ROCK PHOSPHATE: A COST-EFFECTIVE ALTERNATIVE TO MEET PHOSPHORUS DEMAND IN AGRICULTURE

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Phosphorus (P) is one of the three primary macronutrients essential for plant growth, alongside nitrogen (N) and potassium (K). It plays a critical role in various physiological processes, including photosynthesis, energy transfer, and the synthesis of nucleic acids and proteins. P is a key component of adenosine triphosphate (ATP), which is vital for energy transformation in plants. It also contributes to root development, flower formation, seed production, and overall crop quality. Despite it being the 11th most abundant element in the earth's crust, the complex chemistry of P in soil renders it highly deficient in most of the arable soils worldwide. Only about 0.1 % of the total P in the soil is available for plant uptake, as it is often fixed into various insoluble compounds depending on the soil pH. A deficiency in P can lead to stunted growth, poor flowering, and reduced yield, making it crucial for farmers to ensure adequate P levels in the soil throughout the growing season. P is a limiting factor for crop yield on more than 40% of the world's arable land. Global P reserves are getting depleted at a faster rate, and some estimates suggest that no soil P reserves may remain by the year 2050. P deficiency is one of the greatest limitations particularly in low-input agricultural systems, which cover about 5.7 billion hectares globally.

In the Indian context, about 49.3% of districts are reportedly low in available P content, based on data from 9.6 million soil test values (Dey et. al., 2017). Another study indicated that 42% of the total districts in India fall into the "low available P" category (Rao et.al., 2015). Thus, application of P fertilizers has become imperative to maintain soil fertility and sustain crop productivity in today's input intensive agriculture. Consequently, the use of commercially available P-fertilizers-though costly-has increased among farming communities and the global consumption of P-fertilizer increased from 5.5 million metric tonnes in 1960 to 44.8 million metric tonnes in 2020 (see Figure 1) which indicate a nearly 8.2-fold increase in the consumption (FAO, 2020).

Rock phosphate (RP), a naturally occurring mineral and a vital source of P, is the backbone of the P-fertilizer industry. RP is a highly priced commodity in the world market due to geographically concentrated distribution of the reserves. India, the world's largest importer of high-grade RP, has recently faced the impact of rising prices of RP as well as Diammonium phosphate (DAP). According to the recent data of Fertilizer Association of India (FAI), DAP consumption in India has declined by about 25%. Given these challenges, research priorities are increasingly being directed towards identifying alternative P sources such as indigenous RP to meet the P-fertilizer demand in the country. However, availability of RP from domestic sources falls under low-grade category and do not meet the specifications required for commercial production of P-fertilizers. The solubilization of RP is another major challenge, as it requires proton (H^+), which can be produced either chemically or through microbial interventions. Organic acids play a key role in P solubilization within the rhizosphere. Due to these limitations, the wider use of indigenous RP in crop production remains limited

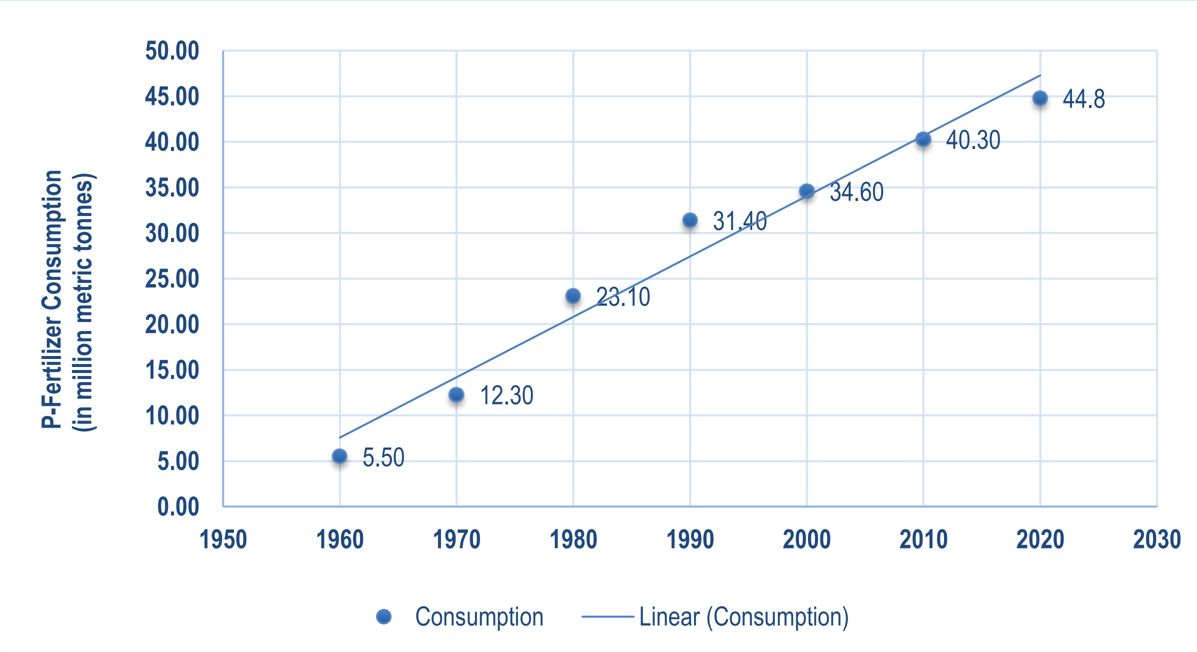

Figure 1. Global Phosphorus Fertilizer Consumption (1960-2020) (Source: FAO, 2020)

As agricultural practices evolve, the significance of RP in sustainable and organic farming systems has become prominent. U.S. Geological Survey in 2023 identified the world phosphate resources as 300 billion tonnes, with 95% being sedimentary and 5% igneous in origin. Igneous phosphate ores are generally associated with Phanerozoic carbonatites and silica-deficient alkalic intrusions, typically contain 5% to 15% P_2O_5 by weight. These can be beneficiated into high-grade concentrates of at least 30% P_2O_5 by weight with minimal contaminants, while sedimentary phosphorite is a marine bio-elemental sedimentary rock, generally contains >18% P_2O_5 by weight. Globally, Morocco holds about 70% of the total phosphate reserves, followed by Egypt, Tunisia, Algeria and China. In India, out of the total reserves of 312.68 million tonnes of RP reserves, 34% are in located in Jharkhand, 31% in Rajasthan, 19% in Madhya Pradesh, and 8% each in Uttar Pradesh and Uttarakhand, with meagre quantities in Gujarat and Meghalaya.

Despite these challenges, RP have several advantages. It acts as a slow-release source of P, unlike synthetic fertilizers that offers immediate nutrient availability. Use of RP have many environmental advantages since it is a natural mineral and require minimal processing for its agricultural use, thereby reducing the carbon footprint associated with fertilizer manufacturing. The lower cost per unit of P makes it an attractive input for sustainable agriculture. However, its limited solubility in neutral to alkaline soils restricts its agronomic effectiveness. The gradual nutrient release may also fail to meet the immediate P needs of fast-growing crops, prompting farmers to opt for more soluble fertilizers. Additionally, RP performance is region-specific; it is more effective in soils with high acidity compared to alkaline ones. Hence, improving the solubility of RP is vital for enhancing its efficacy as a P-fertilizer. To make RP a viable option for sustainable nutrient management methods including chemical treatments, microbial inoculants, and co-application with organic amendments can be explored.

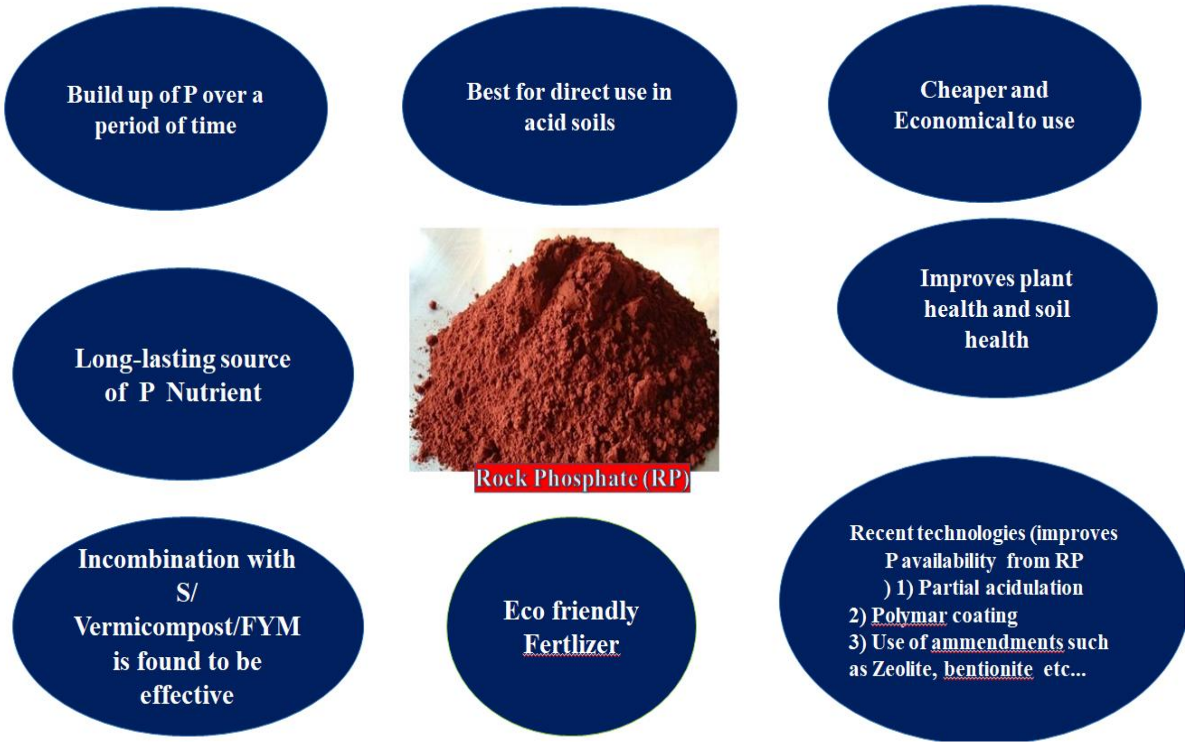

Fig 1: Benefits of rock phosphate use in agriculture

ROCK PHOSPHATE PROCESSING METHODS

1. Partial Acidification

Partial acidification involves treating RP with acids such as phosphoric and sulfuric acid to enhance its solubility. This process enhances the release of P from RP by converting insoluble phosphate compounds into soluble forms. The reaction can be represented as:

$$Ca_3(PO_4)_2 + 2H_2SO_4 \rightarrow 3CaSO_4 + 2H_3PO_4$$

Pyrite (iron sulfide, FeS_2) can also improve the solubility of P from RP through chemical as well as biological mechanisms. The oxidation of pyrite produces sulfuric acid, which aids solubility of P in RP. The representative reaction is:

$$FeS_2 + 4O_2 + 4H_2O \rightarrow 2Fe_2 + 2H_2SO_4$$

Additionally, researchers identified that incorporation of minerals with high phosphate adsorption capacity or high cation exchange capacity, such as pillared clays (PILC) and zeolites, into partially acidulated phosphates improves RP solubility. Since calcium is released during RP dissolution, it can be held by negative charges of the PILC or zeolites, favoring further solubilization and preventing calcium-phosphate (Ca-P) retrogradation.

Mixing RP with organic acids is an effective method to enhance its solubility and make it available to plants. Organic acids such as oxalic, citric and gluconic acid promote dissolution of RP (Mahawar et al., 2022). Since citric acid is a tricarboxylic acid, it can act as a strong chelating agent, binding metal cations and improve P release from RP.

$$Ca_3(PO_4)_2 + 6H^+ \rightarrow 3Ca^{2+} + 2H_2PO_4^-$$

2. Phosphate Solubilizing Microorganisms

The potential of phosphate-solubilizing microorganisms, particularly rhizobacteria in solubilizing RP, is gaining the attention of researchers in recent years. These microorganisms employ mechanisms such as proton secretion, organic and mineral acid production, and siderophore production, to convert insoluble phosphate into plant available forms. In fact, release of free Pi is facilitated by gluconic acid, lactic acid, glycolic acid, acetic acid, formic acid and pyruvic acid released by microorganisms of strains predominantly belonging to *Bacillus* and *Paenibacillus* genera. Maharana & Dhal (2022) identified some efficient RP-solubilizing bacterial strains such as *Bacillus cereus S0B4*, *Solibacillus isronensis S0B8*, and *Bacillus amyloliquefaciens S0B17* from effluent treatment plant sludge. The release of H^+ ions and organic anions from these microbes was the key factor in RP solubilization.

3. Composting with Organic Materials

Solubility of RP can be improved through co-composting with different organic residues. P-enriched composts, or phosphocomposts prepared by combining fresh cow dung (100 kg), low-grade RP (200 kg), and crop residue (1000 kg) can have a higher P_2O_5 concentration of about 5-6%. This composting process is a cost-effective way to make better use of agriculture waste and locally available low-grade RP in an eco-friendly manner.

4. Physical Methods

Reducing the particle size of RP increases its surface area, thereby enhancing its interaction with soil and microbial activity. Smaller particles dissolve more readily than larger ones due to their increased surface area. Combining RP with more soluble fertilizers provide a dual benefit of immediate P availability RP and long-term release of P from RP.

IMPACT OF ROCK PHOSPHATE ON CROP YIELD AND PHOSPHORUS UPTAKE

Several studies have demonstrated that the application of RP can enhance crop productivity and improve P uptake. The effectiveness of RP is influenced by its solubilization-achieved through techniques like partial acidulation, composting, and microbial inoculation, as well as soil properties, including pH, texture, and organic matter content. Acidulated low-grade RP fertilizers have shown a good performance like that of conventional commercial P-fertilizers across a variety of soil types and fertility conditions. Similarly, Rahman et al. (2018) reported that RP with 100% acidulation, applied in two splits, improved crop yield, P use efficiency, and could serve as a viable substitute for commercial fertilizers.

A meta-analysis conducted by Rajan and Upsdell (2021) concluded that RP premixed with elemental sulfur and *Acidithiobacillus* sp. bacterial culture was agronomically more effective than chemically processed fertilizers, particularly for permanent pastures and short-term crops across a range of soil and climatic conditions. Further supporting this, Chtouki et al. (2022) observed that the agronomic efficiency of pretreated RP was significantly higher when applied to soil through phosphocompost, compared to chemical or physical treatments, leading to enhanced P uptake and P use efficiency. In a related study, Yadav et al. (2017) found that application of compost and RP at a ratio of 75:25 yielded maximum soluble P and promoted higher plant growth compared to the use of compost or RP alone.

Huang & Hue (2022) reported that combined application of RP and green manure not only improved soybean growth but also reduced soil acidity and enhanced nutrient availability, resulting a better crop yield. Another study conducted by Fan et al. (2024) revealed that RP when applied with reactive minerals (e.g., zeolite, kaolin and bentonite) altered P morphology and improved P fertilizer utilization. Nunes et al. (2021) also highlighted that application of reactive RP improved P uptake, biomass production, and grain yield in soybean and corn, particularly in no-tillage systems, highlighting its effectiveness in enhancing crop performance.

CONCLUSIONS

As P reserves in soils continue to deplete, low-grade RP has emerged as a viable alternative source of phosphatic fertilizer. Although RP has certain limitations—most notably its low solubility, especially in neutral to alkaline soils—recent studies have demonstrated that its effectiveness can be significantly enhanced when applied in combination with green manures, organic manures, phosphate-solubilizing bacteria (PSB), and poultry litter. These integrated applications improve P availability to levels comparable to synthetic P fertilizers, while also contributing to increased crop yields.

In addition to its agronomic potential, RP offers several notable advantages: it is cost-effective, has a lower carbon footprint, and is environmentally friendly. Overall, rock phosphate holds significant promise as a sustainable and eco-friendly solution for phosphorus fertilization in modern agriculture.

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