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INTEGRATED APPROACHES TO ENHANCE PHOSPHORUS AVAILABILITY IN CALCAREOUS SOILS: A REVIEW

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ABSTRACT

Farmers frequently apply excessive synthetic phosphatic fertilizers, which adversely affect the environment, groundwater, microbial populations, and soil fertility. To mitigate these impacts, sustainable agriculture requires environmentally friendly, economically viable, and safe alternatives. Calcareous soils, with their high pH and $CaCO_3$ content, often limit nutrient availability, as much of the native and applied phosphorus (P) becomes adsorbed onto clay minerals and $CaCO_3$ surfaces or precipitates as calcium phosphates, resulting in utilization efficiencies of less than 20%. Climate change further complicates nutrient management by altering temperature, soil pH, and moisture conditions, thereby reducing crop productivity. Beneficial microbes such as arbuscular mycorrhizal fungi (AMF) and phosphate-solubilizing bacteria (PSB) play a crucial role in enhancing P solubility and nutrient bioavailability through various processes. Trichoderma species, notably *T. harzianum* and *T. reesei*, are effective in solubilizing phosphorus by producing phytase, which reacts with insoluble tricalcium phosphate to make it available for plant uptake. Composting processes also mobilize phosphorus in rock phosphate while providing secondary and micronutrients. For instance, farmyard manure (FYM) combined with rock phosphate through co-composting techniques enhances phosphorus release, improving nutrient dynamics. Organic amendments positively impact microbial biomass, diversity, and enzyme activities such as phosphatase production, contributing to long-term soil fertility. However, the benefits of these strategies, including improved P availability for plant growth, can vary across farming systems, emphasizing the need for tailored management practices.
***Keywords*:** Arbuscular Mycorrhizal Fungi, Calcareous soil, Phosphorus, Phosphate Solubilizing Micro-organisms, Organic amendments, Rock Phosphate

Introduction

Phosphorus (P) is the second most limiting nutrient for crop production after nitrogen. It plays a vital role in plant physiological processes, including carbon metabolism, energy generation and transfer, enzyme activation, membrane formation, and nitrogen fixation (Schachtman *et al.*, 1998). Additionally, phosphorus is a key component of essential biological molecules such as ATP, nucleic acids, and phospholipids (Marrchner, 1995). In the Indo-Gangetic plain, phosphorus deficiency is widespread, making its application critical for improving the productivity of cropping systems. In Indian soils, phosphorus exists primarily in inorganic forms, contributing 54-84% of total phosphorus, with organic phosphorus contributing 16-46% (5). While soils contain a considerable amount of phosphorus, ranging from 400-1200 mg/kg, the concentration of soluble or inorganic phosphorus (orthophosphate) is low, limiting its availability to plants and reducing crop yields.

Plants absorb phosphorus in the form of $H_2PO_4^-$ and HPO_4^{2-} within an optimal soil pH range of 6.5-7.5. However, when soil pH exceeds 7.0, inorganic phosphorus (Pi) becomes predominantly mineralized and immobilized as calcium phosphates, reducing its bioavailability. In many cases, the phosphorus balance remains negative, even when recommended fertilizer rates are applied. Consequently, the efficient use of phosphorus is critical for sustainable crop production. To compensate for low phosphorus availability, farmers often rely on synthetic phosphatic fertilizers. However, excessive use of these fertilizers adversely impacts the environment, groundwater, microbial populations, and soil fertility. Thus, there is a growing need for environmentally friendly, economically viable, and sustainable alternatives.

Beneficial microbes, such as arbuscular mycorrhizal fungi (AMF) and phosphate-solubilizing bacteria (PSB), have gained attention for their role in improving phosphorus solubility and enhancing crop productivity. These microorganisms contribute to the turnover and bioavailability of insoluble soil nutrients through various functional processes, making them an integral part of sustainable phosphorus management strategies.

Climate change presents additional challenges in nutrient management, including phosphorus. Variations in temperature, soil pH, drought, and elevated CO_2 levels significantly influence nutrient availability and translocation, thereby affecting crop productivity. Both excessively low and high soil temperatures hinder phosphorus uptake and translocation. Elevated soil pH reduces microbial activity, transpiration rates, phosphorus uptake, and its efficient utilization. Moreover, elevated CO_2 levels decrease phosphorus uptake by plants. Addressing these challenges requires innovative phosphorus management strategies to protect soil fertility, mitigate the adverse effects of climate change, and ensure sustainable agricultural production.

Phosphorus Constraints in Calcareous Soil

Calcareous soils account for more than 30% of the world's soil, with $CaCO_3$ content ranging from a few percent to as high as 95% (Marschner, 1995). In India, these soils cover approximately 69.4% (228.8 million hectares) of the total geographical area. Calcareous soils typically contain more than 15% $CaCO_3$, which may exist in various forms. These soils are commonly found in arid and semi-arid regions due to limited leaching, but they also occur in humid and semi-humid areas when the parent material is enriched with $CaCO_3$ and the soils are relatively young with minimal weathering.

The high pH and $CaCO_3$ content in calcareous soils significantly reduce the availability of essential nutrients to plants. Native phosphorus (P) and a substantial portion of applied P in these soils tend to become adsorbed onto clay minerals and $CaCO_3$ surfaces or precipitated as calcium phosphates. As a result, the efficiency of phosphorus utilization is often less than 20% (Tisdale *et al.*, 1993). This low availability of phosphorus presents a major challenge for plant growth and productivity in calcareous soils, necessitating the development of effective strategies to improve phosphorus bioavailability and utilization.

Phosphorus Management in Calcareous Soil

In India, the cost of applying conventional water-soluble phosphorus (P) fertilizers is high due to the expense associated with importing high-grade rock phosphate (RP) and sulfur. It is estimated that approximately 300 million tonnes (Mt) of RP deposits are available in India (TIFAC, 2011), but only about 25% of these deposits meet the specifications of the fertilizer industry due to their low phosphorus content. Most rock phosphates are suitable for direct application in acidic soils, where low pH facilitates RP solubilization and increases the availability of phosphorus to plants. However, these materials have not shown satisfactory results in neutral to alkaline soils (Narayanasamy and Biswas, 1998).

The depletion of high-grade rock phosphate, the primary source of phosphorus fertilizers, is expected by the year 2050 (Vance *et al.*, 2003). Direct application of rock phosphate in alkaline or calcareous soils is generally ineffective due to high pH, which inhibits phosphorus solubilization (Caravaca *et al.*, 2004). However, rock phosphate can be made more effective if allowed to react with organic acids produced during composting. This process significantly enhances the solubility of RP, making it more available for plant uptake (Singh and Reddy, 2011). In calcareous soils, phosphorus typically exists in forms such as tricalcium phosphate, dicalcium phosphate, and other mineral complexes, further complicating its bioavailability. Effective management strategies are needed to address these challenges and improve phosphorus utilization in such soils.

Phosphate-Solubilizing Microorganisms

Phosphate-solubilizing microorganisms (PSM) encompass a diverse group of organisms, including bacteria, fungi, arbuscular mycorrhizae, cyanobacteria, and actinobacteria. These microorganisms hydrolyze organic and inorganic phosphorus into soluble forms, making it bioavailable for plant uptake (Rawat *et al.*, 2021). Phosphate-solubilizing bacteria are widely present in soils and, under in vitro conditions, improve phosphorus bioavailability through several mechanisms. These include lowering soil pH, solubilizing inorganic phosphorus (Pi), activating synthesized phosphatases, mineralizing organic phosphorus, and/or chelating phosphorus from cations like Al^{3+}, Ca^{2+}, and Fe^{3+} (Sharma *et al.*, 2013; Etesami, 2020).

PSM play a crucial role in contributing to soil phosphorus pools, which constitute 0.4% to 2.4% of total phosphorus in arable soils. They maintain equilibrium in the soil solution phosphorus pool by decomposing organic residues through immobilization and mineralization. Phosphorus solubilizing activity largely depends on the microbes' ability to release metabolites, such as organic acids. The hydroxyl and carboxyl groups in these acids chelate the cations bound to phosphate, converting them into soluble forms. Additional mechanisms, including acid production, ion chelation, and exchange reactions in the microbial growth environment, have also been identified as key processes in phosphorus solubilization (Rajankar *et al.*, 2007).

Acidic soils, predominantly found in tropical and subtropical regions, are often highly deficient in phosphorus due to their strong phosphorus fixation capacity. In these soils, phosphorus is commonly associated with aluminum and iron compounds. Conversely, calcium phosphate is the primary form of inorganic phosphorus in calcareous soils. Phosphate-solubilizing microbes have demonstrated the potential to enhance soluble phosphorus availability, thereby improving plant growth. Their activity supports increased efficiency in biological nitrogen fixation and enhances plant uptake of trace elements such as iron and zinc. Additionally, these microbes produce plant growth-promoting regulators, further benefiting crop productivity.

Bacteria

The application of bacterial inoculants significantly enhances plant growth by improving phosphorus (P) availability, increasing crop yields, and releasing plant growth hormones such as indole acetic acid (IAA) and gibberellic acid, which promote cell elongation and overall plant development. Phosphate-solubilizing bacteria (PSB) are particularly important, comprising 1% to 50% of the total microbial population in soils. Among various bacterial communities, Bacillus and Pseudomonas are highly effective phosphate solubilizers. Key strains include *Bacillus megaterium, B. circulans, B. subtilis, B. polymyxa, B. sircalmous, Pseudomonas striata*, and *Enterobacter*. These bacteria facilitate the solubilization and mineralization of phosphorus, converting organic phosphorus into inorganic forms available to plants (Tandon *et al.*, 2020).

PSB secrete organic acids, such as citric and gluconic acids, which solubilize phosphorus reserves by breaking down complex phosphate compounds. Additionally, they produce enzymes like phytases and nucleases, which mineralize organic phosphorus reservoirs (Novo *et al.*, 2018). PSB are also known to produce secondary metabolites, including IAA and siderophores, which further enhance plant growth.

Numerous microbes, such as Pseudomonas, Bacillus, Xanthomonas, Nostoc, and Achromobacter, have been reported to effectively solubilize phosphorus in soils (Oteino *et al.*, 2015). Beneficial rhizobacteria, also known as plant-growth-promoting rhizobacteria (PGPR), release low molecular weight organic acids, particularly gluconic and keto-gluconic acids, that dissolve phosphatic minerals (He *et al.*, 2002). Certain PSB strains, such as Pseudomonas striata, are highly effective in solubilizing native soil phosphorus, thereby increasing its availability to plants.

In addition to phosphorus solubilization, PSB also enhance plant growth by stimulating biological nitrogen fixation, improving the uptake of trace elements, and synthesizing essential growth-promoting substances (Mittal *et al.*, 2008). These multifaceted roles make phosphate-solubilizing bacteria a valuable tool in sustainable agriculture and soil fertility management.

Fungi

Fungi are the second most important group of phosphate-solubilizing microorganisms (PSM), constituting approximately 0.1% to 0.5% of the total microbial population involved in phosphorus solubilization. Fungi generally produce more acids than bacteria, resulting in higher phosphorus solubilization activity. Additionally, fungi can traverse greater distances in soil compared to bacteria, making them more effective in solubilizing phosphorus.

Among the various fungal genera, Aspergillus, Penicillium, Trichoderma, Mucor, and Rhizoctonia solani are notable phosphate solubilizers. Other fungi, including Fusarium, Alternaria, and different species of Aspergillus and Penicillium, have also demonstrated significant phosphate-solubilizing activity (Sindu *et al.*, 2014). Studies have shown that microbial strains such as Aspergillus, along with Bacillus, Escherichia, Arthrobacter, and Pseudomonas, can solubilize up to 30-35 kg P_2O_5 per hectare.

Trichoderma harzianum, a beneficial fungus found in the rhizosphere, establishes strong root colonization by penetrating the epidermis of plant roots. This enhances root growth, crop productivity, and resistance to abiotic stresses by increasing mineral absorption (Harman, 2000). Arbuscular mycorrhizal fungi (AMF) also play a crucial role in improving phosphorus nutrition by colonizing the roots of host plants growing in soils with low or sparingly soluble phosphorus. AMF facilitate nutrient uptake through their extensive hyphal networks, which access phosphorus pools unavailable to plant roots alone (Shenoy and Kalagudi, 2005).

Fungi's ability to solubilize phosphorus and support plant health makes them an essential component of sustainable agricultural systems and soil fertility management.

Arbuscular Mycorrhizal Fungi (AMF)

Arbuscular mycorrhizal fungi (AMF) colonize almost all crop species and are instrumental in exploiting larger soil volumes for phosphorus (P) uptake, particularly in P-deficient soils. The use of AMF inoculants, combined with plant growth-promoting microbes, plays a significant role in phosphate mineralization from both organic and inorganic sources. AMF contribute to phosphorus mobilization, nutrient cycling, and the enhancement of microbial biomass in the soil. Indigenous AMF, commonly found in soils, colonize plant roots and stimulate growth, forming a symbiotic relationship that is especially beneficial for cereals and horticultural plants.

Key AMF genera, including Scutellospora, Glomus, Acaulospora, and Gigaspora, are frequently used as biofertilizers due to their ability to improve phosphorus bioavailability. Funneliformis mosseae (syn. Glomus mosseae), Rhizophagus irregularis (syn. Glomus irregulare), Clarodeoglomus, Ambispora, Archaeospora, and Diversispora have been identified in association with potato roots. Bhardwaj *et al*. (2007) demonstrated that F. mosseae is an effective colonizer of potato in greenhouse experiments, while Glomus intraradices showed higher colonization rates in arable soils (Cesaro *et al*., 2008). Phosphate-solubilizing bacteria (PSB) have been shown to positively influence AMF spore density and colonization rates.

Research highlights that sustainable soil fertility depends on harnessing the synergistic benefits of plant growth-promoting bacteria (PGPB), nitrogen-fixing microbes, PSB, Mycorrhiza Helper Bacteria (MHB), endophytes, and AMF (Barera *et al*., 2005; Smith *et al*., 2008). Recent studies have focused on microbial inoculation effects on potato, demonstrating yield enhancement (Davies *et al*., 2005; Yao *et al*., 2002), disease biocontrol (Whipps, 2004), and quality improvement (Duffy and Cassells, 2000). The dominance of Glomus intraradices among AMF associated with potato has been consistently reported (Cesaro *et al*., 2008; Pathak *et al*., 2017). Insufficient phosphorus availability in soils has been linked to underdeveloped potato tubers due to the translocation of P to tubers during maturity (Martin *et al*., 2018).

The primary benefits of PGPB and AMF lie in improving phosphorus uptake by plants. This is achieved through the activities of PSB and the external mycelium of AMF, which act as a bridge between plant roots and the surrounding soil microhabitats (Barera *et al*., 2005). Organic fertilizers made from composted materials are increasingly recognized for improving soil organic matter content, supplying nutrients, reducing dependency on chemical fertilizers, and promoting environmental health.

While AMF inoculation can be performed in greenhouses under controlled environments or directly in the field, large-scale application remains challenging. AMF are obligate symbionts, meaning they cannot be easily cultured in laboratories, and their inoculation on a commercial scale is cumbersome (Alori *et al*., 2017). However, studies indicate that inoculating potato plants with a mixture of AMF species, such as Glomus intraradices and Glomus mosseae (30 spores), results in enhanced fresh and dry matter production, along with increased root length and diameter compared to non-inoculated plants (Lone *et al*., 2015).

The combined effects of PSB and AMF on nutrient content and uptake have been extensively studied. Integrated use of chemical fertilizers, enriched compost, and seed treatments with PSB or AMF has shown significant improvements in seed yield, nutrient uptake, and soil fertility. This approach also enhances soil nitrogen and phosphorus availability, further contributing to sustainable agricultural practices.

Mechanisms of Arbuscular Mycorrhizal Fungi in Phosphorus Availability to Crops

Arbuscular mycorrhizal fungi (AMF) enhance plant growth and nutrition by efficiently accessing nutrients located beyond the root depletion zone. AMF achieve this by extending their hyphal networks into the soil, transferring phosphorus (P) from the soil to the plant at specialized interfaces such as hyphal coils, arbuscules, and vesicles (Smith *et al*., 2001). The uptake of phosphorus by AMF involves active transport mechanisms, facilitated by specific P transporters, highlighting the dynamic role of AMF in nutrient acquisition.

In addition to phosphorus uptake, AMF play a critical role in improving soil structure and aggregation (Rilling and Mummey, 2006). AMF influence the shoot-to-root ratio, plant physiology, and nutrient uptake, while also contributing significantly to soil aggregate formation during symbiosis. By interacting with plant root systems, AMF enhance the ability of roots and root hairs to bind soil particles more effectively, improving soil stability (Rilling and Mummey, 2006).

AMF hyphae bind microparticles of soil into larger macroparticles, a process supported by the production of glomalin-related proteins and mucilage. These proteins form a coating around soil particles, increasing their stability and preventing disintegration (Wright *et al*., 2007). The biochemical and biological processes facilitated by AMF not only improve soil aggregation but also create a more favorable rhizosphere environment for nutrient uptake and plant growth.

Through these mechanisms, AMF significantly contribute to sustainable agriculture by enhancing phosphorus availability, improving soil health, and supporting robust plant development.

Actinomycetes

Actinomycetes are saprophytic soil microorganisms known for their ability to produce biologically active compounds, including antifungal and antibacterial substances, as well as plant growth-promoting compounds used in agriculture. They are widely distributed across diverse natural habitats such as soils, freshwater systems, organic matter, and within plant communities (Chandramohan, 1991).

Lo *et al*. (2002) identified approximately 100 genera of actinomycetes present in soil. For example, a study conducted at the Agricultural Research Centre in Semongok, Sarawak, isolated 62 actinomycetes from seven soil samples (Jeffrey, 2008). Among these, 20% were found to have phosphate-solubilizing abilities. Key genera of phosphate-solubilizing actinomycetes include Streptomyces and Micromonospora.

Actinomycetes are filamentous, sporulating bacteria capable of thriving in diverse and extreme soil conditions. They produce a wide range of bioactive substances such as antifungal agents, insecticides, and phytohormone-like compounds, all of which benefit plant growth (Jain and Jain, 2007). These unique characteristics make actinomycetes an invaluable component in sustainable agricultural practices, particularly for enhancing soil health and promoting plant development.

Trichoderma

Trichoderma species are highly effective biocontrol agents against various soil-borne pathogens and are also recognized for their ability to promote plant growth (Benitez *et al*., 2004; Harman *et al*., 2004). These fungi are widely utilized as biofertilizers across different crop types, with or without soil amendments, due to their capacity to enhance nutrient uptake, produce growth hormones, and protect plants from pathogens (Kamal *et al*., 2018; Zhang *et al*., 2013; Chang and Baker, 1986). Trichoderma strains produce organic acids such as gluconic acid, citric acid, and coumaric acid, which acidify the surrounding environment to solubilize phosphorus, micronutrients, and mineral cations like Fe^{3+}, Mn^{4+}, and Mg^{2+}, making them more accessible to plants (Kamal *et al*., 2018; Shoresh *et al*., 2010).

The phytohormones and enzymes secreted by Trichoderma enhance plant growth, yield, nutrient absorption, phosphate solubilization, antioxidant activity, and soil conditioning (Macias-Rodriguez *et al*., 2020; Sandle, 2014). For instance, the presence of Trichoderma during seed germination promotes the production of growth hormones like gibberellic acid and indole-3-acetic acid, improving germination rates and seedling vigor (Juan *et al*., 2021). Specific species, such as *T. harzianum* and *T. reesei*, are particularly known for their ability to solubilize phosphorus through the production of the enzyme phytase, which reacts with insoluble tricalcium phosphate to release phosphorus for plant absorption (Yu *et al*., 2021; Eslahi *et al*., 2020; Yin *et al*., 2021). Additionally, T. koningiopsis produces alkaline phosphatase enzymes, further enhancing the solubilization of insoluble phosphates in the soil. Yadav *et al*. (2009) demonstrated that the presence of *T. viride* in soil significantly improved the uptake of nitrogen, phosphorus, potassium, and organic carbon in sugarcane crops, showcasing Trichoderma's potential in sustainable agriculture.

Interaction of Microbial Inoculants for Plant Nutrition

The interaction between microbial inoculants such as arbuscular mycorrhizal fungi (AMF) and Trichoderma species plays a crucial role in enhancing plant nutrition. Galindo *et al*. (2018) evaluated the interaction between AMF and *Trichoderma harzianum* in potato plants (*Solanum phureja*), demonstrating significant increases in leaf area, total biomass, aerial and root biomass, and root length compared to untreated plants and those treated with chemical fertilizers. AMF interactions with phosphate-solubilizing bacteria (PSB) have also been extensively documented. Since the 1990s, studies have shown that PSB produce organic acids that solubilize both organic and inorganic forms of phosphorus (P). These solubilized forms are made accessible to plants with the assistance of AM hyphae (Zhang *et al.*, 2014; Wahid *et al.*, 2016).

Artursson *et al.* (2006) reported that bacterial strains such as *Pseudomonas*, *Bacillus*, *Paenibacillus*, and *Rhizobia* exhibit positive associations with AMF species like *Glomus mosseae*, *G. calrum*, *G. versiforme*, and *G. intraradices*. Co-inoculation of these microbes enhances AMF growth, spore formation, root colonization, P solubility, and pathogen suppression. However, some findings suggest that the direct interaction between AMF and PSB may not always be significant, as *Glomus intraradices* lacks the phytase protein required for the utilization of phytate in soils. Despite this limitation, combined inoculation of AMF and PSB has been shown to improve rock phosphate mineralization and P uptake (Kohler *et al.*, 2006).

The synergistic application of AMF and *Trichoderma* has been reported to enhance the nutritional composition of crops such as marigold, tomato, cucumber, and melon (Calvet *et al.*, 1993; Datnoff *et al.*, 1995; Chandanie *et al.*, 2009; Martinez-Medina *et al.*, 2009). However, conflicting results exist, with some studies reporting negative effects when these two fungi are applied together (Green *et al.*, 1999; Martinez *et al.*, 2004). These interactions highlight the complexity of microbial inoculant applications and the importance of understanding their specific roles to optimize plant growth and nutrition.

Rock Phosphate

Rock phosphate (RP) is a natural and cost-effective source of phosphorus (P). However, its direct use in agriculture, especially in calcareous soils, is limited due to its low solubility and factors such as high soil pH, drought stress, bicarbonate-rich irrigation water, and the lack of organic matter in agricultural soils. The availability of phosphorus from RP can be improved through acidulation with sulfur-based minerals, sulfur, or organic matter. Composting also enhances phosphorus mobilization in RP and provides secondary and micronutrients (Cicek *et al.*, 2020).

Rock phosphate contains about 5-13% phosphorus and exists in nature mainly in igneous and sedimentary forms. Approximately 13-15% of RPs are igneous, 80-82% are sedimentary, and 2-3% are biogenic in origin (Sarikhani *et al.*, 2019). The primary mineral type in RP is apatite, which can be extracted commercially for direct application or further processing for industrial or agricultural use (Ditta *et al.*, 2018). Sedimentary RPs typically contain 30-35% P_2O_5, while igneous RPs often have less than 5% P_2O_5. However, phosphorus concentrations in RP can be increased to about 35-40% or higher through processing (El Bamiki *et al.*, 2021).

Global resources of all grades and types of RP are estimated to be approximately 163,000 million tonnes (Hellal *et al.*, 2019; Cicek *et al.*, 2020). The distribution of RP reserves worldwide includes Africa (41%), the USA (21%), the USSR (13%), the Middle East (10%), Asia (8%), South America (3%), Australia (2%), and Europe (1%) (Kumari *et al.*, 2008; Elmaadawy *et al.*, 2015). India is deficient in apatite and RP availability, relying heavily on imports for apatite. Domestically, RP is predominantly sourced from Rajasthan and Madhya Pradesh.

Table 1 : Rock phosphate reserves of the world

Countries	IFDC Reserves (product) (Mmt)	IFDC (Resources) (Mmt)
USA	18,000	49,000
Australia	82	3500
Brazil	400	2800
Canada	5	130
China	3700	16,800
Egypt	51	3400
Israel	220	1600
Jordan	900	1800
Morroco	51,000	170,000
Russia	500	4300
Senegal	50	250
South Africa	230	7700
Syria	250	2000
Togo	34	1000
Tuiisia	85	1200
Other countries	600	22,000
Total	60,000	290,000

Source: www.ifdc.org; Mmt: million metric ton; Reserves: usable or marketable product; Resources: unprocessed rock phosphate of varying grades concentration.

According to NMI data based on the UNFC system as of April 1, 2020, India's total reserves/resources of rock phosphate are estimated at 311.25 million tonnes, comprising 30.87 million tonnes of reserves and 280.37 million tonnes under the remaining resource category. India also has substantial reserves of low-grade phosphorus, which can be utilized as a nutrient source (Sharma *et al.*, 2010). Total RP resources in India are estimated at 312.67

million tonnes, of which only 45.80 million tonnes constitute reserves (Singh *et al*., 2011). Of the total resources, only 8% is fertilizer-grade, while around 37% is classified as low-grade reserves.

Organic Amendments and Phosphorus Status

Organic amendments such as livestock manures, plant residues, and compost serve as alternatives or supplements to mineral fertilizers. These amendments influence microbial biomass and diversity, leading to long-term benefits such as improved soil nutrient turnover and enhanced extracellular enzyme activities, including phosphatase production. However, the effectiveness of these amendments in improving phosphorus (P) availability for plant growth varies depending on the farming system. For instance, co-composting farmyard manure (FYM) with rock phosphate (RP) enhances P solubility and prevents its re-fixation in the soil. The product, termed phosphate-rich organic manure (PROM), can replace commercial P fertilizers. Studies have shown that combining FYM (0.5-4.0 MT/ha) with RP (40 kg/ha) significantly improves P solubility, depending on soil conditions.

Poultry manure, enriched with essential nutrients, is a more concentrated source of P compared to cattle and goat manure. However, higher amounts of P tend to be immobilized in soils with cattle and goat manure due to their elevated Al and Fe content. Composting RP with poultry manure and effective microorganisms (EM) enhances RP dissolution and P release (Khan and Sharif, 2012). Vermicompost also plays a vital role in increasing the availability of P in soils. Earthworm enzymes facilitate the breakdown of organic matter, releasing nutrients like nitrate, orthophosphate, potassium, and calcium, which improve soil fertility and plant growth (Bhat *et al*., 2018; Ghosh *et al*., 2018).

Sugar industry by-products like pressmud (PM) can also be utilized for P enrichment. Annually, India produces around 5.45 million tonnes of PM, 7.5 million tonnes of molasses, and bagasse as sugar industry waste (Satisha and Devranjan, 2007). PM is used to prepare RP-enriched pressmud compost (RPEPMC), which serves as an alternative to diammonium phosphate fertilizers. Studies have demonstrated the efficacy of enriched compost in increasing crop yields, nutrient uptake, and soil fertility (Biswas, 2011). Additionally, integrating crop residues such as rice straw into composting processes provides a sustainable way to recycle nutrient-rich biomass back to the fields. For example, rice residues, often burned in northern India, contain significant amounts of N, P, K, and S, making them valuable for compost production (Singh *et al*., 2005).

The impact of combined organic amendments has been highlighted in various studies. For instance, the application of sulphinated pressmud cake (SPMC) with *Trichoderma viride* and phosphorus-solubilizing bacteria (PSB) significantly improved the availability of macro- and micronutrients in calcareous soils (Ram *et al*., 2024). Similarly, the incorporation of rice straw (5 t/ha), biofertilizers (Azotobacter, PSB, *T. viride*, 5 kg/ha each), and vermicompost (7.5 t/ha) enhanced potato growth, yield, and nutrient uptake at the TCA Research Farm in Bihar. In mustard-rice cropping systems, FYM proved superior to biogas slurry in increasing nutrient uptake by rice, while biogas slurry performed better for mustard (Rakesh and Kumari, 2020). These findings underline the importance of organic amendments in enhancing soil fertility, nutrient cycling, and sustainable crop production.

Conclusion

Managing phosphorus (P) nutrition in calcareous soils is essential for sustainable agriculture, given the limitations of synthetic fertilizers. This review emphasizes the potential of organic amendments and microbial inoculants as effective alternatives to improve P availability and soil health. Organic amendments such as livestock manures, plant residues, and compost, along with enriched products like phosphate-rich organic manure (PROM), enhance P solubility, microbial activity, and enzyme production. The integration of rock phosphate (RP) with composting and microbial inoculants, such as phosphate-solubilizing bacteria (PSB) and fungi, further improves P mobilization and uptake, especially in nutrient-deficient soils.

Microbial inoculants, including arbuscular mycorrhizal fungi (AMF), *Trichoderma* spp., and actinomycetes, not only solubilize P but also support nutrient cycling and plant growth. Synergistic interactions between AMF, PSB, and organic amendments demonstrate their potential to enhance crop yields and maintain soil fertility. However, results can vary based on soil type, crop systems, and environmental conditions, necessitating tailored approaches. Adopting these sustainable strategies reduces reliance on synthetic fertilizers, lowers costs, and fosters long-term productivity while mitigating environmental impacts. These findings highlight the importance of integrating organic and microbial approaches for effective P management in calcareous soils.

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