

Review

Phosphorus Mobilization in Plant–Soil Environments and Inspired Strategies for Managing Phosphorus: A Review

Muhammad Ibrahim^{1,2}, Muhammad Iqbal³, Yu-Ting Tang⁴ , Sardar Khan⁵, Dong-Xing Guan⁶ and Gang Li^{1,7,8,*} 

- ¹ CAS Engineering Laboratory for Recycling Technology of Municipal Solid Waste, CAS Key Lab of Urban Environment and Health, Institute of Urban Environment, Chinese Academy of Sciences, Xiamen 361021, China
- ² Department of Environmental Sciences, Faculty of Life Sciences, University of Okara, Okara 56130, Pakistan
- ³ Department of Botany, Faculty of Life Sciences, University of Okara, Okara 56130, Pakistan
- ⁴ School of Geographical Sciences, Faculty of Science and Engineering, University of Nottingham, Ningbo 315100, China
- ⁵ Department of Environmental Sciences, University of Peshawar, Peshawar 25120, Pakistan
- ⁶ Zhejiang Provincial Key Laboratory of Agricultural Resources and Environment, Institute of Soil and Water Resources and Environmental Science, College of Environmental and Resource Sciences, Zhejiang University, Hangzhou 310058, China
- ⁷ Zhejiang Key Lab of Urban Environmental Processes and Pollution Control, CAS Haixi Industrial Technology Innovation Center in Beilun, Ningbo 315830, China
- ⁸ Jiaying Key Lab of Soil Health, Yangtze Delta Region Healthy Agriculture Institute, Jiaying 314503, China
- * Correspondence: gli@iue.ac.cn



Citation: Ibrahim, M.; Iqbal, M.; Tang, Y.-T.; Khan, S.; Guan, D.-X.; Li, G. Phosphorus Mobilization in Plant–Soil Environments and Inspired Strategies for Managing Phosphorus: A Review. *Agronomy* **2022**, *12*, 2539. <https://doi.org/10.3390/agronomy12102539>

Academic Editor: Wei Zhang

Received: 13 August 2022

Accepted: 10 October 2022

Published: 17 October 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Abstract: Crop productivity and yield are adversely affected by the deficiency of P in agricultural soil. Phosphate fertilizers are used at a large scale to improve crop yields globally. With the rapid increase in human population, food demands are also increasing. To see that crop yields meet demands, farmers have continuously added phosphate fertilizers to their arable fields. As the primary source of inorganic phosphorous, rock phosphate is finite and the risk of its being jeopardized in the foreseeable future is high. Therefore, there is a dire need to improve plant-available P in soil, using feasible, environmentally friendly technologies developed on the basis of further understanding of P dynamics between soil and plants. This study systemically reviews the mechanism of P uptake and P-use efficiency by plants under starvation conditions. The recent advances in various strategies, especially imaging techniques, over the period 2012–2021 for the measurement of plant-available P are identified. The study then examines how plants fulfill P requirements from tissue-stored P during P starvation. Following this understanding, various strategies for increasing plant-available P in agricultural soil are evaluated. Finally, an update on novel carriers used to improve the P content of agricultural soil is provided.

Keywords: phosphorus; soil mobilization; speciation; plant uptake; strategies

1. Introduction

Phosphorus (P) is a fundamental macronutrient required for optimum plant growth and development in the agricultural sector [1]. Phosphorus was discovered in 1669 by Hennig Brandt, a German merchant. It is one of the 12 most abundant elements in the Earth's crust. The only isotope that occurs naturally is phosphorus-31 (³¹P). Phosphorus non-availability is a serious issue and is considered the main limiting factor for decreased crop yields in the modern agricultural ecosystem [2]. In acidic soil, soil P is mostly immobilized in two forms, i.e., inorganic phosphorus (Pi) and organic phosphorus (Po). It may be trapped with mineral compounds of iron (Fe) or aluminum (Al) hydroxides, or it can be incorporated into rocks rich in mineral oxides, such as hematite, goethite, and gibbsite [3]. In alkaline soil, P is trapped in less soluble mineral compounds (variscite, strengite, and

apatite) of magnesium (Mg) and calcium (Ca) [4]. Po accounts for 30% to 50% of the total phosphorus (Pt) present in soil, primarily in the form of inositol phosphates, phospholipids, and sugar phosphates [5]. Soil mineralization reactions are generally activated by soil microbes coupled with enzyme phosphatase in the plant rhizosphere to release Pi from fixed P reservoirs. Environmental factors, such as soil pH, temperature, moisture content, and physicochemical properties (texture, organic matter, and electric conductivity), affect the mineralization process. Plants naturally uptake Pi from soil solutions in the form of H_2PO_4^- , and HPO_4^{2-} , which are available in a narrow pH range (6.0–6.5). Pi accounts for 35% to 70% of the Pt present in soil solutions [6]. However, if Pi is immobilized in soil solid or transformed to Po, it will largely be unavailable to plants.

In modern agricultural practice, farmers apply chemical phosphate fertilizers to increase crop growth and yield. Intensive use of P fertilizer causes excessive P accumulation in soil [7]. Only 10–20% of the total P applied to soil is taken up by plants as Pi [8]. Part of the accumulated P in fertilizers applied to soil leaches into surrounding water bodies, thus affecting water quality. This is the reason artificially applied P fertilizers are not recommended for soil fertility, due to the risks of underground water contamination. Chemical fertilizers boost soil P levels temporarily. Furthermore, rock phosphate reserves (non-renewable P sources) are continuously declining. In the coming 50–100 years, it is estimated that natural sources of P reservoirs will be exhausted [9]. Therefore, it is essential to understand P dynamics in the soil environment, specifically the way plants uptake P, so as to identify possible alternatives to enhance P uptake from soil. This review first updated knowledge about P immobilization in the soil environment and the mechanism of plant P uptake and then discussed the inspired strategies applied for the improvement of available P in low-P soil in the agricultural sector. The recommendation of a suitable approach (strategy) was then summarized for sustainable soil P management.

2. Phosphorus Mobilization in the Plant Rhizosphere

The rhizosphere is the central and critical zone in the plant–soil environment, where maximum adsorption of nutrients, especially P, takes place from soil to plants [10]. Various biochemical and physiological processes, particularly the excretion of hormones, organic acids, and phosphatases, change the plant rhizosphere zone [11]. These processes are the main drivers of many changes occurring in the plant rhizosphere. Nutrient-use efficiency and crop yields are controlled not only by the physiological and biological processes that take place in the plant rhizosphere but also by microbial dynamics and their abundance in the rhizosphere zone [12]. Phosphorus is gradually being depleted in the plant-root rhizospheric zone due to slow mobility and solubility coupled with root uptake, resulting in P dynamics away from the root rhizosphere to upper plant parts. The decreased mobility of available P results in that plant requirements cannot be met. To maintain the constant requirements of plants, rhizospheric soluble P should be replaced 20 to 50 times per day by P supplements from bulk soil [13]. Soil is a medium for the storage and transformation of nutrients, including P. Many soil biochemical processes occur at various spatial and temporal scales, influencing the bioavailability and cycling of P. Diffusive gradients in thin films (DGT) is an in situ technique that has been used to study P bioavailability in soils and P dynamics in the plant rhizosphere at two-dimensional high resolution [14]. The DGT method employs a passive sampler composed mainly of a binding layer and a diffusive layer. For P imaging using DGT, available P firstly flows through the diffusive layer and is immediately-bound onto the binding layer. Afterwards, post-deployment assessment of P in the binding layer by 1D/2D slicing-colorimetry, computer/colorimetric imaging densitometry (CID), or laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) acquires available P distributions at sub-mm spatial resolution. Table 1 represents DGT imaging technique data for different plant rhizospheres. The introduction of DGT as an imaging tool for measuring in-situ high-resolution P distribution in the rhizosphere is a large step toward a comprehensive understanding of P dynamics in soil-plant system.

Table 1. Publications on the diffusive gradients in thin films technique (DGT) over the period 2012–2021.

Soil	Plant Species	References
Low-P soil	<i>Brassica napus</i> L.	[15]
Soils and sediments	<i>Zea mays</i> L., <i>Zostera marina</i> L.	[16]
High- and low-P soils	<i>Orayza sativa</i> L.	[17]
Flooded paddy soils	<i>Orayza sativa</i> L.	[18]
Soils and sediments	<i>Zea mays</i> L.	[19]
Calcareous and non-calcareous soil	<i>Triticum aestivum</i> L., <i>Lupinus albus</i> L., <i>Fagopyrum esculentum</i> L.	[10]
High- and low-P soil	<i>Brassica napus</i> L.	[13]
Paddy soil	<i>Zea mays</i> L.	[20]
Halosols and Cambosols	<i>Orayza sativa</i> L. (grain)	[21]

3. Mechanism of P Uptake and Consumption by Plants

Soil contains a high amount of total phosphorus (Pt), composed of inorganic phosphorus (Pi) and organic phosphorus (Po), but only a small amount of P is available for plant uptake [22]. From soil solutions, plants obtain Pi in the form of orthophosphate anions (H_2PO_4^- and HPO_4^{2-}) (Figure 1). A study [23] reported that, in most agricultural soil, the concentration of orthophosphate is very low. In P-deficient conditions, P might be supplied from other P pools to meet plant nutritional requirements. A large P concentration difference occurs between plant roots and bulk soil when P is rapidly depleted [24]. The rate of P diffusion in plant roots in most soils is not high enough to overcome the localized P difference (created due to P uptake in soil); therefore, P deficiency occurs in most cases. Previous studies have shown that, for plant growth and developmental processes, P uptake capacity is insufficient and has become a limiting factor in many regions globally [25]. Therefore, for sufficient P uptake, the importance of root architecture cannot be ignored. In many cases, roots show active responses towards P deficiency in soil [17]. The root characteristics for high P uptake include sharp, long, and deep root systems, as well as high root-to-shoot biomass ratios [26]. The common characteristics of plants include extensive root branching [27], the occurrence of a large number of root hairs, and long specific roots developed to reach P-nutrient-rich regions (sub-layers) in the soil [28]. *Brassica napus* L., *Zea mays* L., and *Triticum aestivum* L. have fibrous roots and exhibit high P uptake as compared to the plant species *Vicia faba* L., *Glycine max* L., and *Lupinus albus* L. [29].

Nutrient P is the main component of membrane lipids and nucleic acids (DNA) in plant cells and is essential for many biochemical and physiological processes. In the absence of sufficient P, plants sharply develop adaptive mechanisms not only to gain sufficient P by facilitating P uptake but also to utilize internal tissue-stored P by maintaining the P life cycle in the plant–soil environment, thus decreasing P utilization and readjusting old tissue-stored P for better performance of plant functions (Figure 1). In the cellular vacuole, about 85% to 95% of Pi is present. In P-deficient conditions, the vacuolar Pi flux is insufficient to fill the rapid gap due to cytosolic Pi reduction [15]. Therefore, in the Golgi membrane, a phosphate transporter, PHT4;6, is present, which might transport Pi from the Golgi complex [30] to fulfill the shortage of P. In plant-cell chloroplasts, another phosphate transporter, PHT2; 1, is also available, which might maintain concentrations of Pi in plant cells in P-deficient circumstances. A previous study revealed that, under P-deficient conditions, dual-targeted purple acid phosphatase isozyme (At PAP26) was necessary for Pi accumulation and that phosphatase enzymes were needed for the secretion of Pi from phosphate monoesters in *Arabidopsis thaliana* [31]. For the mobilization of P from RNA, two genes (At RNS1 and RNS2) and ribonucleases are essential during P deficiency. Leaf senescence also stimulates these two ribonuclease genes and phosphatase enzymes during P-remobilization processes, further supporting this phenomenon [32]. Under P-scarcity conditions, membrane lipid composition can be changed through increased non-P lipid and decreased phospholipid formation [33]. At the cellular level, the decomposition of

diacylglycerol by phospholipases C and D and degradation of phospholipids into Pi is mediated under P deficiency [34]. In addition, by the action of two enzymes, SQD1 and SQD2, cellular diacylglycerol is further converted into sulfolipids and galactolipids [35].

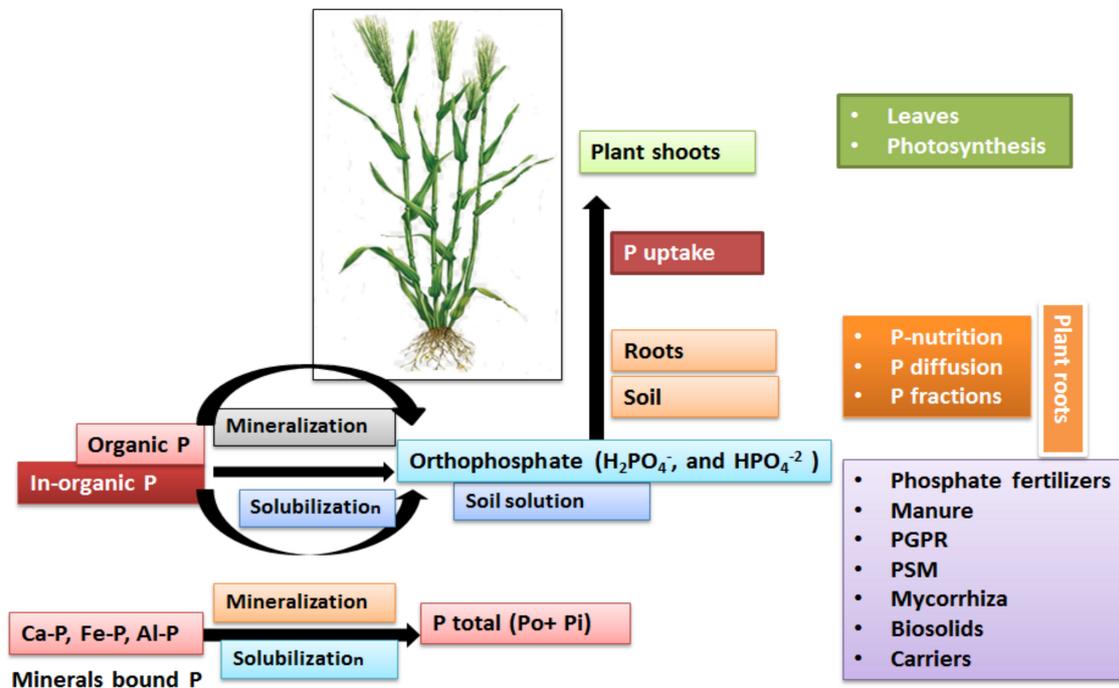


Figure 1. Mechanism of P uptake from soil to plant and associated biochemical process in the plant–soil environment.

Furthermore, plant cells in P-scarcity and starvation conditions could also utilize respiratory cellular routes, bypassing Pi reactions and adenylate [36]. Shortly, for efficient uptake and utilization of available P, plants effectively adopt several biochemical, physiological, and morphological changes [37]. Efficient P utilization and nutrition for the complex network in plants are necessary. Phosphate signaling pathways and their molecular mechanisms respecting P have been reported previously [38]. Transcriptional factors (PHR1), ubiquitin E2 conjugate (PHO₂), and microRNA (miRNA) are important players in this network for the regulation of PHO1, PHT, RNS, and ATPase genes at various levels during P deficiency. The hormonal network and sugar-signaling pathways might also be involved during P deficiency [39].

4. Inspired Strategies for Managing Phosphorus in Agricultural Soil

Several inspired strategies have been used for the improvement of plant-available P and its fractions, as shown in Figure 2. The progress of these strategies is a focus of this subsection.

4.1. Phosphate Fertilizer Application

Chemical P fertilizer application in arable fields is the most widely and long-used strategy to increase as well as precipitate the fixed P in agricultural soil for efficient utilization by crop plants [40]. This strategy is helpful for the initial depletion of fixed P and enhances crop yields to some extent. However, due to the massive application of inorganic phosphate fertilizers by the agricultural sector, the P use efficiency (PUE) in crop farming continues dropping in the developing countries. This makes the P concentration in soil cannot catch up with that required to reach the optimum level for crop growth and development. Anthropogenic activities, such as fertilization, have significantly affected the terrestrial P cycle [41]. In soil, the level of P is much lower (10 μM) than levels of plant tissue-stored P (5–10 mM) [42]. Applications of chemical P fertilizers are required because

of low P availability and fixed P in the soil to enhance crop growth and yield [43]. In addition, phosphate fertilizers are applied to low-P soil in the form of monocalcium phosphate (MCP) and monopotassium phosphate (MPP). Monophosphate fertilizer application prominently affects soil biochemical and physiological processes and, through the wetting process, creates huge amounts of protons and phosphate and finally establishes a P-rich zone in the soil to which it is applied [44]. Further processes create precipitation reactions, direct reactions, and adsorption reaction zones.

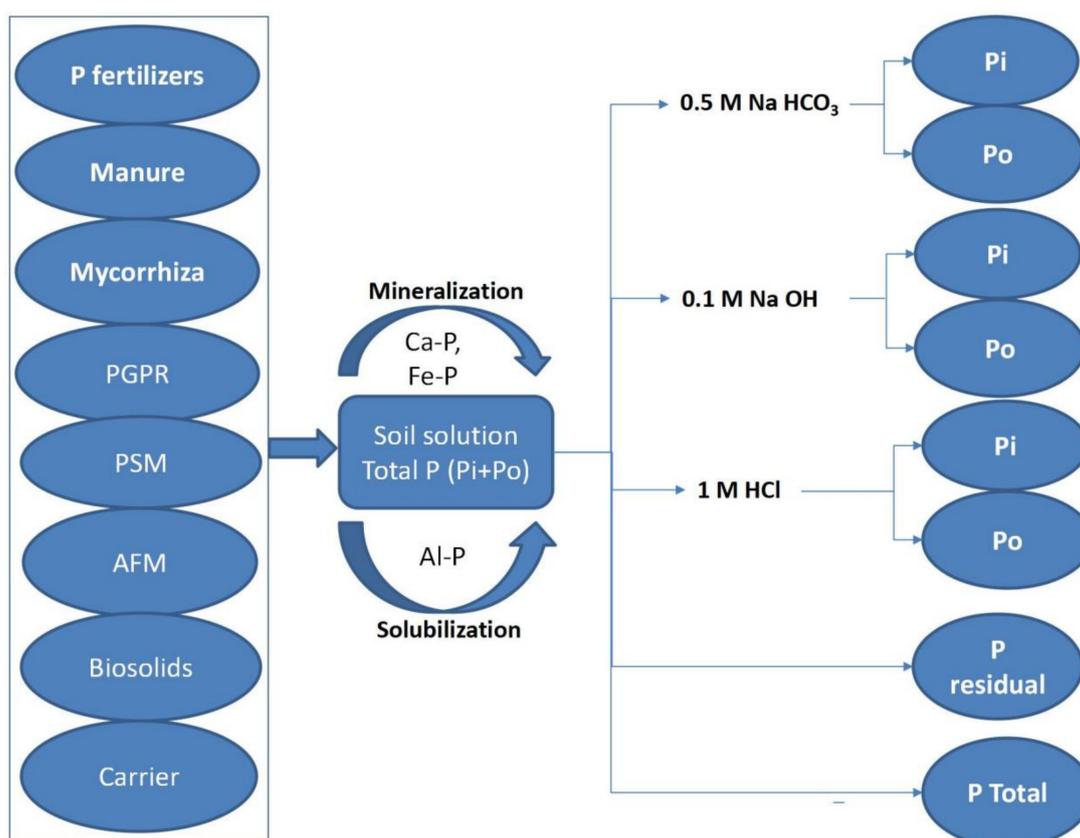


Figure 2. Inspired strategies for managing phosphorus and its fractionation. Abbreviations: PGPR: plant growth-promoting bacteria, PSM: phosphate-solubilizing microorganism, AFM: arbuscular mycorrhizal fungi, Pi: inorganic phosphorus, Po: organic phosphorus, P: phosphorus, Ca-P: calcium phosphate, Fe-P: iron phosphate, Al-P, aluminum phosphate, NaHCO_3 : sodium bicarbonate, NaOH: sodium hydroxide, HCl: hydrochloric acid.

The P-saturated region (direct reaction zone) is acidic, ranging from pH 1.0 to 1.6 [45]. Due to its acidic nature, rapid movement of metal ions occurs. These released metal ions react with Pi in the direct reaction zone, thus enhancing further precipitation of Pi. Metal ions and P chemically interact and form complex molecules of Fe-P, Al-P, and Mg-P compounds [46]. Phosphorus is tightly bound in such compounds and is scarcely accessible to various plant species. Thus, new aggregates of monocalcium and dicalcium phosphate are produced in calcareous soil gradually. With the passage of time, these aggregates are converted into apatite (a stable form of calcium phosphate). The addition of balanced fertilizer matching the treated soil's physical and chemical characteristics might be an efficient and suitable approach for enhancing plant growth and development in P-deficient agricultural soil.

4.2. Manure Application

Manure application is also a promising strategy to enhance P-use efficiency in agricultural soil. To increase soil fertility and P concentration, manure is frequently used as an

amendment in agricultural soil on a routine basis. In manure, the concentration of total P is variable [47]. Manure contains approximately 70% of total P in the labile form, while Pi constitutes 50% to 90% [48]. In addition, organic phosphorus (Po) is also present in the form of nucleic acids and phospholipids [49]. The mineralization process increases the soil Po content in manure-amended soil. Furthermore, mineralization reactions dissolve molecules of organic acids into calcium phosphate [50]. With soil amendment of manure, P adsorption on soil particles greatly decreased. Manure soil application also changes the P availability and pH level. Large molecules of hydroxyls and carboxyls of humic acid, as well as negatively charged sites in manure, strongly compete with Pi in amended soil for adsorption [51]. However, the transformation mechanism of P between Pi and Po pools needs further research in manure-amended soil.

4.3. Mycorrhizal Application

Mycorrhizal fungal application to P-deficient soil is an alternative strategy to the use of phosphate fertilizers for enhancing plant growth and available P. Mycorrhiza, particularly arbuscular mycorrhizal fungi (AMF), establish symbiotic associations (70%) with the roots of higher plants called angiosperms and contribute to P nutrition significantly [52]. Mycorrhiza associated with complex root systems have the same P reservoirs in soil as available to other plant species [53]. A previous study [54] investigated alternative reservoirs of P that are used both by ectomycorrhiza and AMF. In such symbiotic associations, AMF receive carbon (C) sources from host plants while constantly supplying P nutrition through an extensive hyphal system to their host plants. In stress conditions, for sustainable agricultural productivity, the nutritional effect of AMF is very beneficial in the formation of soil aggregates and the establishment of plants. Through a symbiotic relationship, the chief advantage of AMF is increased P uptake. Mycorrhizal plants showed better growth than non-mycorrhizal plants, having AMF pathways as well as increased P uptake, in a previous report [55]. However, in some reported cases, even mycorrhizal plants with AMF pathways did not show sufficient P uptake, and plant growth was stopped. A previous study [56] revealed that, via the solubilization process, AMF hyphal exudates alone solubilized more P from soil reservoirs than plant-root exudates, suggesting that, through the solubilization process, mycorrhiza can enhance P uptake of the plants. The secretion of phosphatase enzymes from the fungal hyphal mycelia of AMF fungi has been investigated and it was found that it could significantly increase the utilization and mineralization of organic P [57]. Mycorrhizal plant P acquisition increases through extraradical mycelia that penetrate deep into P reservoir sources in the soil and transform it into roots and subsequently into other plant parts. Large surface areas, as well as high mycorrhizal hyphal densities, could also contribute to enhanced orthophosphate uptake by plants. In mycorrhizal-associated plants, elevated uptake can usually be explained in terms of enhanced P utilization through the hyphal system from indigenous soil P reservoirs [58]. Mycorrhizal plants use two pathways (direct and mycelial) for sufficient P uptake. The first one occurs at the soil-plant interface via root hairs called direct pathways. The second pathway occurs through fungal mycelia and is called the mycorrhizal pathway [59].

4.4. Plant Growth-Promoting Bacteria Application

The inoculation of plant growth-promoting bacteria (PGPB), applied as an alternative to chemical fertilizers, is based on P solubilization, N₂ fixation, phytohormone secretion, vitamin synthesis, and organic P mineralization [60]. Plant growth-promoting bacteria application to soil is a natural method for increasing soil P concentrations by the P-solubilization mechanism [61]. Numerous PGPB have been isolated from different soil environments, and their effects on plant growth and development have been reported [62]. Most of the studies have concentrated on PGPR, which perform functions associated with P solubilization to increase P availability to the host plant [63]. A diverse array of PGPR, such as species of *Bacillus*, *Enterobacter*, *Pseudomonas*, and *Serratia*, have been found to be involved in P mobilization, e.g., dissolving Ca-P by lowering pH, unlocking P bound to Al

and Fe oxides through the exudation of organic acids, as well as mineralization of organic P through enzyme phosphatase. The mentioned PGPR have been considered as potentially effective inoculants for improved crop growth and yield. However, some researchers have reported that the direct inoculation of PGPR into soil did not enhance plant biomass and P uptake capacity, due to variations in P-related soil properties as well as enzyme activities that were limited by certain environmental factors [64]. Previous findings [65] revealed a low survival rate for PGPR due to low nutrient concentrations as well as competition with indigenous soil microbial, fungal, protozoan, and nematode populations.

Phosphate-solubilizing microorganisms (PSMs) solubilize orthophosphate from different inorganic and organic sources [66]. Phosphate-solubilizing microorganisms include *Rhizobium*, *Bacillus*, and *Pseudomonas* species, as well as different species of fungi, such as *Penicillium* and *Aspergillus* species [67]. In laboratory experiments, rock phosphates ($\text{Ca}_5(\text{PO}_4)_3\text{OH}$, $\text{Ca}_{10}(\text{PO}_4)_6\text{F}_2$) and calcium compounds, such as tricalcium phosphate ($\text{Ca}_3(\text{PO}_4)_2$), are mainly used for the identification of PSMs. The quantity of released soluble P is particularly dependent on the P source; therefore, various microorganisms solubilize different sources of P [68]. Fungal species were previously extensively studied with respect to their abilities to effectively solubilize Al and Fe phosphate sources [69]. Variation in the pH of culture media plays an important role in the solubilization of calcium phosphate. The secretion of organic anions, such as lactate, oxalate, citrate, and gluconate, by PSMs is linked to the acidification of solution media [70]. PSMs improve the solubilization and, ultimately, mobilization of poorly soluble P-binding Ca-P and Al-P compounds by chelating organic anions (Table 2). Many studies have reported increased P uptake and solubilization by various crops inoculated with PSMs in controlled conditions [71,72].

Table 2. Different amendment/inoculation methods used and concentrations of available and total P (mg kg^{-1}) in agricultural soil.

Amendment	Soil pH	Available P	Total P	Amendment/ Inoculation	Plant Species	References
Pig manure	6.54	28.07	810	15,000 kg ha^{-1}	<i>Oryza sativa</i> L.	[28]
Poultry manure	5.20	45.03	975	42 Mg ha^{-1}	<i>Lolium perenne</i> L.	[73]
Compost	7.79	12.20	98	20 t ha^{-1}	<i>Phaseolus vulgaris</i> L.	[74]
Biosolids	7.40	25.21	7600	100 kg ha^{-1}	<i>Saccharum officinarum</i>	[75]
Willow and pine biochar	6.20	33.31	1981	10 t ha^{-1}	<i>Lotus pedunculatus</i> L.	[76]
Cow-dung biochar	5.61	10.61	265	10 t ha^{-1}	<i>Cyperus esculentus</i> L.	[77]
PSM	7.20	17.41	145	3×10^{-4} per seed	<i>Triticum aestivum</i> L.	[78]
PSM	7.80	39.15	9500	4×10^{-5} per seed	<i>Lolium perenne</i> L.	[79]
AMF and PSM	8.50	8.00	183	20 g kg^{-1}	<i>Solanum lycopersicum</i> L.	[80]
Nano-rock phosphate and PSB	8.39	ND	296.23	250 kg ha^{-1} , 250 mL seeds kg^{-1}	<i>Zea mays</i> L.	[81]
PSB	ND	7.00	ND	1×10^7 C.F.U.mL $^{-1}$	<i>Zea mays</i> L.	[82]
PSB and P_2O_5	4.70	8.11	ND	180 kg ha^{-1} 2×10^{-8} C.F.U.mL $^{-1}$	<i>Saccharum officinarum</i>	[83]

Abbreviations: AMF: Arbuscular mycorrhizal fungi, PSM: Phosphate-solubilizing microorganism, PSB: Phosphate-solubilizing bacteria, ND: Not detected.

In field experiments, the functional mechanism of PSM is more complicated and has proved very difficult to explain clearly in the presence of many indigenous soil microbes and varying environmental conditions [84]. This may be due to a lack of suitable and precise methods for the introduction of PSMs into soil environments, gaps in knowledge about the interactions of PSMs with indigenous organisms, and poor understanding of P dynamics in soil [85]. *Penicillium* significantly solubilized P and enhanced wheat growth in laboratory experiments [86]. Microbes play a key role in unlocking soil-bound organic P through a process called mineralization. PSM inoculation enhanced organic P availability as well as plant biomass in greenhouse experiments. In addition, microbial biomass is essential for maintaining an optimum level of P_o and P_i in soil solutions. Upon the death and decay of microbial biomass, P is available to plants in soil [87].

The PSM inoculation technique has proved effective, helpful, and efficient respecting plant rhizospheres, where there are large quantities of microbial biomass that are quickly

metabolized into carbon [88]. However, P mobilization in the plant rhizosphere associated with PSMs requires additional confirmation and investigation. The mineralization of organic and inorganic P and microbial-activated phosphate solubilization are essential processes through which microbes obtain P from soil. However, in some cases, PSMs are unable to mobilize enough P above their demands to meet plant requirements. The P cycle in soil and microbial biomass indeed demonstrate an essential pathway for P mobilization in different, available, including soil, P pools. Different physiological processes disturb organic P pools and thus render them unavailable to the plant–soil ecosystem [89]. The importance of this mechanism in plant rhizospheres needs further research in detail in complex environments. The inoculation of crops with PSMs is a method frequently used, and some PSMs are already commercialized [90]. However, in long-term field applications, these inoculants have to compete for their survival with native soil nematodes and microbes. This technology is still in its infancy and suitable approaches for the solubilization of mineral-fixed P are being explored. The issues with the application of this technology include (1) inoculum survival and colonization, (2) host plant inoculum specificity, and the (3) limited commercialization value and insufficient effects on plant growth and developmental processes [91]. PSM inoculants are applied to the soil and fixed P becomes solubilized; however, plant P uptake and biomass production are negatively affected by phosphorus fixation in the microbial biomass [92]. A previous study [93] reported that the application of phosphate-solubilizing bacteria along with nematodes efficiently enhanced plant P uptake and available P. Phosphorus solubilization is also influenced by soil texture. Aluminum (Al) and iron (Fe) chemical reactions with P in acidic or low-pH soil result in P reduction. However, tricalcium phosphate (Ca_3PO_4)₃ is formed in alkaline or high-pH soil, reducing plant-available P in soil [94]. Thus, soil alkalinity causes P unavailability—a process known as P fixation. Sorghum yield increased significantly after PSM inoculation [95]. To increase P availability, bacterial species, such as *Bacillus* spp., *Pseudomonas* spp., and *Agrobacterium* spp., are used as soil inoculants [96]. Phosphorus solubilization, which involves local acidification or alkalization, has been observed in some *Pseudomonas*, *Cyanobacteria*, and *Bacillus* species isolated from plant rhizospheres [97]. Organic phosphate is the most abundant source of soil phosphate, but its compounds are complex (nucleic acids, phospholipids, etc.) and must be transformed by microorganisms before they can be absorbed by plants [98].

4.5. Biosolid Application

In the 1990s, the term “biosolid” was first introduced for the selection of liquid, solid, and semi-solid materials produced from the treatment of domestic sewage sludge [99]. A satisfactory production process is needed for sludge to be applied to land [100]. For decades, biosolids have been recommended economically, are socially acceptable, and are part of traditional practices of land applications globally [101]. In addition, land application of biosolids is a viable technology for industrial-waste management, generally proposed by environmentalists. Biosolids contain large amounts of micro- and macroelements, such as copper (Cu), zinc (Zn), iron (Fe), manganese (Mn), potassium (K), nitrogen (N), calcium (Ca), sulphur (S), organic carbon (C), and phosphorus (P) [102,103]. These are essential elements for plant growth processes and faunal survival in soil. Usually, in biosolids, most P is in the form of aluminum phosphate, commonly adsorbed on the surfaces of calcium phosphate and iron phosphate [104]. The total inorganic P present in biosolids ranges from 70% to 90% [105]. Furthermore, biosolids contain smaller amounts of water-soluble P [80] as well as organic P in the form of phospholipids, orthophosphate monoesters, and orthophosphate diesters [106]. Wastewater-treatment-plant operations strongly affect the P concentrations in biosolids [107].

Phosphate fertilizer application affects the dynamics of P in biosolids; however, not all of the P in biosolids is available to plants [108]. Precipitation, dissolution, microbial decomposition, desorption, and sorption of P occurs when biosolids are land-applied [109]. The above-mentioned processes may be slow or fast, depending on the biological and

physicochemical processes that occur in the applied soil. P availability in biosolid-treated soil increases with the rate of biosolid application [110]. Thus, elevated contents of inorganic P in biosolids may be linked to enhanced concentrations of P in the soils to which they are applied. However, in soils that have the highest capacities to retain P, or in P-concentrated soils, such variations were found to be less obvious [111]. The conversion of lower labile P to higher labile P species may also be linked to enhanced contents of bioavailable P in amended soils [112]. Another study revealed that calcium (Ca)-concentrated biosolids also contributed to enhanced levels of water-soluble P in amended soil [113]. Mineralization also increases with amendments of biosolids, which could unlock biosolid-borne organic P, thus contributing to enhanced contents of extractable P [114].

The relationship between plant-available P and the degradation of biosolids is more complicated. A previous study revealed that biosolid amendment not only changes soil physicochemical properties, such as pH, EC, dissolved organic matter, and biological properties, but also the adsorption capacity of amended soil [115]. The enzymes phosphodiesterase and phosphomonoesterase mainly hydrolyze organic phosphate esters into orthophosphate anions biochemically and secrete most of the assimilated P through soil microbes. Plant roots and soil microbes both passively and actively participate in the secretion of extracellular enzymes to make them available for plants through the mineralization of S, C, P, and N from complicated forms [116]. In the plant rhizosphere, phosphomonoesterase enzyme activity was identified as the major mechanism for the acquisition of P by plants, catalyzing a large number of anhydrides and orthophosphate minerals and thus releasing bound P [117]. In agricultural soils, enzyme phosphatase activity mainly contributes to agricultural activities, and, in forest soils, it responds to seasonal variations in moisture as well as temperature [118].

According to economic theory, in biosolid-applied soils, P is amended together with other nutrients, such as S, N, and S, thus stimulating the activity of phosphatase enzymes, and is utilized by soil microbes as an energy source, while, in soil amended with chemical fertilizers, phosphatase enzyme activity is suppressed [119], thereby revealing the clear difference between inorganic P amendment and fertilizer application [18]. Previously, in the agricultural sector, biosolid applications to soil enhanced acid phosphatase activity, nutrient concentrations, and microbial biomass [120]. In different soils, various persistence and production rates of enzyme activities have been studied. Soil pH-buffering capacity also varies with biosolid application, resulting in changes in phosphatase enzyme activities [121]. In biosolid-applied soil, the enzymes phosphomonoesterase and diesterase might be used as signals of P secretion from biosolids because, usually, sewage sludge includes different P forms [122]. The higher the microbial or plant origin of the enzyme, the greater the demand for mineral P [123]. Thus, competition or cooperation between plant roots and rhizosphere microbes is primarily determined by soil P status.

4.6. Carrier Application

China and India, as the largest consumers of P fertilizers [124], are facing the great challenge of gradually decreasing P resources [125]. Excessive and unbalanced P fertilization applications in most regions have been extensively reported [126]. To maintain high crop productivity, high rates of chemical P fertilizers ($120 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1}$) have been applied by farmers, resulting in dramatic increases in P accumulation in agricultural soil [127], as well as P loss via runoff and leaching to the aquatic environment. Therefore, to achieve environmental, ecological, and economic goals, it is necessary to minimize the input of P fertilizers and improve the P status of agricultural soils through the feasible application of new materials in the modern agricultural sector. The application of biochar (a carbon-rich material) is an environmentally friendly and cost-effective approach to improve nutrient-deficient agricultural soil [128]. Biochar is produced from waste residues and is frequently recommended for the fertility of agricultural soil and carbon sequestration [129]. Using biochar as a carrier material for plant growth-promoting bacteria (PGPB) offers unique opportunities and benefits in the agricultural sector. Plant growth-promoting bacteria

inoculation with biochar increases the value of biochar and enhances its commercialization as a biofertilizer [130]. Applications of biochar as a carrier have many benefits, as they ensure the survival of introduced PGPB in the treated soil and provide hot spots for microbial movements. Furthermore, biochar carrier amendment of soils alters many physicochemical properties, which enhances the survival efficiency of the introduced PGPB in treated soils. The positive results of biochar amendment of agricultural soil include increased soil pH, bulk density, fertility, water-holding capacity, nutrient retention, and aeration capacity [131].

In agricultural soils, the total concentration of P (Pt) ranges from 400 to 1200 mg kg⁻¹. However, in available forms, such as the orthophosphate ions H₂PO₄⁻ and HPO₄⁻², only 1 mg kg⁻¹ of Pt is present [132]. The non-soluble form of P is present in inorganic (Pi) and organic forms (Po). In soil, non-soluble Pi ranges from 20 to 50% in the form of PO₄⁻ ions [133]. These ions are adsorbed to various compounds of Ca, Fe, and Al—Ca-P, Fe-P, and Al-P—producing stable complexes. Due to the short and poor survival of PGPR in soil, post-soil inoculation is usually not recommended [134]. Furthermore, direct inoculation of liquid PGPR in soil becomes complex due to the adhesion of soil particles, which reduces their ability to colonize host root surfaces, as well as vertical transport [135]. Ordinary carriers, such as peat and vermiculate, have some drawbacks which limit their application at large scales [136]. However, compared to peat and vermiculate, biochar carriers seem to be environmentally friendly and cost-effective. Furthermore, biochar sterilization offers a reliable and premium-quality preparation for alternative carriers (PSMs loaded on biochar). Due to these benefits, biochar is considered an alternative, cost-effective carrier. The attachment of PSMs on biochar surfaces might provide defensive colonization as well as a safe zone [137]. One study [138] reported that when loaded on a biochar surface, *Azospirillum* had a 6-month long shelf life at room temperature. However, it is not clear whether PSMs loaded on biochar surfaces ensure survival; the matter needs further investigation. We applied different biochar carriers (PSMs loaded on biochar), such as rice-straw biochar (RSB), soybean-straw biochar (SSB), rice-husk biochar (RHB), peanut-shell biochar (PNB), wood biochar (WB), and corn-cob biochar (CCB), to agricultural soil collected from an agricultural field in Hailun City, Heilongjiang Province, China (Figure 3). The tested soil had a pH of 6.52 units and a total P concentration of 5.59 mg kg⁻¹ [139]. The incubation experiment was conducted at lab scale in a complete randomized block design (CRBD) in four replicates. Each carrier was amended separately at a rate of 3% to the tested soil. After one month of incubation experiment, the RSB and SSB amended-soil showed significantly higher concentrations of NaHCO₃ extractable Pi and Po, NaOH extractable Pi and Po, HCl Pi, residual P, and total P in the treated soils than RHB, PNB, WB, CCB, and CK-amended soil (Table 3). This increase in total P and P fractions in carrier-amended soils may have been due to the increased solubilization and mineralization of mineral-bound P.

Table 3. Sequentially extracted P fractionation (mg kg⁻¹) after application of different carrier materials into agricultural soil. Mean values are shown ±1 standard deviation (n = 4) (unpublished data).

Parameters	0.5 M NaHCO ₃ Extractable Pi	0.5 M NaHCO ₃ Extractable Po	0.1 M NaOH Extractable Pi	0.1 M NaOH Extractable Po	1 M HCl Pi	P Residual	P Total	Extraction Efficiency (%)
CK	0.58 ± 0.03 a	0.32 ± 0.08 a	0.63 ± 0.09 a	1.72 ± 0.20 a	1.46 ± 0.14 a	0.88 ± 0.15 a	5.59 ± 0.51 a	99
RSB	0.69 ± 0.08 b	0.77 ± 0.15 b	0.67 ± 0.04 a	1.20 ± 0.15 b	2.49 ± 0.27 b	1.21 ± 0.23 b	6.98 ± 0.96 c	100
SSB	0.94 ± 0.09 c	0.64 ± 0.16 b	0.71 ± 0.12 a	0.96 ± 0.15 b	2.99 ± 0.36 c	1.41 ± 0.34 c	7.61 ± 1.06 c	100
RHB	0.66 ± 0.12 b	0.27 ± 0.08 a	0.64 ± 0.08 a	1.46 ± 0.23 a	2.08 ± 0.23 b	1.62 ± 0.35 c	6.83 ± 0.19 b	98
PNB	0.70 ± 0.06 b	1.03 ± 0.27 c	0.69 ± 0.14 a	0.73 ± 0.15 b	2.00 ± 0.29 b	1.53 ± 0.26 b	7.01 ± 0.98 bc	95
WB	0.65 ± 0.02 b	0.48 ± 0.29 b	0.62 ± 0.05 a	1.29 ± 0.23 a	2.20 ± 0.26 b	1.43 ± 0.28 b	7.11 ± 0.18 b	93
CCB	0.73 ± 0.05 b	0.35 ± 0.08 a	0.61 ± 0.09 a	0.96 ± 0.18 b	2.43 ± 0.34 b	1.42 ± 0.24 b	6.65 ± 0.19 b	97

Abbreviations: CK: Control, RSB: Rice-straw biochar carrier, SSB: Soybean-straw biochar carrier, RHB: Rice-husk biochar carrier, PNB: Peanut-shell biochar carrier, WB: Wood biochar carrier, CCB: Corn-cob biochar carrier. Extraction efficiency for each of the P fractions was calculated from the sum of P fractions divided by total P and multiplied by 100. Pi (inorganic P) and Po (organic P), P residual, and P total. Different letters in columns indicate significant differences ($p \leq 0.05$) between treatments, while similar letters indicate non-significant differences.

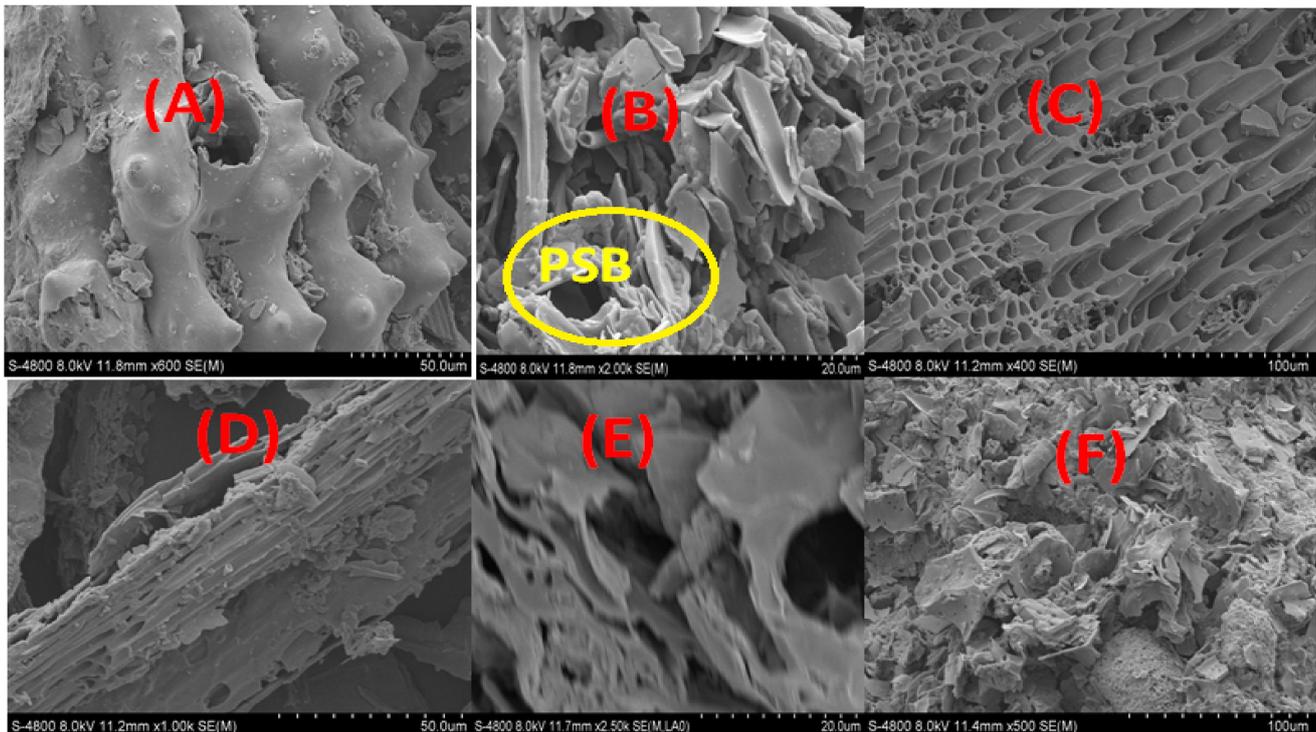


Figure 3. SEM images of carrier materials: (A) RHB, (B) SSB, (C) WB, (D) RSB, (E) PNB, and (F) CCB (unpublished data).

5. Conclusions

The current review has brief understanding of phosphorus mobilization and P dynamics between Pi and Po pools in agricultural soil. It has been discussed how, in P-deficient conditions, plants maintain P concentrations and utilize internal tissue-stored P. Progress in the development of the diffusive gradients in thin films technique to study P bioavailability was systematically reviewed. In addition, different inspired strategies for the improvement of plant-available P in soil were also reviewed. Finally, an update about the application of novel carriers was provided.

Author Contributions: Conceptualization, M.I. (Muhammad Ibrahim) and M.I. (Muhammad Iqbal); Methodology, S.K.; Data collection and analysis, G.L.; Writing—original draft preparation: M.I. (Muhammad Ibrahim); Data presentation, reviewing and editing, G.L., Y.-T.T. and D.-X.G. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by Ningbo Bureau of Science and Technology (2022Z169, 2021Z101) and the National Natural Science Foundation of China (42177194).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could appear to have influenced the work reported in this review.

References

1. Wahid, F.; Fahad, S.; Danish, S.; Adnan, M.; Yue, Z.; Saud, S.; Siddiqui, M.H.; Brtnicky, M.; Hammerschmidt, T.; Datta, R. Sustainable management with mycorrhizae and Phosphate solubilizing bacteria for enhanced Phosphorus uptake in calcareous soils. *Agriculture* **2020**, *10*, 334. [[CrossRef](#)]
2. Metson, G.S.; MacDonald, G.K.; Haberman, D.; Nesme, T.; Bennett, E.M. Feeding the Corn Belt: Opportunities for phosphorus recycling in U.S. agriculture. *Sci. Total. Environ.* **2016**, *542*, 1117–1126. [[CrossRef](#)] [[PubMed](#)]

3. Muhmood, A.; Lu, J.; Dong, R.; Wu, S. Formation of struvite from agricultural waste waters and its reuse on farmlands: Status and hindrances to closing the nutrient loop. *J. Environ. Manag.* **2019**, *230*, 1–13. [[CrossRef](#)] [[PubMed](#)]
4. Hummel, C.; Boitt, G.; Santner, J.; Lehto, N.J.; Condrón, L.; Wenzel, W.W. Co-occurring increased phosphatase activity and labile P depletion in the rhizosphere of *Lupinus angustifolius* assessed with a novel, combined 2D-imaging approach. *Soil Biol. Biochem.* **2021**, *153*, 107963. [[CrossRef](#)]
5. Nesme, T.; Metson, G.S.; Bennett, E.M. Global phosphorus flows through agricultural trade. *Glob. Environ. Chang.* **2018**, *50*, 133–141. [[CrossRef](#)]
6. Wilson, H.; Elliott, J.; Macrae, M.; Glenn, A. Near surface soils as a source of Phosphorus in snow melt runoff from crop land. *J. Environ. Qual.* **2019**, *23*, 445–455.
7. Jiang, B.; Shen, J.; Sun, M.; Hu, Y.; Jiang, W.; Wang, J.; Wu, J. Soil phosphorus availability and rice phosphorus uptake in paddy fields under various agronomic practices. *Pedosphere* **2021**, *31*, 103–115. [[CrossRef](#)]
8. Helfenstein, J.; Tamburini, F.; von Sperber, C.; Massey, M.S.; Pistocchi, C.; Chadwick, O.A.; Frossard, E. Combining spectroscopic and isotopic techniques gives a dynamic view of phosphorus cycling in soil. *Nat. Commun.* **2018**, *9*, 312–320. [[CrossRef](#)]
9. Scholz, R.W.; Wellmer, F.W. Endangering the integrity of science by misusing unvalidated models and untested assumptions as facts: General considerations and the mineral and phosphorus scarcity fallacy. *Sustain. Sci.* **2021**, *16*, 2069–2086. [[CrossRef](#)]
10. Kreueder, A.; Santner, J.; Scharsching, V.; Oburger, E.; Hoefler, C.; Hann, S.; Wenzel, W.W. In situ observation of localized, sub-mm scale changes of phosphorus biogeochemistry in the rhizosphere. *Plant Soil* **2018**, *424*, 573–589. [[CrossRef](#)]
11. Tian, J.; Lu, X.; Chen, Q.; Kuang, X.; Liang, C.; Deng, L.; Lin, D.; Cai, K.; Tian, J. Phosphorus fertilization affects soybean rhizosphere phosphorus dynamics and the bacterial community in karst soils. *Plant Soil* **2022**, *475*, 137–152. [[CrossRef](#)]
12. De la Fuente Cantó, C.; Simonin, M.; King, E.; Moulin, L.; Bennett, M.J.; Castrillo, G.; Laplaze, L. An extended root phenotype: The rhizosphere, its formation and impacts on plant fitness. *Plant J.* **2020**, *103*, 951–964. [[CrossRef](#)]
13. Kruse, J.; Abraham, M.; Amelung, W.; Baum, C.; Bol, R.; Kühn, O.; Leinweber, P. Innovative methods in soil phosphorus research: A review. *J. Plant Nutr. Soil Sci.* **2015**, *178*, 43–88. [[CrossRef](#)]
14. Guan, D.X.; He, S.X.; Li, G.; Teng, H.H.; Ma, L.Q. Application of diffusive gradients in thin-films technique for speciation, bioavailability, modeling and mapping of nutrients and contaminants in soils. *Crit. Rev. Environ. Sci. Technol.* **2021**, *52*, 3035–3079. [[CrossRef](#)]
15. Santner, J.; Zhang, H.; Leitner, D.; Schnepf, A.; Prohaska, T.; Puschenreiter, M.; Wenzel, W.W. High-resolution chemical imaging of labile phosphorus in the rhizosphere of *Brassica napus* L. cultivars. *Environ. Exp. Bot.* **2012**, *77*, 219–226. [[CrossRef](#)]
16. Santner, J.; Larsen, M.; Kreuzeder, A.; Glud, R.N. Two decades of chemical imaging of Solutes in sediments and soils—A review. *Anal. Chim. Acta* **2015**, *878*, 9–42. [[CrossRef](#)]
17. Wang, Y.; Yuan, J.-H.; Chen, H.; Zhao, X.; Wang, D.; Wang, S.-Q.; Ding, S.-M. Small-scale interaction of iron and phosphorus in flooded soils with rice growth. *Sci. Total Environ.* **2019**, *660*, 911–919. [[CrossRef](#)]
18. Wang, Y.; Chen, H.; Wang, L.; Zhu, W.; Yuan, J.; Jaisi, D.P.; Zhao, X.; Wang, S. Using diffusive gradients in thin films technique for in-situ measurement of labile phosphorus around *Oryza sativa* L. roots in flooded paddy soils. *Pedosphere* **2021**, *31*, 76–82. [[CrossRef](#)]
19. Kreuzeder, A.; Santner, J.; Prohaska, T.; Wenzel, W.W. Gel for simultaneous chemical imaging of anionic and cationic solutes using diffusive gradients in thin films. *Anal. Chem.* **2013**, *85*, 12028–12036. [[CrossRef](#)]
20. Hong, C.; Su, Y.; Lu, S. Phosphorus availability changes in acidic soils amended with biochar, fly ash, and lime determined by diffusive gradients in thin films (DGT) technique. *Environ. Sci. Pollut. Res.* **2018**, *25*, 30547–30556. [[CrossRef](#)]
21. Tian, K.; Xing, Z.; Liu, G.; Wang, H.; Jia, M.; Hu, W.; Huang, B. Cadmium phytoavailability under greenhouse vegetable production system measured by diffusive gradients in thin films (DGT) and its implications for the soil threshold. *Environ. Pollut.* **2018**, *241*, 412–421. [[CrossRef](#)]
22. Wang, Y.; Lambers, H. Root-released organic anions in response to low phosphorus availability: Recent progress, challenges and future perspectives. *Plant Soil* **2020**, *447*, 135–156. [[CrossRef](#)]
23. Penn, C.J.; Camberato, J.J. A Critical Review on Soil Chemical Processes that Control How Soil pH Affects Phosphorus Availability to Plants. *Agriculture* **2019**, *9*, 120. [[CrossRef](#)]
24. Darch, T.; Giles, C.D.; Blackwell, M.S.A.; George, T.S.; Brown, L.K.; Menezes Blackburn, D.; Shand, C.A.; Stutter, M.I.; Lumsdon, D.G.; Mezeli, M.M.; et al. Inter and intra specific intercropping of barley cultivars and legume species as affected by soil phosphorus availability. *Plant Soil* **2018**, *427*, 125–138. [[CrossRef](#)]
25. Luo, X.; Mahdi, A.-K.; Han, X.-Z.; Chen, X.; Yan, J.; Biswas, A.; Zou, W.-X. Long-term application of fertilizer and manures affect P fractions in Mollisol. *Sci. Rep.* **2020**, *10*, 14793. [[CrossRef](#)]
26. Hill, J.O.; Simpson, R.J.; Moore, A.D.; Chapman, D.F. Morphology and response of roots of pasture species to phosphorus and nitrogen nutrition. *Plant Soil* **2006**, *286*, 7–19. [[CrossRef](#)]
27. Duque, L.O.; Villordon, A. Root Branching and Nutrient Efficiency: Status and Way Forward in Root and Tuber Crops. *Front. Plant Sci.* **2019**, *10*, 237. [[CrossRef](#)]
28. Lyu, Y.; Tang, H.; Li, H.; Zhang, F.; Rengel, Z.; Whalley, W.R.; Shen, J. Major crop species show differential balance between root morphological and physiological responses to variable Phosphorus supply. *Front. Plant Sci.* **2016**, *7*, 1939. [[CrossRef](#)]
29. Liu, J.; Yang, L.; Luan, M.; Wang, Y.; Zhang, C.; Zhang, B.; Luan, S. A vacuolar phosphate transporter essential for phosphate homeostasis in *Arabidopsis*. *Proc. Natl. Acad. Sci. USA* **2015**, *112*, E6571–E6578. [[CrossRef](#)]

30. Hassler, S.; Jung, B.; Lemke, L.; Novák, O.; Strnad, M.; Martinoia, E.; Neuhaus, H.E. Function of the Golgi-located phosphate transporter PHT4;6 is critical for senescence-associated processes in Arabidopsis. *J. Exp. Bot.* **2016**, *67*, 4671–4684. [[CrossRef](#)]
31. Hurley, B.A.; Tran, H.T.; Marty, N.J.; Park, J.; Sneddenn, W.A.; Mullen, R.T.; Plaxton, W.C. The dual-targeted purple acid phosphatase isozyme At-PAP26 is essential for efficient acclimation of Arabidopsis to nutritional phosphate deprivation. *Plant Physiol.* **2010**, *153*, 1112–1122. [[CrossRef](#)] [[PubMed](#)]
32. Deller, Y.; Clouet, V.; Marnet, N.; Pellizzaro, A.; Dechaumet, S.; Niogret, M.-F.; Bouchereau, A. Leaf status and environmental signals jointly regulate proline metabolism in winter oilseed rape. *J. Exp. Bot.* **2020**, *71*, 2098–2111. [[CrossRef](#)] [[PubMed](#)]
33. Dissanayaka, D.M.S.B.; Ghahremani, M.; Siebers, M.; Wasaki, J.; Plaxton, W.C. Recent Insight into the Metabolic Adaptations of Phosphorus Deprived Plants. *J. Exp. Bot.* **2020**, *72*, 199–223. [[CrossRef](#)] [[PubMed](#)]
34. Li, M.; Welti, R.; Wang, X. Quantitative profiling of Arabidopsis polar glycerolipids in response to phosphorus starvation: Roles of phospholipases Dz1 and Dz2 in Phosphatidyl choline hydrolysis and digalactosyl diacylglycerol accumulation in Phosphorus-starved plants. *Plant Physiol.* **2006**, *142*, 750–761. [[CrossRef](#)]
35. Wang, F.; Ding, D.; Li, J.; He, L.; Xu, X.; Zhao, Y.; Xu, J. Characterization of genes involved in galactolipids and sulfolipids metabolism in maize and Arabidopsis and their differential responses to phosphate deficiency. *Funct. Plant Biol.* **2020**, *47*, 279–292. [[CrossRef](#)]
36. Mehta, D.; Ghahremani, M.; Pérez-Fernández, M.; Tan, M.; Schläpfer, P.; Plaxton, W.C.; Uhrig, R.G. Phosphate and phosphite differentially impact the proteome and phosphoproteome of Arabidopsis suspension cell cultures. *Plant J.* **2020**, *105*, 924–941. [[CrossRef](#)]
37. Toscano, S.; Romano, D. Morphological, Physiological, and Biochemical Responses of Zinnia to Drought Stress. *Horticulturae* **2021**, *7*, 362. [[CrossRef](#)]
38. Rouached, H.; Arpat, A.B.; Poirier, Y. Regulation of phosphate starvation responses in plants: Signaling players and cross-talks. *Mol. Plant* **2010**, *3*, 288–299. [[CrossRef](#)]
39. Matsoukas, I.G. Interplay between sugar and hormone signaling pathways modulate floral signal transduction. *Front. Genet.* **2014**, *5*, 218. [[CrossRef](#)]
40. Menezes-Blackburn, D.; Inostroza, N.; Gianfreda, L.; Greiner, R.; Mora, M.L.; Jorquera, M.A. Phytase-producing *Bacillus* sp. inoculation increases phosphorus availability in Cattle manure. *J. Soil. Sci. Plant Nutr.* **2016**, *16*, 200–210. [[CrossRef](#)]
41. Yuan, Z.; Jiang, S.; Sheng, H.; Liu, X.; Hua, H.; Liu, X.; Zhang, Y. Human Perturbation of the Global Phosphorus Cycle: Changes and Consequences. *Environ. Sci. Technol.* **2018**, *52*, 2438–2450. [[CrossRef](#)]
42. Irfan, M.; Aziz, T.; Maqsood, M.A.; Bilal, H.M.; Siddique, K.H.M.; Xu, M. Phosphorus (P) use efficiency in rice is linked to tissue-specific biomass and P allocation patterns. *Sci. Rep.* **2020**, *10*, 4278. [[CrossRef](#)]
43. Elgharably, A. Effects of rock phosphate added with farm yard manure or sugar juice residues on wheat growth and uptake of certain nutrients and heavy metals. *J. Soils Sediments* **2020**, *20*, 3931–3940. [[CrossRef](#)]
44. Alori, E.T.; Glick, B.R.; Babalola, O.O. Microbial Phosphorus Solubilization and Its Potential for Use in Sustainable Agriculture. *Front. Microbiol.* **2017**, *8*, 971. [[CrossRef](#)]
45. Lovio-Fragoso, J.P.; de Jesús-Campos, D.; López-Eliás, J.A.; Medina-Juárez, L.Á.; Fimbres-Olivarría, D.; Hayano-Kanashiro, C. Biochemical and molecular aspects of Phosphorus limitation in diatoms and their relationship with biomolecule accumulation. *Biology* **2021**, *10*, 565. [[CrossRef](#)]
46. Prüter, J.; Leipe, T.; Michalik, D.; Klysubun, W.; Leinweber, P. Phosphorus speciation in sediments from the Baltic Sea, evaluated by a multi-method approach. *J. Soils Sediments* **2020**, *20*, 1676–1691. [[CrossRef](#)]
47. Laconi, A.; Mughini-Gras, L.; Tolosi, R.; Grilli, G.; Trocino, A.; Carraro, L.; Piccirillo, A. Microbial community composition and antimicrobial resistance in agricultural soils fertilized with livestock manure from conventional farming in northern Italy. *Sci. Total. Environ.* **2021**, *760*, 143404. [[CrossRef](#)]
48. Dou, Z.; Toth, J.D.; Galligan, D.T.; Ramberg, C.F., Jr.; Ferguson, J.D. Laboratory procedures for characterizing manure phosphorus. *J. Environ. Qual.* **2000**, *29*, 508–514. [[CrossRef](#)]
49. Neina, D. The role of soil pH in plant nutrition and soil remediation. *Appl. Environ. Soil Sci.* **2019**, *2019*, 5794869. [[CrossRef](#)]
50. Martins, M.A.; Santos, C.; Almeida, M.M.; Elisabete, M.; Costa, V. Hydroxy apatite micro and nanoparticles: Chelation and growth mechanisms in the presence of citrate species. *J. Colloid Interface Sci.* **2008**, *318*, 210–216. [[CrossRef](#)]
51. Omar, L.; Hasbullah, N.A. Phosphorus Transformation in Soils Following Co-Application of Charcoal and Wood Ash. *Agronomy* **2021**, *11*, 2010. [[CrossRef](#)]
52. Brundrett, M.C. Mycorrhizal associations and other means of nutrition of vascular plants: Understanding the global diversity of host plants by resolving conflicting information and developing reliable means of diagnosis. *Plant Soil* **2009**, *320*, 37–77. [[CrossRef](#)]
53. Borie, F.; Aguilera, P.; Castillo, C.; Valentine, A.; Alex Seguel, A.; José Miguel Barea, J.M.; Cornejo, P. Revisiting the Nature of Phosphorus Pools in Chilean Volcanic Soils as a Basis for Arbuscular Mycorrhizal Management in Plant P Acquisition. A review. *J. Soil. Sci. Plant Nutr.* **2019**, *19*, 390–401. [[CrossRef](#)]
54. Teste, F.P.; Jones, M.D.; Dickie, I.A. Dual mycorrhizal plants: Their ecology and relevance. *New Phytol.* **2019**, *225*, 1835–1851. [[CrossRef](#)] [[PubMed](#)]
55. Ghobadi, M.; Dehnavi, M.M.; Yadavi, A.R.; Parvizi, K.; Zafari, D.M. Reduced P fertilization improves Fe and Zn uptake in potato when inoculated with AMF in conditions of deficiency of phosphorus, iron and zinc in the soil. *Rhizosphere* **2020**, *15*, 100239. [[CrossRef](#)]

56. Tawarayama, K.; Naito, M.; Wagatsuma, T. Solubilization of insoluble inorganic phosphate by hyphal exudates of arbuscular mycorrhizal fungi. *J. Plant Nutr.* **2006**, *29*, 657–665. [[CrossRef](#)]
57. Richardson, A.E.; George, T.S.; Jakobsen, I.; Simpson, R.J. Plant utilization of inositol Phosphates. In *Inositol Phosphates: Linking Agriculture and the Environment*; Turner, B.L., Richardson, A.E., Mullaney, E.J., Eds.; CABI: Wallingford, UK, 2007; pp. 242–260.
58. Schnepf, A.; Roose, T.; Schweiger, P. Impact of growth and uptake patterns of arbuscular Mycorrhizal fungi on plant phosphorus uptake—a modelling study. *Plant Soil* **2008**, *312*, 85–99. [[CrossRef](#)]
59. Begum, N.; Qin, C.; Ahanger, M.A.; Raza, S.; Khan, M.I.; Ashraf, M.; Zhang, L. Role of Arbuscular Mycorrhizal Fungi in Plant Growth Regulation: Implications in Abiotic Stress Tolerance. *Front. Plant Sci.* **2019**, *10*, 1068. [[CrossRef](#)]
60. Saxena, J.; Rana, G.; Pandey, M. Impact of addition of biochar along with *Bacillus* sp. on growth and yield of French beans. *Sci. Hortic.* **2013**, *162*, 351–356. [[CrossRef](#)]
61. Etesami, H.; Adl, S.M. Plant growth-promoting rhizobacteria (PGPR) and their action mechanisms in availability of nutrients to plants. In *Phyto-Microbiome in Stress Regulation: Environmental and Microbial Biotechnology*; Kumar, M., Kumar, V., Prasad, R., Eds.; Springer: Singapore, 2020.
62. Glick, B.R.; Gamalero, E. Recent Developments in the Study of Plant Microbiomes. *Microorganisms* **2021**, *9*, 1533. [[CrossRef](#)]
63. Khatoon, Z.; Huang, S.; Rafique, M.; Fakhra, A.; Kamran, M.A.; Santoyo, G. Unlocking the potential of plant growth-promoting rhizobacteria on soil health and the sustainability of agricultural systems. *J. Environ. Manag.* **2020**, *273*, 111–118. [[CrossRef](#)]
64. Martinez, O.; Crowley, D.; Mora, M.L.; Jorquera, M.A. Short-term study shows that phytate-mineralizing rhizobacteria inoculation affects the biomass, phosphorus (P) uptake and rhizosphere properties of cereal plants. *J. Soil Sci. Plant Nutr.* **2015**, *15*, 153–166.
65. Hale, L.; Luth, M.; Kenney, R.; Crowley, D. Evaluation of pinewood biochar as a carrier of bacterial strain *Enterobacter cloacae* UW5 for soil inoculation. *Appl. Soil Ecol.* **2014**, *84*, 192–199. [[CrossRef](#)]
66. Barea, J.M.; Pozo, M.J.; Azcón, R.; Azcón-Aguilar, C. Microbial co-operation in the rhizosphere. *J. Exp. Bot.* **2005**, *56*, 1761–1778. [[CrossRef](#)]
67. Breitzkreuz, C.; Buscot, F.; Tarkka, M.; Reitz, T. Shifts between and among Populations of Wheat Rhizosphere *Pseudomonas*, *Streptomyces* and *Phyllo bacterium* Suggest Consistent Phosphate Mobilization at Different Wheat Growth Stages under Abiotic Stress. *Front. Microbiol.* **2020**, *10*, 3109. [[CrossRef](#)]
68. Basu, S.; Kumar, G.; Chhabra, S.; Prasad, R. *New and Future Developments in Microbial Biotechnology and Bioengineering Phytomicrobiome for Sustainable Agriculture*; Elsevier: Amsterdam, The Netherlands, 2021; pp. 149–157.
69. Nahas, E. Factors determining rock phosphate solubilization by microorganisms isolated from soil. *World J. Microbiol. Biotechnol.* **2007**, *12*, 567–572. [[CrossRef](#)]
70. Zheng, B.X.; Ibrahim, M.; Zhang, D.P.; Bi, Q.-F.; Li, H.-Z.; Zhou, G.-W.; Yang, X.-R. Identification and characterization of inorganic-phosphate-solubilizing bacteria from agricultural fields with a rapid isolation method. *Appl. Microbiol. Biotechnol.* **2018**, *8*, 47. [[CrossRef](#)]
71. Guo, S.; Feng, B.; Xiao, C.; Wang, Q.; Chi, R. Phosphate-solubilizing microorganisms to enhance phytoremediation of excess phosphorus pollution in phosphate mining wasteland soil. *Biomed. J.* **2021**, *25*, 271–281. [[CrossRef](#)]
72. Amadou, I.; Houben, D.; Faucon, M.P. Unravelling the Role of Rhizosphere Microbiome and Root Traits in Organic Phosphorus Mobilization for Sustainable Phosphorus Fertilization. A Review. *Agronomy* **2021**, *11*, 2267. [[CrossRef](#)]
73. Waldrip, H.M.; He, Z.; Erich, M.S. Effects of poultry manure amendment on phosphorus uptake by ryegrass, soil phosphorus fractions and phosphatase activity. *Biol. Fertil. Soils* **2011**, *47*, 407–418. [[CrossRef](#)]
74. Rady, M.M.; Semida, W.M.; Hemida, K.A.; Abdelhamid, M.T. The effect of compost on growth and yield of *Phaseolus vulgaris* plants grown under saline soil. *Int. J. Recycl. Org. Waste Agric.* **2016**, *5*, 311–321. [[CrossRef](#)]
75. Silva-Leal, J.A.; Pérez-Vidal, A.; Torres-Lozada, P. Effect of biosolids on the nitrogen and phosphorus contents of soil used for sugarcane cultivation. *Heliyon* **2021**, *7*, 63360. [[CrossRef](#)]
76. Shen, Q.; Hedley, M.; Camps Arbestain, M.; Kirschbaum, M.U. Can biochar increase the bioavailability of phosphorus? *J. Soil Sci. Plant Nutr.* **2016**, *16*, 268–286. [[CrossRef](#)]
77. Adekiya, A.O.; Olaniran, A.F.; Adenusi, T.T.; Aremu, C.; Ejue, W.S.; Iranloye, Y.M.; Olayanju, A. Effects of cow dung and wood biochars and green manure on soil fertility and tiger nut (*Cyperus esculentus* L.) performance on a savanna Alfisol. *Sci. Rep.* **2020**, *10*, 21021. [[CrossRef](#)]
78. Zaidi, A.; Khan, S. Interactive effect of rhizotrophic microorganisms on growth, yield, and nutrient uptake of Wheat. *J. Plant Nutr.* **2005**, *28*, 2079–2092. [[CrossRef](#)]
79. Castanheira, N.L.; Dourado, A.C.; Pais, I.; Semedo, J.; Scotti-Campos, P.; Borges, N.; Carvalho, G.; Crespo, M.T.B.; Fareleira, P. Colonization and beneficial effects on annual ryegrass by mixed inoculation with plant growth promoting bacteria. *Microbiol. Res.* **2017**, *198*, 47–55. [[CrossRef](#)]
80. El Maaloum, S.; Elabeda, A.; El Alaoui-Talibia, Z.; Meddicha, A.; Filali-Maltouf, A.; Douirac, A.; Ibsouda-Koraichid, S.; Amire, S.; El Modafar, C. Effect of arbuscular mycorrhizal fungi and Phosphate-solubilizing bacteria consortia associated with Phospho-compost on Phosphorus solubilization and growth of tomato seedlings (*Solanum lycopersicum* L.). *Commun. Soil Sci. Plant Anal.* **2019**, *51*, 622–634. [[CrossRef](#)]
81. Yasmeen, T.; Arif, M.S.; Shahzad, S.M.; Riaz, M.; Tufail, M.A.; Mubarik, M.S.; Ahmad, A.; Ali, S.; Albasher, G.; Shakoob, A. Abandoned agriculture soil can be recultivated by promoting biological phosphorus fertility when amended with nano-rock phosphate and suitable bacterial inoculant. *Ecotoxicol. Environ. Saf.* **2022**, *234*, 113385. [[CrossRef](#)]

82. Soumare, A.; Boubekri, K.; Lyamlouli, K.; Hafidi, M.; Ouhdouch, Y.; Kouisni, L. Efficacy of phosphate solubilizing Actinobacteria to improve rock phosphate agronomic effectiveness and plant growth promotion. *Rhizosphere* **2020**, *17*, 100284. [[CrossRef](#)]
83. Rosa, P.A.L.; Mortinho, E.S.; Jalal, A.; Galindo, F.S.; Buzetti, S.; Fernandes, G.C.; Teixeira Filho, M.C.M. Inoculation with growth-promoting bacteria associated with the reduction of phosphate fertilization in Sugarcane. *Front. Environ. Sci.* **2020**, *8*, 32. [[CrossRef](#)]
84. Richardson, A.E.; George, T.S.; Hens, M.; Simpson, R.J. Utilization of soil organic phosphorus by higher plants. In *Organic Phosphorus in the Environment*; Turner, B.L., Frossard, E., Baldwin, D.S., Eds.; CABI: Wallingford, UK, 2005; pp. 165–184.
85. Msimbira, L.A.; Smith, D.L. The Roles of Plant Growth Promoting Microbes in Enhancing Plant Tolerance to Acidity and Alkalinity Stresses. *Front. Sustain. Food Syst.* **2020**, *4*, 106. [[CrossRef](#)]
86. Raymond, N.S.; Gómez-Muñoz, B.; van der Bom, F.J.T.; Nybroe, O.; Stoumann Jensen, L.; Müller-Stöver, D.S.; Richardson, A.E. Phosphate solubilising microorganisms for improved crop productivity: A critical assessment. *New Phytol.* **2021**, *229*, 1268–1277. [[CrossRef](#)] [[PubMed](#)]
87. Oberson, A.; Joner, E.J. Microbial turnover of phosphorus in soil. In *Organic Phosphorus in the Environment*; Turner, B.L., Frossard, E., Baldwin, D.S., Eds.; CABI: Wallingford, UK, 2005; pp. 133–164.
88. Brimacombe, M.J.; De Leij, F.A.A.M.; Lynch, J.M. Rhizodeposition and microbial populations. In *The Rhizosphere Biochemistry and Organic Substances at the Soil-Plant Interface*; Pinton, R., Varanini, Z., Nannipieri, P., Eds.; CRC Press: Boca Raton, FL, USA, 2007; pp. 73–109.
89. Tian, J.; Ge, F.; Zhang, D.; Deng, S.; Liu, X. Roles of Phosphate Solubilizing Microorganisms from Managing Soil Phosphorus Deficiency to Mediating Biogeochemical P Cycle. *Biology* **2021**, *10*, 158. [[CrossRef](#)] [[PubMed](#)]
90. Owen, D.; Williams, A.P.; Griffith, G.W.; Withers, P.J.A. Use of commercial bio-inoculants to increase agricultural production through improved phosphorus acquisition. *Appl. Soil Ecol.* **2015**, *86*, 41–54. [[CrossRef](#)]
91. Maharana, R.; Basu, A.; Dhal, N.K.; Adak, T. Biosolubilization of rock phosphate by *Pleurotus ostreatus* with brewery sludge and its effect on the growth of maize (*Zea mays* L.). *J. Plant Nutr.* **2020**, *44*, 395–410. [[CrossRef](#)]
92. Martinez-Viveros, O.; Jorquera, M.; Crowley, D.; Gajardo, G.; Mora, M.L. Mechanisms and practical considerations involved in plant growth promotion by rhizobacteria. *J. Soil Sci. Plant Nutr.* **2010**, *10*, 293–319. [[CrossRef](#)]
93. Menezes-Blackburn, D.; Jorquera, M.A.; Gianfreda, L.; Greiner, R.; Mora, M.L. A novel phosphorus biofertilization strategy using cattle manure treated with phytase-nanoclay complexes. *Biol. Fertil. Soils* **2014**, *50*, 583–592. [[CrossRef](#)]
94. Irshad, U.; Brauman, A.; Villenave, C.; Plassard, C. Phosphorus acquisition from phytate depends on efficient bacterial grazing, irrespective of the mycorrhizal status of *Pinus pinaster*. *Plant Soil* **2012**, *358*, 155–168. [[CrossRef](#)]
95. Islam, M.K.; Sano, A.; Majumder, M.S.; Hossain, M.A.; Sakagami, J.I. Isolation and molecular characterization of phosphate solubilizing filamentous fungi from subtropical soils in Okinawa. *Appl. Ecol. Environ. Res.* **2019**, *1*, 9145–9157. [[CrossRef](#)]
96. Joy, J.M.; Ravinder, J.; Rakesh, S.; Somashekar, G. A review article on integrated nutrient management in wheat crop. *Int. J. Chem. Stud.* **2018**, *6*, 697–700.
97. Babalola, O.O.; Glick, B.R. The use of microbial inoculants in African agriculture: Current practice and future prospects. *Agric. Environ.* **2012**, *10*, 540–549.
98. Billah, M.; Khan, M.; Bano, A.; Hassan, T.U.; Munir, A.; Gurmani, A.R. Phosphorus and phosphate solubilizing bacteria: Keys for sustainable agriculture. *Geomicrobiol. J.* **2019**, *36*, 904–916. [[CrossRef](#)]
99. Demirbas, A.; Edris, G.; Alalayah, W.M. Sludge production from municipal wastewater treatment in sewage treatment plant. *Energy Sources Part A Recovery Util. Environ. Eff.* **2017**, *39*, 999–1006. [[CrossRef](#)]
100. Lu, Q.; He, Z.L.; Stoffella, P.J. Land application of biosolids in the USA: A review. *Appl. Environ. Soil Sci.* **2012**, *2012*, 201462. [[CrossRef](#)]
101. Larney, F.J.; Angers, D.A. The role of organic amendments in soil reclamation: A review. *Can. J. Soil Sci.* **2012**, *92*, 19–38. [[CrossRef](#)]
102. Chambers, B.J.; Nicholson, F.A.; Aitken, M.; Cartmell, E.; Rowlands, C. Benefits of biosolids to soil quality and fertility. *Water Environ. J.* **2003**, *17*, 162–167. [[CrossRef](#)]
103. Tian, H.Q.; Lu, C.; Jerry, L.; Melillo, J.; Ren, W.; Huang, Y.; Xu, X.; Liu, M.; Zhang, C.; Chen, G.; et al. Food benefit and climate warming potential of nitrogen fertilizer uses in China. *Environ. Res. Lett.* **2012**, *7*, 044020. [[CrossRef](#)]
104. Ali, M.; Ahmed, T.; Abu-Dieyeh, M.; Al-Ghouti, M. Environmental Impacts of Using Municipal Biosolids on Soil, Plant and Groundwater Qualities. *Sustainability* **2021**, *13*, 8368. [[CrossRef](#)]
105. He, Z.; Zhang, H.; Toor, G.S.; Dou, Z.; Honeycutt, C.W.; Haggard, B.E.; Reiter, M.S. Phosphorus distribution in sequentially extracted fractions of biosolids, poultry litter, and granulated products. *Soil Sci.* **2010**, *175*, 154–161. [[CrossRef](#)]
106. Torri, S.I.; Alberti, C. Characterization of organic compounds from biosolids of Buenos Aires City. *J. Soil Sci. Plant Nutr.* **2012**, *12*, 143–152. [[CrossRef](#)]
107. White, J.W.; Coale, F.J.; Sims, J.T.; Shober, A.L. Phosphorus runoff from waste water treatment biosolids and poultry litter applied to agricultural soils. *J. Environ. Qual.* **2010**, *39*, 314–323. [[CrossRef](#)]
108. Codling, E.E. Long-term effects of biosolid-amended soils on phosphorus, copper, manganese and zinc uptake by wheat. *Soil Sci.* **2014**, *179*, 21–27. [[CrossRef](#)]
109. Shaheen, S.; Tsadilas, C. Phosphorus sorption and availability to canola grown in an Alfisol amended with various soil amendments. *Commun. Soil Sci. Plant Anal.* **2013**, *44*, 89–103. [[CrossRef](#)]

110. Ippolito, J.A.; Barbarick, K.A.; Norvell, K.L. Biosolids impact soil phosphorus accountability fractionation, and potential environmental risk. *J. Environ. Qual.* **2007**, *36*, 764–772. [[CrossRef](#)] [[PubMed](#)]
111. Haney, C.H.; Samuel, B.S.; Bush, J.; Ausubel, F.M. Associations with rhizosphere bacteria can confer an adaptive advantage to plants. *Nat. Plants* **2015**, *1*, 15051. [[CrossRef](#)] [[PubMed](#)]
112. Brandt, R.C.; Elliott, H.A.; O'Connor, G.A. Water-extractable phosphorus in biosolids: Implications for land-based recycling. *Water Environ. Res.* **2004**, *76*, 121–129. [[CrossRef](#)] [[PubMed](#)]
113. Moreira, J.G.; Delvaux, J.C.; Magela, M.L.M.; Pereira, V.J.; de Carmargo, R.; Lana, R.M.Q. Chemical changes in soil with use of pelletized organomineral fertilizer made from biosolids and sugarcane filter cake. *Aust. J. Crop Sci.* **2021**, *15*, 67–72. [[CrossRef](#)]
114. Scharenbroch, B.C.; Meza, E.N.; Catania, M.; Fite, K. Biochar and biosolids increase tree growth and improve soil quality for urban landscapes. *J. Environ. Qual.* **2013**, *42*, 1372–1385. [[CrossRef](#)]
115. Nannipieri, P.; Giagnoni, L.; Renella, G.; Puglisi, E.; Ceccanti, B.; Masciandaro, G.; Fornasier, F.; Marinari, S. Soil enzymology: Classical and molecular approaches. *Biol. Fertil. Soils* **2012**, *48*, 743–762. [[CrossRef](#)]
116. Arif, M.S.; Shahzad, S.M.; Yasmeen, T.; Riaz, M.; Ashraf, M.; Ashraf, M.A.; Kausar, R. Improving plant Phosphorus (P) acquisition by phosphate-solubilizing Bacteria. In *Essential Plant Nutrients*; Springer: Cham, Switzerland, 2017; pp. 513–556. [[CrossRef](#)]
117. Renella, G.; Szukics, U.; Landi, L.; Nannipieri, P. Quantitative assessment of hydrolase production and persistence in soil. *Biol. Fertil. Soils* **2007**, *44*, 321–329. [[CrossRef](#)]
118. Margalef, O.; Sardans, J.; Maspons, J.; Molowny-Horas, R.; Fernández-Martínez, M.; Janssens, I.A.; Peñuelas, J. The effect of global change on soil phosphatase activity. *Glob. Chang. Biol.* **2021**, *27*, 5989–6003. [[CrossRef](#)]
119. Dodor, D.E.; Tabatabai, M.A. Effect of cropping systems on phosphatases in soils. *J. Plant Nutr. Soil Sci.* **2003**, *66*, 7–13. [[CrossRef](#)]
120. Asemaninejad, A.; Langley, S.; Mackinnon, T.; Spiers, G.; Beckett, P.; Mykytczuk, N.; Basiliko, N. Blended municipal compost and biosolids materials for mine reclamation: Long-term field studies to explore metal mobility, soil fertility and microbial communities. *Sci. Total Environ.* **2020**, *760*, 143393. [[CrossRef](#)]
121. Jiang, J.; Wang, Y.; Yu, D.; Yao, X.; Han, J.; Cheng, R.; Cui, H.G.; Zhang, X.; Zhu, G. Garbage enzymes effectively regulated the succession of enzymatic activities and the bacterial community during sewage sludge composting. *Bioresour. Technol.* **2021**, *327*, 124792. [[CrossRef](#)]
122. Moorhead, D.L.; Sinsabaugh, R.L. Simulated patterns of litter decay predict patterns of extracellular enzyme activities. *Appl. Soil Ecol.* **2000**, *14*, 71–79. [[CrossRef](#)]
123. IFA. IFASTAT. Consumption Database. International Fertilizer Association. 2021. Available online: <https://www.ifastat.org/databases/plant-nutrition> (accessed on 11 October 2021).
124. Lu, R.K. Effect of long-term fertilization on soil properties. In *Soil-Plant Nutrients Principles and Fertilization*; Lu, R.K., Xie, J.C., Cai, G.X., Eds.; Chemical Industry Press: Beijing, China, 1998; pp. 102–110. (In Chinese)
125. Wang, Y.; Zhao, X.; Wang, L.; Wang, Y.; Li, W.; Wang, X.; Xing, G. The regime and availability of omitting P fertilizer application for rice in rice/wheat rotation in the Taihu lake region of southern China. *J. Soils Sediments* **2015**, *15*, 844–853. [[CrossRef](#)]
126. Vanden Nest, T.; Amery, F.; Fryda, L.; Boogaerts, C.; Bilbao, J.; Vandecasteele, B. Renewable P sources: P use efficiency of digestate, processed animal manure, compost, biochar and struvite. *Sci. Total Environ.* **2020**, *750*, 141699. [[CrossRef](#)]
127. Ibrahim, M.; Li, G.; Chan, F.K.S.; Kay, P.; Liu, X.; Firebank, L.; Xu, Y. Biochar effects potentially toxic elements and antioxidant enzymes in *Lactuca sativa* L. grown in multi-metals contaminated soil. *Environ. Technol. Innov.* **2019**, *15*, 100427. [[CrossRef](#)]
128. Choudhary, T.K.; Khan, K.S.; Hussain, Q.; Ashfaq, M. Nutrient Availability to Maize Crop (*Zea mays* L.) in Biochar Amended Alkaline Subtropical Soil. *J. Soil Sci. Plant Nutr.* **2021**, *21*, 1293–1306. [[CrossRef](#)]
129. Melaku, T.; Ambaw, G.; Nigussie, A.; Woldekirstos, A.N.; Bekele, E.; Ahmed, M. Short-term application of biochar increases the amount of fertilizer required to obtain potential yield and reduces marginal agronomic efficiency in high phosphorus-fixing soils. *Biochar* **2020**, *2*, 503–511. [[CrossRef](#)]
130. Santos-Torres, M.; Romero-Perdomo, F.; Mendoza-Labrador, J.; Guti ´errez, A.Y.; Vargas, C.; Castro-Rincon, E.; Caro-Quintero, A.; Uribe-Velez, D.; Estrada-Bonilla, G.A. Genomic and phenotypic analysis of rock phosphate-solubilizing rhizobacteria. *Rhizosphere* **2021**, *17*, 100290. [[CrossRef](#)]
131. Major, J.; Rondon, M.; Molina, D.; Riha, S.J.; Lehmann, J. Nutrient leaching in a Colombian savanna oxisol amended with biochar. *J. Environ. Qual.* **2012**, *41*, 1076. [[CrossRef](#)]
132. Balla Kovács, A.; Kremper, R.; Kátai, J.; Vágó, I.; Buzetzky, D.; Kovács, E.M.; Kónya, J.; Nagy, N.M. Characterisation of soil phosphorus forms in the soil-plant system using radio isotopic tracer method. *Plant Soil Environ.* **2021**, *67*, 367–375. [[CrossRef](#)]
133. Nunes, R.d.S.; de Sousa, D.M.G.; Goedert, W.J.; de Oliveira, L.E.Z.; Pavinato, P.S.; Pinheiro, T.D. Distribution of Soil Phosphorus Fractions as a Function of Long-Term Soil Tillage and Phosphate Fertilization Management. *Front. Earth Sci.* **2020**, *8*, 350. [[CrossRef](#)]
134. Pereira, S.I.A.; Abreu, D.; Moreira, H.; Vega, A.; Castro, P.M.L. Plant growth-promoting rhizobacteria (PGPR) improve the growth and nutrient use efficiency in maize (*Zea mays* L.) under water deficit conditions. *Heliyon* **2020**, *6*, e05106. [[CrossRef](#)]
135. Ajeng, A.A.; Abdullah, R.; Ling, T.C.; Ismail, S.; Lau, B.F.; Ong, H.C.; Chang, J.-S. Bioformulation of biochar as a potential inoculant carrier for sustainable agriculture. *Environ. Technol. Innov.* **2020**, *20*, 101168. [[CrossRef](#)]
136. Albareda, M.; Rodríguez-Navarro, D.N.; Camacho, M.; Temprano, F.J. Alternatives to peat as a carrier for rhizobia inoculants: Solid and liquid formulations. *Soil Biol. Biochem.* **2008**, *40*, 2771–2779. [[CrossRef](#)]

137. Pagnani, G.; Galieni, A.; Stagnari, F.; Pellegrini, M.; DelGallo, M.; Pisante, M. Open field inoculation with PGPR as a strategy to manage fertilization of ancient *Triticum aestivum* genotypes. *Biol. Fertil. Soils* **2020**, *56*, 111–124. [[CrossRef](#)]
138. Saranya, K.; Krishnan, P.S.; Kumutha, K.; French, J. Potential for biochar as an alternate carrier to lignite for the preparation of biofertilizers in India. *Int. J. Agric. Environ. Biotechnol.* **2011**, *4*, 167–172.
139. Murphy, J.; Riley, J.P. A modified single-solution method for the determination of phosphorus in natural waters. *Anal. Chim. Acta* **1962**, *27*, 31–36. [[CrossRef](#)]