Review

Phosphorus recovery from municipal and fertilizer wastewater: China’s potential and perspective

Kuangxin Zhou1,2,⁎, Matthias Barjenbruch2, Christian Kabbe1, Goulven Inial3, Christian Remy1

1. Berlin Centre of Competence for Water, Berlin 10709, Germany
2. Department of Urban Water Management, Technical University of Berlin, Berlin 13355, Germany
3. Research & Innovation Asia, Veolia Environment, Beijing 10004, China

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ABSTRACT

Phosphorus (P) is a limited resource, which can neither be synthesized nor substituted in its essential functions as nutrient. Currently explored and economically feasible global reserves may be depleted within generations. China is the largest phosphate fertilizer producing and consuming country in the world. China’s municipal wastewater contains up to 293,163 Mg year of phosphorus, which equals approximately 5.5% of the chemical fertilizer phosphorus consumed in China. Phosphorus in wastewater can be seen not only as a source of pollution to be reduced, but also as a limited resource to be recovered. Based upon existing phosphorus-recovery technologies and the current wastewater infrastructure in China, three options for phosphorus recovery from sewage sludge, sludge ash and the fertilizer industry were analyzed according to the specific conditions in China.

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Introduction

Phosphorus (P) is a non-regenerable and non-replaceable limited resource (Asimov, 1959). Currently explored and economically feasible global reserves may be depleted within only a few generations (Childers et al., 2011). By 2050, the world’s population is estimated to reach 9.1 billion; in order to feed the growing population, agricultural production would need to increase by 70% overall and nearly 100% in developing countries (FAO, 2009).

China is a big country with a large population and limited farmland area per capita, with only 0.08 ha per capita in 2012 compared with the world average of 0.2 ha per capita, according to the World Bank (2014). The production of sufficient food to feed the population is of vital importance to the country. In the year 2001, P was identified by the Ministry of Land and Resources of the People’s Republic of China (MLR, 2012) as one of the most important 20 minerals which, after 2010, cannot meet the development needs of the national economy.

According to statistics from the United States Geological Survey (USGS, 2015), China’s P reserves are 3.7 billion Megagrams, 5.52% of the global total volume. Based on the current phosphate rock mine production of 100 million Mg in 2014 (USGS, 2015), Chinese P ore may run out within 37 years. It is a remarkable fact that there is only a small amount of high-grade phosphorus ore, but the country is rich in low-grade phosphorus ore. More than 80% is low grade

⁎ Corresponding author. E-mail: Kuangxin.zhou@kompetenz-wasser.de (Kuangxin Zhou).

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phosphate rock and the average grade only reaches 17% of the phosphorus content of phosphorus pentoxide (P₂O₅) (Huang et al., 2014; Lu, 2004).

In Europe, phosphate rock was officially considered to be one of the 20 critical raw materials by the European Commission in 2014 (EC, 2014). The recovery of phosphorus has been repeatedly discussed due to the strong dependency on imports, above 90%, (De Ridder et al., 2012) and the food security needs of the growing population worldwide. Various P recovery technologies have been developed and tested at pilot or industrial scale. Among these technical options, P is mostly recovered by precipitation or crystallization processes in the form of HAP (hydroxyapatite, Ca₅(PO₄)₂(OH)) or struvite (MgNH₄PO₄·6H₂O). The recovered products can be utilized as fertilizer in agriculture or in specific industries.

Consequently, closure of the anthropogenic P cycle through recovery and recycling of P from municipal wastewater and sludge, as well as from special industry wastewater, may help to avoid eutrophication, promote resource conservation and increase the value chain efficiency of this precious resource.

1. Status of the municipal wastewater infrastructure in China

1.1. The development of urban sewage treatment

In 1984, as the first large-scale wastewater treatment plant (WWTP), the Tianjin Jizhuangzi Wastewater Treatment Plant was built and put into operation with a treatment capacity of 260,000 m³ (Fu et al., 2008). After 1990, with the rapid development of the economy, rapid urbanization and industrialization and the increasing environmental standards in China, the wastewater treatment infrastructure stepped into a rapid development period and improved the quantity of wastewater treatment facilities and also the effectiveness of treatment.

Fig. 1 shows the development of treatment capacity for urban sewage and the number of facilities from 2005 to 2013. During the past several years, China's sewage treatment sector has experienced rapid development. In April 2015, the General Office of the State Council issued the "National Water Pollution Prevention and Treatment Action Plan of China" (MEP, 2015) to address nationwide water protection; the objective of municipal wastewater treatment is that by the end of 2020, the city and county municipal wastewater treatment rates should reach 95% and 85% respectively.

Although China's urban wastewater treatment industry has seen much progress in terms of scale and number since the 1990s, the conditions of the municipal water networks and the treatment rate in rural areas still need to be improved. In 2013, the wastewater treatment rate of the cities, counties, towns and villages was respectively 89%, 79%, 19%, and 5% (MOHURD, 2016). The majority of wastewater generated in rural areas undergoes limited treatment or discharge to water bodies without treatment. According to the corresponding population distribution in different areas (MOHURD, 2016), 37% of the population is connected to wastewater treatment systems in China.

1.2. Wastewater treatment process

There are three major steps in state-of-the-art wastewater treatment schemes, i.e., primary physical treatment, secondary biological treatment and tertiary treatment (Halling-Sørensen and Jorgensen, 1993). Most sewage treatment plants in China are centralized, with biological wastewater treatment.

Fig. 2 shows the variety and distribution of different processes in WWTP in China. According to the statistics of the Ministry of Environmental Protection of the People’s Republic of China (MEP, 2014) for 4136 commissioned wastewater treatment plants in 2013, the most widely used technologies are the Oxidation Ditch Process with a share of 27%, the Anaerobic–Anoxic–Oxic (A²O) process with a share of 26% and the Sequencing Batch Reactor (SBR) process with a share of 19%. 3% of super-large-scale (>30 × 10⁴ m³/day) and 13% of large-scale (10 × 10⁴-30 × 10⁴ m³/day) WWTPs were generally built in large and medium-sized cities. Most of these plants apply the A²O process. The percentage of medium-scale (1 × 10²-10 × 10² m³/ day) WWTPs was 75%. They were generally built in medium and small size cities and commonly apply the oxidation ditch and SBR processes (Jin et al., 2014).

1.3. Phosphorus removal in WWTPs

Two methods are currently being used around the world to remove P in wastewater: biological and chemical P removal and combinations of both. In China, influent NH₄-N ranges from 40 to 55 mg/L, and total P ranges from 4 to 9 mg/L (Jin et al., 2014). According to the “Discharge standard of pollutants for municipal wastewater treatment plant” (GB18918-2002), the primary A standard of total P concentration in WWTPs effluent built after 2005 should not exceed 0.5 mg/L. It is quite difficult to meet this requirement with biological P removal alone (Qu and Ding, 2002). A potential reason for the low efficiency of enhanced biological phosphorus removal is the competition for carbon sources between denitrification and P release in sludge under an anoxic condition with respect to the sludge retention time demand, and the nitrate inhibition of phosphate release, which is not easily resolved (Chen et al., 2011; Peng et al., 2010; Qiu and Ting, 2014).

1.4. Sewage sludge treatment in China

In China, thickening, conditioning and dewatering are the three most applied methods for sludge treatment (Yang et al., 2015). There are no accurate official data on sludge disposal in China, rather conflicting sources with different estimates. According to Yang et al. (2015), more than 84% of sludge is disposed by improper dumping. Regarding proper disposal, the most commonly used method is sanitary landfill (13%), followed by land application (2%), incineration (0.4%) and use in building materials (0.2%). Data from Wang et al. (2015) indicates that the most widely used disposal route was landfiling with a ratio of 63%, followed by composting and agricultural use with the ratio of 14%, and incineration with the ratio of 2%. The disposal route for around 22% of sludge was unknown. Many WWTPs in China did not report clearly on the treatment and final disposal of their sludge (Jin et al., 2014). In general, the majority of sludge is often disposed to
sanitary landfill or dumping sites without stabilization or drying. So far, anaerobic sludge digestion (AD) is not widely used in China. Until 2010, only about 50 WWTPs adopted AD to stabilize sludge, and some of them were not under stable operation or were even closed (Kong, 2012). The main problems for sludge digestion are the lack of an overall development plan for AD, and the technical design parameters of sludge digestion not matching the specific local conditions. On the other side, the utilization and efficiency of sludge digestion in China is not high due to the low production of gas and the lower economic benefit. The technical reasons are the high sand content and lower amounts of volatile organic compounds in the sludge (Dai et al., 2014). According to the overall situation in China, thickening–anaerobic digestion–dewatering and subsequent land application (does not include agricultural use) can be considered as the main technical route for sludge treatment and disposal in the future. This route is favorable for large-scale and medium-scale WWTPs due to the limited land resources in the city and shortage of energy supply in economically developed regions (Yang et al., 2015).

2. Materials and methods

P recovery and recycling options need to be ecologically sound, taking into consideration both social acceptance and economical and technical feasibility. Based on real operational data and samples from selected WWTPs in China and available technical solutions from the EU research and demonstration project P-REX (www.p-rex.eu), a systematic analysis of different options was conducted.

The total concentrations of P and nitrogen in sludge water, supernatants and concentrates were determined by spectrophotometry according to the respective Chinese standards (GB11893-1989) and (HJ636-2012). Ammonia nitrogen was determined by titration according to (GB7478-1987). For the determination of iron (Fe) and aluminum (Al) in sludge and sludge ash, samples were digested with nitric acid/hydrochloric acid according to ASTM D3974-09 and measured in accordance with US EPA 6010/ICP-OES and US EPA 6020/ICP-MS. For the determination of P, samples were digested with sulfuric acid according to APHA 4500P B, H.

3. Potential and options for phosphorus recovery in China

In the year 2013, there was a total of 45.1 billion m$^3$ (MOHURD, 2016) of municipal wastewater treated in counties and cities. The total P concentration in the WWTP influents ranged from 4 to 9 mg/L (Jin et al., 2014). Based on the average value of 6.5 mg/L, the P discharged to municipal wastewater in cities and counties added up to approximately 293,163 Mg in the year 2013. This quantity of this P in municipal wastewater in 2013 corresponds to 6% of the chemical fertilizer P consumption of 5.3 teragram (Tg) (Li et al., 2015) in 2010 in China.

According to a statistical analysis of 98 WWTPs in China (Guo et al., 2009), the total P concentration in municipal sewage sludge varies significantly, from a low of 2.2 g/kg of sludge dry matter to a high of 51.3 g/kg (Li et al., 2003), with a mean value of $22.2 \pm 6.64$ g/kg. The treatment plants with high P concentration in sludge are mostly located in phosphate mining areas or in highly developed areas, e.g., Yunnan or Hong Kong. With the dry sludge production of
7.55 million Mg in 2013 (MOHRUD, 2016) and the mean content value for P, the total P contained in the current Chinese sewage sludge is estimated to be 167,634 Mg/year, or in other words, 57% of the total discharged P. This low rate of P in sludge might be due to dilution in sanitary sewers by infiltration and inflow, which causes low P in the influent with the average value of 6.5 mg/L.

At a municipal wastewater treatment plant, P can be recovered and recycled in three main ways (Fig. 3). The first is direct land utilization of sewage sludge, the second includes recovering the dissolved P in the aqueous sludge phase prior to dewatering and sludge liquor after dewatering, and the third is recovery from mono-incineration ash.

The maximum recovery potential from the aqueous phase and sludge phase without extraction is respectively 25% and 20% with regard to the WWTP influent (Kabbe, 2015). For recovery by sludge leaching (2a, 2b in Fig. 3), a maximal P recovery rate of 70% can be achieved at high chemical and/or energy cost. Large amounts (70%–85% of WWTP influent) of P can be recovered from mono-incineration ash (Egle et al., 2015; Niewersch et al., 2014). However, the energy demand of ash treatment can vary depending on the process (ash leaching, thermo-chemical, metallurgical) and the potential integration of thermal processes into existing incineration facilities for efficient heat management (Remy, 2015).

P uptake from different P products of P recycling has been tested (Achat et al., 2014; Kataki et al., 2016; Römer, 2013; Wilken et al., 2015). Regarding products from precipitation processes, Mg compounds consistently showed better P supply in relation to comparable Ca compounds. With struvite, the same P uptake as triple super phosphate was reached.

The traditional land utilization of sewage sludge in agriculture is considered one of the most economical ways for sludge disposal, but the presence of toxic heavy metals, organic contaminants and pathogens in the sewage sludge greatly limits its direct use as a fertilizer. According to a study of heavy metals in sewage sludge over China (Guo et al., 2014), regarding the concentrations of Cu, Zn, Cd, Hg, and Ni in alkaline soils, about 2%, 6%, 6%, 3%, and 4% of the samples exceeded the limits set by "Discharge standard of pollutants for municipal wastewater treatment plant" of China (GB18918-2002). In acid soils the non-attainment rates for Cu, Pb, Zn, Cd, Hg, Cr and Ni were 7%, 1%, 10%, 27%, 20%, 2% and 12%, respectively. The main sources of the heavy metals may be derived from high-density industrial zones, non-ferrous metal ores and anthropogenic activities (Guo et al., 2014). The source control of wastewater, especially industrial wastewater, can help decrease the amount of heavy metals entering the sewer and ensure the quality of sludge.

Agricultural soils are also significantly influenced by Cd, Hg and Pb derived from anthropogenic activities (Wei and Yang, 2010). Sewage sludge use on agricultural land is strictly limited. The amount, duration and quality of sludge applied to agriculture should meet the requirements of "Control standards for pollutants in sludges from agricultural use" (GB4284-1984) and other existing relevant agricultural standards and regulations. Hence, cost-effective alternative strategies and technologies for P recovery for agriculture are needed.

4. Results and discussion

4.1. Option: recovery in sludge

Dissolved P is recovered directly from the digested sludge. In the AirPrex® process, struvite is crystallized within the wet sludge and can, therefore, prevent down-stream struvite scaling and at the same time improve the sludge dewatering ability by 3%-6% dry matter content and save on polymer costs for sludge dewatering (Heinzmann and Lengemann, 2014).

In Table 1, selected sewage sludge digestion projects in China are listed. These WWTPs are mostly operated with combined biological and chemical P removal. Among them, several plants have reported that struvite precipitation has been an problematic issue, e.g., Shanghai Bailonggang (jiang et al., 2013) and Haikou Baishamen (Pan et al., 2006). For most of these plants using anaerobic digestion, land application is the first choice for sewage disposal.

This option is significantly more efficient for WWTPs with biological P elimination and sludge digestion. For the P that is fixed within the sludge, after chemical precipitation with ferrous or ferric salts or aluminum, direct struvite crystallization is not a suitable option for recovery. Hence, with the current sewage and wastewater treatment facilities in China, only a few WWTPs are adapted to this option, such as Dalian Xialiahe, Wuhan Sanjintan Beijing Xiaohongmen WWTP etc. The current limits of this option for the WWTPs in China are the shortage of combined biological phosphorus removal and anaerobic sludge digestion.

4.2. Option: recovery from sludge water

P is recovered from the supernatants of the digested sludge after liquid–solid separation. In the Struvia™, Pearl®, and AirPrex® processes, an important component of these technologies are crystallization reactors. In these processes, struvite is precipitated by dosing with MgCl2 and increasing the pH by adding NaOH or aeration.

Municipal wastewater treatment plant A in south China has a capacity of 300,000 m3/day, and the wastewater is treated with an activated sludge process before discharge to the deep sea. After digestion, P is released into the liquid phase, in which total P increases from 205 to 289 mg/L (Table 2). Under specific conditions, this phosphate reacts with magnesium and ammonium, creating buildup of struvite in pipes and dewatering facilities, which needs to be cleaned every one or two weeks by high pressure water in this plant. The replacement of pipelines with external mechanical cleaning is also used to cope with the scaling problem in another WWTP in the east coast of China. The mechanical treatment is preferred due to economic reasons, i.e., the low cost of manpower, compared to chemical treatment by anti-crustation agents. In the Tianjing Chennan sludge treatment plant, a new project with recovery of phosphate from sludge water with the AirPrex® process is under construction.

Regarding the high soluble P and ammonia concentration in concentrates in such plants in China, techniques are available to recover 80%-90% of the dissolved P (Niewersch et al., 2014) in sludge water. The limits of this option are that no more than 20%
of a WWTP’s P load can be recovered, and this only if enhanced biological P removal is applied, thus its economic viability should be considered.

### 4.3. Option: recovery from sludge water with sludge extraction

P is recovered from the supernatant of the digested sludge after acidic leaching or thermal hydrolysis pre-treatment and followed by liquid–solid separation e.g., the Gifhorn, Stuttgart and Budenheim process.

Due to the additional increase of P dissolved in the sludge supernatant caused by acidic treatment, the processes with a sludge extraction step are applicable for digested sludge from WWTPs with both enhanced biological P removal and chemical P elimination. Hence, with the current sewage and wastewater treatment facilities in China, Shanghai Bailonggang, Haikou

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**Fig. 3 – Hot spots for P recovery in wastewater treatment plant (Kabbe and Remy, 2013). 1. Direct agricultural utilization of dewatered sludge; 2a. undrained sludge after anaerobic digestion; 2b. sludge liquor after dewatering; 3. from ash after undiluted incineration.**

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<table>
<thead>
<tr>
<th>Table 1 – Anaerobic sludge digestion projects in China.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sewage sludge digestion projects</strong></td>
</tr>
<tr>
<td>Beijing Gaobeidian</td>
</tr>
<tr>
<td>Beijing Xiaohongmen</td>
</tr>
<tr>
<td>Chongqing Jiguanshi</td>
</tr>
<tr>
<td>Dalian Xiajihe</td>
</tr>
<tr>
<td>Haikou Baishamen</td>
</tr>
<tr>
<td>Qingdao Maidao</td>
</tr>
<tr>
<td>Shanghai Bailonggang</td>
</tr>
<tr>
<td>Zhengzhou Wangxin</td>
</tr>
<tr>
<td>Tianjing Jishuangzi (Tianjing Jinnan sludge treatment plant)</td>
</tr>
</tbody>
</table>

Baishamen and Tianjing Jinnan WWTP, among others, are technically suitable for this option. However, it was shown that with the current reagent strategies and investment costs, the struvite recovery process was not economically feasible for WWTPs with AD and P-physicochemical removal, only in the case of biological P elimination removal WWTPs with AD (García-Belinchón et al., 2013).

4.4. Option: phosphorus recovery from sewage sludge ash

The P recovery from sewage sludge ash (SSA) is generally divided into two approaches: the wet-chemical (LeachPhos) and thermal (AshDec) processes. Wet-chemical approaches consist of an acidic or alkaline digestion of SSA followed by a separation of P from dissolved (heavy) metals and organics. In Germany, 54.7% (Wiechmann et al., 2015) of the sludge is incinerated, and only about 3.45% (Fang et al., 2012) of sludge in China is treated by incineration. The quantity of recoverable P in sludge ash in China is not calculable due to the lack of reliable mono-incineration data.

The Sludge Treatment Facility in Hong Kong is the world’s largest sludge incineration facility, with a capacity of 600 Mg of dry sludge per day. The facility adopts fluidized bed incineration technology to decompose sewage sludge at 850°C. In Table 3, the selected parameters of the composite sludge feed to the incinerator and sludge ash are presented.

SSA in the Sludge Treatment Facility of Hong Kong contains a P concentration of around 4%, which, compared to the mean P content in Germany of 8.9% (Krüger and Adam, 2015) is only half the content in Germany. The concentrations of Al 3.3% and Fe 11.8% in Hong Kong are similar to the mean values in Germany, 5.2% and 9.9% respectively (Krüger and Adam, 2014). For elemental white phosphorus (P₄) production with the Thermphos process, the molar ratio of Fe/P reaches about 0.6 in Hong Kong, which exceeds the limiting value of 0.2 (Petzet and Cornel, 2009). The high iron concentration in SSA increases the energy demand and reduces the output of P₄. Although with the current available technology approximately 2000 tons P/year can be recovered in this plant, the relatively low phosphorus concentration should be considered to ensure economic viability. The limitation of this option in China is the low P concentration in sludge ash compared to Europe.

5. Phosphate fertilizer industry

Various industries produce wastewater that contains a high concentration of P. This includes fertilizer, semiconductor, phosphoric acid processing and swine wastewater (Hao et al., 2011). The mentioned processes (Struvia™, Crystallactor, Pearl®, AirPrex® etc.) for sludge water are also applicable to industrial wastewater containing a significant concentration of dissolved ortho-phosphate.

China is not only the largest P consumer but also the largest producer. There were 1118 phosphate fertilizer enterprises in China in 2005 (Zhang et al., 2009), and in the plants, a significant amount of wastewater containing phosphate and fluoride is generated. The use of lime as a precipitating agent for fluoride and phosphate can be considered as the most common technique for wastewater from phosphate fertilizer plants (Grzmił and Wronkowski, 2006); but the large amount of P in the wastewater cannot be directly recycled in agriculture due to the low plant availability of fluorapatite (Manahan, 1997; Ndala et al., 2010). A controlled P recovery with separate precipitation of fluorides and phosphates in a two-stage process would be a useful adapted option. It was found that, by adjusting the precipitation to pH ranging from 2.6 to 3.7, a “selective” removal of 97–98% fluoride from phosphoric acid/hydrofluoric acid mixture was possible, while that of phosphate did not exceed 6%–8% (Goudier et al., 2009).

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**Table 2 – Parameters of sludge water in wastewater treatment plant A in China (mean value) *.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Influent</th>
<th>Effluent</th>
<th>Supernatant before digester</th>
<th>Supernatant post-thickener after digester</th>
<th>Centrate after dewatering</th>
<th>Total returns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total nitrogen (mg/L)</td>
<td>23.9</td>
<td>19.8</td>
<td>391</td>
<td>614</td>
<td>533</td>
<td>320</td>
</tr>
<tr>
<td>NH₄-N (mg/L)</td>
<td>19.0</td>
<td>15.6</td>
<td>325</td>
<td>489</td>
<td>398</td>
<td>249</td>
</tr>
<tr>
<td>Total P (mg/L)</td>
<td>3.5</td>
<td>2.0</td>
<td>205</td>
<td>289</td>
<td>238</td>
<td>180</td>
</tr>
</tbody>
</table>

* The sludge water samples were taken from wastewater treatment plant A in China from January to May 2014. The influent and effluent of the wastewater treatment plant were analyzed every two days. Other supernatants and centrates were analyzed every second week.

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**Table 3 – Analysis of selected parameters of composite sludge feed to incinerator and sludge ash in the sludge treatment facility in Hong Kong, China *.**

<table>
<thead>
<tr>
<th>Sludge</th>
<th>Moisture content (dried at 103°C)</th>
<th>P (dry matter)</th>
<th>Al</th>
<th>Fe</th>
<th>Sludge ash</th>
<th>Moisture content (dried at 103°C)</th>
<th>P (dry matter)</th>
<th>Al</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test on December 4th, 2014</td>
<td>69.3%</td>
<td>0.925%</td>
<td>0.577%</td>
<td>3.1%</td>
<td>Test on December 4th, 2014</td>
<td>0.1%</td>
<td>2.74%</td>
<td>2.74%</td>
<td>10.9%</td>
</tr>
<tr>
<td>Test on January 2nd, 2015</td>
<td>67.2%</td>
<td>1.12%</td>
<td>0.78%</td>
<td>2.85%</td>
<td>Test on January 2nd, 2015</td>
<td>2.1%</td>
<td>5.25%</td>
<td>3.8%</td>
<td>12.7%</td>
</tr>
<tr>
<td>Mean</td>
<td>68.25%</td>
<td>1.023%</td>
<td>0.679%</td>
<td>2.975%</td>
<td>Mean</td>
<td>1.1%</td>
<td>3.995%</td>
<td>3.27%</td>
<td>11.8%</td>
</tr>
</tbody>
</table>

* The tested sludge and sludge ash samples were taken from incineration sludge treatment facility in Hong Kong from December 2014 to January 2015.
It was also observed that, using calcium, fluorides were mainly separated (pH 3) in the first stage, and phosphates (pH 8) were mainly separated in the second stage, amounting to ca. 85%–88% and ca. 63–73%, respectively. (Grzmil and Wronkowski, 2006).

Table 4 shows the different streams and compositions of wastewater in a big fertilizer plant in East China. The WWTP has two major types of wastewater: respectively ammonia wastewater with 300 mg/L ammonia-nitrogen from synthetic ammonia production and P-containing wastewater with 240 mg/L total P from phosphate fertilizer production. The high concentration of both components in the wastewater provides a good possibility for producing magnesium ammonium phosphate. The excess ammonium in the wastewater, with a molar ratio of N:P of more than 1, is also beneficial for struvite precipitation. For struvite formation in this fertilizer wastewater plant, an additional magnesium source is needed. The high calcium content in wastewater resulted in more calcium compounds rather than struvite in the precipitates (Hao et al., 2008). In this wastewater treatment plant, approximately 1800 tons of struvite can be recovered annually by the (Hao et al., 2008). In this wastewater treatment plant, approximately 1800 tons of struvite can be recovered annually by the (Hao et al., 2008). In this wastewater treatment plant, approximately 1800 tons of struvite can be recovered annually by the.

The average concentration of P in SSA in China is lower than that in Germany due to the high sand content in sludge and a lack of separation of rain water and municipal sewage. Therefore, the ash option is limited due to the low rate of mono-incineration and the low P concentration in SSA.

Therefore, the following suggestions for the future P recovery in China are: (1) Increase wastewater collection and improve the P removal; (2) promote sludge digestion and biological P elimination and reduce the precipitation with iron salts; (3) develop the strategy for a long-term perspective in sustainable P-recovery; (4) build up the legal framework governing recycling and the market for fertilizers, (5) develop the business models for companies utilizing P streams from wastewater; and (6) encourage the research and promote a new treatment technology for P rich wastewater.

7. Conclusions

There is no doubt that phosphorus is a finite resource. Although there is no “one-size-fits-all” option for P recovery and most of the P recovery technical options for municipal WWTPs face strong limitations in China, more efforts should be taken to increase both energy and resource efficiency. The recovery from industrial wastewater with a high concentration of P shows higher potential than in municipal WWTPs due to easier market access and benefits to its operators. With an expected increasing percentage of municipal sewage sludge digestion and biological P removal, P recovery as struvite and recycling as fertilizer is recommended as one of the favorable options for P recycling.

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