Sustainable use of phosphorus through bio-based recycling

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Concise definition of subject (Abstract):

Phosphorus (P) is one of the most critical elements in biological building blocks and plays a crucial role in the cellular energy metabolism of all living organisms. Increased attention has been paid to closing the loop on the anthropogenic P cycle, thereby enabling the sustainable use of P. Biotechnology is involved in the demand and consumption chain of P, ranging from agriculture, livestock farming, and food processing to waste treatment. Therefore, biotechnology has the potential to improve the efficiency of anthropogenic P use, if adequate and full consideration is given to its role in the demand and consumption chain. Bio-based P recycling is just starting and needs to fully exploit the potential of microbes to valorize P-containing wastes.
1 Introduction

Phosphorus (P) is one of the most critical elements in biological building blocks and plays a crucial role in the cellular energy metabolism of all living organisms [1]. Since no other element can substitute for P in biochemical processes, humans ultimately rely on P availability. Modern farming is reliant on phosphate (P\textsubscript{i})-derived fertilizers to enhance agricultural production in soils [2]. Therefore, P availability is critical to our present and future food security [3]. Moreover, P is widely used as an important raw material in a variety of industrial products, including beverages, food, and pharmaceuticals [4].

Today, P is mostly obtained from mined P\textsubscript{i} rock, which is nonrenewable on a human time scale [5]. However, natural reserves of high-grade P\textsubscript{i} rock (27-37 wt% P\textsubscript{2}O\textsubscript{5}) are limited and rapidly running out on a global scale. P\textsubscript{i} rock is becoming more and more valuable and a strategic material, because P scarcity is linked to our food security [3]. On the other hand, increased input of P\textsubscript{i} to lakes, bays, and other surface waters causes nuisance phytoplankton growth known as eutrophication [6]. Eutrophication is a complex problem with serious effects on the state and health of aquatic ecosystems, imposing large economic and ecological costs [7]. Algal blooms degrade water quality by producing an offensive odor and taste. The nuisance growth of algae renders boating and fishing difficult and discourages swimming. Excessive growth of algae consumes dissolved oxygen, when they are decomposed by aerobic bacteria. Algal toxin production is also a serious problem in drinking water supplies [8]. Hence, it should be noted that the inefficient use of P not only accelerates the depletion of high-grade P\textsubscript{i} rock but also causes environmental damage to aquatic systems by turning this essential resource into a pollutant.

Despite the potential shortage of P\textsubscript{i} rock, a substantial amount of P in eroded soil particles and also in urban waste flows into the ocean from where P recovery is practically infeasible [9]. To prevent the P loss associated with human activities, increased attention has been paid to closing the loop on the anthropogenic P cycle [10]. Two main pathways toward the sustainable use of P are (i) minimizing P losses in the supply and demand chain and (ii) recycling P from potential secondary resources [3]. Improving P\textsubscript{i} rock mining, beneficiation technologies, and agricultural practices can contribute to preventing P losses in the supply and demand chain [3,10]. Biotechnology, as well as physico-chemical technologies, has the potential to contribute to recovering and recycling P from secondary resources [11,12].

Agriculture is a major user of P, accounting for 80-85% of the world P consumption [9]. The majority of P consumed from food and feed ends up in human wastes and animal manures that are large sources of recyclable P. Since human wastes are discharged in municipal wastewater, it is one of the major P sinks in urban areas [13]. Aiming to control the eutrophication problem, various technologies have already been developed for removing P from wastewater [11,13]. However, not all the P removal technologies can be applied to P recovery for recycling, because the quality of the recovered product is critical to P recycling. For instance, chemical precipitation with Al\textsuperscript{3+} or Fe\textsuperscript{3+}, which is a commonly used technology for P removal, makes P recycling more difficult compared to biological P removal. These cations form insoluble P precipitates that are poorly utilized by plants when applied to agricultural land as fertilizer. If P is removed by precipitation with Al\textsuperscript{3+} or Fe\textsuperscript{3+}, it needs to be converted to a more plant-available form using wet
chemical or thermochemical technologies [13]. Biological P removal is more amenable to P recycling, because P is accumulated by sludge microorganisms in the form of polyphosphate (polyP), which can be further recovered as soluble P for recycling [12].

2 Microbiological basis

2.1 P acquisition in bacteria Bacteria use P as the preferred P source (Fig. 1). When P is available in excess, P is taken up by the P inorganic transport (Pit) system that is expressed constitutively [14]. Under these conditions, bacteria can store P in excess of their requirement for growth in the form of polyP [14]. On the other hand, since bacteria are often subjected to P deficiency in nature, they have evolved complex systems to survive under P starvation conditions. P starvation induces the P-specific transport (Pst) system, which serves as a major scavenger of P residues [15]. The Pst system of *Escherichia coli* comprises four distinct subunits encoded by the *pstS*, *pstA*, *pstB*, and *pstC* genes [16]. These genes, together with the *phoU* gene, form the *pst* operon and are involved in the regulation of the P (pho) regulon [17]. The *phoU* gene encodes a negative regulator of the pho regulon.

Biologically synthesized polyP is a linear polymer of P with a chain length of up to 1000 residues or more [17]. The enzyme responsible for polyP biosynthesis is polyP kinase (PPK), which polymerizes the terminal P of ATP into polyP in a freely reversible reaction [18]. The utilization and degradation of polyP is catalyzed by polyPases, including an exopolyPase (PPX), and several polyP-specific kinases, including polyP-glucokinase and polyP-fructokinase [18].

![Figure 1](image.png)
2.2 Bacterial polyP accumulation

Bacteria exhibit two distinct patterns of polyP accumulation, known as P_i luxury uptake and polyP overplus [12]. P_i luxury uptake occurs when bacterial cells are subjected to nutritional imbalance unfavorable for growth. For example, *E. coli* can accumulate polyP when it is subjected to amino acid (nitrogen) starvation [19]. The molecular mechanism of polyP accumulation under nitrogen starvation has been described by Kuroda et al. [20]. Briefly, guanosine pentaphosphate (pppGpp), which is the major regulatory signal for amino acid starvation, inhibits PPX activity without affecting PPK. This leads to polyP accumulation in *E. coli* in response to the nitrogen starvation. The resulting polyP forms a complex with Lon protease, enabling the activation of protein degradation to supply free amino acids. On the other hand, many bacteria exhibit polyP overplus, when P_i is added to cells previously subjected to P_i starvation. The molecular mechanism of polyP overplus has been determined with *Klebsiella aerogenes* [21]. Induced expression of the *ppk* gene encoding PPK and the *pst* genes under P_i starvation is responsible for polyP overplus in *K. aerogenes*.

Bacterial polyP accumulation can be enhanced by genetic modification [22]. A genetically modified strain of *E. coli* could accumulate approximately 16% of its dry weight as P (73% as P_2O_5). This P content of the *E. coli* recombinant far exceeded that of high-grade P_i rock. Genetically modified microorganisms have no practical use in an open system such as activated sludge process. However, spontaneous mutations of the *phoU* gene enable bacteria to accumulate high levels of polyP even under P_i excess. Such mutations can be caused by the *N*-methyl-*N'*-vitro-*N*-nitrosoguanidine (NTG) mutagenesis [23]. Since the *phoU* mutants express alkaline phosphatase constitutively, they can be easily screened as blue-colored colonies on P_i-excess agar plates containing 5-bromo-4-chloro-3-indolyl-phosphate (X-P_i). This simple technology allows us to enhance the ability of sludge bacteria to accumulate polyP without using the recombinant DNA technology [24].

3 Bio-based P recycling

Basically, bio-based P recycling from wastewater consists of (i) biological P removal from wastewater; (ii) P_i release in a more condensed form from P-rich sludge biomass or P_i leaching from sludge incineration ash; and (iii) P_i precipitation from solution with inorganic cations such as Ca^{2+} or Mg^{2+}. Through this process, P is recovered in the form of either calcium hydroxyapatite (Ca_{10}(PO_4)_6(OH)_2, HAP) or struvite (MgNH_4PO_4·6H_2O, magnesium ammonium phosphate) [13,25,26]. The recovered products can be used as an effective slow-release fertilizer in agriculture, depending on the pH [25]. From the industrial viewpoint, HAP recovery is more promising because it has versatile applications in the manufacturing industry [26]. There are many technological options to remove, release and precipitate P_i.

3.1 Biological P removal

Although many technologies have been proposed to remove P from wastewater, biological P removal is a relatively inexpensive and environmentally sustainable option [13,27]. Biological P removal can avoid consuming a lot of chemicals and correspondingly reduce the cost of sludge disposal [11]. In addition, it is achievable in existing activated sludge processes with a minimum modification on the operating
Activated sludge processes, which are commonly used for treating wastewater, can remove 50 to 70% of the P normally found in municipal wastewater [13]. Moreover, when activated sludge is subjected to alternate anaerobic and aerobic cycles, sludge microorganisms can accumulate high levels of cellular P in the form of polyP [12,28]. This phenomenon is known as enhanced biological phosphorus removal (EBPR).

EBPR has already become a well-established process applied in many full-scale wastewater treatment plants (WWTPs). There is no doubt that EBPR primarily relies on the ability of sludge microorganisms to accumulate polyP. However, despite extensive works on EBPR microbiology and biochemistry, the detailed mechanism still remains unclear [29]. This is attributable to the complex nature of activated sludge. The complexity and variability of the microbial population hinder taking molecular and genetic approaches except fluorescence in situ hybridization (FISH), denaturing gradient gel electrophoresis (DGGE), and metagenomic techniques. It seems difficult, if not impossible, to clarify the detailed mechanism of EBPR at a molecular level.

EBPR processes can remove typically 80-90% of influent P in WWTPs. The alternate anaerobic-aerobic cycle can be installed by introducing an anaerobic zone ahead of an aerobic stage [11]. In a conventional WWTP, this can be readily realized by shutting off aeration at the upstream part of an aeration tank and returning the sludge to this region from a secondary settler. EBPR sludge contains considerable amounts of P (typically 3-5 dry wt%), together with organic matter and other plant nutrients such as nitrogen, sulphur, and potassium. However, it also contains residues formed from the addition of precipitating agents in the wastewater treatment, organic contaminants, and potentially toxic trace elements such as chromium, mercury, and cadmium [30]. These potential pollutants may become enriched in the soil in the long run if the sludge is directly applied to agricultural land. To avoid these potential risks, it is recommended to process EBPR sludge into fertilizers that are safer to store, handle and apply [31].

3.2 P<sub>i</sub> release from polyP-rich sludge

P<sub>i</sub> is released from EBPR sludge in the more concentrated form by various technologies, including heat treatment [32], anaerobiosis [33], anaerobic digestion [34], and incineration followed by chemical leaching [30]. PolyP can be released from sludge by heating at 70°C for about 1 h [32]. The released polyP is degraded to P<sub>i</sub> in solution during heat treatment. Since sludge settleability is unchanged before and after heat treatment, the P-rich solution can be readily separated from sludge solids by sedimentation [35]. An obvious disadvantage of this technology is the additional cost for heating sludge at 70°C. Heat exchangers may help minimize heat energy loss, thereby enabling cost reduction [12].

PolyP-rich activated sludge can release P<sub>i</sub>, but not polyP, back into solution when it is subjected to anaerobiosis [33]. Although the detailed mechanism is unclear, this is considered as a simple and the most inexpensive option to release P<sub>i</sub> from sludge biomass in a side stream [33]. For instance, this phenomenon has been applied to releasing P<sub>i</sub> from sludge biomass in a small anaerobic P<sub>i</sub> stripper tank [33]. The addition of a readily decomposable organic acid such as acetate and propionate can significantly enhance the rate of anaerobic P<sub>i</sub> release. However, the rate and extent of P<sub>i</sub> release by anaerobiosis are less prominent than those achieved by heating at 70°C.
Anaerobic sludge digestion is a well-established process to stabilize waste sludge from the EBPR process [34]. It is one of the most technically mature and cost-effective processes to convert sludge to methane-rich bioenergy (biogas), thereby reducing volume, odors, and pathogens [34]. During anaerobic sludge digestion, P_i is released to the sludge liquor in a more condensed form. However, P_i derived from polyP-rich sludge often causes uncontrolled precipitation of struvite on pipe walls and equipment surfaces of anaerobic digestion processes [25]. This leads to operational problems and significantly increases maintenance costs in waste sludge management. The possibility of struvite formation increases with a rise in the P content of waste sludge. Hence, P_i recovery prior to anaerobic digestion may reduce the potential of struvite deposition. One technical option for P_i removal prior to anaerobic digestion is the above-mentioned heat treatment [32]. Many studies have shown that heat treatment prior to anaerobic digestion can improve digestibility and methane productivity [36]. Therefore, the heat treatment prior to anaerobic digestion may be beneficial not only for controlling the struvite deposition problem but also for improving methane productivity [35].

Sludge incineration followed by chemical P_i leaching is another option for P_i release from polyP-rich sludge [37]. When EBPR sludge is incinerated in a mono-incineration plant, P is concentrated in the ash and can be released by acid or alkaline leaching. One issue of the chemical P_i leaching is how to separate the valuable P from problematic heavy metals. Various separation technologies, including solvent extraction [38] and ion exchange [39], are available to remove heavy metals. Solvent extraction involves the transfer of metal compounds from an aqueous solution to an organic solvent using extracting chemical agents [38]. Ion exchange is achieved by ion exchangers with specific affinity to definite metal ions or groups of metals. This enables replacing heavy metal ions by non-toxic ones such as Na^+ and K^+ [39]. However, it is unavoidable that the P recovery cost is increased with increasing consumption of chemicals. The main alternative for chemical P_i leaching from sludge incineration ash is via thermochemical methods [31]. For instance, problematic heavy metals can be removed from sludge incineration ash by heating at 900-1000\(^\circ\)C in the presence of KCl or MgCl_2. P loss during the thermo-chemical treatment can be minimized by granulating sludge incineration ash into pellets as a pretreatment. The thermochemically treated sludge ash can be used as NPK fertilizer after being supplemented with NH_4NO_3 and K_2SO_4. Since fertilizer is a relatively inexpensive commodity, the potential of the thermochemical method as a P recycling option depends on the fuel cost for heating sludge incineration ash [40].

### 3.3 P_i recovery from aqueous solution

P_i can be recovered from aqueous solution in the form of either HAP or struvite. HAP has a chemical formula similar to bone mineral and is commonly used as a bioceramic owing to its biological properties of biocompatibility [41]. HAP is formed from unstable calcium phosphates such as dicalcium phosphate dehydrate (CaHPO_4·2H_2O, brushite) and amorphous calcium phosphate (Ca_3(PO_4)_2·nH_2O, ACP) during and after P_i precipitation with Ca^{2+} [42]. P_i precipitation with Ca^{2+} is influenced by many factors such as the Ca/P molar ratio, pH, ionic strength, temperature, and coexisting ions [43]. Extensive studies have been carried out on P_i precipitation with Ca^{2+}, enabling this process to become a well-established P_i recovery option. P_i recovered in the form of HAP can be used as a raw
Figure 2  Settleability, filterability, and dewaterability of P recovered by A-CSHs, CaCl$_2$, and Ca(OH)$_2$ [36]. The settleability (a), filterability (b), and dewaterability (c) of recovered P were assessed by the method described previously [36]. Symbols are A-CSHs (circles), Ca(OH)$_2$ (squares), and CaCl$_2$ (triangles).

material for the manufacturing of commercial fertilizer.

As mentioned earlier, struvite often forms in anaerobic sludge digestion processes where high concentrations of P$_i$ and ammonium are present. The blockage of pipes by struvite precipitation causes significant operational problems that lead to an increase in maintenance costs of WWTPs. However, if struvite precipitation is minimized in the digester, high struvite production from P$_i$-rich stream can be achieved in the downstream crystallization process [25]. P$_i$ recovery by controlled struvite crystallization has been one of the most widely recommended technologies for treating sludge digestion liquors [25]. A high-quality struvite pellet product has been marketed as a slow-release fertilizer [43].

P$_i$ can also be recovered from aqueous solutions using crystalline calcium silicate hydrates (CSHs) [44]. CSHs occur naturally and produced technically during the production of gas concrete [13]. CSHs release Ca$^{2+}$ into P$_i$-bearing water, thereby triggering the Ca-P crystallization and its deposition onto the surface of CSHs. This technology has the merit of reducing the consumption of chemicals and correspondingly decreasing the cost of P recovery [44]. To avoid struvite scaling problems, it is effective to directly add CSHs to an anaerobic digester, thereby decreasing the P$_i$ concentration in the digested sludge [45].

The use of amorphous calcium silicate hydrates (A-CSHs) is a new cost-effective option to recover P$_i$ from aqueous solution [42]. A-CSHs can be synthesized using unlimitedly available materials such as siliceous shale and Ca(OH)$_2$ at low costs. Since the reaction of P$_i$ with A-CSHs occurs at pH 7-9, it is not required to adjust the solution pH to a high alkaline pH. The high settleability, filterability, and dewaterability of recovered P are the advantages of A-CSHs over conventional CaCl$_2$ and Ca(OH)$_2$ (Fig. 2). No chemical coagulants are required for P$_i$ recovery by A-CSHs. Moreover, unlike Ca(OH)$_2$, no significant carbonate inhibition occurs with P$_i$ recovery with A-CSHs. Although the detailed mechanism for P$_i$ recovery by A-CSHs
remains unclear, it seems likely that $P_i$ is exchanged with soluble silicate polymers in A-CSHs, enabling $P_i$ to bind to them. Importantly, the $P$ recovered by A-CSHs can be directly used as by-product $P_i$ fertilizer. *In situ* experiments at a WWTP have shown that heavy metals such as As, Cd, Cr, Cu, Hg, Pb, and Zn are not enriched in recovered products [46]. A-CSHs have great potential as a beneficial material for $P$ recycling.

Biological $P$ removal has been implemented in many wastewater treatment plants, aiming to control eutrophication in aquatic systems. However, only a minor portion of removed $P$ is currently recycled for the manufacture of fertilizer. Despite the precious resource potential, it is mostly disposed of as landfill or construction materials without being recycled. This is because essentially no regulation requires $P$ reuse and recycling. Lack of policy measures allows the wastewater treatment sector to neglect $P$ recycling, which may be considered as an extra service. Emerging issues for the implementation of $P$ recycling include the high capital cost for plant construction and the difficulty in establishing stable channels for the distribution and sale of recovered products. To overcome these challenges, it is critical that the wastewater treatment sector works in close collaboration with government agencies and the fertilizer industry.

4 Other options for $P$ recycling

4.1 Land application of biosolids The application of biosolids (treated sewage sludges) to agricultural land is the simplest option to recycle $P$ from wastewater. The nutrient-rich organic solids are considered as a low-grade fertilizer and soil amendment to improve the chemical and physical properties of soil [47]. However, a number of factors make the land application of biosolids increasingly difficult [40]. As mentioned earlier, the residual sludge from wastewater treatment contains a variety of organic contaminants, heavy metals, and pathogens. Although most risk assessments demonstrate that the majority of the contaminants do not place human health at risk, continued vigilance in assessing the significance and implications of potential pollutants is necessary to ensure the long-term security of the land application of biosolids [48].

Urine diversion is another option for the application of human waste to agriculture [49]. Urine diversion sanitation technology, which can divert urine away from human excreta via a specially designed toilet, has been developed and applied in mainly developing countries [50]. The source separation of urine can improve effluent quality and save energy utilization and investment costs of the receiving wastewater treatment. Recycling urine as a liquid fertilizer has the potential to provide approximately 15% $P$ required to fertilize cereal crops on a global basis. However, human urine also contains ingested pharmaceuticals and hormones. If urine sources are sterile and lack chemical contaminants, they may be used as liquid fertilizer after a precautionary waiting period [50].

4.2 Animal manure management Animal manure has often been considered as a waste product and disposed of by application to land within a narrow region of where it is produced [51]. However, animal manure is one of major secondary $P$ resources that have the potential to reduce reliance on mineral $P$ fertilizer. Animal manure is a valuable source of plant nutrients and organic matter if it is adequately managed and applied. Reuse
of animal manure is currently hindered by its bulky nature, the risk of transmitting pathogens, the contamination of heavy metals, undesirable odor, and the geographical separation of livestock farming from crop production. Additionally, where animal manure has been applied as organic fertilizer in a long term, P\textsubscript{i} overaccumulation in soil causes increased transfer of P\textsubscript{i} to surrounding water bodies, leading to eutrophication [51].

To sustainably use animal manure as fertilizer, manure treatment technologies have been developed and are still being developed [52]. Among them is anaerobic digestion of animal manure, which can offer substantial benefits, including on-site energy generation, production of stable, liquid fertilizer and high-quality soil amendment, reduction in odors, and reduction in ground and surface water contamination [53]. The unavoidable issue is the associated investment costs for large-size reactors and the handling, dewatering, and disposal of the digested residues. Like biosolids, animal manure contains potential organic pollutants such as veterinary medicines, antibiotics, and biocides. To minimize the health and environmental risks, P needs to be recovered from animal waste and transformed into a form of marketable product, thereby easing the storage, movement, and application of manure nutrients. Incineration ash of animal manure, particularly chicken manure, contains a considerable amount of P and can be easily processed into fertilizers.

### 4.3 Biosolubilization of immobilized P\textsubscript{i}

P is present in inorganic and organic forms in agricultural soil. Although chemical fertilizers contain large amounts of soluble inorganic P\textsubscript{i}, it is easily and rapidly immobilized by forming complexes with Al\textsuperscript{3+}, Fe\textsuperscript{3+}, Ca\textsuperscript{2+}, and Mn\textsuperscript{2+}, depending on the soil type [54]. Many microorganisms are able to solubilize and mineralize P pools in soil. They produce organic acids such as butyrate, citrate, and gluconate, which can convert unavailable P to soluble P\textsubscript{i} at decreased pH [55,56]. P-solubilizing microorganisms, predominantly bacteria, can contribute to the P efficiency of plants by increasing the P cycling in agricultural soil. P-solubilizing bacteria can also be economically and environmentally useful for bioleaching P\textsubscript{i} from high-P iron ore and low-grade P\textsubscript{i} rock [57]. Molecular breeding of plants that can use P\textsubscript{i} efficiently may be a helpful strategy for agriculture. However, taking into account public acceptance issues on genetically modified plants, investments may be more effective if aimed at the use of P-solubilizing microorganisms.

### 4.4 Industrial P recycling

Approximately 15% of the global P demand is consumed in the manufacturing industry [3,58]. For instance, high-grade phosphoric acid is used as an iron-coating material in the automotive industry, etching agents for aluminum line pattern substrates of computer chips and liquid crystal panels, food additives, chemical catalysts, and flame retardants. P is also one of the crucial raw materials for the production of rechargeable batteries such as lithium ion batteries. In the industrial manufacturing sector, considerable attention has been paid to P\textsubscript{i} removal from wastewater, because P\textsubscript{i} emission is strictly regulated by national or local governments to control eutrophication [59,60].

Recently, P recycling has been considered as an economically beneficial option, because it may lead to the reduction of waste disposal costs by turning P-rich waste into a resource [46]. For instance, considerable attention has been paid to P recovery
in wastewater treatment processes of the fermentation and food industries [61]. Nucleic acid fermentation processes use Pi as an essential raw material, thereby generating Pi-rich wastewater. Pi is removed from the wastewater by biological Pi removal and precipitation with Ca(OH)₂ [61]. Pi recovery has also been implemented in an edible oil refining process, which uses high-grade phosphoric acid to remove impurities from crude vegetable oil [46]. Since no harmful substance is used in the edible oil refinery process, the quality of the recovered product makes it suitable for use in fertilizer for agricultural purposes. The Pi recovered in the form of HAP is sold as a raw material to local fertilizer companies [46].

In the manufacture of liquid crystal glass substrates, Pi is commonly used as an aluminum etching agent [62]. Although the Pi-rich wastewater can be chemically treated with FeCl₃ or Ca(OH)₂, this generates large amounts of precipitates, which must be disposed of as industrial wastes. A membrane system has been developed for recovering Pi from the spent etching solution of a liquid crystal substrate manufacturing process [46]. Pi is separated from spent etching solutions using a two-step reverse osmosis membrane system. This technology uses essentially no chemicals to recover Pi from spent etching solutions. The resulting Pi solution contains no impurities such as heavy metals.

In terms of quantity, Pi recycling in the steel-making industry is particularly important [63]. For instance, the amount of Pi emitted into steel-making slag is estimated to be approximately two-times larger than that ending up in sewage sludge in Japan [64]. Coal and iron ore, which are essential raw materials for the manufacture of iron and steel, contain small amounts of Pi (typically less than 0.03 mass% of P₂O₅). Since Pi has detrimental effects on the mechanical properties of steel, it is removed into steel-making slag at concentrations as high as 2-10 mass% of P₂O₅ [64]. Hence, dephosphorization slag from the steel-making industry is considered as a quantitatively important secondary Pi resource. Laboratory experiments have demonstrated that Pi is potentially recovered from dephosphorization slag using the wet magnetic separation [64] and the carbonate flux treatment [65]. Dephosphorization slag can also be reduced in an iron bath furnace to simultaneously extract iron, manganese, and Pi [66]. Pi-enriched slag can be separated from the hot metal yield and used as Pi fertilizer. The global production of iron ore is approximately 2,000 million tons per year (mt/y) [67]. Assuming that iron ore contains 0.05% of Pi on an average, approximately 1.0 mt/y of Pi could be potentially recovered from dephosphorization slag. This is equivalent to one third of industrial Pi demand worldwide (2.8 mt/y).

5 Conclusions

The cheap supply of Pi is crucial to our food security [3]. Sustainable Pi use must ensure that all the world’s farmers have sufficient access to Pi in the long run to produce enough food to support humanity, whilst minimizing adverse environmental and social impacts [3]. However, because of the limited supply and increasing demand of Pi worldwide, cheap Pi fertilizer is becoming a thing of the past.

Much Pi is lost along the way when passing from mine to field to fork [3]. The losses are significant in arable land and livestock production because of overuse of Pi fertilizer and improper management of animal manure. Improved agricultural efficiency can
Figure 3  P<sub>i</sub> refinery technology.

Contribute much to achievement of P sustainability [68]. In addition to cutting usage, recycling P is crucial to the sustainable use of P. Biotechnology is involved in the demand and consumption chain of P, ranging from crop production, livestock farming, and food processing to waste treatment. Hence, biotechnology has the potential to improve the efficiency of anthropogenic P use, if adequate and full consideration is given to its role in the demand and consumption chain. To fully realize P recycling, it is necessary to establish P<sub>i</sub> refinery technology that can recover P from a wide variety of secondary P resources and use it for recycling (Fig. 3). P-solubilizing microorganisms play fundamental roles in bio-geochemical P cycling in natural and agricultural ecosystems [69]. A biotechnological option for P<sub>i</sub> refinery may be given by the use of P-solubilizing microorganisms. Microbial P<sub>i</sub> refinery technology is just starting and needs to fully exploit the potential of microbes to valorize P-containing wastes.

Despite the recent development of P recovery technology, implementation of P recycling is hindered by a variety of socio-economic reasons such as a lack of public awareness, immature markets for recovered P, and insufficient support from governments. As a result, only a limited amount of potential secondary P resources has been used for recycling. When compared with P removal from wastewater, P recycling is
more difficult to implement, because it needs to create channels for the distribution and sale of recovered products. The implementation of P recycling requires the integration of technology innovation, corporate strategies and public policies. It is particularly important to realize synergies with pollution control, energy/materials recovery, and reducing wastes. A sustainable and safe strategy for P recycling is expected to benefit our present and future society.

6. References


