

Development and Implementation of Technologies for Recycling Phosphorus in Secondary Resources in Japan

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Abstract

The recovery of phosphorus (P) from secondary resources is critical to closing the anthropogenic P loop. The recovered P should be recycled effectively for agricultural and industrial purposes without jeopardizing human health and the environment. Although various technologies are potentially applicable to P recovery and recycling, their implementation remains hindered by socioeconomic factors such as insufficient policy support, an immature market for recovered P and a lack of public awareness. Recently, Japan has experienced good practices in recycling P in secondary resources despite these hindrances. Japan's experience may provide a clue on how to develop and implement technologies for P recovery and recycling, even if the legal, social and economic structures are not fully developed for the security of future P supplies.

Key words: phosphorus recycling, phosphorus recovery, sustainable use of phosphorus

1. Introduction

Since Japan has no economically viable phosphate (P_i) rock reserves, it is almost entirely dependent on imported phosphorus (P). According to a P flow analysis by Matsubae *et al.* (2011), total P imports into Japan are estimated to be approximately 630 kilotons of P per year (ktP/y) (Fig. 1). Of this, approximately 160 ktP/y is associated with the importation of food and animal feed from abroad. In addition, approximately 140 ktP/y is

related to the importation of mineral resources such as iron ore and coal for the iron and steel industry. Taken together, they account for about 48% of the total P imports into Japan. Since P goes almost entirely to food waste, animal manure, sewage sludge and steel-making slag, P recovery from these secondary resources has a potential for recycling a total of 330 ktP/y within Japan.

On the other hand, approximately 300 ktP/y is used as mineral fertilizer and animal feed additives in Japan's agricultural sector. The current use of P in the agricultural

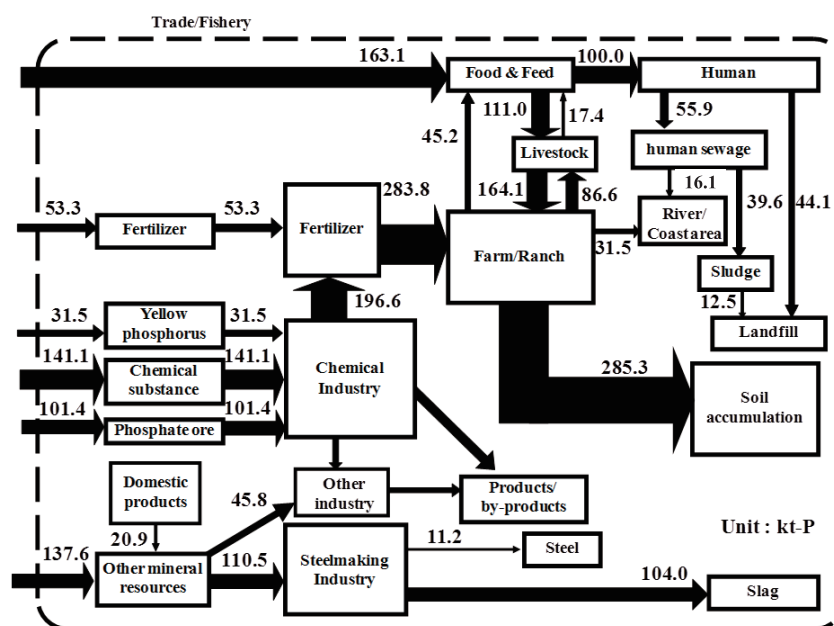


Fig. 1 P flow in Japan (2005). Source: Matsubae *et al.* (2011).

sector, however, is by no means sufficiently efficient, since it is common for farmers to apply P in excess to make it more available to crops and livestock. Consequently, the Ministry of Agriculture, Forest and Fisheries of Japan (MAFF) has adopted a package of measures to reduce P use in the agricultural sector by 20–30% for economic and environmental reasons. If the P loss in the agricultural sector is reduced by improving P management practices as expected, P recycling from the above-mentioned secondary resources could supply the majority of P demand from the agricultural sector of Japan.

P recovery from secondary resources is critical to closing the anthropogenic P loop (Cordell *et al.*, 2011). Although various technologies are potentially applicable to P recovery and recycling, their implementation remains hindered by socioeconomic factors such as insufficient policy support, an immature market for recovered P and a lack of public awareness. Recently, Japan has experienced good practices in P recycling despite these hindrances. Japan's experience may provide a clue on how to develop and implement technologies for P recovery and recycling, even if the legal, social and economic structures are not fully developed for the security of this essential element.

In this paper, we provide an overview of the current state of development and implementation of technologies for P recovery and recycling in Japan. The locations of full-scale operating plants for recovering and recycling P from secondary resources in Japan are shown in Fig. 2.



Fig. 2 Locations of full-scale plants operating for P recovery and recycling in Japan. Only full-scale operating plants in the public sector are shown in this figure.

2. P Recycling in the Public Sector

Municipal wastewater is a major secondary P resource. P is removed from municipal wastewater in wastewater treatment plants (WWTPs), aiming to control eutrophication in natural bodies of water. The P removed from wastewater ultimately ends up in sewage sludge at WWTPs. Obviously, the direct application of sewage sludge to agricultural land is the simplest option for recycling P from municipal wastewater. The nutrient-rich organic solids may be considered a low-grade fertilizer or soil amendment to improve the chemical and physical properties of soil. A number of factors, however, are making land application of sewage sludge increasingly difficult (Laturnus *et al.*, 2007). Sewage sludge contains a variety of organic contaminants, heavy metals and pathogens, which may place human health at risk. Long-distance transportation of sewage sludge from urban areas to arable land where it may be applied is another problem. In Japan, both land filling and land application of sewage sludge are prohibited for practical purposes, because of land scarcity, environmental protection and potential health risks. P needs to be recovered from sewage sludge and used for the manufacture of fertilizers that are safer to store, handle and apply.

Various technologies have already been developed for removing P from wastewater (Morse *et al.*, 1998). Not all the P removal technologies, however, 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^{3+} or Fe^{3+} , which is a commonly used technology for P removal, is unsuitable for P recycling. These cations form insoluble P precipitates that are unavailable to plants when applied to agricultural land as fertilizer. In addition, Al^{3+} and Fe^{3+} often hamper P_i recovery from secondary resources such as sewage sludge and its incinerated ash (Kalmykova & Karlfeldt Fedje, 2013). Biological P removal (Bio-P) is more amenable to P recycling, because P is bio-accumulated by sludge microorganisms in the form of polyphosphate (polyP), which can be readily recovered as soluble P_i (Kato *et al.*, 1993, Kuroda *et al.*, 2001, Hirota *et al.*, 2010). For example, polyP can be released from Bio-P sludge by heating at 70°C for about one hour (Kuroda *et al.*, 2002). P_i is readily obtained by the degradation of polyP. On the basis of this evidence, a simple process (named the Heatphos process) has been developed to recover P_i from Bio-P sludge by heating it at 70°C (Kuroda *et al.*, 2002).

2.1 P recovery from incinerated sludge ash

P_i is thermally stable and does not volatilize during sludge incineration at 800–900°C (Donatello & Cheeseman, 2013). P_i can be concentrated in the incinerated sludge ash as whitlockite-type, tricalcium phosphates ($\text{Ca}_3(\text{PO}_4)_2$). In particular, ashes from a mono-incinerator, which is fed solely with sewage sludge, have a high P content, typically ranging between 4 and 8 wt% (10–20 wt% P_2O_5). The direct application, however, of

incinerated sludge ash to farmland as P_i fertilizer is not possible because it contains toxic heavy metals. In addition, the P accumulated in incinerated sludge ash exhibits low bioavailability when applied as P_i fertilizer. The P in incinerated sludge ash needs to be transformed to a more biologically available form for recycling.

Chemical P_i leaching is a technology option for recycling P in incinerated sludge ash (Kalmykova & Karlfeldt Fedje, 2013). Full-scale plants for recovering P from incinerated sludge ash have been implemented at WWTPs in Gifu and Tottori cities (Figs. 3 and 4). At the WWTPs of both cities, P_i is released from incinerated sludge ash by alkaline (NaOH) leaching technology at 20–50°C and pH above 11 for 6 h. Alkaline leaching technology was adopted because acid leaching inevitably dissolves heavy metals, thereby contaminating the recovered product. In addition, the relatively low level of Ca (typically less than 10 wt% CaO) in the incinerated sludge ash makes alkaline leaching sufficiently efficient. After P_i is extracted with NaOH, it is precipitated with $\text{Ca}(\text{OH})_2$ from the leach solution without removing heavy metals. The NaOH solution is returned to the P_i leaching reactor for recycling. The recovered product, which is calcium hydroxyapatite (HAP), is dewatered, dried and granulated into pellets to obtain P_i fertilizer. The P_i fertilizer, whose efficacy has been demonstrated in farmland, is sold to farmers through fertilizer companies. The solid residues that are left after P_i recovery are subjected to weak-acid cleaning with a dilute H_2SO_4 solution for 5–30 min at 50–70°C to remove heavy metals. After drying, they are used as construction materials or soil amendments for street trees.

Gifu is a medium-size city with a population of about 410,000 (Fig. 2). This city owns four WWTPs (North, South, Central and Northwest), which generate a total of 29,000 t/y of dewatered sludge. Two WWTPs (North and South) have a mono-incinerator fed solely with dewatered sludge. No biogas production plants have been installed at the Gifu WWTPs, mainly because of land

scarcity. The Central and Northwest WWTPs transport dewatered sludge by road to the North WWTP, where it is incinerated in the mono-incinerator. Since the incinerated sludge ash of the South WWTP is also transported by road to the North WWTP, a total of 700–1,000 t/y of ash piles up at the North WWTP. Until 2008, incinerated sludge ash was used for the manufacture of construction bricks at the North WWTP. The price spike of P_i rock in 2008, however, spurred the initiation of P recovery from incinerated sludge ash at the North WWTP, as it had a P content comparable to that of high-grade P_i rock (25–29 wt% P_2O_5).

After a two-year feasibility study, called the LOTUS (Lead to Outstanding Technology for Utilization of Sludge) project, which was supported by the Ministry of Land, Infrastructure, Transport and Tourism (MLITT), a full-scale P recovery plant started operation in April 2010 (Fig. 3). Since then, this plant has been recovering P in the form of HAP, thereby generating P_i fertilizer at approximately 300 t/y. The heavy metal contents, including As, Cd, Hg, Ni, Cr and Pb, have never exceeded their standards in the commercial P_i fertilizer. Although a stable supply of HAP is somewhat difficult to guarantee, farmers favor the use of P_i fertilizer as long as the quality is stable (Wemyss, 2012). The P recovery operation has brought some economic benefits to the Gifu WWTPs, since it reduces the total operating cost compared with the manufacture of construction bricks. The manufacture of bricks requires quite high fuel costs for firing at high temperatures (800–1,300°C). Compared with ash disposal as industrial waste, however, the cost of P recovery is still high owing to the cost of the chemicals (NaOH and $\text{Ca}(\text{OH})_2$). Further cost reduction will be required to make P recovery from incinerated sludge ash economically viable.

Tottori City has ten WWTPs, most of which are relatively small (capacity of 1,000–3,000 m³ of wastewater per day). Among them, only the Akisato WWTP, which has the largest capacity, of 72,400 m³/d, has a mono-



Fig. 3 Full-scale plant for recovering P from sludge incineration ash in Gifu City. Photograph courtesy of K. Goto (Gifu City Office).



Fig. 4 Full-scale plant for recovering P from sludge incineration ash in Tottori City (inset, recovered product, calcium hydroxyapatite (HAP)). Photograph courtesy of M. Hashimoto (University of Tokyo).

incinerator that handles 40 t/d of dewatered sludge. Other WWTPs transport their dewatered sludge by road to the Akisato WWTP, where it is incinerated in the mono-incinerator. The Akisato P recovery plant started operation in April, 2013 (Fig. 4). When the Akisato WWTP needed to renovate its sludge treatment facilities, including an anaerobic thermophilic sludge digestion plant, Tottori City decided to recover P from the incinerated sludge ash. This was because approximately 50% of the renovation expenses could be covered by a government subsidy if it embarked on P recycling from sewage sludge. The struvite precipitation problem in the thermophilic sludge digestion plant was another reason for converting the operation of the Akisato WWTP to facilitate P recovery. On the other hand, there was no need to remove P_i for eutrophication control, because the effluent concentration of total P (T-P) was below the regional effluent standard of 16 mgP/L.

The P recovery technology at the Akisato WWTP is essentially the same as that employed by the Gifu WWTP. In full operation, it is expected to recover approximately 150 t/y of HAP from 500 t/y of incinerated sludge ash with 25–30 wt% P_2O_5 . Solid residues after P extraction are accepted by a cement company, because their low P content makes them suitable for cement production. Stable channels for the distribution and sale of the recovered HAP (citric acid-soluble P (C-P) >15 wt%) have been established within the local area. In this respect, the Japanese Agriculture Association (JA Zen-noh) provides help in manufacturing a marketable fertilizer from the recovered product. As described above, the experiences of Gifu and Tottori cities have demonstrated the significant potential of incinerated sludge ash as a secondary P resource for the manufacture of P_i fertilizer. The expanded use of this technology, however, requires reduced operating costs, which strongly depend on the amount of chemicals needed for P_i extraction and precipitation.

2.2 Struvite recovery from sludge digestion liquor

Anaerobic sludge digestion is a well-established process for stabilizing sewage sludge and reducing its volume through biogas (methane) production. If an anaerobic sludge digestion process is available, P can be released from P-rich sludge biomass into the liquid phase of the digester. Struvite formation, however, has often caused difficult scaling problems in pumps, pipes and dewatering facilities of WWTP sludge lines (Marti *et al.*, 2010). The blockage of pipes by struvite precipitates causes significant operational problems, leading to an increase in maintenance costs at WWTPs. Conversely, if struvite precipitation is minimized in the digester, struvite can be recovered from the P_i -rich stream in the downstream process of the digester (Jaffer *et al.*, 2002).

Fukuoka and Matsue cities (Fig. 2) needed to remove P_i from wastewater for the control of eutrophication in Hakata Bay and Lake Shinjiko, respectively. They employed a Bio-P process, the sludge from which was subjected to anaerobic digestion followed by solid-liquid

separation for dewatering. Although the Bio-P process could remove approximately 90% of P_i from the wastewater, difficulties soon occurred owing to struvite precipitation in the downstream processes. Struvite precipitates were particularly visible in the anaerobic sludge digesters and ancillary facilities. To solve this problem, both cities decided to implement struvite recovery from anaerobic sludge digestion liquor at the North, South and Wasui WWTPs in Fukuoka city and the Lake Shinji-East WWTP in Matsue city. Their processes are technologically identical but have different struvite-recovery capacities. Briefly, struvite particles are formed in a fluidized-bed tower reactor (Fig. 5). They are circulated in the tower reactor by air bubbles until being withdrawn via the corn-shaped bottom part of the reactor.

Full-scale plants for struvite recovery in Fukuoka started operation in 1997. They currently recover a total of 100–140 t/y of struvite for recycling. The recovered struvite is sold to fertilizer companies as a chemical fertilizer. Struvite precipitation, however, still poses difficult problems in sludge manipulation. Because of unwanted struvite wall growth, frequent washing of the reactor with citric and acetic acids is required. In addition, the pipes of the downstream lines need to be replaced by plastic tubes, which are easily removable at onset of clogging. Owing to these operational difficulties, only one-third of the anaerobic sludge digestion liquor is processed by the struvite recovery plants in Fukuoka. As a result, struvite recovery in itself has failed to bring economic benefits to the Fukuoka WWTPs. About half of the operating cost comes from chemicals. As a whole, only 2% of influent P is recovered as struvite at the Fukuoka WWTPs.

The Lake Shinji-East WWTP has long suffered from high levels of P in the anaerobic sludge digestion liquor, which is rejected by a solid-liquid separator. The high P_i concentration (more than 1,000 mg/L) increases the concentration of chemicals for P_i removal, inevitably increasing the operating cost. The aims of struvite recovery at the WWTP are threefold: (i) to lower the P_i concentration in the sludge return stream, (ii) to reduce



Fig. 5 Full-scale plant for recovering struvite from anaerobic sludge digestion liquor in Matsue City.

chemical costs for P_i removal, and (iii) to recycle P as a chemical fertilizer (Ueno & Fujii, 2001). The Matsue struvite recovery plant started operation in 1998 (Fig. 5). There are three fluidized-bed reactors with capacities of 500, 150, and 500 m^3/d of anaerobic sludge digestion liquor. $MgCl_2$ is added to the reactor at Mg/P molar ratios of 0.7–0.9. The pH is controlled in the range of 8.5–9.0 using NaOH solution. Since suspended solids (SS) in the rejected liquor can adsorb struvite and inhibit its crystal growth, special attention is paid to making the concentration of influent SS lower than 200 mg/L.

Struvite particles, which grow in a granular shape (0.5–1.0 mm in diameter), are withdrawn from the bottom of the reactor at a retention time of 10 days. Approximately 100–150 t/y of struvite (10–15 t/y as P) is recovered by the Matsue plant. This accounts for about 20% of the P in the inflow to the Lake Shinji-East WWTP. The remaining 80% of the P ends up in the sludge cake from the solid-liquid separator. The recovered struvite is sold to a fertilizer company as a slow-release P_i fertilizer. The fertilizer company manufactures commercial fertilizers adapted to specific local requirements by blending the recovered product with appropriate inorganic and organic components. The cost of transportation is covered by the fertilizer company. Struvite recovery at Matsue city is currently unprofitable mainly owing to the cost of chemicals.

2.3 P recovery from blackwater

Blackwater is a type of wastewater containing human feces and urine. In local areas without sewage treatment facilities, human feces and urine are separately collected and transported by truck to a blackwater treatment plant. The blackwater treatment plant at Senboku City has a capacity of approximately 60 m^3 of blackwater per day (Fig. 6). Blackwater is collected and transported by road from households and decentralized septic tanks in the local area. Senboku City needed to renovate an old blackwater treatment plant to deal with complaints of foul odors from local residents. The new plant was completed in 2009, equipped for nitrogen (N) and P removal and mainstream sludge treatment processes. N and P removal was needed to secure an agreement with local residents on the construction of the new plant. N is removed from undiluted blackwater using a jet aeration system. Since approximately 50% of dissolved organics are converted to acetic acid in the reactor, it is not necessary to add methanol as a carbon source for denitrification. As a result, the concentration of BOD: Biological Oxygen Demand is decreased by nearly 100% in the liquid phase concomitantly with N removal.

P_i is precipitated with $CaCl_2$ from the liquid rejected by a membrane-type solid-liquid separator after N removal. On average, the liquid contains approximately 45 mg/L P. The reactor for P_i precipitation is a continuously stirred tank, to which a $CaCl_2$ solution is fed in a continuous mode. HAP crystals are allowed to grow to an average diameter of 370 μm in the reactor during a retention time of two hours. Approximately 72% of the P

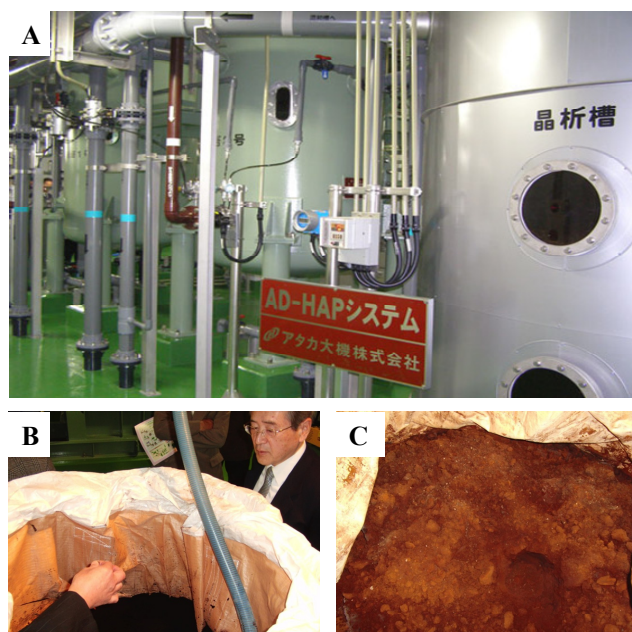


Fig. 6 P recovery plant at the blackwater treatment plant in Senboku City. (A) Continuous reactor to recover P from the liquid fraction of blackwater; (B) Flexible container bag that can serve as a separation filter to collect recovered P products; (C) Recovered P product as calcium hydroxyapatite (HAP). Photograph courtesy of H. Sasaki (Hitachi Zosen Corp.).

can be removed, thereby reducing the effluent T-P concentration to below 20 mg/L. HAP particles are withdrawn from the reactor and transferred into a flexible container bag that can serve as a separation filter. The recovered product contains approximately 30 wt% citrate-soluble P_2O_5 (C- P_2O_5) on a dry weight basis. It is shipped out in wet form containing about 30–40% water. The production rate of HAP is approximately 50 kg per day (about 10–15 t/y). Approximately 20% of the P is recovered as HAP, whereas the remaining 80% ends up in dewatered sludge, which is incinerated and landfilled. The HAP obtained is sold to a fertilizer company, which manufactures a more versatile fertilizer using HAP as a raw material in the local area. The Senboku blackwater treatment plant started operation in April 2009. Currently, the P recovery cost is less than one tenth of the total operating cost. Its chemical costs, however, are higher than the cost of using polyferric chloride for P_i precipitation. About 60% of the construction costs were covered by a government subsidy from the Ministry of Environment (MOE), with the remaining 40% covered by local government bonds. The government subsidy offers a financial incentive for promoting resource recycling in the waste management sector. Up to now, five cities other than Senboku have been recovering HAP from blackwater using processes similar to that described above.

3. P Recycling in the Private Sector

3.1 Phosphoric acid production using incinerated sludge ash

In Japan, only two companies manufacture indus-

trial-grade phosphoric acid. Nippon Phosphoric Acid Co. (NPA) is the principal supplier of phosphoric acid, mainly for agricultural purposes. This company produces approximately 90 kt/y of phosphoric acid (P_2O_5) and 14.3 kt/y of diammonium P_i ($(NH_4)_2HPO_4$) for the manufacture of fertilizers. NPA employs the wet acid process in which sulfuric acid is used to extract P_i from imported P_i rock. In the wet acid process, gypsum ($CaSO_4$) is generated as a byproduct, the market for which is an indispensable prerequisite for the phosphate industry in Japan. NPA uses P_i rocks imported from Morocco, China and Jordan. Phosphoric acid is made from a mixture of P_i rocks to reduce cadmium and radioactive contamination, the levels of which are relatively high in Morocco P_i rock.

In 2009, NPA began a feasibility study for the use of incinerated sludge ash for the manufacture of phosphoric acid. This was triggered by the P_i rock price surge in 2008. NPA intended to diversify P resources, thereby minimizing the risk associated with the instability of the P_i rock supply. NPA saw the possibility of using incinerated sludge ash as a substitute for P_i rock, because sufficient amounts of P_i -rich incinerated sludge ash were available at WWTPs. Additionally, MLITT encouraged NPA to use incinerated sludge ash as a secondary P resource for agricultural purposes. Incinerated sludge ash samples, with P_2O_5 levels in the range of 24–35 wt%, were collected from different WWTPs and examined for their suitability for the wet acid process. The collected ash samples contained less As, Cd and Hg than P_i rock did. Their Pb and Zn levels, however, were significantly higher than those of P_i rock. Accordingly, NPA needed to blend incinerated sludge ash with imported P_i rock to guarantee the quality of the phosphoric acid as well as the

byproduct gypsum.

Currently, incinerated sludge ash is transported over 400 km to the phosphoric acid manufacturing plant from a WWTP using an 8-ton powder-conveying motor truck. NPA chose this WWTP because it is equipped with a Bio-P process to remove P_i without using ferric- or aluminum-based flocculants. The transportation cost is covered by the WWTP. Incinerated sludge ash is blended with roller-milled P_i rock and fed to a noncompartmentalized reactor (Fig. 7). The mixture is then dissolved in concentrated sulphuric acid to generate phosphogypsum slurry. The phospho-gypsum slurry is continuously filtered to separate the phosphoric acid from the gypsum. The gypsum is used as a raw material for the manufacture of building boards and cement. At present, NPA uses a total of 1,000 t/y of incinerated sludge ash for the manufacture of phosphoric acid. In full operation, the manufacturing plant has the capacity to accept 5,000 t/y of incinerated sludge ash.

The blend ratio of incinerated sludge ash with roller-milled P_i rock is currently less than 2.5% (<97.5% P_i rock). This is needed to guarantee the quality of both the phosphoric acid and the gypsum. Increasing the blend ratio changes the structure of gypsum from rhombic to the needle-type form. This structural change makes it difficult to use gypsum for the production of building boards. It is also necessary to meet restricted levels of toxic heavy metals such as Cd, Pb and Hg in gypsum. These requirements are currently satisfied by choosing incinerated sludge ash with less heavy metal content and controlling the blend ratio between the ash and powdered P_i rock. As long as the blend ratio is lower than 2.5%, there is no need to remove or detoxify heavy metals.

NPA acquired a business license from the government

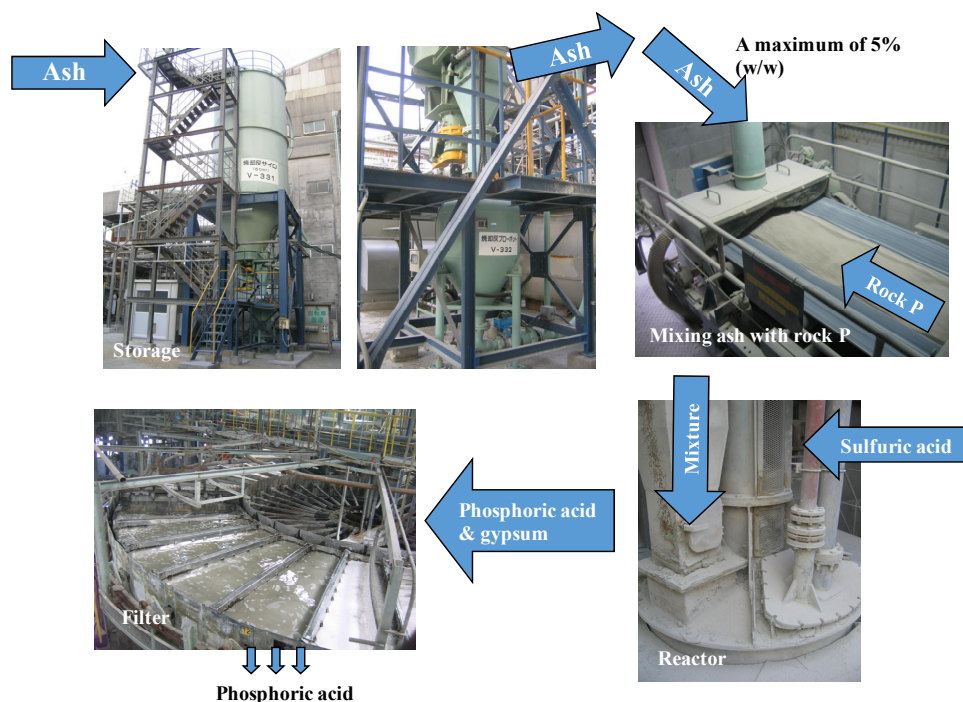


Fig. 7 Wet acid process for the manufacture of phosphoric acid using incinerated sludge ash as a substitute for P_i rock. Photograph courtesy of T. Mochiyama (Nippon Phosphoric Acid Co.).

to purchase incinerated sludge ash from WWTPs. Importantly, it was not necessary for it to modify its existing facilities to accept incinerated sludge ash as a raw material. NPA could reduce its raw material costs, depending on the amount of incinerated sludge ash used. At the same time, the WWTPs could cut waste disposal expenses by valorizing incinerated sludge ash. To increase the blend ratio of ash with P_i rock, it will be critical to reduce the Pb and Zn levels in incinerated sludge ash. Currently, Japan's phosphate industry imports a total of 334 kt/y of P_i rock. If 7.5 kt/y of incinerated sludge ash is used as a substitute for P_i rock, NPA can save a tanker-load of P_i rock.

3.2 P recovery from industrial wastewater

Approximately 15% of the global P demand is consumed in the manufacturing industry (Cordell *et al.*, 2009). For example, high-grade phosphoric acid is used as an iron-coating material in the automotive industry, etching agents for liquid crystal glass substrates, and feedstock for food additives, chemical catalysts and flame retardants. P is also one of the crucial raw materials for the manufacture of rechargeable batteries.

Recently, the manufacturing industry has begun to consider P recycling as an economically beneficial option in waste management. This is because P recycling can potentially reduce waste disposal costs by turning P-rich waste into a resource. Japan Synthetic Alcohol Co., Ltd. (JSA) is a principal supplier of chemically synthesized ethanol for industrial purposes. This company can potentially produce ethanol (95 v/v%) by a direct ethylene hydration process, in which high-grade P_i is used as a chemical catalyst. In addition, JSA can potentially generate 99 v/v% ethanol by dehydration of hydrous ethanol. In the process used by JSA, fresh ethylene gas is fed into a tower reactor, where P_i is impregnated in silica beads, and converted to ethanol as it passes through the reactor. Wastewater from the tower reactor contains high levels of P_i , which leaches from the packed silica beads.

JSA needed to remove P_i from the wastewater to meet the strict regulation of total P emissions to Tokyo Bay (less than 18.2 kgP/d). This company adopted a P recovery process for wastewater in 1998. The process employs a commonly used technology involving P_i precipitation with $\text{Ca}(\text{OH})_2$ at a high pH. To avoid unwanted CaCO_3 formation, decarbonation is carried out by lowering the pH with H_2SO_4 before adding $\text{Ca}(\text{OH})_2$. The formed HAP is partially recycled to increase its pellet size before dewatering and drying. Approximately 75% of the P is recovered as HAP from the wastewater. The HAP pellets, which contain 30 wt% P_2O_5 and 10% water, are sold to a fertilizer company at a low price. Unexpectedly, about 25% of the P in the wastewater failed to be precipitated with $\text{Ca}(\text{OH})_2$. This is probably due to the presence of reduced P_i , which is generated during the ethylene hydration reaction.

Because the wastewater is basically a P_i solution, the recovered product is excellent for the manufacture of

fertilizer. JSA can reduce its sludge disposal costs by selling the recovered product to a fertilizer company. At the same time, the fertilizer company also benefits from this deal, since P is available at a low price. The used silica beads need to be replaced with new ones once a year. Currently, the used silica beads are disposed of as industrial waste, thereby wasting approximately 38 t/y of P_2O_5 without recycling. JSA is looking into the possibility of selling the used silica beads as a raw material for the manufacture of Si and P fertilizer.

KYOWA HAKKO BIO CO., LTD. (KHB) is one of the major Japanese companies in the fermentation industry. This company manufactures nucleic acids and amino acids as feedstocks for foods, seasonings and pharmaceutical agents. The company applies a fermentation process using P_i as an essential raw material, thereby generating P_i -rich wastewater at about 60 kgP/d. The P_i concentration in the wastewater is as high as 1,000 mg/L. KHB has a treatment plant that can handle 60,000 m³/d of wastewater. KHB began to recover P_i from the wastewater to meet legal standards for total P emissions to the Seto Inland Sea in 2006. Importantly, the company considers P recycling a zero-emissions target. P is removed from the wastewater by precipitation with $\text{Ca}(\text{OH})_2$ (P removal > 90%) (Fig. 8). The recovered product is HAP (typically 29 wt% P_2O_5 and 59 wt% CaO). After drying, the HAP is sold to a fertilizer company,

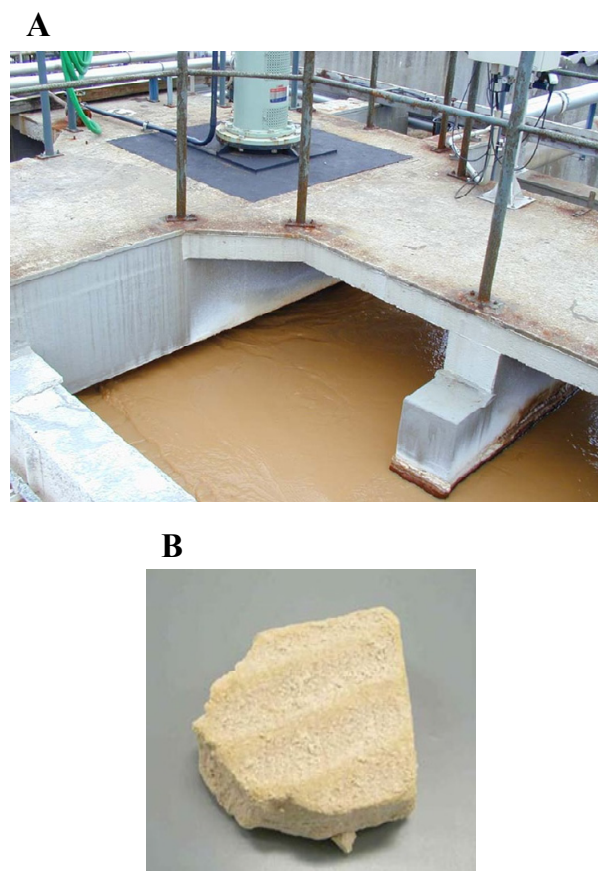


Fig. 8 P recovery from fermentation wastewater at KYOWA HAKKO BIO CO., LTD. (A) P_i precipitation tank; (B) Recovered P product (HAP). Photograph courtesy of H. Hidaka (KYOWA HAKKO BIO CO., LTD.).

which covers the transportation expenses. At present, approximately 60–90 t/y of P is recycled from fermentation wastewater at KHB.

P recovery at KHB has decreased P emissions by approximately 4 t/y, thereby contributing to the preservation of water quality in the Seto Inland Sea. Since P recycling is part of the company's commitment to corporate social responsibility (CSR), it is not important whether KHB benefits economically from P recycling. The recovery product from the fermentation wastewater has no harmful substances and is suitable for the manufacture of fertilizer. Although P is essential for the growth of microorganisms in fermentation processes, P_i recycling in the fermentation process appears difficult because of quality control reliability.

J-Oil Mills, Inc. (JOM) is a principal supplier of vegetable oil in Japan. Edible oil is purified from crude oils extracted from grains and fruits including soybeans, grapes, peanuts and walnuts. Crude vegetable oil contains various phosphatides such as phosphatidyl choline, phosphatidyl inositol, phosphatidyl ethanolamine, and phosphatidic acid. They need to be removed in the early refining stage, because they are responsible for refining losses due to emulsion formation (Van Nieuwenhuyzen & Tomas, 2008). The elimination of phosphatides from crude vegetable oil (called degumming) is a key step in vegetable oil refining. High-grade P_i is used to remove nonhydratable phosphatides by the liberation of phosphatides from Ca and Mg salts.

In acid degumming processes, P_i is added as an 85% solution to crude oil at a concentration in the range of 0.05–0.15 v/v%. Since P_i is added excessively to crude oils, wastewater from the acid degumming process contains high levels of P_i . JOM recovers P_i from the wastewater by chemical precipitation with $\text{Ca}(\text{OH})_2$. Since the wastewater contains essentially no harmful substances, the quality of the recovered product (HAP) is suitable for the manufacture of fertilizer. JOM sells the recovered HAP as a byproduct P_i fertilizer (approximately 260 t/y). JOM needed to remove P to meet stringent effluent standards on P. P_i precipitation with Al^{3+} and Fe^{3+} , however, increased the amount of waste sludge and therefore its disposal costs. JOM could reduce waste disposal costs by selling HAP to a fertilizer company. At the same time, the P supply at a low price brought economic benefits to the fertilizer company.

In the manufacture of liquid crystal glass substrates, P_i is commonly used as an aluminum etching agent. Wastewater from aluminum chemical etching processes contains P_i at concentrations as high as 5,000 mg/L. Although the P_i -rich wastewater can be chemically treated with FeCl_3 or $\text{Ca}(\text{OH})_2$, this generates large amounts of precipitates, which must be disposed of as industrial wastes. Waste reduction (ideally, zero emissions) is critical to the manufacturing industry for environmental and economic reasons. Kurita Water Industries Ltd. (KWI) has developed a system for recovering P from the spent etching solution of a liquid crystal substrate manufacturing process. The wastewater contains P_i ,

acetic acid, nitric acid and aluminum (pH 2.0). After removing SS by filtration, aluminum is removed from the wastewater using an H-type cation exchange column. Then, P_i is separated from the acetic and nitric acids using a two-step reverse osmosis membrane system at 0.7–2 and 4 MPa, respectively. Since P_i is blocked by the reverse osmosis membrane, it can be concentrated to 4–7%, which is 40–60 times higher than that of the spent etching solution.

This technology uses essentially no chemicals to recover P_i from the spent etching solution. P_i can be further condensed to 50% or higher by reduced-pressure distillation. The resulting P_i solution contains no impurities such as heavy metals. This process has been installed in three liquid crystal manufacturing plants (two in Japan and one in Taiwan). About 2.7 m³ of 50% P_i solution can be generated from 800 m³/d of spent etching solution with 3,000 mg P_i /L. More than 1,000 t/y (about 3 t/d) of P has been recovered, leading to a reduction of 120 t/d of waste product (60% water). The recovered P can be used as a raw material for the manufacture of P-containing chemicals.

3.3 P recycling from other secondary resources

Animal manure has often been considered a waste product and disposed of by applying it to land within a limited distance from where it is produced (Bateman *et al.*, 2011). Animal manure, however, is a major secondary P resource with a potential to reduce reliance on mineral P_i fertilizers. P is added to the diet of pigs and poultry to prevent health problems, weak bones and impaired fertility. Since much of the P ingested by animals is excreted in their feces, animal manure can be a valuable source of plant nutrients and organic matter if it is adequately managed and applied.

Use of animal manure is currently hindered by its bulky nature, the risk of transmitting pathogens, contamination by heavy metals, its undesirable odors and the geographical separation of livestock farming from crop production. Many farms do not have enough land on which they can use the manure produced as organic fertilizer. Since the concentration of P in animal manure is not high, transporting it, especially over long distances, costs more than the P is worth. Additionally, if animal manure is applied as organic fertilizer over long periods, P_i overaccumulation in soil can lead to transference of P_i to surrounding water bodies, causing eutrophication (Bateman *et al.*, 2011).

The incineration of animal manure to minimize the logistical difficulties of handling surplus manure and to recover energy is practiced in regions with high animal densities (Ro *et al.*, 2009). Although the incineration of animal manure has been proposed as a solution to manure disposal problems, it has remained economically infeasible due to the high cost of ash disposal. Miyazaki Biomass Recycle Co. (MBR) implemented a power plant to generate electricity by incinerating broiler chicken manure in 2005 (Fig. 9). Broiler chicken manure, with a water content of typically 43 wt%, can produce about



Fig. 9 Power plant for generating electricity by incinerating broiler chicken manure. Photograph courtesy of K. Yano (Miyazaki Biomass Recycle Co.).

1,900 kcal/kg when incinerated. MBR intended to reduce excess animal manure, thereby solving problems such as nutrient over-accumulation, offensive odors and nitrate contamination of ground water. Additionally, it needed to respond to enhanced regulations on animal manure disposal by the government in 1999.

The MBR power plant has an incineration capacity of 132,000 t/y of broiler chicken manure, thereby generating electricity of 11,350 kW. Of this, about 20% is consumed locally, while the remaining 80% is sold to a local power company. About 500 t/d of broiler chicken manure (more than 50% water) is transported by road from 400 poultry houses in the Miyazaki area to the MBR plant. Approximately 45% is transported less than 40 km, while the remaining 55% is transported more than 40 km to the power plant. The collected manure is incinerated in a self-sustaining combustion furnace at 7.43 MPa and 468°C. After incineration, approximately 13,000 t/y of ash (about 10% of the original weight) is transported by road to a fertilizer company. Subsequently, the ash disposal problem is solved by recycling incineration ash as PK fertilizer (20 wt% P_2O_5 and 15 wt% K on average).

P recovery from incinerated chicken manure ash has also been investigated using an acid leaching-alkali precipitation method at a pilot scale (Kaikake *et al.*, 2009). Approximately 92% P could be recovered, demonstrating the potential of incinerated chicken manure ash as a secondary P resource. Approximately 6.6 mt/y of manure is generated from broiler chicken houses in Japan. If all of the manure were incinerated, it is estimated that a total of 61 kt/y of P could end up in the incineration ash. This is comparable to 8% of the total P imports into Japan.

Monoammonium P_i ($NH_4H_2PO_4$) has been used as a dry chemical, fire-extinguishing agent, since it shows good flame suppression properties. Spent fire-extinguishing agents are potentially usable as NP fertilizer. However, since fire-extinguishing agents need to be buoyed over water for extinguishing fires, they are coated with silicon to make them water-repellent. Because of this, they cannot be used directly as fertilizers for plants.

Although fire-extinguishing agents must be replaced with new ones at regular periods, they have been considered as industrial wastes and landfilled without recycling.

Kanesada Kosan Co. recycles spent extinguishing agents as NP fertilizer (28 wt% P_2O_5 and 16 wt% N) after a physicochemical treatment. The patented treatment technique can remove silicon coatings from fire-extinguishing agents, thereby improving P availability for plant growth. Since the steel container of a fire extinguisher is also recyclable, this company has developed a win-win business model with the manufacturer through recycling. The manufacturer no longer needs to pay for disposal of spent fire-extinguishing agents. Currently, it is estimated that approximately 10,000 t/y of old fire-extinguishing agents are disposed of as industrial waste in Japan. This company plans to recycle about 1,000 t/y of spent fire-extinguishing agents as NP fertilizer.

4. Technologies Being Developed

4.1 Solid adsorbents for P recovery

Although P_i can be recovered from wastewater by chemical precipitation, the recovered product inevitably contains a considerable amount of organic and inorganic impurities. In addition, after chemical precipitation, it is difficult to remove the low concentration of P_i remaining in the secondary treatment effluent of a WWTP. Asahi Kasei Chemicals Corporation (AKC) has developed a high-speed P adsorbent made of ion-exchangeable ceramic beads (Midorikawa *et al.*, 2008). The ceramic beads, which have an average diameter of 0.55 mm and 85% porosity, exhibit a high specificity for P_i (Fig. 10). The high porosity allows fast P_i diffusion and smooth P_i adsorption on the ceramic beads. In addition, the ceramics are very stable across a wide pH range from 2 to 14. Their P_i adsorption capacity is maintained even after being used more than 100 times.

Large-scale demonstration experiments have been conducted by the Ibaraki Prefectural Government and Japan Sewage Works Agency to examine the performance of these beads for removing P_i from the secondary treatment effluent at the Kasumigaura WWTP (89,000 m³/d). The Kasumigaura WWTP employs a conventional activated sludge process and discharges the secondary treatment effluent to Lake Kasumigaura. To control eutrophication in Lake Kasumigaura, it is desirable to remove P from the secondary treatment effluent, which contains 1–3 mg P/L. The AKC system consists of (i) P_i removal from the secondary treatment effluent by adsorption, (ii) P_i desorption from the adsorbent with NaOH solution, and (iii) P_i recovery from the alkaline solution by precipitation with $Ca(OH)_2$. The AKC system has been approved by MLITT as an innovative technology for P recovery at WWTPs.

In the demonstration experiments, P_i removability was examined using three packed column tower reactors at a space velocity (SV) of 20 h⁻¹. While two tower reactors were removing P_i from the secondary treatment effluent, P_i was detached in the remaining column using a

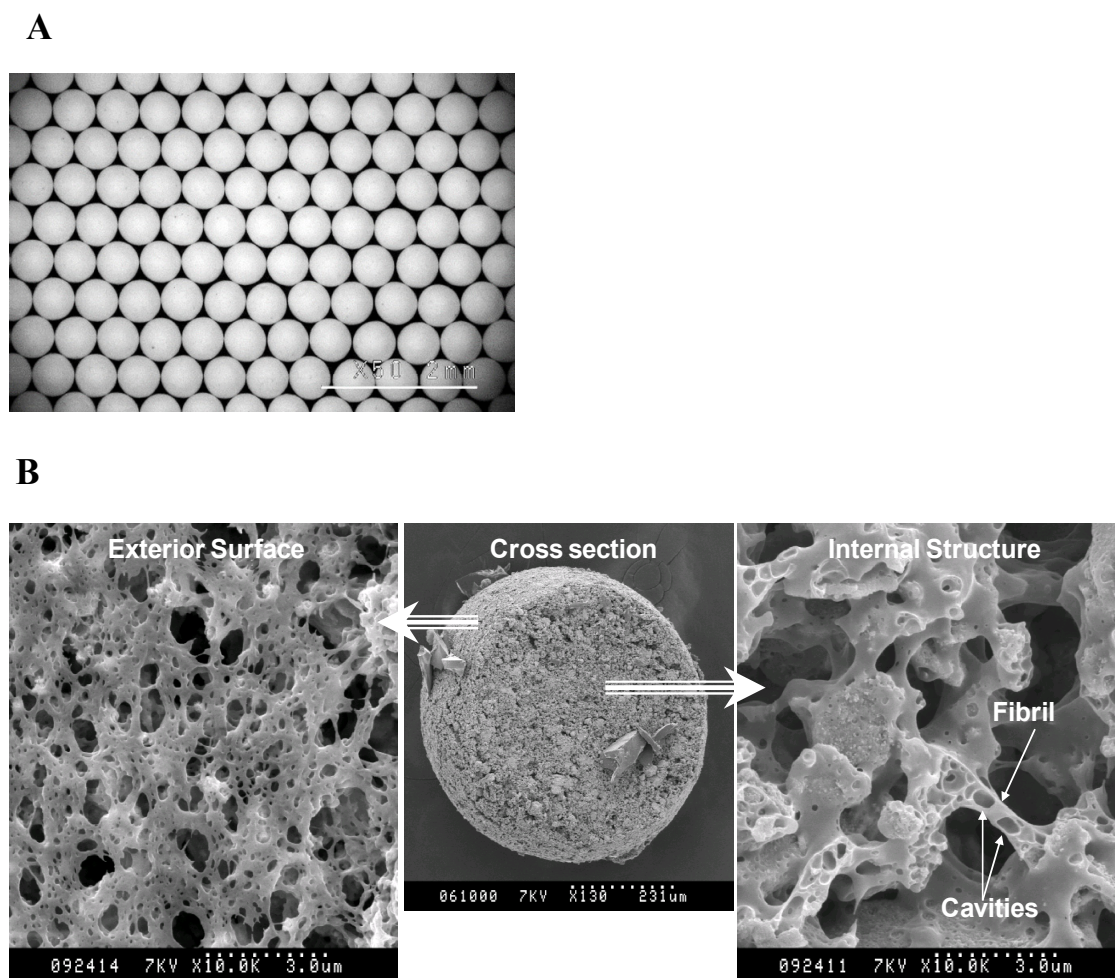


Fig. 10 High-speed P adsorbent made of ion-exchangeable ceramic beads. (A) Ceramic beads packed in a column (bar, 0.5 mm); (B) Scanning electron microscopy image of the ceramic beads (bar, 2 μm). Photograph courtesy of I. Midorikawa (Asahi Kasei Chemicals Corp.)

5% NaOH solution at $\text{SV} = 3 \text{ h}^{-1}$. P_i was detached when the amount of P_i adsorbed reached 2 g P/L-adsorbent. To prevent the packed column tower reactors from clogging, SS was removed from the secondary treatment effluent by sand filtration. The demonstration plant had a capacity to treat an average of 500 m^3/d of secondary treatment effluent (max., 600 m^3/d). The P recovery process was operated using a fully automated control system.

Approximately 97% of the P was removed from the secondary treatment effluent, reducing the T-P concentration of the treated water to less than 0.05 mg/L. After detachment, the P_i was recovered by adding $\text{Ca}(\text{OH})_2$ at a Ca/P molar ratio in the range of 2.0–2.5. The recovered product contained approximately 16% of its dry weight as P. The levels of heavy metals such as As, Cd, Cr, Cu, Hg, Pb and Zn were negligible, compared with those in imported P_i rock. Importantly, there was no significant carbonate inhibition of P recovery. The adsorbent can be repeatedly used for P removal after being washed with 7.5% NaOH. The NaOH solution can also be recycled for P_i detachment from packed ceramic beads.

This process has several advantages over P_i recovery by chemical precipitation: (i) it requires smaller quanti-

ties of chemicals for P recovery than does chemical precipitation; (ii) because of the high P_i selectivity, the recovered product has a lower impurity content than P_i precipitated with Ca^{2+} ; (iii) it produces no significant amount of waste sludge, and (iv) the high speed of P removal makes the reactor compact. It is estimated that the implementation of this technology at the Kasumigaura WWTP may enable the recovery of approximately 250 t/y of HAP from the secondary treatment effluent, thereby reducing the P load to Lake Kasumigaura.

Another solid adsorbent for P recovery is prepared from concrete sludge, which is an alkaline industrial byproduct consisting of hydrated cement aggregates and water (Iizuka *et al.*, 2012). Concrete sludge is commonly available at construction sites where more concrete materials are generated than required. Until recently, concrete sludge has been used as a landfill material after solid-liquid separation followed by neutralization with a strong acid (Tsunashima *et al.*, 2012). This is costly, however, and a wasteful consumption of resources. Nippon Concrete Industries Co., Ltd. (NCI) has developed an inexpensive solid adsorbent, named PAdeCS (Phospho-

rus Adsorbent derived from Concrete Sludge), for recovering P_i from wastewater (Iizuka *et al.*, 2012). The development of an inexpensive adsorbent is one of the key issues for economic incentives to encourage the implementation of P recovery. The aims for developing PAdeCS were twofold: economical recycling of concrete sludge and an inexpensive supply of adsorbents for P recovery.

To produce PAdeCS, concrete sludge is mixed with water at room temperature and atmospheric pressure. After solid-liquid separation, the solids are dewatered, dried and pulverized. Since the liquid phase is strongly alkaline and rich in calcium, it can be used as an aqueous solution for CO_2 absorption. The resulting precipitates can be recovered as marketable $CaCO_3$ with a purity of more than 95 wt%. Various sizes of PAdeCS particles can be prepared, depending on their application. PAdeCS can rapidly remove P_i from aqueous solutions, simultaneously acting as the calcium source, alkali substance and seed material. P_i is removed in the form of low-crystallinity HAP on PAdeCS particles. NCI suggests that P recovered by PAdeCS can be used as a substitute for P_i rock. Since PAdeCS can be supplied in large quantities, it is also possible to use it as a pH neutralizer for acidic drainage water from abandoned mine sites and hot springs.

4.2 Direct struvite recovery from digested sludge

Direct removal of struvite from digested sludge is effective not only for preventing scaling problems but also for improving sludge dewaterability. Improvement of sludge dewaterability leads to a significant reduction in sludge disposal costs, since it reduces the volume of sludge that needs to be transported and incinerated. More struvite can be recovered directly from digested sludge than from liquor rejected by a solid/liquid separator. In addition, since struvite is naturally formed in digested sludge, it is not necessary to supply crystal seeds for struvite growth.

Swing Corporation (SC) has been operating a full-scale demonstration plant to recover struvite directly from digested sludge at the Higashi-Nada WWTP (capacity of 70,000 m³/d) in Kobe City since 2012 (Fig. 11). This project has been supported by MLITT as a B-DASH (Breakthrough by Dynamic Approach in Sewage High technology) project. The Higashi-Nada WWTP has three anaerobic sludge digesters (each 6 m high and 3 m in diameter). Digested sludge, which contains P_i at concentrations as high as 600 mgP/L, is fed to the continuously stirred reactor at a retention time of 6 h. $Mg(OH)_2$ is supplied to the reactor as a source of magnesium. Digested sludge in the reactor is mechanically mixed to enhance the contact between solid and liquid, because it has a relatively high viscosity. The mechanical mixing also causes decarbonization and collision of struvite crystals, thereby controlling their sizes in the reactor. After struvite crystals grow in the reactor, they are continuously withdrawn from the reactor and collected by centrifugation. By this process, the



Fig. 11 Full-scale plant for recovering struvite directly from digested sludge (Higashi-Nada WWTP at Kobe). Photograph courtesy of N. Ishigami (Swing Corp.).

struvite concentration in the reactor remains nearly constant.

The recovered struvite is washed with water to obtain high-purity products (5 wt% nitrogen, 27.3 wt% C-P₂O₅, and 15 wt% MgO). This plant is expected to recover approximately 360 kg/d of struvite from 239 m³/d of digested sludge with P recovery efficiencies of 30–40%. This amounts to about 130 t/y of struvite, which is equivalent to one-tenth of the annual consumption of P_i fertilizer in the Kobe area. Approximately 90% of the P can be recovered from the liquid phase of the digester. The struvite recovery plant will be put into full operation at the Higashi-Nada WWTP in a year or less.

4.3 P recovery using amorphous calcium silicate hydrates

Cost reduction is critical to the expanded use of P recovery technologies. Amorphous calcium silicate hydrates (A-CSHs) are a new cost-effective adsorbent for recovering P_i from aqueous solutions. Taiheiyo Cement Corporation (TCC) and Onoda Chemical Industry Co., Ltd. (OCI) have been developing a simple technology to recover P using A-CSHs as an inexpensive adsorbent (named Rintoru®). A-CSHs, which have a Ca/Si molar ratio of 1.0 or greater, can be synthesized using unlimitedly available, inexpensive materials such as siliceous shale and calcium hydroxide (Okano *et al.*, 2013). Since the reaction of P_i with A-CSHs occurs at pHs 7.0–9.0, it is not necessary to adjust the solution to an alkaline pH. The high settleability, filterability and dewaterability of recovered P are the advantages of A-CSHs over conventional $CaCl_2$ and $Ca(OH)_2$. Because of the high settleability, no chemical coagulant is required for P_i recovery by A-CSHs. Moreover, unlike $Ca(OH)_2$, no significant carbonate inhibition occurs in P_i recovery using A-CSHs.

A-CSHs consist of inorganic silicate residues having an average chain length of 3.5 in the form of liquid slurry. The short-length silicate polymers are linked to each other through ion bindings with Ca^{2+} . A-CSHs release short-length silicate polymers when they are dispersed in an aqueous solution. This allows the divalent hydrogen phosphate anion (HPO_4^{2-}) to form ion bindings with Ca^{2+} .

in place of the silicate polymers. Conventional P recovery from wastewater is a multiple-step reaction process that requires costly automatic process control. In this respect, A-CSHs have a potential to simplify P recovery processes. A-CSHs can be added to a P_i -rich aqueous solution in slurry form. After 10–20 minutes of mixing, P adsorbed by A-CSHs is recovered by settling without using any chemical coagulant. Importantly, the recovered P can be directly used as a byproduct P_i fertilizer. TCC plans to produce large amounts of inexpensive A-CSHs using unlimitedly available materials for P recovery from wastewater.

A mobile pilot plant for *in situ* P recovery experiments has been developed by Mikuni Pharmaceutical Industry Co., Ltd. (Fig. 12). Because of the simplicity of the P recovery process using A-CSHs, the experimental equipment can be loaded on a two-ton motor truck and transported to a WWTP where P is recovered from anaerobic sludge digestion liquor. *In situ* experiments have demonstrated that approximately 70–80% of P could be recovered from anaerobic sludge digestion liquor at a WWTP. The levels of heavy metals such as As, Cd, Cr, Cu, Hg, Pb and Zn were below their regulatory standards. Since the mobile pilot plant is designed to be easily transported and installed, it enables cost-effective demonstration experiments at WWTPs. It is also possible to obtain inexpensive Ca and silicates from acid digestion of concrete sludge and cement materials.

A-CSHs (originally named “CSH-lime”) have also been examined for their ability to remove color and P_i simultaneously from treated swine wastewater (Yamashita *et al.*, 2012). Colored wastewater often contains nonbiodegradable and recalcitrant substances such as melanoidin, humic substances and bile pigments. In addition, the intense coloration of swine wastewater is problematic because it makes local residents uncomfortable. A-CSHs can effectively remove P and color at pH 10 or higher at a concentration of 2.0 w/v%. In addition, A-CSHs are effective for inactivating total heterotrophic and coliform bacteria in treated swine wastewater. This is probably due to the increased pH after the addi-

tion of A-CSHs to swine wastewater. After P removal, A-CSHs are recovered by filtration through a cloth filter. The recovered product, which contains approximately 20 wt% C- P_2O_5 , can be used as fertilizer. More recently, A-CSHs have been examined by Mitsubishi Kakoki Kaisha, Ltd. for their ability to remove P_i from blackwater.

4.4 P recovery from swine solids and wastewater

Intensive livestock production generates animal manure in such large quantities that the supply of nutrients greatly surpasses the needs of crops. It is estimated that approximately 234 kt/y of P_2O_5 (101 kt/y of P) ends up in animal manure in Japan. Carbonization is highlighted as one of the important technological options for recovering P from swine manure (Ro *et al.*, 2009). Carbonization can promote the conversion of animal manure into charcoal, thereby reducing the solid volume. It is used as a pretreatment of raw biomass which is not suitable for direct combustion because of the low energy density and high moisture content (Liu & Balasubramanian, 2014). Since carbonization requires relatively low technical resources, it is suitable for small-scale swine farms (Ro *et al.*, 2009).

Hitachi Zosen Corporation (Hitz) has implemented a pilot-scale plant for the carbonization of pig manure in Kobayashi City (Fig. 13). The main aim of this project is to reduce surplus compost, which is generated by large-scale hog farms much beyond the local demand. Excess compost, as well as pig manure, leads to nutrient overuse in farmland and illegal manure dumping into the natural environment. The Hitz process was designed to carbonize compost with a self-sustained heating system. Importantly, the process can generate bio-char, which adsorbs P in a condensed form from compost. Since essentially no fuel is required for carbonizing compost, it is an energy-effective, inexpensive process, compared with energy-intensive incineration. The P_i -rich bio-char is easily transported and sold as a valuable P source, since it is readily soluble in citric acid.

Composts from swine farms contain approximately



Fig. 12 Mobile pilot-scale plant for the *in situ* examination and demonstration of P_i recovery from wastewater.



Fig. 13 Pilot-scale plant for carbonization of pig manure in Kobayashi City. Photograph courtesy of K. Ueda (Hitachi Zosen Corp.).

6 wt% P and 35% water. Composts are collected from local farms and anaerobically heated at 400°C using a rotary kiln at a rotation speed of 0.2–2.0 min⁻¹. Most organic matter is converted to an energy-rich combustible gas and charcoal. The combustible gas is mixed with air to burn in a secondary combustion chamber, whereby the gas temperature reaches approximately 850°C. The combustible gas is used to heat the rotary kiln indirectly.

Nearly all of the P present in pig manure can be accumulated on the surface of the hydrothermally prepared bio-char. This is possible when pig manure is heated indirectly and evenly at a constant temperature of 400°C. P can be recovered in condensed form (20 wt% P₂O₅) by mechanically collecting the P-rich surface fraction of the bio-char (P-rich bio-char). The remaining fraction of bio-char contains less P (typically 12 wt% P₂O₅). Approximately 120 kg of P-rich bio-char is produced from 1,000 kg of pig manure compost. These P-rich materials can be effectively used as P fertilizer. Bio-char can easily be transported and stored without the nuisances of odors and deterioration. Approximately 59 kt/y of P₂O₅ can be potentially recovered from pig manure in Japan. This process is potentially applicable to P recovery from poultry manure and also digested sludge at WWTPs.

Feces, urine, and washing water from piggeries are usually separated into solid and liquid fractions by a solid-liquid separator. The solid fraction is composted, while the liquid fraction must be treated before being discharged into the environment. A total of approximately 10 kt/y of P is lost by discharging swine wastewater in Japan. Since swine wastewater contains high levels of P_i (100–600 mgP/L), NH₄⁺, Ca, and Mg, struvite is easily formed at alkaline pHs. If struvite formation is effectively controlled, P_i can be recovered as struvite from swine wastewater.

The National Institute of Livestock and Grassland Science (NILGS) has developed a reactor system to recover struvite from swine wastewater (Suzuki *et al.*, 2007). Aeration is employed to decarbonize swine wastewater, thereby increasing the pH to over 8.0 for struvite formation. This is of practical importance for struvite recovery, because alkaline addition is a costly and laborious work for small-scale farms. Essentially pure struvite can be recovered using an accumulator submerged in the aeration column of the reactor. Demonstration experiments were carried out using a reactor of about 3.5 m height and 1.5 m diameter with a capacity of 4 m³/d. The retention time of swine wastewater in the aeration column of the reactor was 3.6 h. While the swine wastewater contained P in a range from 50 to 350 mg/L, the effluent P concentration was stably maintained at approximately 30 mg/L. Struvite could be easily recovered by scraping the surface of the submerged accumulation device by light brushing. A maximum of 170 g of struvite was recovered from 1 m³ of swine wastewater without adding any chemicals. The recovered product contained struvite at 95% of the dry weight and could be directly applied to farmland as

fertilizer. This is a simple, inexpensive process so it is economically adaptable to small-scale pig farms.

4.5 Thermochemical conversion of incinerated sludge ash to fertilizer

P leaching from incinerated sludge requires large amounts of chemicals, thereby making it difficult to reduce the cost below the economic value of the recovered product. If heavy metals need to be removed, additional costs are required to obtain safe recovered products. An alternative for chemical P_i leaching from sludge incineration ash is via thermochemical methods (Donatello & Cheeseman, 2013). Problematic heavy metals can be removed from sludge incineration ash by heating at 900–1000°C in the presence of KCl or MgCl₂. P loss during the thermo-chemical treatment can be minimized by granulating the sludge ash into pellets. Thermochemically treated sludge ash can be used as an NPK fertilizer after being supplemented with NH₄NO₃. Since fertilizer is a relatively inexpensive commodity, the potential of the thermochemical method as a P recycling option will depend on finding ways to reduce the fuel costs for calcination.

Taiheiyo Cement Corporation (TCC) has developed a thermo-chemical treatment technology to convert incinerated sludge ash directly to mineral fertilizer (Fig. 14). TCC has accepted sewage sludge and its incineration ash from WWTPs as raw materials for the manufacture of cement. Recently, however, the P contents of sewage sludge and its incinerated ash have been significantly

A



B



Fig. 14 Pilot-scale kiln system for directly converting incinerated sludge ash to fertilizer by calcination. (A) Rotary kiln for demonstration experiments; (B) Calcined silicate P_i fertilizer (left) and calcined mixed fertilizer (right). Photograph courtesy of H. Takano (Taiheiyo Cement Corp.).

increased by enhanced P removal from wastewater. Since P degrades the quality of cement, the amounts of sewage sludge or its incinerated ash that are difficult to use for the manufacture of cement have been increasing.

Demonstration experiments have been carried out using a rotary kiln (3.2 m long and 0.37 m in diameter). CaCO_3 is added as a calcium source (50 wt% CaO) to incinerated sludge ash (typically 35 wt% P_2O_5). Pelletized sludge ash is continuously fed to the rotary kiln at a rate of 30 kg dry wt/h and heated at 1,200–1,350°C. This treatment can convert citrate-insoluble AlPO_4 to citrate-soluble $\text{Ca}_5(\text{PO}_4)_2\text{SiO}_4$, thereby increasing the C- P_2O_5 /total P_2O_5 ratio from 44 to 98%. As a result, the calcined product contains approximately 17.5 wt% C-P. The calcination treatment is also effective at improving the water solubility of SiO_2 , which is critical to wet-rice cultivation. Heavy metals such as Cd, Hg and Pb are partially evaporated during calcination, thereby lowering heavy metal contents below the regulation levels. The calcined product is sieved to make mineral fertilizer that can slowly release P_i for plant growth. Together with P recovery from aqueous solution by A-CSHs, TCC has developed a total system that can recover approximately 90% of P in wastewater for recycling. This technology is potentially applicable to low-grade P_i rock and incinerated sludge ash from a blackwater treatment plant.

Sanki Engineering Co. has developed a melting system to convert incinerated sludge ash to fertilizer (named EcoRin®) using an electric resistance furnace (Sanki Engineering Co., 2005). P-rich incinerated sludge ash is mixed with additives such as MgO and CaO and fed into a melting furnace, which is kept in a reducing atmosphere at approximately 1,400°C. In the melting furnace, P is immobilized in molten slag, thereby separating it from molten metals. The molten slag is withdrawn from the melting furnace, quenched in water and pulverized to obtain EcoRin®, which is easily handled as a fertilizer. EcoRin® can be used as fused P_i fertilizer, which is rich in P, Mg and Ca. Toxic heavy metals can be removed from incinerated sludge ash as molten metals in the melting furnace. The efficacy of EcoRin® as P_i fertilizer has been demonstrated by plant growth testing. EcoRin® can be used as a slowly released P fertilizer containing 15–20 wt% C- P_2O_5 .

4.6 P recovery from steel-making slag

In the steel-making process, P is present in raw materials such as iron ore, coal and limestone at concentrations as low as 0.03 wt% P_2O_5 (Yamasue *et al.*, 2013). Since P has detrimental effects on the mechanical properties of steel, it needs to be removed into hot metal pretreatment slag (dephosphorization slag). Dephosphorization slag contains approximately 2–10 wt% P_2O_5 . Since steel-making is a large industry in Japan, P emitted into dephosphorization slag amounts to 100 kt/y, which is about two times more than that of sewage sludge. Hence, dephosphorization slag should be a quantitatively important secondary P resource, but it is currently landfilled

or used as cement and road construction materials (Matsubae-Yokoyama *et al.*, 2009).

The main components of dephosphorization slag are CaO , FeO , MnO , SiO_2 and P_2O_5 . Dephosphorization slag generally contains a P-rich $\text{Ca}_3\text{P}_2\text{O}_8\text{-Ca}_2\text{SiO}_4$ phase, a Mn-rich FeO-MnO phase, and a FeO-CaO-SiO_2 matrix phase (Matsubae-Yokoyama *et al.*, 2009). Since P-rich particles exhibit antimagnetic properties, it is possible to separate P-rich particles after pulverizing dephosphorization slag using wet magnetic separation technology (Yokoyama *et al.*, 2007). In laboratory experiments, pulverized particles were suspended in water to avoid coagulation during the magnetic separation. P-rich particles (< 30 μm) could be separated from pulverized dephosphorization slag by applying a strong magnetic field (0.30 tesla (T)). The recovered P-rich particles contained approximately 31 wt% P_2O_5 . This technology is also applicable to the recovery of Mn-rich particles from pulverized dephosphorization slag. P-free residues could potentially be returned to steel-making processes, enabling a reduction of the total input of new resources such as FeO , CaO and SiO_2 . The composition and morphology of dephosphorization slag must be controlled to improve the efficiency of P recovery by wet magnetic separation technology.

Dephosphorization slag can be reduced in an iron bath furnace to extract Fe, Mn and P simultaneously (Dippenaar, 2005). P-enriched slag can be separated from the hot metal yield and used as P fertilizer. Modification of slag composition would likely be effective at increasing the P content of the recovered product. Microwave irradiation has also been investigated for recovering P from steel-making slag at a bench scale (Morita *et al.*, 2002). P is carbothermally reduced into its metallic phase and then extracted from the metal by carbonate flux treatment at 1,200°C. As a result, P is concentrated in the fluxes at more than 9 wt%. Microwave processing is a simple and efficient way of heating steel-making slag.

Recently, the iron and steel industry has paid considerable attention to P removal from dephosphorization slag for economic and environmental reasons. The global production of iron ore is approximately 2,000 mt/y. Assuming that the P content of iron ore is 0.03 wt% on average, it can be estimated that approximately 0.6 mt/y of P ends up in dephosphorization slag. This is equivalent to one-fifth of the annual world demand for industrial P (2.8 mt/y).

4.7 Elemental P regeneration from secondary resources

The wet acid process for the manufacture of phosphoric acid requires highly beneficiated P_i ores as a raw material and makes a rather impure grade of phosphoric acid. High-purity phosphoric acid, which is an essential raw material in high-tech industries, is obtained mainly by burning elemental P (P_4) to phosphorus pentoxide (P_4O_{10}). Currently, production of elemental white P is limited to China, Vietnam, the USA and Kazakhstan (Schipper *et al.*, 2004). In particular, China accounts for

approximately 70% of the world production. Japan imports approximately 30 kt/y of white P. The manufacturing industry, however, has often struggled with the soaring price of imported elemental P. Consequently, the manufacturing sector has paid considerable attention to the sustainable supply of industrial-grade P, particularly white P.

P_i can be reduced to elemental P using coke at a temperature of over 500°C (Schipper *et al.*, 2004). With a boiling point of 280°C, elemental P is evaporated as tetrahedral P₄ gas. AlPO₄ and Ca₃(PO₄)₂ can release P₄ when they are heated anaerobically at over 1,000 and 1,050 °C, respectively. Consequently, P_i in incinerated sludge ash can be reduced to white P at over 1,200°C as long as the iron content is sufficiently low. Iron forms ferrophosphorus with P, thereby disrupting the formation of P₄ gas. The reductive melting of incinerated sludge ash requires the use of an electrical heating furnace with an enclosed structure. P₄ gas from the furnace can be recovered in liquid form using a cooling condenser at a temperature higher than the melting point of white P (44°C). P₄ can also be oxidized to P₂O₅ and absorbed in water.

The usage of incinerated sludge ash as a secondary feedstock in the production of white P has been investigated at a pilot-scale level by JFE Engineering Corporation. Incinerated sludge ash was mixed with powdered coke (a reducing agent) at a wt/wt ratio of 10:1 and granulated to produce hard pellets (9 × 6 mm²). Since incinerated sludge ash is rich in silicates, it was not necessary to supply pebbles (SiO₂) for slag formation. A furnace of 0.56 m height and 0.2 m diameter was heated to 1,400°C by an external carbon heater (32 kw). Approximately 90% of the P in the incinerated sludge ash vaporized in the furnace. Because of a mechanical seal failure, however, only 16% of the P could be recovered as elemental P from the incinerated sludge ash. The emitted P₄ gas was condensed in water at 60°C. The recovered P had a purity of 99.75%. The impurity was mainly arsenate (As), which was present in the incinerated sludge ash. On the basis of this result, it has been proposed to recover 0.5 kt/y of elemental P from 10 kt/y of incinerated sludge ash using an electric resistance furnace (30,000 kwh).

It is also possible to use a high-temperature kiln-based process to generate P₄ gas from P-rich incinerated sludge ash as a substitute for high-grade P_i rock (Megy and Hard, 1982). Interestingly, it has been observed that a detectable amount of P is removed from steel-making slag to the gas phase as diphosphorus (P₂) in a bench-scale experiment using an arc plasma furnace (Jiang *et al.*, 2013). This observation suggests the possibility of recovering elemental P from steel-making slag, if the arc plasma furnace is kept sealed.

5. The Phosphorus Recycling Promotion Council of Japan

Despite increased attention toward sustainable P issues, Japan was slow to formulate an effective national

policy on P recycling. To turn the situation around, the Phosphorus Recycling Promotion Council of Japan (PRPCJ) was founded as a nationwide association among industry, academia, and government in 2008. The price volatility of P_i rock and elemental P in 2008 was another trigger for its establishment. Since then, the PRPCJ has promoted P recycling in Japan by (i) taking action without delay, (ii) trying everything possible and (iii) bringing economic benefits to industry. Collaborative approaches (i) and (ii) reflected a consensus that a long period of time would be necessary to implement P recycling fully in Japanese society. Another consensus was that the manufacturing industry should play a visible role in the promotion of P recycling in Japan, because advocating industrial concern over sustainable P supply could effectively call government attention toward P issues.

To fully realize P recycling in Japan, the PRPCJ engages in a wide variety of activities with the support of MAFF, the Ministry of Economy, Trade and Industry (METI), the Ministry of the Environment (MOE), and MLITT. At present, this platform has more than 150 members, including 13 stakeholder associations and 62 private companies mainly in the manufacturing, agricultural and wastewater treatment sectors. Among them are small- and medium-sized fertilizer companies. Their participation is particularly important for P recycling, because they are the principal end-users of recovered P on the basis of local production for local consumption. PRPCJ aims to (i) bring together a wide range of stakeholders, (ii) fill knowledge and information gaps between different sectors, (iii) raise public awareness, (iv) develop a strategy for implementing P recycling, (v) stimulate research and technology development, (vi) promote international collaboration, (vii) cooperate with local governments and (viii) create market and business opportunities for P recycling. Since the PRPCJ's interest is oriented toward technology and business, it gives emphasis to the development and implementation of innovative technologies for P recovery and recycling. The PRPCJ, however, has also paid strong attention to cooperative learning and problem solving at a global scale, particularly for developing policy recommendations. The platform functions on a paid membership basis and is open to public involvement.

6. Conclusions

Currently, approximately 48% of total P imports into Japan are associated with food, animal feed and mineral resources such as iron ore and coal (Matsubae-Yokoyama *et al.*, 2009). P_i rock accounts for only 15% of total P imports from abroad. Hence, it seems understandable that the Japanese people are unaware of how dependent Japan is on imported P. The sustainable supply of P is critical to not only agricultural production but also industrial manufacturing in this country. In a wide variety of manufacturing processes, high-grade phosphoric acid is used as an essential raw material, such as an iron-coating material in the automotive industry, etching agents for

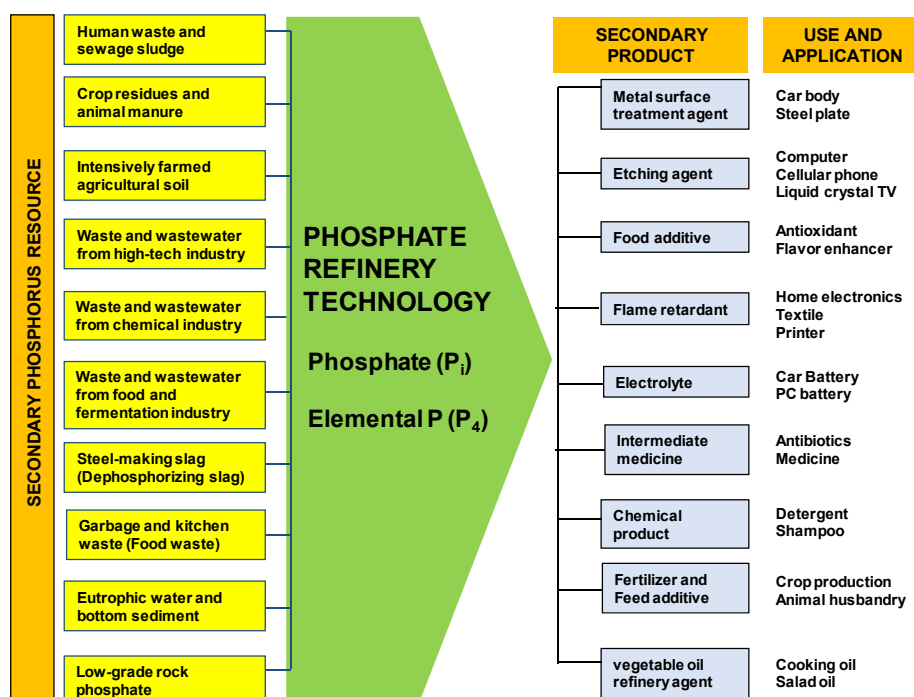


Fig. 15 P_i refinery technology.

liquid crystal glass substrates, and feedstock for food additives, chemical catalysts, and flame retardants. Disruptions in the supply of high-grade phosphoric acid could severely damage the manufacturing industry.

Although Japan has essentially no P_i rock reserves, there are sufficient amounts of secondary P resources such as food wastes, animal manure, sewage sludge and steel-making slag. P recycling has been implemented at several WWTPs and blackwater treatment plants in Japan. Given, however, that approximately 2,000 WWTPs and 1,000 blackwater treatment plants are operating in Japan, their operation should be considered as the beginning of the P sustainability movement. In the future, high-grade phosphoric acid and, therefore, high-purity elemental P will be required for food safety and quality control of industrial products. To realize P recycling fully, it will be necessary to develop P_i refinery technology, which enables the production of high-purity phosphoric acid and elemental P from a wide variety of secondary resources (Fig. 15).

P recycling is more difficult to implement than P removal from wastewater, because channels need to be created for the distribution and sale of recovered P products. It is, therefore, critically important to realize synergies with pollution control, energy/materials recovery and reduction of surplus manure and compost. In addition, the integration of technology innovation, corporate strategies and public policies is critical to promoting P recycling at a national level. The way toward realizing P recycling may be to tailor national policies toward a P recycling society, to raise public awareness, to accelerate research and innovation, to promote international cooperation and to create business opportunities.

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References

- Bateman, A., D. van der Horst, D. Boardman, A. Kansal and C. Carliell-Marquet (2011) Closing the phosphorus loop in England: The spatio-temporal balance of phosphorus capture from manure versus crop demand for fertilizer. *Resource Conservation and Recycling*, 55: 1146–1153.
- Cordell, D., J. Drangert and S. White (2009) The story of phosphorus: Global food security and food for thought. *Global Environmental Change*, 19: 292–305.
- Cordell, D., A. Rosemarin, J.J. Schröder and A.L. Smit (2011) Towards global phosphorus security: A systems framework for phosphorus recovery and reuse options. *Chemosphere*, 84: 747–758.
- Dippenaar, R. (2005) Industrial uses of slag (the use and reuse of iron and steelmaking slags). *Ironmaking and Steelmaking*, 32: 35–46.
- Donatello, S. and C.R. Cheeseman (2013) Recycling and recovery routes for incinerated sewage sludge ash (ISSA): A review. *Waste Management*, 33: 2328–2340.
- Hirota, R., A. Kuroda, J. Kato and H. Ohtake (2010) Bacterial phosphate metabolism and its application to phosphorus recovery and industrial bioprocesses. *Journal of Bioscience and Bioengineering*, 109, 423–432.
- Iizuka, A., T. Sasaki, T. Hongo, M. Honma, Y. Hayakawa, A. Yamasaki and Y. Yanagisawa (2012) Phosphorus adsorbent derived from concrete sludge (PAdeCS) and its phosphorus recovery performance. *Industrial and Engineering Chemistry*

- Research*, 51: 11266–11273.
- Jaffer, Y., T.A. Clark, P. Pearce and S.A. Parsons (2002) Potential phosphorus recovery by struvite formation. *Water Research*, 36: 1834–1842.
- Jiang, M., Y. Cui, D. Wang, Y. Min and C. Liu (2013) Effect of modification treatment for reduction of dephosphorization slag in hot metal bath. *Journal of Iron and Steel Research International*, 20: 1–6.
- Kaikake, K., T. Sekito and Y. Dote (2009) Phosphate recovery from phosphorus-rich solution obtained from chicken manure incineration ash. *Waste Management*, 29: 1084–1088.
- Kalmykova, Y. and K. Karfeldt Fedje (2013) Phosphorus recovery from municipal solid waste incineration fly ash. *Waste Management*, 33: 1403–1410.
- Kato, J., K. Yamada, A. Muramatsu, Hardoyo and H. Ohtake (1993) Genetic improvement of *Escherichia coli* for the enhanced biological removal of phosphate. *Applied and Environmental Microbiology*, 59: 3744–3749.
- Kuroda, A., K. Nomura, R. Ohtomo, J. Kato, T. Ikeda, N. Takiguchi, H. Ohtake and A. Kornberg (2001) Inorganic polyphosphate: a molecular tag to identify ribosomal proteins for degradation by Lon protease in *E. coli*. *Science*, 293: 705–708.
- Kuroda, A., N. Takiguchi, T. Gotanda, K. Nomura, J. Kato, T. Ikeda and H. Ohtake (2002) A simple method to release polyphosphate from activated sludge for phosphorus reuse and recycling. *Biotechnology and Bioengineering*, 78, 333–338.
- Laturnus, F., K. von Arnold and C. Grøn (2007) Organic contaminants from sewage sludge applied to agricultural soils. *Environmental Science and Pollution Research*, 14: 53–60.
- Liu, Z. and R. Balasubramanian (2014) Upgrading of waste biomass by hydrothermal carbonization (HTC) and low-temperature pyrolysis (LTP): A comparative evaluation. *Applied Energy*, 114: 857–864.
- Marti, N., L. Pastor, A. Bouzas, J. Ferrer and A. Seco (2010) Phosphorus recovery by struvite crystallization in WWTPs: Influence of the sludge treatment line operation. *Water Research*, 44: 2371–2379.
- Matsubae, K., J. Kajiyama, T. Hiraki and T. Nagasaka (2011) Virtual phosphorus ore requirement of Japanese economy. *Chemosphere*, 84: 767–772.
- Matsubae-Yokoyama, K., H. Kubo, K. Nakajima and T. Nagasaka (2009) A material flow analysis of phosphorus in Japan. *Journal of Industrial Ecology*, 13: 687–705.
- Megy, J.A. and R.A. Hard (1982) Rotary kiln process for phosphoric acid manufacture, US patent # 4,351,813.
- Midorikawa, I., H. Aoki, A. Ohmori, T. Shimizu, Y. Kawaguchi, K. Kassai and T. Murakami (2008) Recovery of high-purity phosphorus from municipal wastewater secondary effluent by a high-speed adsorbent, 5th IWA Leading-Edge Conference on Water and Wastewater Technologies.
- Morita, K., M. Guo, N. Oka and N. Sano (2002) Resurrection of the iron and phosphorus resource in steel-making slag. *Journal of Material Cycles and Waste Management*, 4: 93–101.
- Morse, G.K., S.W. Brett, J.A. Guy and J.N. Lester (1998) Review: Phosphorus removal and recovery technologies. *Science of the Total Environment*, 212: 26–81.
- Okano, K., M. Uemoto, J. Kagami, K. Miura, T. Aketo, M. Toda, K. Honda and H. Ohtake (2013) Novel technique for recovering phosphorus from aqueous solutions using amorphous calcium silicate hydrates (A-CSHs). *Water Research*, 47, 2251–2259.
- Ro, K.S., K.B. Cantrell, P.G. Hunt, T.F. Ducey, M.B. Vanotti and A.A. Szogi (2009) Thermochemical conversion of livestock wastes: Carbonization of swine solids. *Bioresource Technology*, 100: 5466–5471.
- Sanki Engineering Co. (2005) Process for producing phosphatic fertilizer and apparatus, European Patent Application EP 1 849 755 A1.
- Schipper W.J., A. Klapwijk, B. Potjer, W.H. Rulkens, B.G. Temmink, F.D.G. Kiestra and A.C.M. Lijmarch (2004) Phosphate recycling in the phosphorus industry. *Phosphorus Research Bulletin*, 15: 47–51.
- Suzuki, K., Y. Tanaka, K. Kuroda, D. Hanajima, Y. Fukumoto, T. Yasuda and M. Waki (2007) Removal and recovery of phosphorus from swine wastewater by demonstration crystallization reactor and struvite accumulation device. *Bioresource Technology*, 98: 1573–1578.
- Tsunashima, Y., A. Iizuka, J. Akimoto, T. Hongo and A. Yamasaki (2012) Preparation of sorbents containing ettringite phase from concrete sludge and their performance in removing borate and fluoride ions from wastewater. *Chemical Engineering Journal*, 200: 338–343.
- Ueno Y. and M. Fujii (2001) Three-year experience of operating and selling recovered struvite from full-scale plant. *Environmental Technology*, 22: 1373–1381.
- Van Nieuwenhuyzen, W. and M.C. Tomas (2008) Update on vegetable lecithin and phospholipid technologies. *European Journal of Lipid Science and Technology*, 110: 472–486.
- Wemyss, D. (2012) Closing the phosphorus nutrient cycle by recovery from wastewater: The social and technical factors of implementation in Japan and Switzerland, Master thesis 05/12, ETH, Zürich.
- Yamashita, T., T. Aketo, N. Minowa, K. Sugimoto, H. Yokoyama, A. Ogino and Y. Tanaka (2012) Simultaneous removal of color, phosphorus and disinfection from treated wastewater using an agent synthesized from amorphous silica and hydrated lime. *Environmental Technology*, 1–9.
- Yamasue, E., K. Matsubae, K. Nakajima, S. Hashimoto and T. Nagasaka (2013) Using total material requirement to evaluate the potential for recyclability of phosphorous in steelmaking dephosphorization slag. *Journal of Industrial Ecology*, 17: 722–730.
- Yokoyama, K., H. Kubo, K. Mori, H. Okada, S. Takeuchi and T. Nagasaka (2007) Separation and recovery of phosphorus from steelmaking slags with the aid of a strong magnetic field. *ISIJ International*, 47: 1541–1548.



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