmkima et al. (2018) findings suggest that biofertilisers, such as Azotobacter, vesicular arbuscular mycorrhiza (VAM), and phosphate-solubilizing bacteria (PSB), contribute to the cost-intensive nature of nutrient management. Zhang et al. (2023) experiment on vermicompost application underscores that while it increases production costs, the subsequent improvement in yield substantially enhances net income and overall economic benefits. Additionally, Kumar and Pandita (2016) study highlights that the combination of biofertiliser inoculation with inorganic fertilisers produces higher mean cost-benefit ratios, demonstrating the positive effects of integrating biofertilisers and chemical fertilisers. These findings align with the broader recommendation that farmers are encouraged to integrate vermicompost and biofertilisers with chemical fertilisers to achieve optimal, economically viable, and sustainable crop production while ameliorating soil health. However, it's crucial to acknowledge the variability in economic outcomes based on different nutrient management strategies, emphasizing the need for informed decision-making and context-specific approaches in agricultural practices.

Upon an extensive review of the available literature, a noticeable void emerges concerning the exploration of social issues that significantly influence the utilization of vermicompost in agricultural systems. The literature survey indicates a lack of comprehensive approaches that delve into the socio-cultural dimensions governing the adoption of vermicomposting methods. However, studies such as that of Shiduzzaman et al. (2018) shed light on farmers' perceptions of the benefits and limitations of vermicompost, revealing that age and training experience significantly influence these perceptions. Hasan et al. (2021) further contributed to this understanding by identifying factors like family size, income, and training received on vermicompost as key determinants of farmers' perceptions regarding vermicomposting as waste management practices and economic contributors. Equally striking is the dearth of literature addressing prevailing policies regarding the use of vermicompost in agricultural systems. Policies are pivotal instruments that guide and regulate agricultural practices, and their absence from the reviewed literature suggests a crucial gap in understanding the institutional frameworks surrounding vermicompost application. Overcoming this knowledge gap is imperative for the development of informed policies that not only promote the technical benefits of vermicompost but also account for the social intricacies influencing its adoption. Pierre-Louis et al. (2021) mentions in their study that vermicomposting is not widely practiced in South Pacific Island countries (SPICs) primarily due to a lack of awareness about its applications. However, public awareness campaigns and educational programs should therefore be integrated into policies promoting vermicompost. Governments and non-governmental organizations (NGOs) can implement programs aimed at educating farmers and the public about the benefits of composting and organic fertilizers. These initiatives are crucial for increasing acceptance and understanding of vermicompost as a valuable resource for sustainable agriculture. Additionally, Rastegari et al. (2023) suggested that enhanced understanding of vermicomposting has the potential to diminish prevailing barriers driven by misconceptions, underscoring the necessity of integrating vermicompost into regional sanitation and agricultural policies in Iran. Nevertheless, the limited awareness of this technology among policymakers constrains the impact of regulatory measures. Successful case studies demonstrating the efficacy and effectiveness of vermicompost could play a pivotal role in garnering political support for its adoption. Devkota et al. (2014) study has emphasized the absence of adequate policy guidelines for vermicompost production, processing, and marketing in Nepal, underscoring the need for comprehensive regulatory frameworks to bolster the vermicompost industry's development and sustainability. This lack of guidance may hinder the scalability and sustainability of vermicompost enterprises, emphasizing the importance of government intervention and industry collaboration in establishing clear standards and regulations. While existing studies have provided valuable insights into the technical efficacy of vermicompost, there appears to be a distinct oversight regarding the broader social landscape that shapes its incorporation into diverse farming systems. Addressing these dual voids in the literature is essential for advancing a more holistic and socially responsive approach to the integration of vermicompost in agricultural systems.

4 Conclusion and way forward

The integration of vermicompost, bio-enriched RP, and inorganic fertilisers heralds a progressive and sustainable approach in agriculture. This strategy not only mitigates the environmental impact of chemical fertilisers but also promotes soil health, striking a balance between agricultural productivity and ecological well-being. Vermicompost, a cornerstone of this approach, enriches soil with organic matter and essential nutrients, thereby improving soil fertility and structure. Meanwhile, bio-enriched RP addresses phosphorus deficiency, a pivotal nutrient for robust plant growth. Inorganic fertilisers, when used judiciously, serve as supplements to rectify nutrient imbalances, and enhance crop yields. However, responsible nutrient management is crucial to avoid adverse environmental consequences.

Unsustainable agricultural practices, characterized by excessive chemical fertiliser usage, can lead to soil degradation over time. To effectively address nutrient management challenges, an Integrated Plant Nutrient System (IPNS) should integrate vermicompost, inorganic fertilizers, and bio-enriched rock phosphate (RP). Nitrogen can be managed by applying 75% to 100% of the recommended dose from mineral fertilizers, supplemented organic sources like vermicompost (2.5 to 10 t ha^{-1}), significantly enhancing yields and growth parameters compared to relying solely on mineral fertilizers. For phosphorus, applying 75% or 100% of the recommended dose of mineral phosphorus (RDP) with phosphate-solubilizing bacteria (PSB) enhances availability and uptake, while using 100% of the recommended dose of RP combined with multiple PSB strains and/or arbuscular mycorrhizal fungi (AMF) improves phosphorus solubility and plant uptake, resulting in improved growth and yield. Biofertilizers play a critical role; PSB strains, either alone or combined with AMF, boost crop yields and nutrient uptake, while integrating AMF enhances phosphorus uptake and overall plant performance. Additionally, incorporating beneficial microorganisms such as plant growth-promoting rhizobacteria (PGPR) improves soil health and crop productivity. This integrated approach balances organic amendments (e.g., vermicompost, green leaf manure, farmyard manure) with inorganic fertilizers to optimize nutrient availability, enhance soil structure, and improve fertility. Adjusting application rates based on soil tests and crop needs, such as using 75% of the recommended NPK fertilizers with 50% to 25% nitrogen from vermicompost, reduces reliance on chemical inputs while ensuring high yields and sustainable agricultural practices. This holistic approach not only enhances soil health and preserves biodiversity but also ensures sustained agricultural production. Various factors such as RP grades, soil properties, and crop requirements influence the effectiveness of this integrated approach. While blending organic and inorganic sources offers numerous benefits, precise recommendations depend on factors like crop type and specific circumstances. The efficacy of bio-enriched RP and vermicompost hinges on processing techniques and financial constraints, although challenges such as limited availability and lack of standardization in biofertiliser production need addressing. Addressing soil fertility and sustainability comprehensively involves adjusting soil pH and adopting eco-friendly practices. The synergy between organic and inorganic fertilisers, tailored to specific crops and environmental conditions, emerges as a pivotal strategy. However, deploying these fertilisers requires a nuanced approach considering various factors influencing crop production, soil health, and economic outcomes.

Economic analysis consistently indicates higher cultivation costs associated with organic fertilisers within integrated nutrient management (INM). Nonetheless, INM treatments yield superior net returns compared to exclusive chemical use, highlighting the benefits of nitrogen from farmyard manure (FYM). Specific treatment combinations, such as those incorporating inorganic nitrogen, vermicompost, Azotobacter, and PSB, maximize benefit-cost ratios. Moreover, chemical fertilisers play a crucial role in providing direct nutrients to plants, thereby enhancing crop growth and productivity. Enriched RP reduces nutrient runoff, enhances soil fertility, and potentially reduces the need for frequent chemical fertiliser applications, ensuring both environmental sustainability and long-term financial rewards for farmers. However, economic outcomes vary based on factors such as crop type, soil characteristics, and management techniques. Addressing social issues in the adoption of vermicompost is crucial, considering the existing gaps in the literature regarding socio-cultural dimensions and policy frameworks. Bridging these knowledge gaps is essential for informed policy development and a more holistic approach to integrating vermicompost into agricultural systems. Further research is needed to unlock the full potential of these components, determine optimal application rates, and promote farmer education for sustainable agricultural practices that contribute to long-term food security.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

TS: Conceptualization, Data curation, Formal analysis, Methodology, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing. HT: Data curation, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing, Visualization. AA: Data curation, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing, Visualization. MS: Data curation, Validation, Writing – original draft, Writing – review & editing. JS: Data curation, Supervision, Validation, Writing – original draft, Writing – review & editing.

Funding

The author(s) declare that no financial support was received for the research, authorship, and/or publication of this article.

Conflict of interest

The authors declare that none of the work reported in this study could have been influenced by any known competing financial interests or personal relationships.

Publisher's note

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