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Influence of Fertilizer Application Method on Phosphorus Availability to Maize Crop in Calcareous Soil

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Abstract:

Low availability of phosphorus and high fixation in soils make it an essential component and a major limiting factor of plant growth. Recent developments in science favor the use of phosphorus fertilizers and animal manure on agricultural land to boost soil P fertility and crop productivity, but it has resulted in environmental damage in recent decades. This review will cover the influence of amended phosphate fertilizer on the availability of phosphorus to Maize in calcareous soil. Increased P uptake efficiency, reduced overuse of inorganic fertilizers P, and improved manure P recycling efficiency are just a few of the measures that can be used to achieve total P management in order to obtain high P use efficiency and Maize productivity.

INTRODUCTION

After wheat and rice, maize is the key cereal crop in the world as it is not only the food source for human beings but it also provides foodstuff for other animals like livestock and poultry. Its nutritional value is also greater than other food crops. As maize grains have several different uses in the food industry such diverse applications require improvement in its quality and nutritional value (Has *et al.*, 2009).

Global use of phosphorus (P) fertilizer has increased in the past decades. It was recorded to be 41.7 million tonnes, with an anticipated amount of 46.6 million tonnes for 2018 (Nations, 2015). The demand for total fertilizers is increasing by 2.2% per annum in the world as documented by FAO. The demand for fertilizers is higher in Asia, which is a primary driving force behind rising phosphatic fertilizer production and supply. The excessive use of fertilizers is causing numerous environmental and ecological problems within and outside of crop fields. The high cost of P fertilizer, environmental hazards, limited resources, and economic and energy crises have all highlighted the need to adopt or improve more effective P sources.

Rock P, a source of P, is expected to end in the next 60 to 80 years (Cordell *et al.*, 2009). Phosphorus is crucial for optimal plant growth in addition to completing the life cycle of the plant. As a macronutrient, P is required in enormous amounts by crops (Lal, 2002). Phosphorus in the soil is chemically reactive. Inorganic P in the soil largely occurs as precipitated or adsorbed P. Moreover, the organic P form constitutes 80% of total surface soil P (Trolove *et al.*, 2003). A minimal percentage of (0.1~10 μM) is in the plant available form, as phosphate ions (Frossard *et al.*, 2000). Phosphorus shares part as a basic structural and functional unit of the cell, like nucleic acids, energy transporters, and phospholipids. Phosphorus regulates the activities of enzymes (Kuo and Chiou, 2011), and is involved in signal transduction chains and pathways of energy metabolism (Péret *et al.*, 2011).

Phosphorus is the yield-determining mineral nutrient of crops (Arshad, 2017; Chaudhary *et al.*, 2003; Khan *et al.*, 2023). In Pakistani soils, due to high calcium (Ca) contents and high pH, the availability of P is a major issue. At high pH (> 8), phosphate ions form compounds with calcium that make P unavailable for plant uptake (Rashid *et al.*, 2005). So, it is a need of the hour to improve the plant's P availability for high yield. To gain a high yield, the management of chemical fertilizers is very important. Managing P fertilization deprivation through chemical methods typically distresses the soil health and affects the cost (Gyaneshwar *et al.*, 2002). Phosphorus deficiency can slow down nucleic acid and protein synthesis results in tissue accumulation of soluble nitrogen compounds and finally affects cell growth. Phosphorus deficiency symptoms include a lowering in plant height, reduction in dry matter, delayed leaf emergence, secondary root development, and a number of tillers and decreased seed production (Hoppo *et al.*, 1999; Meng *et al.*, 2021).

2. Low level of nutrients in tropical areas

As P is a non-renewable resource its natural reserves are undergoing depletion. Between the year 2040 and 2060, about half of the natural reserves of phosphorus are predicted to be depleted (Arshad *et al.*, 2016; Lambers *et al.*, 2006). Such a situation calls for phosphorus fertilization to the land so as to sustain further crop and forage production capacity and also to rehabilitate the crop productivity potential of the land by replenishing the required amount of nutrients and water. Fertilizers containing phosphate depend on the source of phosphate to exhibit their efficiency (Guelfi *et al.*, 2022).

3. Importance of phosphorous

Phosphorus is an essential inorganic nutrient vital for plant growth as it plays a crucial part in root development and the uptake of nitrogen (N) and thus it gives a higher yield of grain (Khan *et al.*, 2023; Rehim *et al.*, 2012). Lesser fertile soil has much less amount of available nutrients in it and has a high capacity to fix phosphorus. High P-fixing capacity is endorsed by the high pH of the alkaline soil in that region. Due to high levels of pH different complexes of phosphate are formed which are insoluble in water (for example, di-calcium phosphate and tri-calcium phosphate) and are unavailable to plants (Zakirullah and Khalil, 2012). In neutral or alkaline soil, organic P occurs in the form of insoluble calcium phosphate (Ca-P) or magnesium phosphate (Mg-P), and soil with low pH (acidic) P forms complex compounds with iron (Fe-P) and aluminum phosphate (Al-P) (Richardson *et al.*, 2009a). Hence availability of phosphorus to the plants is restricted and the percentage of efficiency of phosphorus usage is lowered (Naeem *et al.*, 2013). Application of one kilogram of phosphorus in Pakistan (7.9) yields lesser maize grain than in China (9.7) and India (10.3).

4. Phosphorus status and forms in soil

The soil functions as a buffer between the fertilizer that has been applied and the crop that has been planted because of its involvement in regulating nutrients to plant roots as $H_2PO_4^-$ and HPO_4^{2-}. The accessible concentration of P in soil solution is very low compared to other nutrients (Brady and Weil, 2002). It has been illustrated that phosphatic mineral compounds occur in the soil in three different forms: (i) inorganic compounds, (ii) organic compounds, and (iii) organic and inorganic phosphorus complexes found in living things.

The occurrence of organic forms of phosphorus in the soil accounts for 50% of the total soil P pool (Svara *et al.*, 2006). Plants utilize P deposited in seeds as phytic acid to aid germination (Yadav and Verma, 2012). The distribution of phosphorus presents different forms in soil; only orthophosphates ($H_2PO_4^-$ and HPO_4^{-2}, respectively) are used by the plants. A very low amount of plant-accessible P leads to P deficiency, which results in a deprived root system, flowering inhibition, and stunted growth. Farmers use soluble P fertilizers and manures to overcome P deficiency. The majority of fertilizer applied is lost in the environment (Trenkel, 2010) due to fixation by soil constituents. Studies have shown that P complexes with Al, Fe, and Mn are found in acidic soils, but there is a strong interaction with Ca in alkaline soils (Johan *et al.*, 2021; Knox *et al.*, 2006).

5. Problem of P availability in soils

A previous study of phosphorus extraction for calcareous and alkaline soil following Olsen's method (Olsen, 1954), keeping in view the calcareous ($CaCO_3$ > 3.0%) and alkaline in pH (> 7.0) nature of Pakistani soils (Saleem, 1990), and the phosphorus status of soil vary due to calcareousness. It has been documented that more than 90% of Pakistani soils are poor in P and to achieve better crop production P application is essential (Ahmad *et al.*, 1992). It is required to maintain the optimal level of P to obtain the desired yield of crops (Samadi, 2003). It has been illustrated by many studies that we need to provide supplementary P application for better productivity and crop yield as Pakistani soils are poor in available P and are depleting with every passing day.

The concentration of soil available inorganic P rarely goes above 10 milli molars (Bieleski, 1973), far lesser than the P in tissues that is up to 20 milli molar inorganic P (Raghothama, 1999). The major forms of P amendments are mono-calcium phosphate and mono-potassium phosphate. When mono-calcium phosphate is applied to the soil, di-calcium phosphate (DCP) and many protons are released (Benbi and Gilkes, 1987). Then DCP is converted to octa-calcium phosphate and hydroxyapatite (HAP), which are more stable forms and less plant available at basic pH (Arai and Sparks, 2007). In calcareous soils, > 50% of inorganic P comprised of HAP, is due to long-term fertilizer experiments. At this stage, a decrease in pH increased HAP dissolution (Wang and Nancollas, 2008). Soil mineral P adsorption mostly exists in the outer zone because of the comparatively high inorganic P concentration in that zone (Moody *et al.*, 1995).

The scarcity of phosphorus poses a severe danger to increased crop productivity. Phosphorus fixation is a key issue in alkaline and calcareous soils (Sharif *et al.*, 2000). Various factors like the texture of the soil, organic matter, pH, moisture, $CaCO_3$, temperature, time, and incidence of oxides of Fe and Al influence the transformations of applied P in the soil (Zheng *et al.*, 2001).

Calcareous soil contains free calcium carbonate in its profile (Loeppert and Suarez, 1996). It has been reported that $CaCO_3$ in calcareous soils affects soil–water availability to plants and soil surface crust. Because of chemical stabilization mechanisms, soil carbonates have been identified as an organic matter stabilizing agent. Carbonates alter the chemical processes and availability of nutrients like P, either directly or indirectly (Obreza *et al.*, 2006). Organic matter, accessible nitrogen, and phosphorus levels are low in calcareous soils. The presence of $CaCO_3$ and clay particles creates an ideal surface for adsorption. (Devau *et al.*, 2010). The precipitation of calcium carbonate is well-known in soils mostly under different environmental settings, particularly in soils of arid environments. The presence of Ca is responsible for the precipitation of phosphate that results in the production of dicalcium phosphate, a more stable form, and its availability to plants is reduced.

It has been reported that surface adsorption and precipitation are key mechanisms of P retention in calcareous soils. The presence of Fe and Al oxides in soil minerals can quickly absorb phosphate that may be trapped on the surface of soil minerals. Previous studies suggest that non-carbonate clays supply the majority of the P-adsorbing surfaces in calcareous soils. The availability of P in soil is influenced by Fe oxide redox reactions. It has been reported that the accessibility of P increases during flooding, while in dry periods its accessibility diminishes. It has been documented that an increase in highly reactive forms of Fe contents declines the accessibility of P (Condron *et al.*, 2005). Another study suggests that a 1.6% (w/w) coating of Fe_2O_3 on calcite upsurges the sorption capacity of phosphorus (Hamad *et al.*, 1992). Sorption by carbonates becomes increasingly important as the soil's P level rises.

Several factors like physical, mineralogical, and chemical properties and the management history of soil determine the adsorption of phosphate and its availability in the soil (Ahmed *et al.*, 1963). The addition of manure or litter, as well as natural organic matter, has a substantial impact on the retention of P in the subsurface (Mabagala and Mng'ong'o, 2022). It has been reported that differentiation between adsorption and precipitation of P in calcareous soil is very difficult, as both processes occur simultaneously in these soils. It's also predicted that almost all soluble P from phosphatic fertilizers would be fixed; leaving only a small quantity of P in the soil solution that will be available to plants or precipitated (Leytem and Mikkelsen, 2005). Over time, it becomes more challenging to release the adsorbed P in soil solution, reducing the efficacy of applied phosphatic fertilizers (Delgado *et al.*, 2002).

The release of P in solution and static form is determined by the nature of soils and time. The coarse-textured soil releases more P than fine-textured soil. The soils comprising huge amounts of clay fixed more P than soils with little clay content (Havlin *et al.*, 1999). The greater surface area of clayey soils increases the adsorption process. Carbonate clay considerably influenced the P adsorption with the application of a large amount of P (Zhou and Li, 2001). The ability of acid soils to hold added P after long-term manuring is generally low. The availability of P remained unpredictable in soils differing in textures (Dhillon *et al.*, 2004).

It has been demonstrated that a diminution in soluble phosphorus during the growing season is often detected in calcareous soils and, subsequently an increase in the non-cropping season. The presence of a higher quantity of phosphorus-fixing minerals at higher pH levels stops the availability of phosphorus. At alkaline pH, the less stable form is converted to octacalcium phosphate and hydroxyapatite

(HAP), which are both stable forms (Arai and Sparks, 2007). The decline in pH is responsible for a surge in hydroxyapatite suspension and the acidification in the rhizosphere may escalate P mobility in calcareous soils (Wang and Nancollas, 2008). In heavily weathered acidic soils, dissolved organic matter has been found to have little effect on P sorption (Guppy *et al.*, 2005).

6. Crop response to applied fertilizers

Previous studies have revealed that the level of available plant nutrients in the soil along with crop physiology and morphology influence the crop response to fertilizer application (Barłóg *et al.*, 2022; Qasim *et al.*, 2023). Several physiological and physical factors like photosynthesis and growth and development of roots can be boosted by providing an adequate supply of P to the plant. The utilization of soil nutrients by plant roots is determined by the morphology and physiology of roots. It has been investigated that rapid division and enlargement of cells in meristematic tissues of plants require a large amount of P (Brady and Weil, 2002). We can conclude that P is essential for enhanced growth, and development and for obtaining better quality of crops.

Previous studies showed the deficiency of P due to the calcareous nature of soils in Pakistan results in 10 to 15% reduction in crop yield (Gill *et al.*, 2005). The internal nutrient requirement is described as the minimum nutrient uptake linked to a specified crop yield. The external phosphorus requisite of a crop is described as the maximum phosphorus content in soil solution in equilibration with soil to accomplish maximum crop yield (Sarfraz *et al.*, 2009). The effective application of fertilizers is imperative to minimize loss in crop production. The estimation of plant P uptake, especially at low to medium concentrations determines the amount of phosphorus in the soil (Singh *et al.*, 2003). The absorption of P by the plant is more imperative than P supplying the capacity of soil at a higher concentration of P.

Increased P uptake by the plant does not necessarily provide for an increase in yield. Phosphorus availability causes an increase in the leaf area, the quantity of P in root and shoot and shoot dry weight, (Havlin *et al.*, 2016). Phosphorus deficiency is responsible for delays in maturity and reduced crop growth, due to less consumption of carbohydrates in scarce supply of phosphorus. Crop plants respond to the sufficient and poor supply of phosphorus giving better growth or presenting deficiency symptoms. Phosphorus enhances the reproductive growth of the plant and if P deficiency happens at this stage it reduces the crop yield badly. It has been documented that reduced plant growth and postponement of crop maturity in the deficiency of P. Separation of photosynthates between source and sink is required (Blake *et al.*, 2000).

The targeted production of agronomic crops requires an ample amount of phosphorus in soil solution (Denison and Kiers, 2009). It has been demonstrated that the measurement of the phosphate content in the soil solution and the soil's ability to retain the concentration of soil solution is used to calculate the amount of phosphorus available to the plants. The concentration of available phosphorus in the surface layer of soil is also imperative, due to potential phosphorus runoff from the soil surface into water bodies (Matula, 2009).

7. Possible measures to enhance phosphorus availability

Studies have shown that soil properties restricting P uptake affect root growth and development (Belay *et al.*, 2001). For alkaline and calcareous soils, several P fertilizer management strategies are used to advance P nutrition for plants, namely: 1) Use of complexed P fertilizer, 2) high rates of P fertilizer, 3) cation complexing P fertilizer, 4) balancing P with other nutrients, 5) slow release P fertilizer, and 6) seasonal application of P fertilizer. For plants in calcareous and alkaline soils, these strategies can be used in combination to supply P efficiently. Efficient application of phosphatic fertilizers is essential owing to the following reasons, (i) the finite and nonrenewable nature of the resource which is used to manufacture phosphatic fertilizers, its effective use is essential to escalate its lifetime (ii) the efficient usage of phosphatic fertilizers for enhanced progression of crops (iii) the detrimental changes in the soil solution can happen by phosphorus alterations in soil due to use of fertilizers and organic manures (Kunwar *et al.*, 2018). The diversity and functional activity of the soil-borne organisms contribute to the soil structure and nutrient availability (Iqbal and Ashraf, 2021; Islam, 2018; Majeed *et al.*, 2017; Siyar *et al.*, 2018).

Various Plants developed a variety of mechanisms and special features for acclimatizing to lower P. These mechanisms include biochemical, physiological, and morphological changes. For example, rhizosphere pH changes through the release of protons (Hu *et al.*, 2010), partitioning of dry mass, a higher amount of carboxylates in root areas, the release of phosphatase enzymes (Skene, 2003), and the development of specialized cluster roots (Shane *et al.*, 2004). These changes are collectively called the Pi starvation response (*PSR*) (Niu *et al.*, 2013). Under P deficiency, these responses are a result of a manifestation of *PSI* (Pi-starvation inducible) genes. This involves sustaining and efficient utilization of inner phosphate or consenting better contact with soil phosphate. Thus, phosphate availability is increased by these modifications in the rhizosphere which ultimately results in increased phosphate uptake and use (Plaxton and Tran, 2011).

8. Chemical combinations of P with other elements

Soil P comes in a variety of chemical forms that include inorganic P (Pi) and organic P (Po) showing diverse destiny and conduct in the soils (Turner *et al.*, 2007). Pi contributes between 35 and 70 percent of the total P in the soil. Phosphates of Fe and Al become more soluble at high pH, but the solubility of Ca phosphate decreases (Hinsinger, 2001). The availability of soil P is very complex and requires systematic evaluation as it is linked with P dynamics (Figure 1).

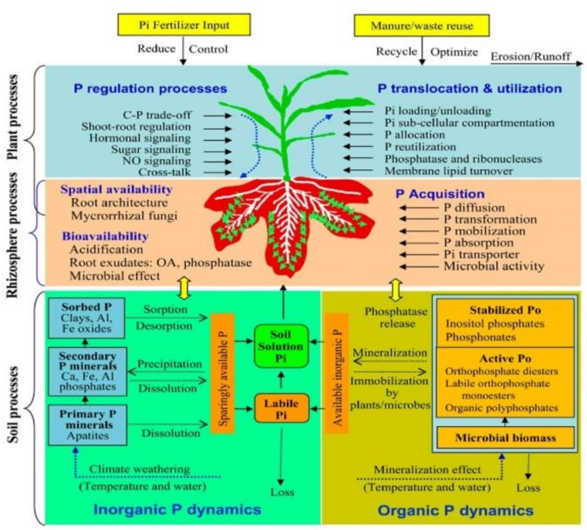

Fig. 1. The dynamics of phosphorus in the soil/rhizosphere/plant continuum OA: organic acids; C-P: carbon-phosphate; NO: nitric oxide; C-P: carbon-phosphate (Shen *et al.*, 2011).

About 80% of phosphorus added from outside sources undergoes fixation by precipitating and adsorbing methods and then becomes available to the subsequent plants by getting desorbed and dissolved. As time progresses, the release of sorbed P into soil solution becomes challenging and the P- P-fertilizer efficiency remains low (Ibrikci *et al.*, 2005). P containing fertilizers may runoff with the surface water or may leach downward to groundwater. Surface water having high levels of phosphate ions may lead to the formation of algal blooms and also cause eutrophication of water thus escalating the contamination of water bodies. Certain new strategies are being used to overcome such problems and for the improvement of P fertilizer's effectiveness. These include the application of single or double furrows, enduing soil micro-organisms, and adding fertilizers of an organic nature (Ipsilantis *et al.*, 2018).

The presence of free carbonates in soil is responsible for nutrient deficiencies and imbalances resulting in reduced crop production. P unavailability serves as a factor that restricts plant growth in such soils (Leytem and Mikkelsen, 2005). The occurrence of carbonates in the soil is a key factor that controls P fixation in arid ecosystems. The synthesis of phosphatic compounds in the soil is affected by the type of minerals and soil pH (Fernández *et al.*, 2007). Chemical fertilizers and manures are used to increase the amount of P in the soil. To prevent the unavailability of P from applying phosphatic fertilizers to plants owing to soil constituent fixation, various approaches are used (Trolove *et al.*, 2003). But still, the biggest challenge in the soil is the availability of P-applied fertilizers.

CRFs are prepared by coating granular plant nutrients with water-soluble, poor permeability, and hydrophobic membranes, and the rate of dissolution of these fertilizers is reduced by using a physical barrier (Shaviv and Mikkelsen, 1993). The use of organic polymers as controlled-release fertilizers is very limited. The organic polymers absorb water to keep the availability of P in the soil, hence providing P to plants consistently (Pauly *et al.*, 2002). Control-released fertilizers release nutrients in the soil following the plant requirement at a consistent level. The reduced rate of fertilizer can prevent seedling damage and provide environmental protection after maximum nutrient uptake by the plant.

9. Phosphorus use efficiency (PUE) in agriculture

In an agricultural production system, phosphorus usage efficiency (PUE) is defined as "the dimensionless proportion of gathered P in agricultural produces (P yield) to total P inputs in this system over a certain time period." Phosphorus (P) management is critical for global food security and aquatic environment protection. Studies have shown the high cost and low efficiency of phosphate fertilizer due to unfavorable physicochemical features of soil, particularly high pH and amount of calcium carbonate in the soil. Plants cannot take up the applied fertilizer because of its transformation into an insoluble form after fertilizer input to the soil. Various factors influence the crop productivity of soil lacking phosphorus, which includes genetic material of the crop, fertilizer brand, and P translocations in the soil, roots, and plant shoots. It has been illustrated that phosphorus-efficient cultivars for local soil conditions can be achieved by studying these parameters (Shenoy and Kalagudi, 2005).

Soil is made up of a combination of solids, liquids, and gases. Soil solid fragments are made up of both inorganic and organic components. Soil solution is a liquid phase that contains dissolved inorganic minerals, salts, and various organic components (Alemayehu and Teshome, 2021). The management of the association between phosphate compounds and soil colloids is different from other nutrients. Owing to their large surface area along with high charges, soil colloids have a high cation exchange capacity (Liu *et al.*, 2017). The issue is not the occurrence of phosphorus in the soil, but rather its absorption by the plant roots. Developing high-yielding cultivars, applying supplementary phosphorus, and limited uptake of applied phosphorus resulted in higher phosphorus build-up in the soil, according to a previous study. When mixed with other substances, the soil colloid has an amorphous structure and does not form a proper solution. The identification of different types of compounds formed by the reaction of phosphorus and other compounds in soil is very imperative, because they play important part in solubility and root absorption. The phosphate fertilizer that has been applied to the soil is likely to act in response to the ions present in the soil, forming a composite that cannot dissolve in the soil solution. The amount of phosphorus in the soil is reduced by the transformation of available phosphorus into metastable Ca-Phosphate ions or plant absorption (Fixen and Ludwick, 1982). The amount of phosphate fertilizer available in the soil, besides the soil's buffering capability, influences crop response to phosphate fertilizer (Sample *et al.*, 1980).

The quantity of total biomass (or yield) generated per unit of P taken up is known as phosphorus usage efficiency (PUE) (Hammond *et al.*, 2009). Various studies have described accounts and calculation methods appropriate for the manifestation of crop phosphorus efficiency. A previous study has established the following formula to estimate phosphorus use efficiency (Berendse and Aerts, 1987),

Phosphorus residence time is considered as a unit of phosphorus that persists in living parts of the plant. The above basic equation states that PUE comprises a variety of structural, functional, and developmental characteristics that govern the use of phosphorus at the tissue level and the dissemination and restructuring of phosphorus among plant parts with numerous functions and productivities. The observation of changes in phosphorus requirements at various developmental stages of plants is very important. It is often designated that phosphorus is used inadequately in agriculture at 10 and 20% recovery of applied phosphorus in fertilizers (Saleem *et al.*, 1988) in 10-1000 g kg^{-1} $CaCO_3$ (calcareous soils).

It has been investigated that in phosphorus deficiency, plants activate a range of mechanisms (Figure 2) to either get an increased acquisition of phosphorus from the soil or use the internal phosphorus in a more proficient way (Vance *et al.*, 2003). Phosphorus (P) limits crop productivity, and this will likely rise in the future (Gautier *et al.*, 2018).

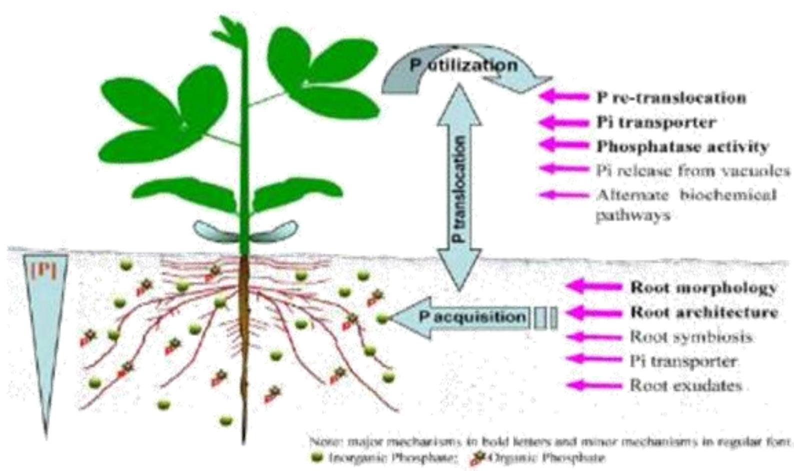

Fig. 2. Schematic illustration of the probable mechanisms of phosphorus procurement and use for improved growth of modern crops (Pandey *et al.*, 2013).

The procurement and utilization of phosphorus can enhance phosphorus use efficiency in crops. The emphasis of research to reduce P fertilizer consumption has been on promoting cultivars that efficiently extract P from P-deficient soil (Richardson *et al.*, 2009b). Modern crop cultivars are chosen to allow for greater phosphorus utilization from phosphorus-rich soils. Breeding for P-efficient varieties is a low-cost option that can be accomplished via two mechanisms: I increasing P acquisition efficiency (PAE) and/or ii) increasing P use efficiency (PUE) (Campos *et al.*, 2018). According to research, some crops have adapted an efficient phosphorus absorption capability with minimal translocation and immobilization. Consequently, PUE turns out to be significant for phosphorus efficiency in crops. Improvement of PUE is possibly a strong approach to enhance phosphorus efficiency in crops (Wang *et al.*, 2010).

9.1. Fertilizer application method

The long-term viability of our restricted land-based farming systems depends on maintaining adequate levels of soil P by the use of inorganic and/or organic P (Sharpley *et al.*, 1994). Continuous and/or long-term solicitation of P, on the other hand, may cause P to accumulate in the soil and change its bio-available form. One of the major determinants of the abundance of distinct P fractions and pools is fertilizer application. The way P is applied has a big impact on how effective it is. Animal manures and other organic additions have been demonstrated to enhance total, available, and soluble P concentrations in soil over time and at different depths (Horta *et al.*, 2018). Reduced P rates can produce a similar yield as a greater quantity of P application (Van der Eijk *et al.*, 2006).

When it comes to improving the P-use efficiency of the fertilizer applied, the time and method of application are more important. Long-term application of various P sources can have a substantial impact on various P fractions and pools (Lu *et al.*, 2020; Wang *et al.*, 2022). Broadcasting is the most common way of applying phosphatic fertilizers in Pakistan, followed by integration before crop sowing, which converts more than 80% of soluble P into insoluble form, resulting in low nutrient usage efficiency (Shah *et al.*, 2006).

9.2. pH

It has been documented that soil pH is only important for soil chemistry and fertility. In the natural world, the pH of the soil has a significant impact on soil biogeochemical activities (Neina, 2019). The use of insecticides Phosphorus reacts with iron and aluminium in acidic soils rendering it unreachable to plants. Though, phosphorus combines with calcium in alkaline soils, sometimes, P remains unavailable to plants due to retention in soil which is the inherent characteristic of the soil. It is challenging to alter these soil features to inhibit P retention. The biology of the soil, along with biological processes, is controlled by pH. The effects of pH changes on extractable P and its retention in soil have been studied, but no progress has been made in terms of consistent P release (Curtin and Syers, 2001). The soil pH impacts numerous biogeochemical processes, while certain biogeochemical processes, consecutively, influence soil pH (Figure 3).

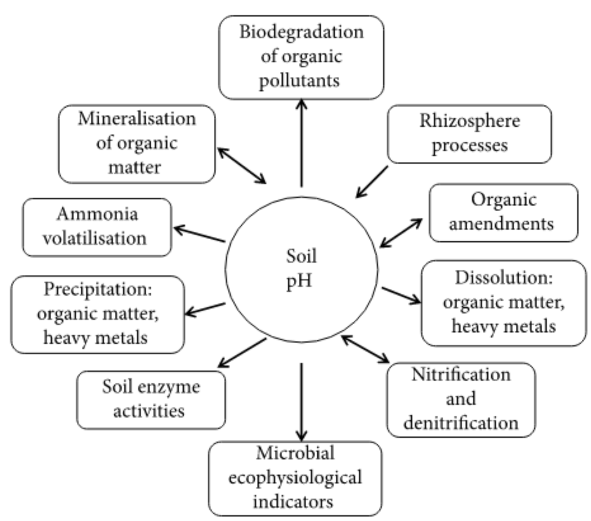

Fig. 3. The relationship of biogeochemical processes with soil pH (Neina, 2019).

9.3. Silication

Phosphorus accessibility in soils is an imperative parameter impelling key production in terrestrial ecosystems. Many practices have been experimented to increase P availability, which include the assimilation of substances that can strive with phosphate ions in soil for adsorption sites. Silica and silicate ions are phosphate ions' competitors, and they can be found in rice husk. When P is coupled with silicate minerals, it binds to soil minerals the least (Schaller *et al.*, 2019). The research on re-silication of highly weathered soil improved P availability (Alovisi *et al.*, 2014). It has been illustrated that silicon is the main element regulating the deployment of phosphorous in the soil, signifying its importance for the workable management of phosphorus accessibility in soils (Schaller *et al.*, 2019).

9.4. Integrated use of nutrients

One of the primary causes threatening agricultural production and food security is soil fertility decline. The management of surface soil is also an essential feature to enhance the effectiveness of phosphatic fertilizers. The stability of soil for nutrient uptake influences that root (Barber, 1984). Organic matter, particle size dissemination, and calcium carbonate content are major factors that affect soil structural stability.

Instead of improving the efficiency of phosphatic fertilizer usage, the utilization of integrated (organic manure, biosolids, and inorganic) sources of P may allow a lower rate of phosphatic fertilizer use (Arshad *et al.*, 2017; Jamal *et al.*, 2023; Johnston and Dawson, 2005; Majeed *et al.*, 2022). Due to the high cost of fertilizer and the absence of soil and crop-specific advice, resource-poor farmers have been using less amounts of mineral fertilizers (Tamene *et al.*, 2017). Sustained use of chemical fertilizers is not a long-term solution because it might lead to deterioration of soil quality (Liu *et al.*, 2010). The ideal technique for boosting soil fertility and enhancing crop productivity is to combine local organic inputs like compost, manures, and crop residues along with mineral fertilizers (Agegnehu *et al.*, 2016). It has been documented that integrated management of fertilizer advances soil characteristics and crop yield (Ejigu *et al.*, 2021).

A strategy that can be adopted for brisk uptake of P by maize and as a result to get good grain yield of maize is the balanced and on-time use of phosphorus-containing fertilizers. The precision of time and application method is crucial in soil as the capability of P to get fixed is improved when the contact duration of solubilized P with soil particles is increased (Amanullah *et al.*, 2010). A new type of fertilizer known as controlled-release fertilizer is also being used. These kinds of fertilizers release nutrients whenever the crop demands it (Geng *et al.*, 2016). In addition to the improvement of the efficacy of nutrient usage, this technique tends to the reduction of water pollution caused by the extreme use of fertilizers. Plants themselves have developed certain schemes to combat P deficiency and to improve P acquisition from soil. One of them is to release organic acid exudates of low molecular weight which can cause the mobility of inorganic P either by directly exchanging the ligands where negative ions of organic acid substitute phosphate on the ligand exchange surface or by complex formation with Ca, Al, or Fe and thus restrict the sites of P absorption from soil and later liberating P from Ca-P, Al-P and Fe-P (Chen *et al.*, 2008). Certain enzymes like phosphatases also mineralize the organic phosphorus though the enzyme-catalyzed reactions are not responsible for mineralizing organic P (Adams, 1992). It is probably because the reason that dissolution of organic phosphorus limits its mineralization besides the enzyme activity (Chen *et al.*, 2008). Citric acid has a significant role in the metabolic activities of all the microorganisms. Plants produce it as root exudates and soil microorganisms make its use as substrate. It forms complexes with Fe and Al. Organic acids also accelerate the potassium (K) discharge because citrate plays a crucial role in the transfer of un-exchangeable K into the extractant solution (Yongfeng *et al.*, 2019). Excessive levels of pesticides in the soil might affect biological processes like plant growth (Iqbal and Ashraf, 2022).

10. Morphological adaptations of plants

10.1. Root architecture

Morphological traits of roots are helpful in P acquisition because of the movement of P in soil (Hodge, 2004). In response to P starvation, root architecture is changed in plants. Changes in root architecture include an increase in R/S ratio, change in metabolite distribution patterns, root elongation, root hairs, root topsoil foraging, root morphology, and topology. Formation of proteoid roots also occurs in some species (Fernandez and Rubio, 2015). Gravitropism in roots controls the root architecture and it adjusts the topsoil root system. Genotypes or species with shallow root systems should be chosen for P uptake because of the high labile P concentration in the surface soil (Gamuyao *et al.*, 2012). In upper soil layers, high root length in wheat is an important characteristic in improving P acquisition in P stress (Manske *et al.*, 2000).

P deprivation results in the enhancement of root length and it also causes primary root growth reduction (Desnos, 2008). Many species also showed the capability to grow more determinative and dense lateral roots with more root hair (Vance, 2008). So, the structural design of the root plays a significant part in enhancing P uptake (Lynch, 1995).

10.2. Root biomass

When P is restrictive for plant growth, many plant species contribute more biomass to roots than shoots (Hermans *et al.*, 2006). Variation in biomass allocation among plants that are grown with a low and high P supply may be due to their genetic makeup (Kemp and Blair, 1994). However, the P application participates in the partitioning of biomass without genetic variability (De Groot *et al.*, 2001). Many species of Lupinus plants are considered P-efficient and do not show a significant change in the partitioning of biomass under P deprivation. This little change is proven in many plants that are even P-efficient (Pearse *et al.*, 2007).

10.3. Root to shoot ratio

In P deficiency, the plant assigns more core carbon to roots resulting in enhanced root growth, an upsurge in root hair length and number, and more root formation laterally (Lynch, 2015). These processes lead to an increased area of roots that helps in extra soil exploration. More soil exploration increases the acquisition of P. When P-efficient genotypes are exposed to P-deficient conditions, these genotypes generally maintain high P content in roots as compared to shoots and result in the improvement of the root system for efficient nutrient uptake (Lynch, 2015; Schneider *et al.*, 2017).

10.4. Root hairs

Root hairs are lateral extensions of roots. The growth of hair of roots is a significant strategy that plants adopt under little P (Li *et al.*, 2016). Root hairs intercept with P diffusing towards roots. Then they enhance the roots depletion zone by exploring more areas for P (Zhu *et al.*, 2010). Out of the total surface area, up to 70% is contributed by root hairs, however, root length differs in inter as well as intraspecies. In legumes increased root hair length and density are reported (Yan *et al.*, 2004). The development of root hairs is very important in response to soil P availability. The length of root hairs of tomato rape and spinach has antagonistic effects on P concentration in the soil solution (Foehse and Jungk, 1983).

Species having longer root hairs are more efficient at acquiring inorganic P from soils e.g. *Lolium perenne* than those species lacking these characteristics like *Podocarpus totara*, and these species show less response towards plant growth (Clarkson, 1981). The genotype of *Hordeum vulgare* tended to yield better in a low P environment due to the formation of longer root hairs as compared to genotypes with less root hair growth (Gahoonia and Nielsen, 2004). *A. thaliana* has shown variation in root hair development due to ethylene and low Pi availability. Low P status leads to increased numbers of root hair-bearing epidermal cells, increased cortical cell number, and decreased size (Zhang *et al.*, 2003). Shoot intellects low P supply and translocate signals to root. Low P status of the root can also trigger the root hair length signals (Jungk, 2001; Lopez *et al.*, 2023).

CONCLUSION

The management of agricultural nutrients for a safe food supply and protection of the environment is one of the major challenges in the current scenario. Better knowledge of soil fertility parameters limiting crop productivity is essential to develop appropriate soil. Previous studies have documented the existence of complex connections between biological, chemical, and physical characteristics of soil. It has been demonstrated that phosphorus use efficiency (PUE) and soil fertility are affected by the reactions occurring in them. Therefore, the use of citric acid-amended phosphorus fertilizer than sole DAP fertilizer is more appropriate to get increased plant biomass and phosphorus use efficiency in calcareous soil.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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