Nutrient recovery from wastewater: From technology to economy

Yuanyao Ye[1], Huu Hao Ngo[1,4,*], Wenshan Guo[1,4], Soon Woong Chang[2], Dinh Duc Nguyen[2,3], Xinbo Zhang[4], Jian Zhang[5], Shuang Liang[5]

[1]*Centre for Technology in Water and Wastewater, School of Civil and Environmental Engineering, University of Technology Sydney, Sydney, NWS 2007, Australia*

[2]*Department of Environmental Energy Engineering, Kyonggi University, 442-760, Republic of Korea*

[3] *Institution of Research and Development, Duy Tan University, Da Nang, Vietnam*

[4]*Joint Research Centre for Protective Infrastructure Technology and Environmental Green Bioprocess, School of Environmental and Municipal Engineering, Tianjin Chengjian University, Tianjin 300384, China*

[5]*Shandong Key Laboratory of Water Pollution Control and Resource Reuse, School of Environmental Science & Engineering, Shandong University, Jinan 250100, China*

***** *Corresponding author: E–mail address: ngohuuhao121@gmail.com*

Abstract

The recovery of fertilizer-used nutrients from wastewater is a sustainable approach for wastewater management and helping social sustainability. This is especially the case given the strict discharge requirements and shortages existing in nutrients supply. Recognizing that wastewater is a very useful resource and the value of recycled nutrients has made researchers consider the recovery of nutrients from wastewater. This review described the current technologies used to recover nutrients in wastewater treatment and their mechanisms, including chemical methods, biological technologies, membrane systems and advanced membrane systems. Also, an economic analysis of these nutrient recovery systems was discussed and compared them in terms of positive and negative aspects. The economic feasibility of recovered nutrients was investigated. Finally, future perspectives expects some possible research directions regarding recovery system which can be more economically accessible for wastewater treatment, in which the osmotic membrane bioreactors (OMBR) and bioelectrochemical systems (BES)-based hybrid systems are highly recommended.

Keywords: wastewater, phosphate recovery, ammonium recovery, membrane technology, economic feasibility.

1. Introduction

In recent years, excessive agricultural production has led to the elevated levels of nutrients (i.e., ammonium and phosphate) in aquatic environments as well as uncontrolled wastewater discharges. This may result in eutrophication of aquatic systems, which wields detrimental impacts on human health and the natural environment (Meena et al., 2019; Ye et al., 2019a). The increasingly stringent discharge standards of nutrients may challenge their removal in the process of wastewater treatment. Conventional technologies for removing nutrients include active sludge process, chemical precipitation, nitrification-denitrification and others (Iorhemen et al., 2019; Nuramkhaan et al., 2019). However, nutrients removal may not be feasible in sustainable wastewater management with low-carbon, low energy consumption and resource recycling (Sun et al., 2016). Ammonium and phosphate are essential elements for all living organisms because they are the key components for biological synthesis (e.g., proteins).

Recent studies have highlighted the high demand for the ammonium and phosphate which are used in fertilizer production, and this situation is attributed to shortages of industrial nutrients production, particularly given that the world’s population is increasing. It has been observed that large amounts of nutrients are contained in wastewater sources, not only the wastewater but also the wastewater sludge, which are now deemed to be a valuable source of nutrients. Therefore, nutrients recovery from wastewater could make the wastewater treatment sustainable, reduce the costs associated with nutrient removal (e.g., less production of surplus sludge), and provide supplementary fertilizers for food production. Currently, many technologies have been investigated for their effectiveness in nutrients recovery, including traditional methods such as chemical precipitation and adsorption, and more advanced approaches such as bioelectrochemical systems (BESs) and osmotic membrane bioreactors (OMBRs). Apart from this, the nutrients recovery can be fulfilled from liquid phase (i.e., anaerobic digestion supernatant, reject water and sludge dewatering filtrate) and sludge phase (i.e., dry surplus sludge and sewage sludge ash), respectively, in the wastewater treatment. Specifically, most technologies used for recovering nutrients are applied in the liquid phase while wet-chemical and thermochemical treatments can extract phosphate from the sludge phase and then integrate with further process for the recovery. Besides, phosphate can be transferred from the liquid phase to the sludge phase for its recovery through the biological method.

In the last decade, many reviews included the detailed information on nutrients recovery from wastewater in terms of mechanisms, the effects of certain influential factors, future directions and so on (Li et al., 2019c; Ma et al., 2018; Yan et al., 2018); however, only a few reviews focus on the economic aspects. Compared to technical feasibility, economic feasibility is a more important factor for determining whether the nutrient recovery system can be applied at plant-scale. In this article, technologies of nutrient recovery in wastewater treatment are briefly summarized. Based on the literature summary and previous studies, the economic feasibility of recovering nutrients is proposed. Furthermore the recovered nutrients were analyzed with reference to their efficiency in soil. The objective of this analysis is to promote more practical applications and further studies of sustainable nutrient recovery in wastewater treatment.

2. Conventional technologies for nutrient recovery

2.1. Chemical process

The chemical nutrient recovery approaches to wastewater treatment mainly contain chemical precipitation and adsorption (Banu et al., 2019; He et al., 2019; Liu et al., 2019; Ye et al., 2017). In the chemical precipitation process, magnesium– and calcium-based materials are often used to react with nutrients, which results in the formation of struvite ($MgNH_4PO_4 \cdot 6H_2O$) and hydroxyapatite ($Ca_5(OH)(PO_4)_3$), respectively. These reactions can be described as follows:

$$Mg^{2+} + PO_4^{3-} + NH_4^{+} + 6H_2O \rightarrow MgNH_4PO_4 \cdot 6H_2O\downarrow \quad (1)$$

$$5Ca^{2+} + 3PO_4^{2-} + OH^{-} \rightarrow Ca_5(OH)(PO_4)_3\downarrow \quad (2)$$

In general, struvite could be utilized as a promising fertilizer in agriculture; on the other hand, the phosphate industry needs hydroxyapatite serving as the raw material. Table 1 gives some important factors related to chemical precipitation for recovering nutrients. The optimum pH, and ratios of Mg:P:N and Ca:P in the chemical precipitation process highly depends on the wastewater composition. Overall, the improvement in effectiveness of the nutrients recovery by chemical precipitation requires a more thorough understanding of the pH's effect as well as the selections of Mg/Ca materials acting as precipitators.

Apart from this, adsorption is considered to be another promising method for the nutrient recovery due to its simple design and operation, low cost and high stability. In this scenario, desorption is necessary and it is conducted after adsorption. Consequently, the nutrient-rich solution or other forms which contain a high amount of nutrients can be produced. Metal-based adsorbents are usually employed to recover phosphate due to their high efficiency and easy accessibility. There are three main mechanisms related to phosphate adsorption, and these are electrostatic attraction (Weng et al., 2008), ion exchange and surface precipitation (Li et al., 2013), in which chemical precipitation may also be involved while applying Mg- and Ca-based adsorbents to recover phosphate (Moon et al., 2007). Those factors affecting the phosphate adsorption are summarized in Table 2. Overall, a more thorough understanding of adsorbent properties and adsorption behavior including adsorption and desorption is a prerequisite to developing more appropriate adsorbents to improve phosphate adsorption. Currently, popular adsorbents include metal- and biochar-based material (Bacelo et al., 2019). Unlike phosphate adsorption, ammonium ions are physically adsorbed by acid solutions (e.g., sulfuric acid), before which ammonium ions need to be converted into volatile ammonia through high reaction temperature and/or pH. In this scenario, the volatile ammonia can be transformed into ammonium salts (e.g., ammonium sulfate) which industry could well utilize.

Additionally, an amount of phosphate can be accumulated in the sludge during wastewater treatment (see section 2.2 below) (Kahiluoto et al., 2015; Qin et al., 2015). In this case, wet-chemical and thermochemical treatments are exploited to release phosphate from the sludge to solution (Appels et al., 2010), making it more accessible for recovery so that plants and crops can use it. Acid and alkaline solutions are often utilized to transfer the phosphate ions from the sludge phase to the liquid phase. The selection of acid and alkaline solutions should also consider the properties of the sludge including its content and treatment technology. For the sludge containing phosphate, thermochemical treatment could be done with chloride additives (e.g., $MgCl_2$ and $CaCl_2$) added at high temperatures, i.e., 800-1000 °C

(Adam et al., 2009). This treatment could remove heavy metals (Herzel et al., 2016) to increase the quality of the recovered phosphate as well as making available to plants the phosphate in the treated sludge (Donatello & Cheeseman, 2013).

2.2. Biological process

Biological phosphate recovery is achieved through the phosphate's incorporation into the activated sludge, in which polyphosphorus accumulating organisms (PAOs) play the most important role in the process (Wong et al., 2013). Under anaerobic conditions, cells release the phosphate to the solution with the help of PAOs, resulting in the phosphate accumulation in wastewater. Some metals ions such as Mg^{2+} and K^{+} could also be released and enriched in wastewater. This process can produce energy which is used to take up carbon sources (mainly the volatile fatty acids (VFAs)) and then stored in the form of poly-β-hydroxyalkanoates (PHAs). While transported to the aerobic environment, the phosphate can be taken up and stored in the biomass through PAOs, in which the energy used in this process is derived from the PHAs. Simultaneously, the metal ions can be adsorbed to the biomass (Yuan et al., 2012). The biomass finally exists in the form of surplus sludge. In conclusion, phosphate recovery in the biological process can be divided into two processes: firstly, phosphate release and accumulation in wastewater in an anaerobic environment; and secondly, phosphate storage in the activated sludge under aerobic conditions. However, biological phosphate recovery has been banned in some European countries because the sludge containing rich phosphate also contains a certain amount of heavy metals and pathogens (Schoumans et al., 2015), which cannot be directly applied to land.

3. Advanced technologies for nutrient recovery

As discussed above, the chemical and biological processes indeed realize the objective of nutrient recovery in wastewater treatment. However, coexisting substances such as metal ions and toxic materials could seriously compromise the quality of recovered products. For this reason, membrane technology is needed due to its effective separation of nutrients from foreign substances, and enrichment of nutrients.

3.1. Membrane system

Generally, the forward osmosis (FO), membrane distillation (MD) and electrodialysis

(ED) processes are the three main membrane technologies employed for the nutrients recovery. Fig.1 depicts their schematic diagrams for nutrient enrichment. The FO process utilizes a semipermeable membrane which is placed between the feed solution and draw solution, and the osmotic pressure gradient between the feed side and draw side forces the water transfer from the feed side to the draw side. In the FO process, the nutrients can be rejected by the FO membrane and enriched in the feed side (Xue et al., 2015; Zhang et al., 2014b), which is then used for recovering nutrients. Moreover, a greater amount of phosphate can be enriched in the feed side when compared to the ammonium due to its larger hydrated radiuses (Kiriukhin & Collins, 2002; Zhang et al., 2014b). The FO membrane's surface is negatively charged in the alkaline environment (Cartinella et al., 2006). Consequently, the electrostatic repulsions between the phosphate ions and membrane may facilitate the phosphate being retained in the feed side; in contrast, the ammonium concentration is inhibited in this case. Given this, a neutral pH may be beneficial for both the enrichment of phosphate and ammonium, especially given the fact that high pH results in the conversion of ammonium into volatile ammonia. In the MD process, the feed solution is moderately heated to generate volatile substances which can transfer to the draw solution through the MD membrane. Therefore, the ammonium ion in the feed solution of the MD process is able to be converted into the volatile ammonia and then received by the draw solution (Ahn et al., 2011; Qu et al., 2013). Acid solutions (e.g., H_2SO_4) are always used as the draw solutions since they can react with the ammonia to generate the ammonium salts. The solution pH and temperature of the feeds solution greatly affect the ammonium transformation and further transport. In the ED process, the cation-exchange membrane (CEM) and anion-exchange membrane (AEM) are utilized to separate ammonium and phosphate from the feed solution under the current field and enrich the nutrients in different chambers. Specifically, the ammonium and phosphate ions are driven to the anode and cathode chambers for their concentration and further recovery (Tran et al., 2014).

3.2. Osmotic membrane bioreactor

Based on the FO membrane technology, Qiu and Ting (2014) developed an OMBR for recovering nutrients, in which the FO process is integrated with aerobically biological processes. In this scenario, direct nutrient recovery could be achieved, in which >95% of phosphate and ammonium could be enriched in the feed side and then recovered/removed in the form of struvite/calcium phosphate precipitates. More importantly, no chemicals were added to realize the objective of nutrient recovery, but additional alkaline chemicals were necessary for the pH elevation. Apart from this, using $MgCl_2$ as the draw solute could supplement the Mg^{2+} ions for nutrient recovery by chemical precipitation, which is attributed to the reverse draw flux, a particular property of the FO process.

To increase the purity of recovered nutrients, microfiltration (MF) (Qiu et al., 2015) and ultrafiltration (UF) (Holloway et al., 2015) membranes were installed in the feed side of the OMBR, respectively, which functions parallel with the FO membrane (see Fig. 2). In this scenario, the MF/UF membrane could extract the nutrient concentrated by the FO membrane and therefore ensure only a few foreign substances were in the permeation containing nutrients. This means there is much potential of nutrient recovery in terms of technical and economic feasibility. A fixed bed biofilm could be added into the OMBR in the feed side (Qiu et al., 2016), in which the suspended growth could be reduced as well as curtailing the risk of FO membrane fouling. To increase the economic feasibility of an OMBR-based system for nutrients recovery, RO or MD membranes could be applied to extract the water from the draw solution in order to make the draw solution recyclable (Chang et al., 2017; Luo et al., 2016). Table 3 presents some significant factors affecting OMBR performance. Improvement of the nutrient recovery within OMBR hybrid systems requires an enhanced rejection rate of the membrane to nutrients as well as effective fouling control.

3.3. Bioelectrochemical system

BESs utilize electrochemical reactions and microbial metabolism to generate electricity. Microbial fuel cells (MFCs) constitute an original type of BES, which has been explored for the purpose of nutrients recovery in the last decade. This has extended to microbial electrolysis cell (MEC) and microbial recovery cell (MRC) (Catal et al., 2019; Li & Chen, 2018; Yadav et al., 2020). A conventional MFC consists of two chambers (i.e., anode chamber and cathode chamber) which are separated by a CEM. The anode chamber is responsible for the generation of protons and electrons, and the electrons react with the electrons acceptor (e.g., air) in the cathode chamber to complete the electrical loop. The MFC reactions (in the case of glucose as the carbon source) are shown as follows:

$$C_6H_{12}O_6 + 6H_2O \rightarrow CO_2\uparrow + 24H^+ + 24e^- \quad (3)$$

$$2H_2O + O_2 + 4e^- \rightarrow 4OH^- \quad (4)$$

For the ammonium ions, they can transfer from the anode chamber to the cathode chamber across the CEM through concentration-gradient-caused diffusion and current-driven migration (see Fig. 3). As a result, the ammonium ions could be concentrated in the cathode chamber (Kelly & He, 2014; Kuntke et al., 2012). The pH localized in the cathode is increased due to the cathode reaction (see Eq. [4]), which could lead to the transformation of ammonium into volatile ammonia (Ye et al., 2019b). The volatile ammonia in the cathode chamber could be driven out of the chamber through air stripping and then adsorbed by acid solution to produce ammonium salts. On the other hand, the phosphate ions could be recovered through chemical precipitation since the cathode chamber can provide a high pH zone for precipitation (Chen et al., 2015; Chen et al., 2017; Cusick & Logan, 2012; Ichihashi & Hirooka, 2012; Kelly & He, 2014; Qin & He, 2014; Ye et al., 2019b; Zang et al., 2012; Zhang et al., 2014a). The precipitates are often found on the surface of the cathode electrode.

The BES could also be integrated with the FO process for nutrient recovery (Qin & He, 2014; Qin et al., 2016; Zou et al., 2017). In this scenario, the volatile ammonia was recovered in the form of ammonium bicarbonate which could be utilized as the draw solute of the FO process. It should be noted here that ammonium bicarbonate is a promising draw solute because it is easily recovered through moderate heating (McCutcheon et al., 2005). The wastewater treated by the BES could be fed to the FO process for further treatment. Integration the BES and FO process enhances the technical and economic feasibility of the nutrient recovery system.

3.4. Membrane photobioreactor

In the last decade, microalgae-based processes have been explored for recovering nutrients from wastewater in a photobioreactor (PBR) (Gao et al., 2015; Jankowska et al., 2017; Ruiz-Martinez et al., 2012; Viruela et al., 2016; Viruela et al., 2018). To enhance the growth and accumulation of biomass in the PBR, the membrane technology is combined with the PBR (MPBR) to decouple the SRT and HRT, which has higher nutrient recovery efficiencies and smaller footprint than PBR. The operation costs of traditional PBRs (US\$0.65–0.96/m^3) are higher than that of MPBRs (US\$0.113/m^3) (Sheng et al., 2017). In the MPBR, solar energy (or other light sources) is needed and photodigestion could covert the organics into hydrogen (González et al., 2017). The nutrients and carbon dioxide could be incorporated into the microalgae with the solar energy being stored. Subsequently, the microalgae can be converted to value-added products such as feed for animals and fertilizer biogas (Jankowska et al., 2017; Xin et al., 2010).

As discussed above, there is only physical separation involved in the membrane system which does not require biological processes, so it is more favorable to use these membrane systems for the nutrients recovery in: (1) some countries having insufficient energy sources; (2) decentralized wastewater treatment systems (e.g., remote regions); (3) some regions which fail to conduct biological process due to extreme climate; and (4) some countries that do not have centralized wastewater treatment systems (Hube et al., 2020). From an economic standpoint, the recovery of nutrients through FO processes in wastewater treatment plants located close to the sea is highly recommended since readily available seawater can be used as the draw solution to decline the overall costs through providing Mg^{2+} ions. Besides, the MD filtration processes can be employed to recover ammonium from complex industrial wastewater, in which the FO processes are ineffective (Li et al., 2019b). More importantly, it is economic for the ammonium recovery by MD processes from wastewater containing high temperature since there is no need for additional energy source and wastewater with available low-grade thermal energy sources (e.g., solar energy) (Hube et al., 2020). To improve the application range of the membrane systems for recovering nutrients, they are often integrated with biological processes, which can be utilized in centralized wastewater treatment systems. In particular, the OMBR system used to recover nutrients can reduce the membrane fouling potential, in which the economic feasibility of the recovery system can be improved. Apart from this, the BES containing anaerobic treatment can treat more complex wastewater (e.g., industrial wastewaters) and liberate nitrogen and phosphorus in the form of ammonium (NH_4^+) and phosphate (PO_4^{3-}), respectively, thus facilitating their recovery by subsequent chemical precipitation. The BES can also produce electrical energy towards being an energy-neutral wastewater treatment. It should be noted here that the BES needs biodegradable organic matter for realizing the energy recovery. It may take a longer time for MPBR to achieve the nutrients recovery with additional light sources despite its lower environmental footprint.

4. Economic feasibility of nutrient recovery systems

Nutrient recovery does not only provide the supplementary fertilizers for food production, but also results in reducing wastewater treatment costs. In Europe, for example, some wastewater treatment plants annually spent €65000 (≈ US$72,284.55) to remove the unexpected struvite precipitates formed in pipes and machinery (Jeanmaire & Evans, 2001), but the nutrients recovery could greatly reduce the costs. Compared to the phosphate removal, the cost of phosphate recovery was less €2-3 (≈ US$2.22-3.33)/kg·P (Dockhorn, 2009). In this scenario, the production of surplus sludge could be decreased by 2–8% (on dry matter basis) (Jeanmaire & Evans, 2001). Consequently, this results in the proportional reduction in the costs associated with the sludge management and the value was reported as AUD$1.13 (≈ US$0.78)/kg·struvite (Shu et al., 2006) and UK 100 pounds (≈ US$130.57)/ton·P (Jeanmaire & Evans, 2001). The differences between the two values may be attributed to the different wastewater sources and recovery processes. With the reference to the overall energy demand, the phosphate recovery may save around €3680 (≈ US$4092.16)/day when compared to the phosphate removal (Daneshgar et al., 2019); similarly, Levlin and Hultman (2003) indicated that up to 27% of energy is reduced while shifting the phosphate removal to phosphate recovery. Another benefit of nutrients recovery in wastewater treatment is to lower the nutrient discharge, which may prevent the eutrophication in aquatic environment. Molinos-Senante et al. (2011) utilized the concept of “shadow price” to describe the environmental benefits of phosphate recovery, through which the value was €42.47 (≈ US$47.23)/kg·P. According to the calculation, appropriately €0.218 (≈ US$0.24)/$m^3$ of treated wastewater could be benefited while conducting the nutrient recovery (Hernández-Sancho et al., 2010). Overall, the environmental benefits of recovering nutrients from wastewater include: (1) less production of surplus sludge; (2) reduction in occurrence potential of eutrophication; and (3) less generation of unexpected precipitates.

The chemical nutrient recovery from the liquid phase (€6-10(≈ US$6.67-11.12)/kg·P) costs less than that from the sludge phase (€9-16(≈ US$10.1-17.79)/kg·P) in wastewater treatment because the phosphate in the sludge needs additional treatment to make it accessible in the solution prior to its recovery (Egle et al., 2016). Furthermore, the phosphate recovered from the sludge may result in the generation of unexpected by-products (e.g., heavy metals), which needs additional disposal while phosphate recovery from liquid could decrease the phosphate loading in the back-flow and thus reduce operational costs. It was also reported that the costs of chemical phosphate recovery range from €2.2 to 8.8 (≈ US$2.45-9.79)/kg·P, which is determined by technologies and processes (Desmidt et al., 2015; Schaum, 2007).

In the chemical precipitation processes, chemicals used for the pH elevation and energy utilized for mixing account for the major proportion of overall costs (Sakthivel et al., 2012). Since most wastewaters are slightly acidic, a large amount of alkaline chemicals have to be used for pH improvement, contributing to more than 90% of the total operational cost (Jaffer et al., 2002). However, additional chemicals increase the solution's ionic strength and the struvite dissolution potential is thereby enhanced (Li et al., 2019a). Therefore, aeration can be an alternative to increase the solution pH through stripping out CO_2 from the solution, which could reduce the caustic chemical addition by over 50% (Fattah et al., 2010). This method is affected by the influent composition (e.g. total alkalinity, temperature and initial dissolved CO_2 concentration) as well as the airflow rate (Korchef et al., 2011). Jaffer et al. (2002) reported that CO_2 stripping is more economical for the pH elevation when compared to adding alkaline chemicals in the chemical precipitation.

To examine these findings, Huang et al. (2015) and Huang et al. (2017) analyzed the costs of phosphate recovery through chemical precipitation (Table 5). In their analyses, manpower costs were not considered as well as the market value of the recovered products. As shown in this Table, aeration costs less than adding NaOH solution for the pH elevation. For example, using NaOH solution and air stripping for the pH increase to recover phosphate cost US$1.85/kg·$P_T$ and 1.56/kg·P_T, respectively, while employing $CaCl_2$ as the precipitator. Compared to the Mg- and Ca-based precipitators, employing Fe- and Al-based materials for the phosphate recovery is expensive; more importantly, the recovered phosphate may not suitable for direct land application (Yan et al., 2018). Wang et al. (2019) reported that using plant ash for the pH elevation and magnesium metal pellet as the precipitator to recover phosphate from swine wastewater was highly feasible economically. In this context, the economic evaluation for the proposed method was US$0.62/kg·P, which does not include the labor and maintenance costs.

Apart from this, it is cheaper to employ Mg/Ca hydroxides than other Mg/Ca-based materials serving as the precipitators. The possible reason for this is that Mg/Ca hydroxides provide additional Mg/Ca ions for chemical precipitation and simultaneously improve the solution pH (Daneshgar et al., 2019). Therefore the overall costs would be greatly reduced. Nevertheless, it is difficult to control the pH and Mg:P:N or Ca:P ratio at the same time. Besides, a large dosage of $Mg(OH)_2$ is always necessary due to its poor alkaline character and low solubility if used as a precipitator (Li et al., 2019a). Liu et al. (2014) reported that 75% of the total operational cost in some chemical precipitation process was occupied by the magnesium dosage, so the options of magnesium materials are important for decreasing costs and simultaneously ensuring the product's quality and quantity. Zeng et al. (2006) compared the effectiveness of different commercial magnesium materials at pH 9 with a Mg:P ratio of 1.75 at 20 °C, and found the order as follows: $MgCl_2 > MgSO_4 > MgO > Mg(OH)_2 > MgCO_3$. The least effectiveness of $MgCO_3$ may be attributed to its poor solubility. In this scenario, acid solutions should be added to dissolve it, which is detrimental to the solution pH. To further reduce chemical costs, Etter et al. (2011) and Sakthivel et al. (2012) investigated different magnesium sources for the struvite precipitation from source-separated urine and their estimated struvite production costs being summarized in Table 6. Overall, in their tests, the phosphate recovery efficiencies were all over 90%. Bittern is a waste product, which means it can be achieved for free, but a high transport cost limits its application. As mentioned above, magnesite can be dissolved by additional acids; besides, it could be calcined at elevated temperature to produce magnesium oxide, both of which would greatly increase the input costs of struvite formation. Adding MgO could be beneficial for both magnesium source and pH increase. However, the addition of $MgSO_4$ can increase the concentration of SO_4^{2-} in solution, which may negatively affect the quality of struvite precipitates. There are several advantages of the usage of $MgCl_2$ as the precipitator, including short dissolution time, high solubility, being non-corrosive and non-toxic, but its cost is high and the pH improvement in the process needs input alkaline chemicals. It is evident that wood ash costs least for the struvite formation if it is used as a precipitator. However, the heavy metals are contained in the wood ash and finally accumulated in the recovered products, which lowers the purity and application prospect of the products as fertilizers. Although it is promising and economically feasible to utilize waste products rich in magnesium in the chemical precipitation process, a controlled process is required to remove foreign substances in their composition before they are applied as magnesium source.

When chemical precipitation is used to recover nutrients near coastal areas, seawater is available as a low-cost source with high magnesium content, which can provide Mg^{2+} ions for the chemical precipitation and thus help to save costs. The high salt concentration will not significantly influence the process in spite of extra maintenance needed for the high salinity (Maaß et al., 2014). For example, Kumashiro et al. (2001) utilized seawater as magnesium source to recover phosphate from municipal wastewater, where the cost of recovered struvite was estimated at US$0.55/kg·struvite. However, high salinity may reduce the quality of the struvite with less market value (Lahav et al., 2013). Thus, the selection of magnesium sources should balance the product quality and overall costs. For the nutrient recovery through wet-chemical treatment from the sludge, the acid extraction of phosphate could produce phosphoric acid with high market values. Besides, the phosphate can be released from the sludge by some microorganisms (Chi et al., 2006), which lowers the costs despite the stability and reliability of bacteria being challenged. In the thermochemical treatment for nutrient recovery, the usage of a heat exchanger facilitates the reduction in energy consumption while methane gas could be used as a supplementary energy source.

Ammonium recovery through ammonia stripping coupled with acid absorption is a mature technology and economically plausible, and subsequently widely explored for wastewater treatment (Tian et al., 2019). Pradhan et al. (2017) used this method to achieve 85–99% of NH_4^+-N being recovered, in which about €2.25(≈ US$2.50)/ m^3·pure urine as the profit was obtained. Similarly, Tian et al. (2019) recovered more than 95% of nutrients from urine with the estimated profit being €0.26(≈ US$0.29)/ m^3·urine. The ammonium sulphate acted as the recovered product in this method, which has an estimated market value of €1.0 (≈US$1.11)/kg·N (Desmidt et al., 2015). In the Nijhuis ammonium recovery (AECO-NAR) system, recovery was conducted in a full-scale plant (75 m^3/d), where it costs €1.0(≈US$1.11)/kg·N for ammonium recovery from the stream containing 4 g·NH_4^+-N/L (Menkveld & Broeders, 2017).

Notably, the overall costs of phosphate recovery could be reduced from €2800 to €520 (≈ US$3113.60 and 578.24)/ton·struvite while increasing the phosphate concentration from 50 to 800 mg·P/L (Dockhorn, 2009). Similarly, the growth in the ammonium concentration from 539 to 2470 mg/L could result in the reduction in costs of ammonia recovery from €10.70 (≈ US$11.90) to 2.63 (≈ US$2.92)/kg·N (De Vrieze et al., 2016). Therefore, it is obvious that nutrient enrichment is necessary to increase the recovery system's economic feasibility. Bradford-Hartke et al. (2012) suggested that nutrient recovery through struvite precipitation in the membrane-based system requires less energy input (260 kWh/kg·P) compared to the normal system (about 510 kWh/kg·P). So, the membrane hybrid system could effectively reduce the costs of nutrient recovery.

Ward et al. (2018) investigated the ammonium recovery through the ED process in a pilot-scale experiment and reported that the power consumption which did not include pumping energy was 4.9± 1.5 kWh/kg·NH_4^+-N. Furthermore, they concluded that the ED process is more competitive for the ammonium recovery once the ammonium concentration is over 1500 mg·N/L. Recently, You et al. (2019) found that nutrient recovery through the adsorption of calcium-activated synthetic zeolites is economically profitable in a large urban wastewater treatment plant due to a payback period of 7.5 years and an internal rate of return of 15%, higher than the considered discount rate. This outcome was achieved in the presence of a UF unit, but otherwise the economic evaluation may not be feasible.

While applying OMBR for nutrients recovery, there is no need to add mineral salts for the precipitates' formation and the costs are thereby reduced. Besides, methane fermentation could produce energy as well as biogas generation in the anaerobic process when the OMBR is conducted under anaerobic conditions for nutrients recovery (Hou et al., 2017). The result is that energy costs associated with the nutrient recovery could be offset to some extent. This is despite the fact that the biogas containing toxic substances may require further purification prior to being used to generate electricity (Weiland, 2010). The recovery of ammonium and phosphate by AnMBR-based systems cost US$1.33/kgN and 3.50/kg·P, respectively (Jensen, 2015); similarly, 0.19 L·CH_4/g·COD could be produced while using anaerobic OMBR (AnOMBR) to recover nutrients (Hou et al., 2017). The BESs for the nutrients recovery indicate high economic feasibility because of electricity generation and pH elevation caused by cathode reaction, yet the possible formation of precipitates on the cathode surface may impair the BES performance for recovering nutrients. Recovery of ammonium via BES is compared to the traditional method in terms of costs, as shown in Fig. 4.

Renewable energy such as solar energy could be used as a supplementary energy source in the nutrient recovery system, resulting in the enhanced economic feasibility; for example, Zhang et al. (2013) utilized a solar panel which is in the €3.32 to 4.92 (≈US$3.69 to 5.47)/$m^3$ price range, in a membrane hybrid system for nutrient recovery. Other energy sources such as waste heat energy can also be employed (Qin & He, 2014). For the nutrient recovery via the membrane-based system, the membrane’s price remains a big challenge for practical applications. Moreover, the membrane fouling control may account for more than 50% of total costs in the membrane hybrid system (Sheng et al., 2017).

5. Economic analysis of recovered nutrients

In the nutrient recovery system either in lab-scale or full-scale, struvite and calcium phosphate precipitates are common recovered products because of the solubility of such products in soil and having high plant nutrient uptake (usually >76%) (Römer & Steingrobe, 2018). In this scenario, calcium phosphate precipitates are more easily obtained than struvite due to the strict stoichiometric ratio of struvite formation. This is despite the fact that struvite is considered to be a promising fertilizer because it simultaneously contains ammonium and phosphate, and soil enhancing properties. Due to low solubility and high P content, calcium phosphate precipitates also have high potential to be used as a fertilizer (de Vries et al., 2016). However, calcium phosphate precipitates’ plant availability are varied and depend on technologies and processes (Egle et al., 2016) and they are only effective in acid soils (Amann et al., 2018; Egle et al., 2016; Tarayre et al., 2016). This is because the disintegration of P in the calcium phosphate precipitates is stronger at lower pH and weaker in alkaline conditions (Cabeza et al., 2011). Apart from this, the heavy metals and other impurities are contained in the recovered nutrients, for instance struvite (Kataki et al., 2016), but the amount is less when compared to the commercial fertilizers (Forrest et al., 2008; Latifian et al., 2012). Furthermore the presence of magnesium in the struvite could enhance the plants' and crops' uptake of phosphate owing to synergistic outcomes (González-Ponce et al., 2009).

Currently, the recovered nutrients have not been widely commercialized, so the precise market values of such products are not available. Nevertheless, some estimated data can still be found online. The struvite's market value was reported at €310 (≈US$344.72)/ton (Etter et al., 2011) and €2.6 (≈ US$2.89)/kg·P (Desmidt et al., 2015) while Münch and Barr (2001) estimated that the market price of struvite is around €220 (≈US$244.64)/ton in Japan and AUS$300–500 (≈US$207.04-345.07)/ton in Australia, which is a little higher than that of raw phosphate rock (€0.6-1.2 (≈ US$0.67-1.33)/kg·P) (Desmidt et al., 2015; Dockhorn, 2009) and TSP (€ 1.2-2.2 (≈ US$1.33-2.45)/kg·P) (Mayer et al., 2016). Desmidt et al. (2015) indicated the phosphate-based fertilizers have an average market price of €1.9–3.3 (≈ US$2.11-3.67)/kg·P, which means these current fertilizers may still be more economically viable for farmers and recovered nutrients still cannot compete with current commercial fertilizers. Calcium phosphate precipitates could be utilized to produce triple superphosphate (TSP) which was reported to have a market value of €498 (≈ US$553.78)/ton (Desmidt et al., 2015). Calcium phosphate precipitates could also be employed as raw material for phosphate rock replacement, which is being sold at prices ranging from €830 to 1120 (≈ US$922.96-1245.44)/ton·P (Desmidt et al., 2015). Nevertheless, Daneshgar et al. (2019) suggested that struvite production in the recovery system consumes less energy than production of other P-containing fertilizers such as TSP.

It should be highlighted here that not all recovered nutrients could be directly applied in the soil (Maltais-Landry et al., 2014). There are two common methods to assess the bioavailability of nutrients in the recover products: one is the pot or field trials, and the other is to use chemical analogues for plant acquisition, i.e. using extractants (Melia et al., 2017).

Investigations of struvite's bioavailability have been widely conducted in pot or field trials such as cultivation of corn and tomato plants, maize and tomato plants, Chinese cabbage and maize (Liu et al., 2011; Rahman et al., 2011; Ryu et al., 2012; Uysal et al., 2014; Uysal & Kuru, 2013). In these tests, it was found that struvite could be biologically taken up by the plants and crops in a wide range of pH conditions and soil types. Cabeza et al. (2011) conducted a 2-year pot experiment with maize to explore the fertilization efficiency of recovered struvite and calcium phosphate precipitates. In this case, the struvite has a similar level of fertilization efficiency to TSP while calcium phosphate precipitates were found to be only effective in acid soils. Studies have reported that the recovered struvite from wastewater promoted the growth of plants and crops in the experiment (Liu et al., 2011; Ryu et al., 2012; Yetilmezsoy & Sapci-Zengin). In contrast, others indicated that smaller yields were obtained while using the struvite as fertilizer (Ackerman et al., 2013; Ganrot et al., 2007), which may be attributed to the quality of struvite obtained when studies were conducted. Furthermore, Bauer et al. (2007) recovered phosphate from liquid swine manure and found the recovered product could be citrate soluble, with high levels of plant-available P

The phosphate recovery through thermochemical treatment could generate supplementary fertilizer (Hirota et al., 2010; Vogel et al., 2010), but the recovered products contained around 10% of input chloride additives, which may negatively affect direct land application (Adam et al., 2007). Phosphate treated through $MgCl_2$ in the thermochemical treatment process presents higher fertilization efficiency compared to that recovered by $CaCl_2$ (Nanzer et al., 2014). More importantly, the recovered products obtained in the presence of $MgCl_2$ are more effective in acid soil with the effectiveness relative to a water-soluble P fertilizer at 88%, followed by the value at 71.2% in neutral soil and 4% in alkaline soil (Nanzer et al., 2014).

Phosphate recovered by the metal(s)-biochar adsorbents can not only help restore soil restoration, but also be utilized for direct land application (de Rozari et al., 2016; Mosa et al., 2018; Yao et al., 2013). It should be noted here that the phosphate-loaded biochar could improve the bioavailability of P, but the applications of recovered products are subject to alkaline soils (Arif et al., 2017). Li et al. (2016) used MgO-impregnated magnetic biochar

(MMSB) for phosphate recovery and the fertilizer efficiency of phosphate-adsorbed MMSB proved to be high in their pot experiment for ryegrass seedling growth. Mosa et al. (2018) summarized the factors affecting the bioavailability of phosphate in the biochar-based adsorbents, including biochar's inherent concentration, the amount of phosphate adsorbed on the biochar, the availability of phosphate in the phosphate-loaded biochar-based adsorbents and antagonism/synergism between the phosphate and other nutrients.

Some researchers utilized the CaO-based adsorbents for phosphate recovery and examined the effectiveness of the recovered products as a fertilizer in soil (Li et al., 2018). As an example, Li et al. (2018) developed a CaO-MgO hybrid carbon composite to recover phosphate. The phosphate-loaded adsorbents performed better compared to the control treatments in the pot experiments with reference to the average growth height and average fresh weight of Chinese brassica seedling above-ground parts. This indicates the recovered phosphate could be applied as a phosphate-based fertilizer substitution. Notably, the calcination of phosphate-loaded adsorbents could remove organics from the recovered phosphate, which improves the quality of recovered products (Xie et al., 2015).

6. Future perspectives

Both the rapid consumption of phosphate-based rocks and costly ammonium production indicate the necessity to recover nutrients. Investing in additional technology may be necessary to handle the increasing heavy metals (uranium and cadmium) content caused by more intense exploitation of mines (Sartorius et al., 2012) and greenhouse gases resulting from the industrial ammonia production (Ye et al., 2018). Thus, looking for techniques to recover nutrients at the wastewater treatment stage is of great significance. This process will provide recovered products such as struvite for agriculture as a supplementary fertilizer and calcium phosphate precipitates for industry as the raw materials. In current times, however, it is still economical to utilize rock phosphate and industrial ammonium for nutrients-based fertilizer production, so there are no economic incentives to recover nutrients (Molinos-Senante et al., 2011). For example, in the NuReSys process for nutrient recovery via struvite precipitation, the operation costs were €1.6 (≈ US\$1.78)/kg·P (Moerman et al., 2009) when the phosphate concentration was 120mg·PO_4^{3-}-P/L. The process enabled struvite to have a market price of €0.38 to 0.46 (≈ US$0.42-0.51)/kg·P (Moerman et al., 2009), so it is obvious that the economic benefits from struvite production will not cover all of the operational costs in this case.

As well, the recovered nutrients are not yet considered to be viable as a commercially sold product. Even though the high operation costs limit the economic feasibility of nutrient recovery, the system could generate a wide range of other benefits. For example, the nutrient recovery from wastewater could substantially reduce the production of sludge and undesired precipitates, so the disposal costs related to the unexpected substances may be better controlled or even lowered. Also, the nutrient recovery from wastewater could improve the dewaterability of the treated sludge and decrease the scaling speed rate, both of which result in the improvement improved wastewater management (Bradford-Hartke et al., 2015). Evidently, nutrient recovery could also reduce the concentration of ammonium and phosphate in the discharge generated by a wastewater treatment plant, which prevents eutrophication in aquatic environments. Thus, both the environmental benefits and government regulations would function to trigger nutrients recovery if there are no sufficient economic incentives. It should be highlighted here that the market price of recovered nutrient does not only rely on product quality and market demand; it is also be determined by government policy (Ye et al., 2016b).

As discussed above, the membrane-based technologies for the nutrient recovery present high technical and economic feasibility, in which the OMBR-based and BES-based hybrid systems are greatly favored due to their low membrane fouling potential and low energy consumption. Although the anaerobic OMBR (AnOMBR)-based hybrid system shows lower membrane fouling and energy consumption compared to the aerobic OMBR-based hybrid system, few studies on the AnOMBR-based hybrid system for the nutrient recovery from wastewater have been done. Therefore, more research on the nutrient recovery through AnOMBR hybrid systems should be considered. As the MFC could generate electricity and offer high pH zone for chemical precipitation, it has great promise for recovering nutrients. Thus, the MFC and its modifications should be widely explored to recover nutrients in wastewater treatment. However, MFCs cannot enrich nutrients. In this scenario, the membrane systems including FO, MD and ED process are favorable to combine with MFCs while applying MFCs to recover nutrients from diluted wastewater. Undoubtedly, such integration could increase the quality and quantity of recovered nutrients and is viable in the future. Another important aspect is to increase the anaerobic release of phosphate in the existing tanks in sufficient amounts (Daneshgar et al., 2019).

In addition, feed solution's property can determine the performance of membrane bioreactor through exerting direct impacts on sludge properties, membrane fouling and permeate flux (Gao et al., 2013). However, the role of feed solution in OMBR systems has not been paid sufficient attention. It is therefore important to conduct further studies to evaluate the feasibility of different wastewater sources with reference to the nutrient recovery and simultaneously propose the appropriate pre-treatment for feed solution if necessary. In this case, the technical feasibility of the nutrient recovery system can be enhanced as well as its performance.

7. Conclusion

Nutrient recovery in wastewater treatment is important for curtailing pollution and damage to the environment, and making societies' production methods more sustainable. Current and conventional technologies cannot obtain high quantity and quality of recovered nutrients until they are integrated with membrane technology. The OMBR- and BES-based hybrid systems are highlighted for their implementation in nutrient recovery, but more efforts are needed to reduce their operation costs and improve their technical feasibility, which would make the recovery system more accessible and efficient. Finally, apart from this, governments should put into place relevant legislation, policies and/or regulations to support and encourage nutrient recovery strategies.

Acknowledgement

This research was supported by the Centre for Technology in Water and Wastewater, University of Technology Sydney, Australia (UTS, RIA NGO) and the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (Grant No. 20173010092470).

References

1. Ackerman, J.N., Zvomuya, F., Cicek, N., Flaten, D., 2013. Evaluation of manure-derived struvite as a phosphorus source for canola. *Can. J. Plant Sci.* **93**(3), 419-424.
2. Adam, C., Kley, G., Simon, F.-G., 2007. Thermal treatment of municipal sewage sludge aiming at marketable P-fertilisers. *Mater. Trans.* **48**(12), 3056-3061.
3. Adam, C., Peplinski, B., Michaelis, M., Kley, G., Simon, F.G., 2009. Thermochemical treatment of sewage sludge ashes for phosphorus recovery. *Waste Manag.***29**(3), 1122-1128.
4. Adnan, A., Dastur, M., Mavinic, D.S., Koch, F.A., 2004. Preliminary investigation into factors affecting controlled struvite crystallization at the bench scale. *J. Environ. Eng. Sci.* **3**(3), 195-202.
5. Ahn, Y., Hwang, Y., Shin, H., 2011. Application of PTFE membrane for ammonia removal in a membrane contactor. *Water Sci. Technol.* **63**(12), 2944-2948.
6. Amann, A., Zoboli, O., Krampe, J., Rechberger, H., Zessner, M., Egle, L., 2018. Environmental impacts of phosphorus recovery from municipal wastewater. *Resour. Conserv. Recy.* **130**, 127-139.
7. Appels, L., Degrève, J., Van der Bruggen, B., Van Impe, J., Dewil, R., 2010. Influence of low temperature thermal pre-treatment on sludge solubilisation, heavy metal release and anaerobic digestion. *Bioresour. Technol.* **101**(15), 5743-5748.
8. Arif, M., Ilyas, M., Riaz, M., Ali, K., Shah, K., Haq, I.U., Fahad, S., 2017. Biochar improves phosphorus use efficiency of organic-inorganic fertilizers, maize-wheat productivity and soil quality in a low fertility alkaline soil. *Field Crops Res.* **214**, 25-37.
9. Bacelo, H., Pintor, A.M., Santos, S.C., Boaventura, R.A., Botelho, C.M., 2019. Performance and prospects of different adsorbents for phosphorus uptake and recovery from water. *Chem. Eng. J.*, 122566.
10. Banu, H.A.T., Karthikeyan, P., Meenakshi, S., 2019. Comparative studies on revival of nitrate and phosphate ions using quaternized corn husk and jackfruit peel. *Bioresour. Technol. Reports* **8**, 100331.

11. Bauer, P.J., Szogi, A.A., Vanotti, M.B., 2007. Agronomic effectiveness of calcium phosphate recovered from liquid swine manure. *Agron. J.* **99**(5), 1352-1356.
12. Bradford-Hartke, Z., Lane, J., Lant, P., Leslie, G., 2015. Environmental benefits and burdens of phosphorus recovery from municipal wastewater. *Environ. Sci. Technol.* **49**(14), 8611-8622.
13. Bradford-Hartke, Z., Lant, P., Leslie, G., 2012. Phosphorus recovery from centralised municipal water recycling plants. *Chem. Eng. Res. Des.* **90**(1), 78-85.
14. Cabeza, R., Steingrobe, B., Römer, W., Claassen, N., 2011. Effectiveness of recycled P products as P fertilizers, as evaluated in pot experiments. *Nutr. Cycl. Agroecosyst.* **91**(2), 173.
15. Cartinella, J.L., Cath, T.Y., Flynn, M.T., Miller, G.C., Hunter, K.W., Childress, A.E., 2006. Removal of natural steroid hormones from wastewater using membrane contactor processes. *Environ. Sci. Technol.* **40**(23), 7381-7386.
16. Catal, T., Liu, H., Fan, Y., Bermek, H., 2019. A clean technology to convert sucrose and lignocellulose in microbial electrochemical cells into electricity and hydrogen. *Bioresour. Technol. Reports* **5**, 331-334.
17. Chang, H.-M., Chen, S.-S., Nguyen, N.C., Chang, W.-S., Ray, S.S., 2017. Osmosis membrane bioreactor–microfiltration with magnesium-based draw solute for salinity reduction and phosphorus recovery. *Int. Biodeterior. Biodegrad.* **124**, 169-175.
18. Chen, X., Sun, D., Zhang, X., Liang, P., Huang, X., 2015. Novel self-driven microbial nutrient recovery cell with simultaneous wastewater purification. *Sci. Rep.* **5**, 15744.
19. Chen, X., Zhou, H., Zuo, K., Zhou, Y., Wang, Q., Sun, D., Gao, Y., Liang, P., Zhang, X., Ren, Z.J., 2017. Self-sustaining advanced wastewater purification and simultaneous *in situ* nutrient recovery in a novel bioelectrochemical system. *Chem. Eng. J.* **330**, 692-697.
20. Chi, R.A., Xiao, C.Q., Gao, H., 2006. Bioleaching of phosphorus from rock phosphate containing pyrites by Acidithiobacillus ferrooxidans. *Miner. Eng.* **19**(9), 979-981.
21. Cusick, R.D., Logan, B.E., 2012. Phosphate recovery as struvite within a single chamber microbial electrolysis cell. *Bioresour. Technol.* **107**, 110-115.

22. Dai, L., Wu, B., Tan, F., He, M., Wang, W., Qin, H., Tang, X., Zhu, Q., Pan, K., Hu, Q., 2014. Engineered hydrochar composites for phosphorus removal/recovery: Lanthanum doped hydrochar prepared by hydrothermal carbonization of lanthanum pretreated rice straw. *Bioresour. Technol.* **161**, 327-332.

23. Daneshgar, S., Buttafava, A., Callegari, A., Capodaglio, A.G., 2019. Economic and energetic assessment of different phosphorus recovery options from aerobic sludge. *J. Clean. Prod.* **223**, 729-738.

24. de Rozari, P., Greenway, M., El Hanandeh, A., 2016. Phosphorus removal from secondary sewage and septage using sand media amended with biochar in constructed wetland mesocosms. *Sci. Total Environ.* **569**, 123-133.

25. de Vries, S., Postma, R., van Scholl, L., Blom-Zandstra, G., Verhagen, J., Harms, I. 2016. Economic feasibility and climate benefits of using struvite from the Netherlands as a phosphate (P) fertilizer in West Africa. Wageningen Plant Research.

26. De Vrieze, J., Smet, D., Klok, J., Colsen, J., Angenent, L.T., Vlaeminck, S.E., 2016. Thermophilic sludge digestion improves energy balance and nutrient recovery potential in full-scale municipal wastewater treatment plants. *Bioresour. Technol.* **218**, 1237-1245.

27. Desmidt, E., Ghyselbrecht, K., Yang, Z., Pinoy, L., Bruggen, B.V.D., Verstraete, W., Rabaey, K., Meesschaert, B., 2015. Global phosphorus scarcity and full-scale P-recovery techniques: a review. *Crit. Rev. Environ. Sci. Technol.* **45**(4), 336-384.

28. Dockhorn, T. 2009. About the economy of phosphorus recovery. *International conference on nutrient recovery from wastewater streams*. IWA Publishing, London, UK. pp. 145-158.

29. Donatello, S., Cheeseman, C.R., 2013. Recycling and recovery routes for incinerated sewage sludge ash (ISSA): A review. *Waste Manag.***33**(11), 2328-2340.

30. Egle, L., Rechberger, H., Krampe, J., Zessner, M., 2016. Phosphorus recovery from municipal wastewater: An integrated comparative technological, environmental and economic assessment of P recovery technologies. *Sci. Total Environ.* **574**, 522-542.

31. Etter, B., Tilley, E., Khadka, R., Udert, K., 2011. Low-cost struvite production using

source-separated urine in Nepal. *Water Res.* **45**(2), 852-862.

32. Fattah, K., Zhang, Y., Mavinic, D., Koch, F., 2010. Use of carbon dioxide stripping for struvite crystallization to save caustic dosage: performance at pilotscale operation. *Can. J. Civ. Eng.* **37**(9), 1271-1275.
33. Forrest, A., Fattah, K., Mavinic, D., Koch, F., 2008. Optimizing struvite production for phosphate recovery in WWTP. *J. Environ. Eng.* **134**(5), 395-402.
34. Ganrot, Z., Dave, G., Nilsson, E., 2007. Recovery of N and P from human urine by freezing, struvite precipitation and adsorption to zeolite and active carbon. *Bioresour. Technol.* **98**(16), 3112-3121.
35. Gao, F., Yang, Z.-H., Li, C., Zeng, G.-M., Ma, D.-H., Zhou, L., 2015. A novel algal biofilm membrane photobioreactor for attached microalgae growth and nutrients removal from secondary effluent. *Bioresour. Technol.* **179**, 8-12.
36. Gao, W., Han, M., Qu, X., Xu, C., Liao, B., 2013. Characteristics of wastewater and mixed liquor and their role in membrane fouling. *Bioresour. Technol.* **128**, 207-214.
37. González-Ponce, R., López-de-Sá, E.G., Plaza, C., 2009. Lettuce response to phosphorus fertilization with struvite recovered from municipal wastewater. *HortScience* **44**(2), 426-430.
38. González, E., Díaz, O., Ruigómez, I., de Vera, C., Rodríguez-Gómez, L., Rodríguez-Sevilla, J., Vera, L., 2017. Photosynthetic bacteria-based membrane bioreactor as post-treatment of an anaerobic membrane bioreactor effluent. *Bioresour. Technol.* **239**, 528-532.
39. He, G.-x., He, L.-h., Zhao, Z.-w., Chen, X.-y., Gao, L.-l., Liu, X.-h., 2013. Thermodynamic study on phosphorus removal from tungstate solution via magnesium salt precipitation method. *T. Nonferr. Metal. Soc. China* **23**(11), 3440-3447.
40. He, H., Zhang, N., Chen, N., Lei, Z., Shimizu, K., Zhang, Z., 2019. Efficient phosphate removal from wastewater by MgAl-LDHs modified hydrochar derived from tobacco stalk. *Bioresour. Technol. Reports* **8**, 100348.
41. Hernández-Sancho, F., Molinos-Senante, M., Sala-Garrido, R., 2010. Economic valuation of environmental benefits from wastewater treatment processes: An empirical

approach for Spain. *Sci. Total Environ.* **408**(4), 953-957.

42. Herzel, H., Krüger, O., Hermann, L., Adam, C., 2016. Sewage sludge ash-A promising secondary phosphorus source for fertilizer production. *Sci. Total Environ.* **542**, 1136-1143.
43. Hirota, R., Kuroda, A., Kato, J., Ohtake, H., 2010. Bacterial phosphate metabolism and its application to phosphorus recovery and industrial bioprocesses. *J. Biosci. Bioeng.* **109**(5), 423-432.
44. Holloway, R.W., Wait, A.S., da Silva, A.F., Herron, J., Schutter, M.D., Lampi, K., Cath, T.Y., 2015. Long-term pilot scale investigation of novel hybrid ultrafiltration-osmotic membrane bioreactors. *Desalination* **363**, 64-74.
45. Hou, D., Lu, L., Sun, D., Ge, Z., Huang, X., Cath, T.Y., Ren, Z.J., 2017. Microbial electrochemical nutrient recovery in anaerobic osmotic membrane bioreactors. *Water Res.* **114**, 181-188.
46. Huang, H., Liu, J., Ding, L., 2015. Recovery of phosphate and ammonia nitrogen from the anaerobic digestion supernatant of activated sludge by chemical precipitation. *J. Clean. Prod.* **102**, 437-446.
47. Huang, H., Zhang, D., Zhao, Z., Zhang, P., Gao, F., 2017. Comparison investigation on phosphate recovery from sludge anaerobic supernatant using the electrocoagulation process and chemical precipitation. *J. Clean. Prod.* **141**, 429-438.
48. Hube, S., Eskafi, M., Hrafnkelsdóttir, K.F., Bjarnadóttir, B., Bjarnadóttir, M.Á., Axelsdóttir, S., Wu, B., 2020. Direct membrane filtration for wastewater treatment and resource recovery: A review. *Sci. Total Environ.* **710**, 136375.
49. Ichihashi, O., Hirooka, K., 2012. Removal and recovery of phosphorus as struvite from swine wastewater using microbial fuel cell. *Bioresour. Technol.* **114**, 303-307.
50. Iorhemen, O.T., Hamza, R.A., Sheng, Z., Tay, J.H., 2019. Submerged aerobic granular sludge membrane bioreactor (AGMBR): Organics and nutrients (nitrogen and phosphorus) removal. *Bioresour. Technol. Reports* **6**, 260-267.
51. Jaffer, Y., Clark, T., Pearce, P., Parsons, S., 2002. Potential phosphorus recovery by struvite formation. *Water Res.* **36**(7), 1834-1842.

52. Jankowska, E., Sahu, A.K., Oleskowicz-Popiel, P., 2017. Biogas from microalgae: Review on microalgae's cultivation, harvesting and pretreatment for anaerobic digestion. *Renew. Sust. Energ. Rev.* **75**, 692-709.

53. Jeanmaire, N., Evans, T., 2001. Technico-economic feasibility of P-recovery from municipal wastewaters. *Environ. Technol.* **22**(11), 1355-1361.

54. Jensen, P., 2015. Integrated Agri-Industrial Wastewater Treatment and Nutrient Recovery, Year 3.

55. Kahiluoto, H., Kuisma, M., Ketoja, E., Salo, T., Heikkinen, J., 2015. Phosphorus in manure and sewage sludge more recyclable than in soluble inorganic fertilizer. *Environ. Sci. Technol.* **49**(4), 2115-2122.

56. Kataki, S., West, H., Clarke, M., Baruah, D., 2016. Phosphorus recovery as struvite: Recent concerns for use of seed, alternative Mg source, nitrogen conservation and fertilizer potential. *Resources, Conser. Recy.* **107**, 142-156.

57. Kelly, P.T., He, Z., 2014. Nutrients removal and recovery in bioelectrochemical systems: a review. *Bioresour. Technol.* **153**, 351-360.

58. Kemacheevakul, P., Chuangchote, S., Otani, S., Matsuda, T., Shimizu, Y., 2014. Phosphorus recovery: minimization of amount of pharmaceuticals and improvement of purity in struvite recovered from hydrolysed urine. *Environ. Technol.* **35**(23), 3011-3019.

59. Kiriukhin, M.Y., Collins, K.D., 2002. Dynamic hydration numbers for biologically important ions. *Biophys. Chem.* **99**(2), 155-168.

60. Korchef, A., Saidou, H., Amor, M.B., 2011. Phosphate recovery through struvite precipitation by CO2 removal: Effect of magnesium, phosphate and ammonium concentrations. *J. Hazard. Mater.* **186**(1), 602-613.

61. Kumashiro, K., Ishiwatari, H., Nawamura, Y. 2001. A pilot plant study on using seawater as a magnesium source for struvite precipitation. second international conference on recovery of phosphates from sewage and animal wastes, Noordwijkerhout, Holland.

62. Kuntke, P., Śmiech, K., Bruning, H., Zeeman, G., Saakes, M., Sleutels, T., Hamelers, H., Buisman, C., 2012. Ammonium recovery and energy production from urine by a

microbial fuel cell. *Water Res.* **46**(8), 2627-2636.

63. Lahav, O., Telzhensky, M., Zewuhn, A., Gendel, Y., Gerth, J., Calmano, W., Birnhack, L., 2013. Struvite recovery from municipal-wastewater sludge centrifuge supernatant using seawater NF concentrate as a cheap Mg (II) source. *Sep. Purif. Technol.* **108**, 103-110.
64. Latifian, M., Liu, J., Mattiasson, B., 2012. Struvite-based fertilizer and its physical and chemical properties. *Environ. Technol.* **33**(24), 2691-2697.
65. Levlin, E., Hultman, B. 2003. Phosphorus recovery from phosphate rich side-streams in wastewater treatment plants. *Polish Swedish seminar, Gdansk March*. pp. 23-25.
66. Li, B., Huang, H.M., Boiarkina, I., Yu, W., Huang, Y.F., Wang, G.Q., Young, B.R., 2019a. Phosphorus recovery through struvite crystallisation: Recent developments in the understanding of operational factors. *J. Environ. Manag.* **248**, 109254.
67. Li, C., Deng, W., Gao, C., Xiang, X., Feng, X., Batchelor, B., Li, Y., 2019b. Membrane distillation coupled with a novel two-stage pretreatment process for petrochemical wastewater treatment and reuse. *Sep. Purif. Technol.* **224**, 23-32.
68. Li, K., Liu, Q., Fang, F., Luo, R., Lu, Q., Zhou, W., Huo, S., Cheng, P., Liu, J., Addy, M., 2019c. Microalgae-based wastewater treatment for nutrients recovery: a review. *Bioresour. Technol.* **291**, 121934.
69. Li, R., Wang, J.J., Zhang, Z., Awasthi, M.K., Du, D., Dang, P., Huang, Q., Zhang, Y., Wang, L., 2018. Recovery of phosphate and dissolved organic matter from aqueous solution using a novel CaO-MgO hybrid carbon composite and its feasibility in phosphorus recycling. *Sci. Total Environ.* **642**, 526-536.
70. Li, R., Wang, J.J., Zhou, B., Awasthi, M.K., Ali, A., Zhang, Z., Lahori, A.H., Mahar, A., 2016. Recovery of phosphate from aqueous solution by magnesium oxide decorated magnetic biochar and its potential as phosphate-based fertilizer substitute. *Bioresour. Technol.* **215**, 209-214.
71. Li, S., Chen, G., 2018. Factors affecting the effectiveness of bioelectrochemical system applications: Data synthesis and meta-analysis. *Batteries* **4**(3), 34.
72. Li, W., Feng, X., Yan, Y., Sparks, D.L., Phillips, B.L., 2013. Solid-state NMR

spectroscopic study of phosphate sorption mechanisms on aluminum (Hydr)oxides. *Environ. Sci. Technol.* **47**(15), 8308-8315.

73. Liu, J., Mu, T., He, W., He, T., Lu, L., Peng, K., Huang, X., 2019. Integration of coagulation, acid separation and struvite precipitation as fermentation medium conditioning methods to enhance microbial lipid production from dewatered sludge. *Bioresour. Technol. Reports* **7**, 100221.
74. Liu, R., Chi, L., Wang, X., Sui, Y., Wang, Y., Arandiyan, H., 2018. Review of metal (hydr)oxide and other adsorptive materials for phosphate removal from water. *J. Environ. Chem. Eng.* **6**(4), 5269-5286.
75. Liu, X., Hu, Z., Mu, J., Zang, H., Liu, L., 2014. Phosphorus recovery from urine with different magnesium resources in an air-agitated reactor. *Environ. Technol.* **35**(22), 2781-2787.
76. Liu, Y., Rahman, M., Kwag, J.-H., Kim, J.-H., Ra, C., 2011. Eco-friendly production of maize using struvite recovered from swine wastewater as a sustainable fertilizer source. *Asian-Australas. J. Anim. Sci.* **24**(12), 1699-1705.
77. Luo, W., Hai, F.I., Price, W.E., Guo, W., Ngo, H.H., Yamamoto, K., Nghiem, L.D., 2016. Phosphorus and water recovery by a novel osmotic membrane bioreactor–reverse osmosis system. *Bioresour. Technol.* **200**, 297-304.
78. Münch, E.V., Barr, K., 2001. Controlled struvite crystallisation for removing phosphorus from anaerobic digester sidestreams. *Water Res.* **35**(1), 151-159.
79. Ma, H., Guo, Y., Qin, Y., Li, Y.-Y., 2018. Nutrient recovery technologies integrated with energy recovery by waste biomass anaerobic digestion. *Bioresour. Technol.* **269**, 520-531.
80. Maaß, O., Grundmann, P., und Polach, C.v.B., 2014. Added-value from innovative value chains by establishing nutrient cycles via struvite. *Resour. Conserv. Recy.* **87**, 126-136.
81. Maltais-Landry, G., Scow, K., Brennan, E., 2014. Soil phosphorus mobilization in the rhizosphere of cover crops has little effect on phosphorus cycling in California agricultural soils. *Soil Biol. Biochem.* **78**, 255-262.
82. Maurer, M., Schwegler, P., Larsen, T., 2003. Nutrients in urine: energetic aspects of

removal and recovery. *Water Sci. Technol.* **48**(1), 37-46.

83. Mayer, B.K., Baker, L.A., Boyer, T.H., Drechsel, P., Gifford, M., Hanjra, M.A., Parameswaran, P., Stoltzfus, J., Westerhoff, P., Rittmann, B.E., 2016. Total value of phosphorus recovery. *Environ. Sci. Technol.* **50**(13), 6606-6620.

84. McCutcheon, J.R., McGinnis, R.L., Elimelech, M., 2005. A novel ammonia-carbon dioxide forward (direct) osmosis desalination process. *Desalination* **174**(1), 1-11.

85. Meena, R.A.A., Yukesh Kannah, R., Sindhu, J., Ragavi, J., Kumar, G., Gunasekaran, M., Rajesh Banu, J., 2019. Trends and resource recovery in biological wastewater treatment system. *Bioresour. Technol. Reports* **7**, 100235.

86. Melia, P.M., Cundy, A.B., Sohi, S.P., Hooda, P.S., Busquets, R., 2017. Trends in the recovery of phosphorus in bioavailable forms from wastewater. *Chemosphere* **186**, 381-395.

87. Menkveld, H., Broeders, E., 2017. Recovery of ammonium from digestate as fertilizer. *Water Pract. Technol.* **12**(3), 514-519.

88. Moerman, W., Carballa, M., Vandekerckhove, A., Derycke, D., Verstraete, W., 2009. Phosphate removal in agro-industry: pilot-and full-scale operational considerations of struvite crystallization. *Water Res.* **43**(7), 1887-1892.

89. Molinos-Senante, M., Hernández-Sancho, F., Sala-Garrido, R., Garrido-Baserba, M., 2011. Economic feasibility study for phosphorus recovery processes. *Ambio* **40**(4), 408-416.

90. Moon, Y.H., Kim, J.G., Ahn, J.S., Lee, G.H., Moon, H.-S., 2007. Phosphate removal using sludge from fuller's earth production. *J. Hazard. Mater.***143**(1), 41-48.

91. Mosa, A., El-Ghamry, A., Tolba, M., 2018. Functionalized biochar derived from heavy metal rich feedstock: phosphate recovery and reusing the exhausted biochar as an enriched soil amendment. *Chemosphere* **198**, 351-363.

92. Nanzer, S., Oberson, A., Berger, L., Berset, E., Hermann, L., Frossard, E., 2014. The plant availability of phosphorus from thermo-chemically treated sewage sludge ashes as studied by 33P labeling techniques. *Plant and Soil* **377**(1-2), 439-456.

93. Nuramkhaan, M., Zhang, Y., Dong, X., Huang, W., Lei, Z., Shimizu, K., Zhang, Z., Utsumi, M., Lee, D.-J., 2019. Isolation of microalgal strain from algal-bacterial

aerobic granular sludge and examination on its contribution to granulation process during wastewater treatment in respect of nutrients removal, auto-aggregation capability and EPS excretion. *Bioresour. Technol. Reports* **8**, 100330.

94. Pradhan, S.K., Mikola, A., Vahala, R., 2017. Nitrogen and phosphorus harvesting from human urine using a stripping, absorption, and precipitation process. *Environ. Sci. Technol.* **51**(9), 5165-5171.
95. Qin, C., Liu, H., Liu, L., Smith, S., Sedlak, D.L., Gu, A.Z., 2015. Bioavailability and characterization of dissolved organic nitrogen and dissolved organic phosphorus in wastewater effluents. *Sci. Total Environ.* **511**, 47-53.
96. Qin, M., He, Z., 2014. Self-supplied ammonium bicarbonate draw solute for achieving wastewater treatment and recovery in a microbial electrolysis cell-forward osmosis-coupled system. *Environ. Sci. Technol. Lett.* **1**(10), 437-441.
97. Qin, M., Molitor, H., Brazil, B., Novak, J.T., He, Z., 2016. Recovery of nitrogen and water from landfill leachate by a microbial electrolysis cell-forward osmosis system. *Bioresour. Technol.* **200**, 485-492.
98. Qiu, G., Law, Y.M., Das, S., Ting, Y.P., 2015. Direct and complete phosphorus recovery from municipal wastewater using a hybrid microfiltration-forward osmosis membrane bioreactor process with seawater brine as draw solution. *Environ. Sci. Technol.* **49**(10), 6156-6163.
99. Qiu, G., Ting, Y.P., 2014. Direct phosphorus recovery from municipal wastewater via osmotic membrane bioreactor (OMBR) for wastewater treatment. *Bioresour. Technol.* **170**, 221-229.
100. Qiu, G., Zhang, S., Raghavan, D.S.S., Das, S., Ting, Y.-P., 2016. The potential of hybrid forward osmosis membrane bioreactor (FOMBR) processes in achieving high throughput treatment of municipal wastewater with enhanced phosphorus recovery. *Water Res.* **105**, 370-382.
101. Qu, D., Sun, D., Wang, H., Yun, Y., 2013. Experimental study of ammonia removal from water by modified direct contact membrane distillation. *Desalination* **326**, 135-140.
102. Römer, W., Steingrobe, B., 2018. Fertilizer effect of phosphorus recycling products.

Sustainability **10**(4), 1166.

103. Rahman, M.M., Liu, Y., Kwag, J.-H., Ra, C., 2011. Recovery of struvite from animal wastewater and its nutrient leaching loss in soil. *J. Hazard. Mater.* **186**(2-3), 2026-2030.
104. Ruiz-Martinez, A., Garcia, N.M., Romero, I., Seco, A., Ferrer, J., 2012. Microalgae cultivation in wastewater: nutrient removal from anaerobic membrane bioreactor effluent. *Bioresour. Technol.* **126**, 247-253.
105. Ryu, H.-D., Lim, C.-S., Kang, M.-K., Lee, S.-I., 2012. Evaluation of struvite obtained from semiconductor wastewater as a fertilizer in cultivating Chinese cabbage. *J. Hazard. Mater.* **221**, 248-255.
106. Sakthivel, S.R., Tilley, E., Udert, K.M., 2012. Wood ash as a magnesium source for phosphorus recovery from source-separated urine. *Sci. Total Environ.* **419**, 68-75.
107. Sartorius, C., von Horn, J., Tettenborn, F., 2012. Phosphorus recovery from wastewater—Expert survey on present use and future potential. *Water Environ. Res.* **84**(4), 313-322.
108. Schaum, C.A. 2007. Verfahren für eine zukünftige Klärschlammbehandlung: Klärschlammkonditionierung und Rückgewinnung von Phosphor aus Klärschlammasche. Inst. WAR.
109. Schoumans, O.F., Bouraoui, F., Kabbe, C., Oenema, O., van Dijk, K.C., 2015. Phosphorus management in Europe in a changing world. *Ambio* **44**(2), 180-192.
110. Sheng, A., Bilad, M., Osman, N., Arahman, N., 2017. Sequencing batch membrane photobioreactor for real secondary effluent polishing using native microalgae: Process performance and full-scale projection. *J. Clean. Prod.* **168**, 708-715.
111. Shu, L., Schneider, P., Jegatheesan, V., Johnson, J., 2006. An economic evaluation of phosphorus recovery as struvite from digester supernatant. *Bioresour. Technol.* **97**(17), 2211-2216.
112. Sun, Y., Chen, Z., Wu, G., Wu, Q., Zhang, F., Niu, Z., Hu, H.-Y., 2016. Characteristics of water quality of municipal wastewater treatment plants in China: implications for resources utilization and management. *J. Clean. Prod.* **131**, 1-9.

113. Tansel, B., Lunn, G., Monje, O., 2018. Struvite formation and decomposition characteristics for ammonia and phosphorus recovery: A review of magnesium-ammonia-phosphate interactions. *Chemosphere* **194**, 504-514.

114. Tarayre, C., De Clercq, L., Charlier, R., Michels, E., Meers, E., Camargo-Valero, M., Delvigne, F., 2016. New perspectives for the design of sustainable bioprocesses for phosphorus recovery from waste. *Bioresour. Technol.* **206**, 264-274.

115. Tian, X., Gao, Z., Feng, H., Zhang, Z., Li, J., Wang, A., 2019. Efficient nutrient recovery/removal from real source-separated urine by coupling vacuum thermal stripping with activated sludge processes. *J. Clean. Prod.* **220**, 965-973.

116. Tran, A.T., Zhang, Y., De Corte, D., Hannes, J.-B., Ye, W., Mondal, P., Jullok, N., Meesschaert, B., Pinoy, L., Van der Bruggen, B., 2014. P-recovery as calcium phosphate from wastewater using an integrated selectrodialysis/crystallization process. *J. Clean. Prod.* **77**, 140-151.

117. Uysal, A., Demir, S., Sayilgan, E., Eraslan, F., Kucukyumuk, Z., 2014. Optimization of struvite fertilizer formation from baker’s yeast wastewater: growth and nutrition of maize and tomato plants. *Environ. Sci.Pollut. R.* **21**(5), 3264-3274.

118. Uysal, A., Kuru, B., 2013. Magnesium ammonium phosphate production from wastewater through box–behnken design and its effect on nutrient element uptake in plants. *CLEAN–Soil, Air, Water* **41**(5), 447-454.

119. Viet, N.D., Cho, J., Yoon, Y., Jang, A., 2019. Enhancing the removal efficiency of osmotic membrane bioreactors: A comprehensive review of influencing parameters and hybrid configurations. *Chemosphere* **236**, 124363.

120. Viruela, A., Murgui, M., Gómez-Gil, T., Durán, F., Robles, Á., Ruano, M.V., Ferrer, J., Seco, A., 2016. Water resource recovery by means of microalgae cultivation in outdoor photobioreactors using the effluent from an anaerobic membrane bioreactor fed with pre-treated sewage. *Bioresour. Technol.* **218**, 447-454.

121. Viruela, A., Robles, Á., Durán, F., Ruano, M.V., Barat, R., Ferrer, J., Seco, A., 2018. Performance of an outdoor membrane photobioreactor for resource recovery from anaerobically treated sewage. *J. Clean. Prod.* **178**, 665-674.

122. Vogel, C., Adam, C., Peplinski, B., Wellendorf, S., 2010. Chemical reactions during the preparation of P and NPK fertilizers from thermochemically treated sewage sludge ashes. *Soil Sci. Plant Nutr.* **56**(4), 627-635.

123. Wang, F., Wei, J., Zou, X., Fu, R., Li, J., Wu, D., Lv, H., Zhu, G., Wu, X., Chen, H., 2019. Enhanced electrochemical phosphate recovery from livestock wastewater by adjusting pH with plant ash. *J. Environ. Manag.* **250**, 109473.

124. Ward, A.J., Arola, K., Brewster, E.T., Mehta, C.M., Batstone, D.J., 2018. Nutrient recovery from wastewater through pilot scale electrodialysis. *Water Res.* **135**, 57-65.

125. Weiland, P., 2010. Biogas production: current state and perspectives. *Appl. Microbiol. Biotechnol.* **85**(4), 849-860.

126. Weng, L., Van Riemsdijk, W.H., Hiemstra, T., 2008. Humic nanoparticles at the oxide-water interface: Interactions with phosphate ion adsorption. *Environ. Sci. Technol.* **42**(23), 8747-8752.

127. Wong, P.Y., Cheng, K.Y., Kaksonen, A.H., Sutton, D.C., Ginige, M.P., 2013. A novel post denitrification configuration for phosphorus recovery using polyphosphate accumulating organisms. *Water Res.* **47**(17), 6488-6495.

128. Xie, T., Reddy, K.R., Wang, C., Yargicoglu, E., Spokas, K., 2015. Characteristics and applications of biochar for environmental remediation: a review. *C Crit. Rev. Env. Sci. Tec.* **45**(9), 939-969.

129. Xin, L., Hong-Ying, H., Ke, G., Ying-Xue, S., 2010. Effects of different nitrogen and phosphorus concentrations on the growth, nutrient uptake, and lipid accumulation of a freshwater microalga Scenedesmus sp. *Bioresour. Technol.* **101**(14), 5494-5500.

130. Xue, W., Tobino, T., Nakajima, F., Yamamoto, K., 2015. Seawater-driven forward osmosis for enriching nitrogen and phosphorous in treated municipal wastewater: effect of membrane properties and feed solution chemistry. *Water Res.* **69**, 120-130.

131. Yadav, R.K., Chiranjeevi, P., Sukrampal, Patil, S.A., 2020. Integrated drip hydroponics-microbial fuel cell system for wastewater treatment and resource recovery. *Bioresour. Technol. Reports* **9**, 100392.

132. Yan, T., Ye, Y., Ma, H., Zhang, Y., Guo, W., Du, B., Wei, Q., Wei, D., Ngo, H.H., 2018. A

critical review on membrane hybrid system for nutrient recovery from wastewater. *Chem. Eng. J.* **348**, 143-156.

133. Yao, Y., Gao, B., Chen, J., Zhang, M., Inyang, M., Li, Y., Alva, A., Yang, L., 2013. Engineered carbon (biochar) prepared by direct pyrolysis of Mg-accumulated tomato tissues: characterization and phosphate removal potential. *Bioresour. Technol.* **138**(6), 8-13.
134. Ye, Y., Hu, Y., Hussain, Z., Li, X., Li, D., Kang, J., 2016a. Simultaneous adsorptive removal of fluoride and phosphate by magnesia–pullulan composite from aqueous solution. *RSC Adv.* **6**(42), 35966-35976.
135. Ye, Y., Ngo, H.H., Guo, W., Chang, S.W., Nguyen, D.D., Liu, Y., Nghiem, L.D., Zhang, X., Wang, J., 2019a. Effect of organic loading rate on the recovery of nutrients and energy in a dual-chamber microbial fuel cell. *Bioresour. Technol.* **281**, 367-373.
136. Ye, Y., Ngo, H.H., Guo, W., Liu, Y., Chang, S.W., Nguyen, D.D., Liang, H., Wang, J., 2018. A critical review on ammonium recovery from wastewater for sustainable wastewater management. *Bioresour. Technol.* **268**, 749-758.
137. Ye, Y., Ngo, H.H., Guo, W., Liu, Y., Chang, S.W., Nguyen, D.D., Ren, J., Liu, Y., Zhang, X., 2019b. Feasibility study on a double chamber microbial fuel cell for nutrient recovery from municipal wastewater. *Chem. Eng. J.* **358**, 236-242.
138. Ye, Y., Ngo, H.H., Guo, W., Liu, Y., Li, J., Liu, Y., Zhang, X., Jia, H., 2017. Insight into chemical phosphate recovery from municipal wastewater. *Sci. Total Environ.* **576**, 159-171.
139. Ye, Y., Ngo, H.H., Guo, W., Liu, Y., Zhang, X., Guo, J., Ni, B.-j., Chang, S.W., Nguyen, D.D., 2016b. Insight into biological phosphate recovery from sewage. *Bioresour. Technol.* **218**, 874-881.
140. Yetilmezsoy, K., Sapci-Zengin, Z., Recovery of ammonium nitrogen from the effluent of UASB treating poultry manure wastewater by MAP precipitation as a slow release fertilizer. *J. Hazard. Mater.* **166**(1), 260-269.
141. You, X., Valderrama, C., Cortina, J.L., 2019. Nutrients recovery from treated secondary mainstream in an urban wastewater treatment plant: A financial assessment case study.

Sci. Total Environ. **656**, 902-909.

142. Yuan, Z., Pratt, S., Batstone, D.J., 2012. Phosphorus recovery from wastewater through microbial processes. *Curr. Opin. Biotechnol.* **23**(6), 878-883.
143. Zang, G.-L., Sheng, G.P., Li, W.W., Tong, Z.H., Zeng, R.J., Shi, C., Yu, H.Q., 2012. Nutrient removal and energy production in a urine treatment process using magnesium ammonium phosphate precipitation and a microbial fuel cell technique. *PCCP* **14**(6), 1978-1984.
144. Zeng, L., Mangan, C., Li, X., 2006. Ammonia recovery from anaerobically digested cattle manure by steam stripping. *Water Sci. Technol.* **54**(8), 137-145.
145. Zhang, D.-m., Chen, Y.-x., Jilani, G., Wu, W.-x., Liu, W.-l., Han, Z.-y., 2012. Optimization of struvite crystallization protocol for pretreating the swine wastewater and its impact on subsequent anaerobic biodegradation of pollutants. *Bioresour. Technol.* **116**, 386-395.
146. Zhang, F., Li, J., He, Z., 2014a. A new method for nutrients removal and recovery from wastewater using a bioelectrochemical system. *Bioresour. Technol.* **166**, 630-634.
147. Zhang, J., She, Q., Chang, V.W., Tang, C.Y., Webster, R.D., 2014b. Mining nutrients (N, K, P) from urban source-separated urine by forward osmosis dewatering. *Environ. Sci. Technol.* **48**(6), 3386-3394.
148. Zhang, Y., Pinoy, L., Meesschaert, B., Van der Bruggen, B., 2013. A natural driven membrane process for brackish and wastewater treatment: photovoltaic powered ED and FO hybrid system. *Environ. Sci. Technol.* **47**(18), 10548-10555.
149. Zou, S., Qin, M., Moreau, Y., He, Z., 2017. Nutrient-energy-water recovery from synthetic sidestream centrate using a microbial electrolysis cell-forward osmosis hybrid system. *J. Clean. Prod.* **154**, 16-25.

Figure caption

Figure 1. Schematic representation of membrane technology to enrich nutrients.

Figure 2. Schematic representation of the OMBR-MF/UF hybrid system for the nutrients recovery (adapted from Qiu et al. (2015) and Holloway et al. (2015))

Figure 3. Schematic representation of the MFC for the nutrients recovery

Figure 4. Energy analysis of different systems for the N recovery (data derived from Kuntke et al. (2012), Maurer et al. (2003) and Qin and He (2014))

[a] The energy consumption involves aeration, recirculation and external power.

[b] The ammonium recovery rate is the daily amount of ammonium being recovered *vs* the surface area of CEM.

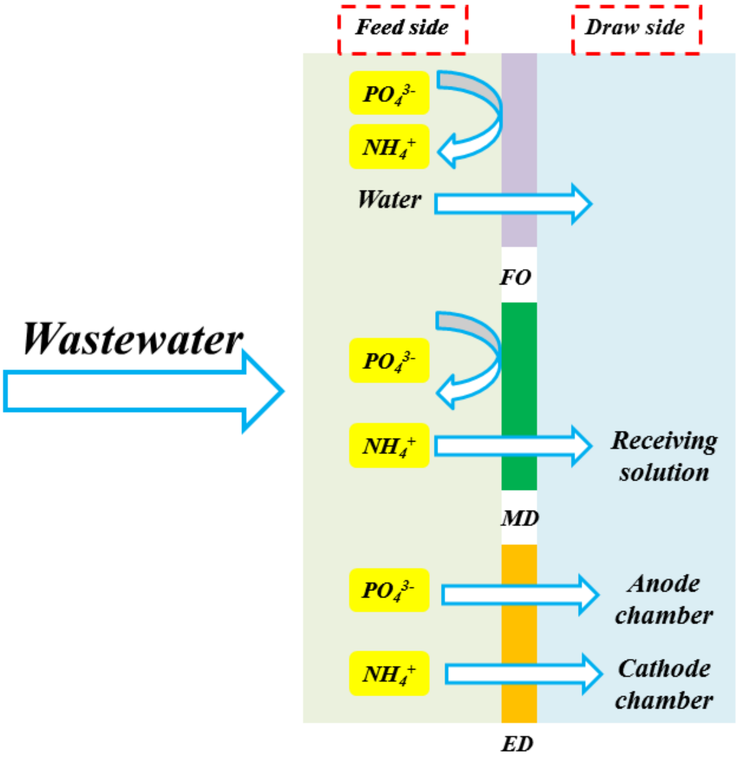
Feed side
Draw side
Wastewater
PO_4^{3-}
NH_4^+
Water
FO
PO_4^{3-}
NH_4^+
Receiving solution
MD
PO_4^{3-}
Anode chamber
NH_4^+
Cathode chamber
ED

Fig. 1

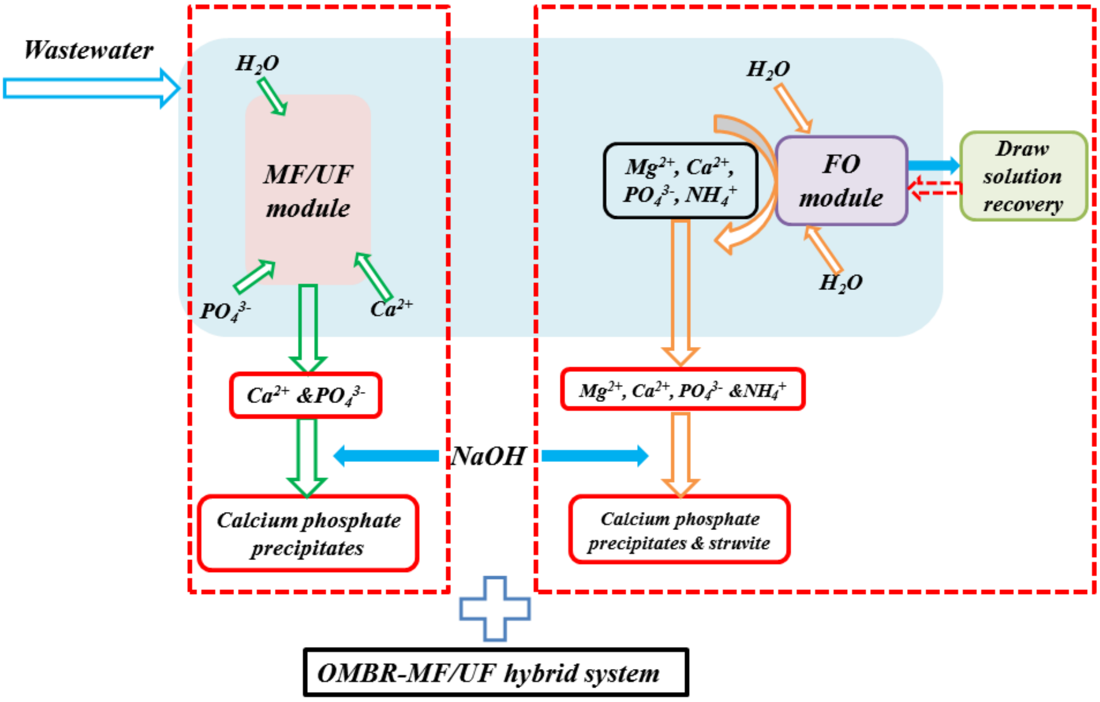
Wastewater
H_2O
MF/UF module
PO_4^{3-}
Ca^{2+}
Ca^{2+} &PO_4^{3-}
Calcium phosphate precipitates
NaOH
H_2O
Mg^{2+}, Ca^{2+}, PO_4^{3-}, NH_4^+
FO module
Draw solution recovery
H_2O
Mg^{2+}, Ca^{2+}, PO_4^{3-} &NH_4^+
Calcium phosphate precipitates & struvite
OMBR-MF/UF hybrid system

Fig. 2

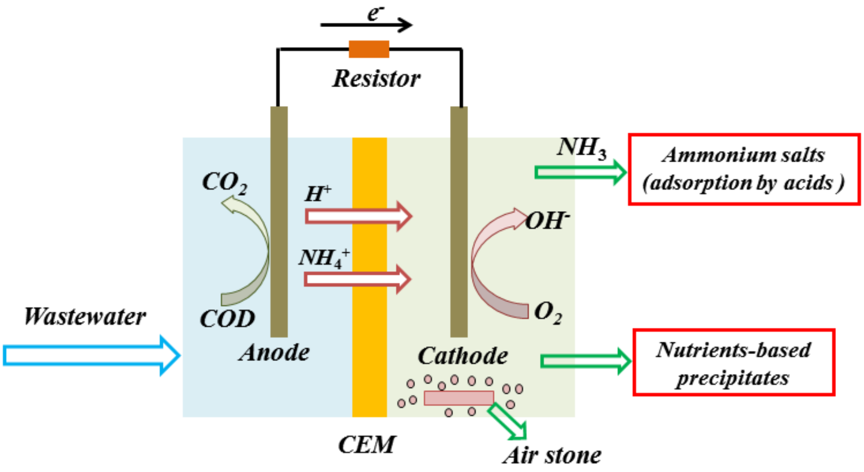
e-
Resistor
NH_3
Ammonium salts (adsorption by acids)
CO_2
H^+
OH^-
NH_4^+
Wastewater
COD
O_2
Anode
Cathode
Nutrients-based precipitates
CEM
Air stone

Fig. 3

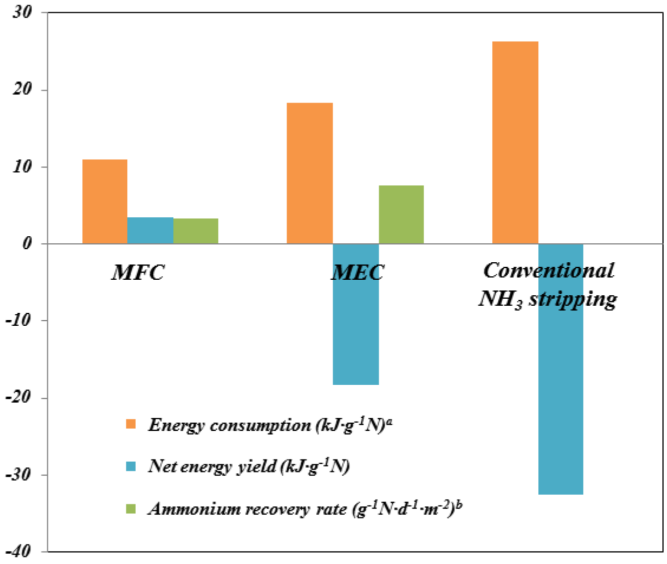
30
20
10
0
-10
-20
-30
-40
MFC
MEC
Conventional NH_3 stripping
Energy consumption ($kJ \cdot g^{-1}N$)[a]
Net energy yield ($kJ \cdot g^{-1}N$)
Ammonium recovery rate ($g^{-1}N \cdot d^{-1} \cdot m^{-2}$)[b]

Fig. 4

Table caption

Table 1 Factors affecting the nutrient recovery through chemical precipitation

Table 2 Factors affecting the nutrient recovery through adsorption

Table 3 Factors affecting the nutrient recovery through OMBR hybrid system

Table 4. Economic analysis of nutrient recovery through chemical precipitation in sewage treatment (data derived from Huang et al. (2015) and Huang et al. (2017))

Table 5. Estimated struvite production costs using different magnesium materials

Table 6. Comparison of technologies for recovering/enriching nutrients from wastewater

Table 1. Factors affecting the nutrient recovery through chemical precipitation

Recovery factors	**Effects on nutrient recovery**	**References**
Solution pH	✓ The reported pH for chemical precipitation is in a range of 7-11. ✓ The pH values affect the speciation profiles of ammonium and phosphate ions in the aquatic environment. ✓ Higher pH values may result in forming unexpected metal-based precipitates while the precipitation rate is small at low pH level, so a pH range of 8.0-10.5 is recommended.	Tansel et al. (2018) Li et al. (2019a) Zhang et al. (2012)
Temperature	✓ Higher temperature makes the precipitates' formation possible at lower pH. ✓ Low temperatures (below 15 °C) are beneficial for struvite precipitation ✓ High temperature causes the loss of NH_4^+ ion because it could be transformed into volatile NH_3.	Tansel et al. (2018) Adnan et al. (2004)
Dose	✓ Struvite can form at low pH level around 5.3 if high concentrations of ammonium and phosphate are present. ✓ Mg:P ratio should be more than one to obtain struvite formation; similarly, Ca/P should be over 1.67 for the calcium phosphate precipitation.	He et al. (2013) Li et al. (2019a) Ye et al. (2017)
Foreign substances	✓ The presence of calcium ions can negatively affect the struvite precipitation. ✓ The impacts of organic matter on chemical precipitation vary according to their properties, while some organics such as pharmaceuticals and hormones were detected in the recovered precipitates, which seriously influenced human health and the environment if used as a fertilizer.	Li et al. (2019a) Kemacheevakul et al. (2014)

Table 2. Factors affecting the nutrient recovery through adsorption

Recovery factors	**Effects on nutrient recovery**	**References**
pH value	✓ The surface charge on a given adsorbent is positive at the solution pH < pH_{ZPC}, so the phosphate adsorption is enhanced due to electronic attraction; by contrast, negatively charged surface of the adsorbent would repulse the phosphate at pH > pH_{ZPC}. ✓ The phosphate forms are highly dependent on solution pH. ✓ Competition is evident between OH- ions and phosphate at high pH, which does not favor phosphate adsorption	Liu et al. (2018) Dai et al. (2014)
Temperature	✓ Generally, the phosphate adsorption is an endothermic process, which means higher temperature can facilitate the phosphate adsorption.	Ye et al. (2016a)
coexistent ions	✓ There are a lot of anions exiting in domestic and industrial wastewaters, such as CO_3^{2-}, NO_3^-, F^- and SO_4^{2-}. They would compete with phosphate ions for adsorption sites and their effects on phosphate adsorption greatly depend on the given adsorbent's property and adsorption mechanisms. ✓ The presence of CO_3^{2-} results in increasing pH value, which weakens the phosphate adsorption.	Liu et al. (2018)
Desorption	✓ Solvent washing and calcination are the main desorption methods, which are determined by the adsorbent property and adsorption mechanism.	Bacelo et al. (2019)

Table 3. Factors affecting the nutrient recovery through OMBR hybrid system

Fouling factors	**Effects on nutrient recovery**	**References**
Membrane property	✓ Flat-sheet cellulose triacetate (CTA) membranes could obtain higher rejection rate for ammonia compared to the thin-film composite (TFC) membranes.	Xue et al. (2015)
Membrane fouling	✓ Fouling layer may increase internal concentration polarization (ICP) and more nutrients can be thereby permeated into the draw side, which declines the nutrient recovery.	Viet et al. (2019)
Draw solution	✓ $MgCl_2$ is preferred to be used as a draw solute because it could provide Mg2+ ions for the chemical precipitation, which can transfer from the draw side to the feed side due to reverse draw flux. ✓ NH_4CO_3 is a promising draw solute because it is easily recovered through moderate heating.	McCutcheon et al. (2005).
Hydraulic retention time (HRT)	✓ Lower HRT could increase salt accumulation and membrane fouling, resulting in higher operating costs.	Viet et al. (2019)
pH	✓ The effects of pH on the performance of the OMBR process remain to be determined, but too high pH can result in the formation of unexpected precipitates.	Qiu and Ting (2014)

Table 4. Economic analysis of nutrient recovery through chemical precipitation in sewage treatment (data derived from Huang et al. (2015) and Huang et al. (2017))

No.	Precipitator	pH increase	Total costs (US$/kg·$P_T$)
1	$CaCl_2$	Aeration supply	1.56
2	$CaCl_2$	Additional NaOH	1.85
3	$MgCl_2$	Aeration supply	0.82
4	$MgCl_2$	Additional NaOH	0.95
5	MgO	Aeration supply	0.38
6	$FeSO_4$	Additional NaOH	1.99
7	$FeCl_3$	Additional NaOH	3.13
8	$AlCl_3$	Additional NaOH	3.54

Table 5. Estimated struvite production costs using different magnesium materials

Mg Source	**Mg content (g/kg)**	**Mg:P**	**Input costs (US$/kg·struvite)**	**References**
Bittern (Mg^{2+})	85	1.1	0.19	Etter et al. (2011)
Magnesite ($MgCO_3$)	244	1	0.11	
Magnesium sulphate ($MgSO_4 \cdot 7H_2O$)	96	1.1	0.32	
Wood ash (Solid MgO)	34.2	1.9	0.024	Sakthivel et al. (2012)
Magnesium chloride ($MgCl_2 \cdot 6H_2O$)	117	1.1	0.13	
Magnesium sulfate ($MgSO_4 \cdot 7H_2O$)	96.6	1.1	0.16	
Magnesium oxide (MgO)	508	1.5	0.10	
Bittern (Mg^{2+})	102	1.1	0.0046-0.19	

Table 6. Comparison of technologies for recovering/enriching nutrients from wastewater

Technology	**Potential spots**	**Advantages**	**Disadvantages**
Chemical precipitation	Liquid phase	✓ High efficiency ✓ High stability	✓ High chemical input
Adsorption	Liquid phase		✓ Further process such as desorption needed ✓ Specific requirement for adsorbents
Wet-chemical process	Sludge phase		✓ Downstream process needed
Thermochemical process	Sludge phase		✓ High energy input ✓ High chemical input
Biological process	Liquid phase	✓ Low environmental footprint	✓ Low stability ✓ Low applicability of recovered products containing foreign substances
FO process	Liquid phase	✓ Low energy input ✓ Low fouling potential ✓ Easy fouling clean	✓ Reconcentration of draw solute needed
MD process	Liquid phase	✓ Low operation pressure ✓ Renewable energy available for being used	✓ Organic accumulation ✓ Membrane wetting
ED process	Liquid phase	✓ High nutrient enrichment	✓ Low current efficiency ✓ High energy input
OMBR	Liquid phase	✓ Low membrane fouling potential ✓ Organic removal ✓ Low energy input ✓ Low salinity level	✓ Reconcentration of draw solute needed
BES	Liquid phase	✓ Low chemical input ✓ Possibility of neutral energy balance	✓ Formation of recovered products on the cathode surface
MPBR	Liquid phase	✓ Low chemical input ✓ Environmental-friendness	✓ Low stability ✓ Long time ✓ Light needed