Phosphorus × Other Plant Nutrient Interactions, Reaction Products, Anion Exchange and Phosphate Fixation in Soil and Strategies to Increase Availability of the Native and Applied P to Crop Plants-A Mini Review and Critique

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ABSTRACT

Phosphorus is a major plant nutrient obtained from non-renewable phosphate rock, which is not much available in India. Over and above in this its recovery efficiency in crops hardly exceeds 15-20 per cent. Utmost care is therefore required in its use. Phosphorus applied to soil gets fixed by the formation of insoluble reaction products by reacting with Fe and Al in acid soils and with calcium in saline and alkaline soils. Two techniques used for identification of reaction products are X-ray diffraction and solubility product principle. In addition, phosphate ions are also held on Fe and Al hydroxides by anion exchange. The reaction products identified are variscite and strengite minerals in acid soils and dicalcium phosphate and hydroxy apatite in calcareous soils. Methods to increase phosphorus recovery by crops include: 1) addition of organic matter to soils; 2) addition of sulphur to composit or to ground rock phosphate or directly to soil and use of phosphorus solubilising organisms including VAM/AM along with ground rock phosphate.

Key words: Anion exchange, Phosphate fixation, Phosphorus, Reaction products.

Phosphorus is the costliest plant nutrient in crop production and is obtained from a non-renewable source, the phosphate rock, at present known stocks, which in the world may not last more than 350 years (Cordell et al., 2009). Phosphate availability is more important for India, because it has no indigenous good quality phosphate rock deposits and has to depend mostly on imports. As a contrast the nutrient use efficiency of P is only 10-15 per cent in most crops, the remaining P is fixed in the soil and becomes lesser and lesser available to crop plants as the period from its application advances. Phosphorus use efficiency in crop production needs more attention than N, because N fertilizers are made from an infinite source, the atmospheric nitrogen. To make this possible a better understanding of interactions of P with other plant nutrients and other elements in soil is necessary. Of the fourteen essential plant nutrients taken up from soil, four (P, S, Cl and Mo) are absorbed by plants as anions (H_2PO_4^-, SO_4^{2-}, Cl and MoO_4^{2-}), eight as cations (K^+, Ca^{2+}, Mg^{2+}, Fe^{3+}, Mn^{2+}, Zn^{2+}, Cu^{2+}, Ni^{2+}), one (N) both as a cation (NH_4^+) and an anion (NO_3^-) and one (B) anion (BO_4^{3-}) and as boric acid molecule [B(OH)_4]^- (Prasad, 2007). The anionic nutrients react with cations in the soil. Nitrites, chlorides and most sulphates form water soluble compounds and application of the fertilizers containing these offer no problem in their absorption by plants. However, water soluble phosphate fertilizers single/ordinary superphosphate (SSP/OSP) and triple/concentrated superphosphate (TSP/CSP) containing monocalcium phosphate (Ca(H_2PO_4)_2) and mono ammonium (MAP) or diammonium phosphate (DAP), when applied to soils react with cations present in soil solution and form less water soluble compounds creating problems in the absorption of P and associated cation.
MAP is first changed to MCP, which with more Ca changes to DCP and then TCP and ultimately to HA. MAP and MCP are water soluble, while DCP is ammonium citrate soluble. TCP and HA are not water or citrate soluble. As per the convention the water + citrate soluble P in a fertilizer is considered available P. Water soluble P is the one extracted by distilled water. The residue left is then extracted by 1 N ammonium acetate adjusted to pH 7.0 to extract citrate soluble P (AOAC, 1960; Prasad and Power, 1997). In India nitrophosphates have been evaluated for their water solubility (WS) in large number of experiments. The results indicated that 50 per cent WS is desirable for upland crops, such as wheat, maize etc, on neutral or above neutral soils, but fertilizers containing less than 50 per cent WSPC can be used in rice and sugarcane and for all crops in acid soils (Mahapatra et al., 1973).

Magnesium is present in much lesser amounts than Ca, but Sample et al. (1986) have suggested the formation of Mg₃(PO₄)₂, MgNH₄PO₄ (struvite), Mg(NH₄)₆(HPO₄)₂·4H₂O (Schertelite) and Mg₆(NH₄)₂(HPO₄)₄ (Hannayite) and some unidentified reaction products.

**Reaction with micronutrients other than Fe**

Of the micronutrients other than Fe, Zn has received the most attention and there are many reports on negative interaction of Zn and P (Adriano et al., 1971; Bukowiec et al., 2003; Christensen and Jackson, 1981; Haldar and Mandal, 1981; Mousavi, 2011; Prasad et al., 2014). Dwivedi et al. (1975) were the first to induce zinc deficiency in a pot experiment with Hybrid maize Ganga 5 and a significant reduction in yield was recorded at a high level of P application. In the zinc-deficient plants, the concentration of zinc significantly increased in the roots and the nodes and decreased in the leaves and the internodes. Haldar and Mandal (1981) reported that application of phosphorus caused a decrease in the concentration of zinc, copper, iron and manganese both in shoots and roots. Application of zinc also similarly lowered the concentration of phosphorus, copper and iron, but increased that of manganese in shoots and roots. Phosphate x zinc interaction has since then received considerable attention in India, particularly with the development of high productive multiple cropping systems involving high yielding varieties and hybrids leading to continued large P applications resulting in an increase in Zn deficient areas and the subject has been extensively reviewed by Subba Rao and Rupa (2003). Singh et al. (1986) reported that applied P increased soil P levels and tissue P concentration, but resulted in a significant decrease of tissue Zn levels. The current global thrust is on identification of genes important for interactions between Pi, Zn and/or Fe transport and signaling is a useful target for breeders for improvement in plant nutrient acquisition (Xie et al., 2019). However, this recognition of the negative interaction has gone too far and farmers are not applying enough P and Zn in their fields, despite majority of soils testing low to medium in available P (Tandon, 1987) and about 50 per cent of the soils in India testing low in available Zn (Singh, 2009) and good responses of most crops to P (Blaise et al., 2014) and Zn (Rattan et al., 2008; Patel, 2011) have been reported. Shukla and Behera (2012) predicted that additional production due to Zn application alone in India could be 11.86, 3.58 and 1.3 million tonnes in rice, wheat and maize, respectively. Not many studies have reported the effect of Zn application on P uptake; however, in general an increase in grain and straw yield of a crop is associated with an increase in P uptake. Shivay et al. (2015) from on-farm trials in Aligarh and Meerut districts in Uttar Pradesh reported a significant increase in grain and straw yield of rice by soil application of 5 kg Zn/ha and total P uptake increased from 20.47 kg P/ha in check plots to 27.08 kg P/ha in Zn applied plots in Aligarh and from 34.02 kg P/ha in check plots to 43.34 kg P/ha in P applied plots in Meerut. However, Zn application reduced Zn translocation to rice kernels from vegetative matter from 75.04 per cent in check plots to 70 per cent in Zn applied plots in Aligarh and from 45.15 per cent in check plots to 44.30 per cent in Zn applied plots in Meerut. This decrease in P concentration should be welcomed, because most P is stored as phytates, which interfere with Zn uptake by humans (Prasad et al., 2016). Sprouting grains reduces phytates (Malleshri and Desikachar, 1986) and efforts are underway to develop low phytate mutants in cereal grains (Gutteri et al., 2006).

**Reactions with aluminium (Al) and iron (Fe)**

Al and Fe are third and fourth elements, respectively in abundance in the earth’s crust after O, and Si and mineral soils are made up of mostly aluminosilicate minerals. Al is not a plant nutrient but is actively involved in reactions with phosphates. Mukherjee et al. (1947) were the first to point out that acid soils contained a lot of exchangeable Al, which was mainly responsible for soil acidity and Foy (1992) pointed out that it was highly toxic to crop plants. Reaction products between Al/Fc and P including minerals have been identified by using two techniques, namely, X-ray diffraction (Ghosh et al., 1996) and solubility product principle (Wright and Peach, 1960). The most frequently reported Al and Fe-phosphate minerals formed as a reaction product are: variscite [Al(OH)₂H₂PO₄] with a pKw value of 30.5 and...
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strengite [Fe(OH)₂H₂PO₄] with a pKᵀ₅ value of 33.6–35.0 (Lindsay and Moreno, 1960). Sometimes K and NH₄⁺ substitute part of Al and give minerals like taranakite (Sample et al., 1986).

In India Bhujbal and Mistry (1986) carried out studies on the isolation and identification of reaction products of ammonium nitrate phosphate (ANP) fertilizers containing 30, 50 and 70 per cent water-soluble phosphorus (WSP) of total phosphorus in representative soils of the Vertisol, Oxisol, Alfisol, Entisol, Mollisol and Aridisol groups. ANP fertilizers were applied in solid form to soil and reaction products formed at and around the site of ANP fertilizer placement were identified after six weeks incubation in moist soils by X-ray diffraction technique. DCP was detected with ANP of 30 and 50 per cent WSP in all soils. Brushtite (dicalcium phosphate dihydrate- Ca HPO₄·2H₂O) was the major reaction product of ANP fertilizers containing 30 and 50 per cent WSP in Vertisols, Entisols, Aridisols, Mollisols, Oxisols and Alfisols and of ANP containing 70 per cent WSP in Vertisols, Entisols, Alfisols, Aridisols and Mollisols. In addition to DCP, FePO₄·2H₂O (metastrengite) and AlPO₄·2H₂O (metavanarsicite) were formed in Alfisols and Oxisols with ANP of 30 and 50 per cent WSP. FePO₄·2H₂O and AlPO₄·2H₂O (metavanarsicite) were identified in Alfisol and Oxisols, while AlPO₄·2H₂O-orthorhombic (Variscite) was formed in Alfisols with ANP of 70 per cent WSP (Roncal-Herrero et al., 2009). In another laboratory study on the characterization of soil-fertilizer P reaction products carried out by Ghosh et al. (1996) reacting three-soils occurring in a topo-sequence in the plateau region of Bihar (India) with saturated solutions of DAP, TSP and ammonium polyphosphate (APP) for 1 hour and 24 hour and the reaction products (precipitates) formed in the solutions after 120 days of incubation were isolated and identified through X-ray diffraction technique, Brushtite (CaHPO₄·2H₂O), Strengite (FePO₄·2H₂O), Variscite (AlPO₄·2H₂O) and Fe₈(P₂O₇)₄ were identified as major soil-fertilizer P reaction products.

In addition to the formation of less soluble reaction products, phosphorus is also fixed by anion exchange with OH in Al and Fe hydroxides and on broken edges of kaolinite (Hingston et al. 1972, 1974) and with CO₃²⁻ (Griffin and Jurinak 1973, 1974) with calcite in calcareous soils. Kanwar and Grewal (1960) reported from Punjab that in acid soils 72 per cent P was fixed by Al/Fe oxides, while in calcareous and alkaline soils 70 per cent P was fixed by carbonates. Chatterjee et al. (2014) reported higher P fixation in an Alfisol containing more kaolinite than a Vertisol. It explains high P-fixation in tropical acid soils, which are rich in Al/Fe oxides (Nakaru and Uehara, 1972).

**Application of organic manures**

Organic manures produce a lot of organic acids that increases phosphorus solubility in soils and other organic molecules, which chelate the cations holding phosphates and make it available to crop plants. Organic manures also produce enzyme phosphatase that dissolves organically bound P in soils. Garg and Bahl (2008) reported that the differential phosphatase activity in the organic manures was reflected in dynamic P availability. The highest amount of Olsen extractable P was in poultry manure (PM)-treated soil followed by farm yard manure, green manure and field pea crop residue (CR). In their study organic manure addition along with inorganic P, irrespective of the source, increased the Olsen extractable P throughout the incubation period and P uptake by maize increased with the increasing level of inorganic P in both soils. The highest uptake was obtained in PM-treated soil and lowest in the CR-amended soil. This is the basis of composting with rock phosphate (Mishra et al., 1984).

**Phosphate solubilizing organisms (PSO)**

PSOs have recently received considerable importance in solubilizing inherent soil P and applied P (Gaur, 1990; Richardson, 2007; Sharma et al., 2013; Prasanna et al., 2014; Shahane et al., 2017; Liang et al., 2020). Quite a group of organisms are involved in the process, mainly fungi (Aspergillus, Penicillium, Rhizoctonia and Trichoderma species) and bacteria (Bacillus and Pseudomonas sp.). Cultures of VAM/AM have also been successfully used in increasing the native and applied P (Kim et al., 1997; Prasanna et al., 2014). The main mechanism of solubilization is secretion of acid organic molecules (Sharma et al., 2013). PSOs have been used for direct use of finely ground rock phosphate (Motsara et al., 1995; Park et al., 2011).

**Addition of sulphur to rock phosphate**

Swaby (1975) used sulphur-oxidizing bacteria (Thiobacillus thi-o-oxidans and Thiobacillus thiotaurus) for increasing the solubility of phosphorus in rock phosphate + sulphur mixtures. This mixture was called as biosuper. Application of elemental sulphur or any other acid forming fertilizers, such as nitrogen fertilizers are likely to increase the solubility of phosphate in soil.

**REFERENCES**

Adriano, D.C., Paulsen, C.M. and Murphy, L.S. (1971). Phosphorus-iron and phosphorus-zinc relationships in corn (Zea mays L.) seedlings as affected by mineral nutrition. Agronomy Journal. 63: 36-39.

Association of Agricultural Chemists (AOAC). (1960). Official Methods of Analysis. Association of Agricultural Chemists, Washington, D.C. 851 p.

Bhujbal, B.M. and Mistry, K.B. (1986). Reaction products of ammonium nitrate phosphate fertilizers of varying water-soluble phosphorus content in different Indian soils. Fertilizer Research. 10: 59-71.

**Strategies to Increase P Availability to Crop Plants**

**Placement of phosphorus:** Phosphorus is mostly absorbed by diffusion through root tips and root hairs and for better absorption it has to be deep placed in the rhizosphere. Phosphorus is never top dressed on the surface of the soil as nitrogen.
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Blaise, D., Venugopalan, M.V. and Singh, G. (2014). Phosphorus Management, pp. 93-121. (In) Textbook of Plant Nutrient Management. Prasad, R., Kumar, D., Rana, D.S., Shivas, Y.S. and Tewalia, R.K. (Editors). Published by Dr D.S. Rana, Secretary, Indian Society of Agronomy, Division of Agronomy, Indian Agricultural Research Institute, New Delhi. pp. 407.

Bukovic, C., Antunovic, M., Popovic, C. and Rastijia, M. (2003). Effect of P and Zn fertilization on biomass yield and its uptake by maize lines (Zea mays L.). Plant, Soil and Environment. 49: 505-511.

Chatterjee, D., Datta, S.C. and Manjaiham, K.M. (2014). Fractions, uptake and fixation capacity of phosphorus and potassium in three contrasting soil orders. Journal of Soil Science and Plant Nutrition. 14(3): 640-656.

Christensen, N.W. and Jackson, T.L. (1981). Potential for phosphorus toxicity in zinc-stressed corn and potato. Soil Science Society of America Journal. 45: 904-909.

Cordell, D., Drangert, J.O. and White, S. (2009). The story of phosphorus: Global food security and food for thought. Global Environment Change. 19: 292-305.

Dwivedi, R.S., Randhawa, N.S. and Bansal R.L. (1975). Phosphorus-zinc interaction I. Sites of immobilization of zinc in maize at a high level of phosphorus. Plant and Soil. 43: 639-648.

Foy, C.D. (1982). Soil chemical factors limiting plant growth. Advances in Soil Science. 19: 97–149.

Garg, S. and Bahl, G.S. (2008). Phosphorus availability to maize as influenced by organic manures and fertilizer P associated phosphatase activity in soils. Bioresource Technology. 99(13): 5773-5777.

Gaur, A.C. (1990). Phosphate solubilizing microorganisms in biofertilizers. Omega Scientific Fertilizers, New Delhi.

Ghosh, G.K., Mohan, K.S. and Sarkar, A.K. (1996). Characterization of soil-fertilizer P reaction products and their evaluation as sources of P for gram (Cicer arietinum L.). Nutrient Cycling in Agroecosystems. 46: 71-79.

Griffin, R.A. and Jurinak, J.J. (1973). The interaction of phosphate with calcite. Soil Science Society of America Proceedings. 37: 847-850.

Griffin, R.A. and Jurinak, J.J. (1974). Kinetics of phosphate interaction with calcite. Soil Science Society of America Proceedings. 38: 75-79.

Gutteri, M.I., Peterson, K.M. and Souza, E.I. (2006). Milling and bulking quality of low phytic acid wheat. Crop Science. 46(6): 2403-2408.

Haldar, M. and Mandal, L.N. (1981). Effect of phosphorus and zinc on the growth and phosphorus, zinc, copper, iron and manganese nutrition in rice. Plant and Soil. 59: 415-425.

Hingston, F.J., Posner, A.M. and Quirk, J.P. (1972). Anion adsorption by goethite and gibbsite. I. The role of proton in determining adsorption envelopes. Journal of Soil Science. 23: 177-192.

Hingston, F.J., Posner, A.M. and Quirk, J.P. (1974). Anion adsorption by goethite and gibbsite. II. Desorption of anions from hydrous oxide surfaces. Journal of Soil Science. 25: 16-26.

Jat, G., Majumdar, M.C., Jat, N.K. and Majumdar, S.P. (2013). Potassium and zinc fertilization of wheat (Triticum aestivum) in arid zone of Rajasthan. Indian Journal of Agronomy. 58(1): 67-71.

Kanwar, J.S. and Grewal, G.S. (1960). Phosphorus fixation in Punjab soils. Journal of the Indian Society of Soil Science. 8: 211-218.

Kim, K.Y., Jordan, D. and McDonald, G.A. (1997). Effect of phosphate-solubilizing bacteria and vesicular-arbuscular mycorrhizae on tomato growth and soil microbial activity. Biology and Fertility of Soils. 26: 79-87.

Liang, J.L., Liu, J., Jia, P., Yang, T., Zeng, Q., Zhang, S.C., Liao, B., Shu, W. and Li, L. (2020). Novel phosphate-solubilizing bacteria enhance soil phosphorus cycling following ecological restoration of land degraded by mining. The ISME Journal. 14(6): 1600-1613. doi: 10.1038/s41396-020-0632-4.

Lindsay, W.I. and Moreno, E.C. (1960). Phosphate phase equilibria in soils. Soil Science Society of America Proceedings. 24: 177-182.

Mahapatra, I.C., Prasad, R. and Leelvathi, C.R. (1973). Efficiency of nitrophosphate as compared to straight N and P fertilizers. Proc. ISMA/FAI Seminar on Nitrophosphate and other NPK fertilizers, FAI, New Delhi. 1–2/1–19.

Malleshi, N.G. and Desikachar, H.S.R. (1988). Nutritive value of milled flour. Plant Food and Human Nutrition. 26(3):193-196.

Mehta, K.M., Patankar, S.S. and Kalamkar, W.G. (1963). Studies on uptake of nutrients as influenced by nitrogen and phosphorus fertilization. Soil Science and Plant Nutrition. 9(6): 29-34.

Mishra, M.M., Khurana, A.L., Dudeja, S.S. and Kapoor, K.K. (1984). Effect of phosphocompost on the yield of red gram. Tropical Agriculture 61: 171-179.

Motsara, M.R., Bhattacharya, P. and Srivastava, B. (1995). Technology, Marketing and Usage Book cum Glossary, Fertilizer Development and Consultation Organization, New Delhi.

Mousavi, S.R. (2011). Zinc in crop production and interaction with phosphorus. Australian Journal of Basic and Applied Science. 5: 1503-1509.

Mukherjee, J.N., Chatterjee, B. and Banerjee, B.M. (1947). Liberation of H+, Al3+ and Fe2+ ions from hydrogen clays by mineral soils. Journal of colloid Science. 1: 247-254.

Nakuru, T. and Uehara, G. (1992). Anion adsorption in ferruginous tropical soils. Soil Science Society of America Proceedings. 36: 296-309.

Park, J.H., Bolan, N., Megharaj, M. and Naidu, R. (2011). Isolation of phosphate-solubilizing bacteria and their potential for lead immobilization in soil. Journal of Hazardous Materials. 185(2): 829-836.

Patel, K.P. (2011). Crop response to Zn-cereal crops. Indian Journal of Fertilizers. 7(10): 84-100.

Prasad, R. (2007). Crop Nutrition-Principles and Practices. New Vishal Publishers, New Delhi. 272 p.

Prasad, R. and Power, J.F. (1997). Soil Fertility Management for sustainable Agriculture. CRC. Lewis, Boca Raton, Fla. USA, 356 p.

Prasad, R., Kumar, D., Sharma, S.N., Gautam, R.C. and Dwivedi, M.K. (2004). Current status and strategies for balanced fertilization. Fertilizer News. 49(12): 73-80.

Prasad, R., Prasad, S. and Lal, R. (2016). Phosphorus in soil and plant in relation to human nutrition and health. (In) Soil Phosphorus (R. Lal and B.A. Stewart, Eds.) CRC Press, Boca Raton, FL. USA. pp. 65-80.

Prasad, R., Shivay, Y.S. and Kumar, D. (2014). Agronomic biofortification of cereal grains with iron and zinc. Advances in Agronomy.
Prasad, R., Shivay, Y.S. and Kumar, D. (2016). Interaction of zinc with other nutrients in soils and plants. Indian Journal of Fertilizers. 12(5): 16-26.

Prasanna, R., Wattal-Dhar, D. and Shivay, Y.S. (2014). Significance of biofertilizers in integrated nutrient management. In: Text book of Plant Nutrient Management (R. Prasad, D. Kumar, D.S. Rana, Y.S. Shivay and R.K. Tewatia, Eds.) Indian Society of Agronomy, New Delhi. pp. 231-248.

Rattan, R.K., Datta, S.P. and Katyal, J.C. (2008). Micronutrient research achievements and future challenges. Indian Journal of Fertilizers. 4(12): 207-247.

Richardson, A.E. (2007). Making microorganisms mobilize soil phosphorus. Proceedings of the First International Meeting on Microbial Phosphate Solubilization (Velazquez, E. and Rodriguez-Barrueco, Eds.), pp. 85-90.

Roncal-Herrero, T., Rodry’ guez-Blanco, J.D., Benning, L.G. and Oelkers, E.H. (2009). Precipitation of iron and aluminum phosphates directly from aqueous solution as a function of temperature from 50 to 200°C. Crystal Growth and Design, 9: 5197-5205.

Sample, E.C., Soper, J. and Racz, G.I. (1986). Reaction of phosphate fertilizers in soils. (In) Role of Phosphorus in Agriculture (E.C. Khaswneh, E.C. Sample and E.J. Kampreth, Eds.), American Society of Agronomy and Soil Science Society of America, Madison, WI, USA. pp. 263-310.

Shahane A.A., Shivay, Y.S., Kumar, D. and Prasanna, R. (2017). Quantifying the contribution of microbial inoculation and zinc fertilization to growth, yield and economics of wheat (Triticum aestivum) in different methods of cultivation. Indian Journal of Agricultural Sciences, 87(8): 1066-1072.

Sharma, S.B., Sayyed, R.Z., Trivedi, M.H. and Gobi, T.A. (2013). Phosphate solubilizing microbes: sustainable approach for managing phosphorus deficiency in agricultural soils. Springer plus 2: 587. (Published online 2013 Oct 31. doi: 10.1186/2193-1801-2-587).

Shivay, Y.S., Prasad, R., Singh, R.K. and Pal, M. (2015). Relative efficiency of zinc coated urea and soil and foliar application of zinc sulphate on yield, nitrogen, phosphorus, potassium, zinc and iron biofortification in grains and uptake by Basmati rice (Oryza sativa). Journal of Agricultural Science, Canada. 7(2): 161-173.

Shukla, A.K. and Behera, S.K. (2012). Micronutrient fertilizers for higher productivity. Indian Journal of Fertilisers 8(4): 100-117.

Singh, J.P., Karamanos, R.E. and Stewart, J.W.B. (1986). Phosphorus induced zinc deficiency in wheat on residual phosphorus plots. Agronomy Journal. 78(4): 668-675.

Singh, M.V. (2009). Micronutrient nutritional problems in soils of India and improvement for human and animal health. Indian Journal of Fertilisers. 5(4): 11-16, 19-26 and 56.

Subba Rao, A. and Rupa, T.R. (2003). Importance of Zn × P interaction in crop production. Fertiliser News. 48(4): 69-82.

Swaby, R.J. (1975). Biosuper superphosphate in Australian Agriculture, (K.D. McLachlan, Ed.), Sydney University Press, Sydney, Australia. pp. 213-220.

Tandon, H.L.S. (1987). Phosphorus Research and Agricultural Production in India. Fertilizer Development and Consultation Organization, New Delhi. 160 p.

Wright, B.C. and Peech, M. (1960). Characterization of phosphate reaction products in acid soil by application of solubility product. Soil Science. 90: 32-43.

Xie, X., Hu, W., Fan, X., Chen, H. and Tang, M. (2019). Interactions between phosphorus, zinc and iron homeostasis in nonmycorrhizal and mycorrhizal plants. Frontiers in Plant Science. 26 September (https://doi.org/10.3389/fpls.2019.01172).