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Chapter 15

Nutrient recovery from wastewater for circular economy

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ABSTRACT

In recent years, the focus of the wastewater management sector has shifted significantly from conventional treatment methods to resource and nutrient recovery techniques to promote a circular economy. The recovery of nutrients such as nitrogen and phosphorus from wastewater marks a sustainable approach to wastewater management and supports ecological and economic sustainability. This chapter includes a comprehensive overview of existing conventional technologies that are used to recover nutrients from different nutrient-rich wastewater generated from domestic, industrial, and agricultural sources as well as from anaerobic digestate. In addition, various advanced methods, such as chemical processes and biological technologies that are used to recover nutrients are also discussed. Furthermore, a few more unique applications of novel futuristic technologies that are in the budding stage or ready for piloting or commercialization are also included. Finally, future perspectives in terms of possible research directions and breakthroughs of a more economic and efficient alternative approach with minimal carbon footprints are also explored.

Keywords: nutrient recovery, phosphorus recovery, nitrogen recovery, wastewater, circular economy

15.1 INTRODUCTION

The advancement of science has facilitated economic and demographic expansion, which unfortunately leads to increased resource exploitation as well as environmental pollution. In this situation, it is necessary to embrace a paradigm shift in which the waste stream is viewed not only as means of eliminating contaminants to comply with environmental regulations but also as extractable resources. Circular economy (CE) denotes an economic model that focuses on the 3R's which are reducing, reusing materials, and recovery of 'waste' to manufacture new products. CE model can allow the recovery of resources such as nutrients, energy, water, and other materials from wastewater streams (Robles *et al.*, 2020). Nutrient (N and P) loading of freshwater systems is the major cause of eutrophication, methaemoglobinemia (blue baby syndrome) in infants and many other problems. Algal blooms could be caused by phosphorus at concentrations as low as 0.03 mg/L. Likewise, nitrogen levels higher than 60 mg N/L could cause severe human health effects (Rodhe, 1969). On the contrary, synthetic N and P are currently used in agriculture, and their production is carried out on an extensive scale globally. The conversion of atmospheric nitrogen into ammonia and nitrate using the Haber process consumes a substantial amount of energy resulting in global warming (Razon, 2014). Similarly, turning phosphorus-rich rocks into fertilizers is energy intensive (Cordell *et al.*, 2009; Craggs *et al.*, 1996). It is estimated that around 15% of phosphate fertilizer demand in the world can be fulfilled by recovering phosphates from wastewater treatment plants (WWTP) alone (Williams *et al.*, 2015).

Therefore, nutrient recovery is gaining increased attention due to both economic and environmental gains, such as improved treatment, reduced carbon footprints and the development of new natural capital in a safe manner. It also improves water quality, reduces sludge and unwanted precipitates, improves operation and performance at waste treatment facilities, and improves food security and social equity (Bradford-Hartke *et al.*, 2015). This chapter discusses the conventional technologies devoted to nitrogen (N) and phosphorus (P) recovery from wastewater and the extent of its contribution to the transition towards a CE-based development model. This chapter discusses various techniques, such as chemical, physical, and biological processes, as well as the challenges associated with N and P recovery. Other novel futuristic technologies that are in the early stages of development or commercialization are also highlighted. Finally, the future prospects of innovations and potential research directions are also investigated.

15.2 CONVENTIONAL PROCESS FOR N AND P RECOVERY

15.2.1 Chemical precipitation

Chemical precipitation of nutrients was investigated and it was found that mixing intensity, pH, and coagulant dosage have an effect on the nutrient recovery efficiency (Bratby, 2006). Various coagulants, synthetic organic polymers, and pre-hydrolysed metal salts, such as poly-aluminium chloride and poly iron chloride, are mostly used for the precipitation of phosphorus (Mehta *et al.*, 2015; Tchobanoglous *et al.*, 2003). The optimum pH depends upon the type of the coagulant. The addition of iron coagulant and calcium or magnesium salts was reported with 91.9% and 85% phosphorus removal (Barua *et al.*, 2019; Wang *et al.*, 2006). Similarly, nitrogen precipitation is observed as struvite along with phosphorus and magnesium as a nutrient source (Perera *et al.*, 2019).

Struvite ($MgNH_4PO_4{\cdot}6H_2O$) is a crystalline mineral composed of equimolar concentrations of magnesium (Mg), ammonium (NH_4), and phosphate (PO_4) and it is an efficient nutrient source for plant growth. Struvite precipitation from aerobically digested municipal wastewater was assessed and about 90% of total phosphate is recovered as struvite (Hallas *et al.*, 2019; Kataki *et al.*, 2016). Studies in the Netherlands reported that the main barriers to the implementation are the variations in the characteristics of struvite, the waste status of struvite, in addition to the high investment cost with uncertainty on return on investment for full-scale onsite plants (De Boer *et al.*, 2018). Also, the value of a single product, struvite, is too low to compete against the relatively low cost of mined P.

15.2.2 Air stripping

Air stripping is a desorption process in which wastewater and air are intensively brought in contact with each other, resulting in the release of the volatile compounds found in wastewater, such as ammonia, into the atmosphere. There are three types of stripping processes, namely, thermal alkali, hyper thermal alkali, and vacuum thermal alkali stripping, that are categorized based on the boiling temperature and applied pressure. Ammonium hydroxide is produced when water combines with ammonia. At pH of around 11, ammonium hydroxide ions are converted into ammonia gas based on two-film theory

$$NH_4^+ + OH^- + \text{air} \Rightarrow H_2O + NH_3(g) \tag{15.1}$$

In vacuum thermal alkali stripping, it can be coupled to a gas absorption column resulting in the production of ammonium sulphate crystals ($(NH_4)_2SO_4$) (Han *et al.*, 2022). Through thermal ammonia stripping, high ammonia concentrations can be reduced to levels below 100 mg/L in a single pass. Hyper thermal alkali (temperature >80°C) stripping can be coupled with struvite precipitation or adsorption for improving the recovery of ammonia.

15.2.3 Adsorption

Successful phosphate adsorption has been reported using modified activated carbon (AC) due to its intrinsic positive charge, high surface area, low cost, availability, and surface porosity. Natural porous adsorbents such as diatomite, clays, zeolite, and biochar are considered suitable for phosphate sorption due to their large specific surface area and low costs. Likewise, red mud, metal oxide/ hydroxide, bentonite, calcite, kaolinite and zeolite and zirconium sorbents are used for P recovery. *Ficus carica*, *Moringa oleifera*, and saw dust are some of the natural phosphorus adsorbents (Subha *et al.*, 2015). Modified zeolite and clinoptilolite can be used for N recovery (Almanassra *et al.*, 2021).

15.2.4 Ion exchange

Ion exchange (IEX) processes hold promise for recovering nutrients from municipal wastewater. Nutrients are recovered in the form of $(NH_4)_2SO_4$ and hydroxyapatite $Ca_5(PO_4)_3(OH)$ from spent regenerants, allowing regenerant reuse. According to Huang *et al.* (2020), compared to traditional WWTPs based on biological nitrogen removal, the whole life costs (WLC) of IEX combined with traditional activated sludge processes and IEX combined with anaerobic membrane were 17% and 27% lower over a 40-year period, respectively. In addition, 98 tonnes of $(NH_4)_2SO_4$ and 3.4 tonnes of $Ca_3(PO_4)_2$ could be recovered each year. The benefits of lower costs, reduction in greenhouse gas emissions, and nutrient recovery are also aligned with the CE module (Huang *et al.*, 2020).

15.2.5 Biological methods of nutrient recovery

Biological processes are utilized for the recovery of nutrients from wastewater due to its cost feasibility and environmental sustainability (Mantzavinos & Kalogerakis, 2005). Microalgae have been found to be a more effective biological process in the removal of nutrients such as nitrogen and phosphorous from a wide range of effluents (Christenson & Sims, 2011; Whitton *et al.*, 2015; Zhou *et al.*, 2012). Also, it generates a significant amount of biomass rich in proteins and lipids, whereas other biological treatments produce additional waste sludge (Chisti, 2013; Mantzavinos & Kalogerakis, 2005). It also minimizes the emission of CO_2, N_2 and greenhouse gases along with the production of biomass of up to 500 kT/year. In addition, microalgae-based treatments require less than half of the energy spent (<0.2 kWh/m^3) during the conventional treatments for nutrient removal (Nagarajan *et al.*, 2020). Microalgae also have the potential to be used as bio-fertilizer.

The two main types of microalgal cultivation are open and closed systems. Open systems or raceway ponds are preferred because they allow an adequate amount of sunlight to penetrate the effluent, are commercially available, and are inexpensive (Oswald & Golueke, 1960). However, its atmospheric exposure results in a temperature rise which leads to water loss (Cai *et al.*, 2013). Closed systems contain flat panel reactors, tubular or column photobioreactors and bag systems, mainly designed for improved light availability and gas exchange, reduced water loss by evaporation, and minimized contamination and biomass production. But comparatively, its maintenance is labour-intensive and expensive (Borowitzka, 1999).

The major challenges faced are extended hydraulic retention time (HRT) and the harvesting of grown microalgae (Matamoros *et al*., 2015). Longer generation time requires more HRT and the same can be overcome by co-culturing with bacteria, increasing the surface area, and settling velocity (Chevalier & de la Noüe, 1988; Manganaro *et al*., 2015). Due to its smaller size and negative charge, harvesting can be done by using less energy-intensive processes like flocculation and sedimentation (Cromar & Fallowfield, 1997; Udaiyappan *et al*., 2017). In addition, turbidity and effluent with high suspended solids will reduce the light penetration which in turn reduces the photosynthetic activity and microalgal productivity (Larsdotter, 2006; Zeng *et al*., 2022). This can be fixed by using flocculants and coagulants to pretreat effluents (Sher *et al*., 2013). Adding proper mixing and turbulence to the effluents also aids in light penetration (Kumar *et al*., 2015).

15.2.6 Electrochemical system

An electrochemical setup of magnesium anode and titanium cathode was used for electrochemical nutrient recovery from nutrient-rich wastewater at alkaline pH of 8.8. Leaching of Mg^{2+} ions from the anode and successful synthesis of struvite was reported along with the reaction mechanism (Cai *et al*., 2022). It was reported that over 90% phosphate removal with higher purity is possible in this technology at elevated pH levels (Bagastyo *et al*., 2022). For efficient precipitation of struvite at neutral pH in electrochemical method, surface-bound amelogenin peptide was used and a promising recovery of pure struvite was observed (Wu *et al*., 2022a, 2022b). Struvite precipitation was also evaluated in acidic wastewater in an electrochemical method using magnesium–aluminium alloy (AZ31) anode and a 4.5-fold increase in struvite recovery was reported (Kékedy-Nagy *et al*., 2020).

Advantages and disadvantages of various N and P recovery processes are compared in Table 15.1.

15.3 HYBRID TECHNOLOGY

15.3.1 Bio-electrochemical method

The integration of one or more nutrient recovery technologies has gained popularity, owing to increased efficiency and economic feasibility. In this method, wastewater treatment, energy in terms of electricity or biofuel recovery, and nutrient recovery are possible (Potter, 1911). A microbial fuel cell (MFC) is a two-chambered setup where wastewater treatment is possible in an anaerobic anodic chamber and the cathodic chamber is aerobic and oxygen acts as a terminal electron acceptor (Logan *et al*., 2006). In MFC, specific reactor orientation can be designed for anodic carbonaceous material oxidation and cathodic precipitation of the nutrient as struvite (Monetti *et al*., 2019; Neethu *et al*., 2018; Ye *et al*., 2019). The membrane systems, which include forward osmosis, membrane distillation, and electrodialysis process, are favourable for combining with MFCs while applying MFCs to recover nutrients from diluted wastewater (Mahmoud *et al*., 2022). Other methods such as capacitive deionization, metal organic frameworks, and microbial desalination cells are also employed in nutrient recovery (Nancharaiah *et al*., 2016).

15.3.2 Hybrid membrane–microbial fuel cells

These systems include bioelectro-Fenton-MFC, microbial desalination cell, MFC-electrosorption cell, microbial solar cell, microbial reverse-electrodialysis cell, plant-MFC, and constructed wetland-MFC. Although MFC-hybrid systems are more promising than standalone MFCs due to their capacity for reducing major obstacles, such as low power densities, high reactor construction and operating costs, further research is needed to overcome significant hurdles for practical deployment (Zhang *et al*., 2019).

15.3.3 Photobioreactor–membrane filtration

Membrane photobioreactors (MPBRs) not only produce highly concentrated biomass but also achieve considerable reduction of nutrient level, mainly due to the ability of MPBRs to enable

Table 15.1 Comparison of N and P recovery process.

Process	Nutrient Recovery	Advantages	Disadvantages
IEX	P	• Can achieve high-quality effluent 100× concentration.	• 100% desorption of nutrients cannot be achieved during media regeneration. • Leaching of other metal cations affects the purity of subsequent struvite precipitation. • Biofouling of resin. • Continuous resin requirement due to reduction of regeneration capacity over time. • Limited selectivity.
Struvite precipitation	P	• Minimum leaching. • Can be crystallized with lower impurities.	• Requires chemical addition and pH adjustment. • Cost of P removal increases with chemical requirement.
Chemical precipitation	P	• Can meet low P discharge limits. • Easy operation. • Can handle shock loadings.	• Primarily used more for P removal than recovery. • Requires chemical dosing. • Excess sludge generation and handling costs. • Heavy metal contamination.
Biological	P	• Economical • PAOs can accumulate P up to 20% of their dry biomass weight.	• Sensitive to influent water characteristics and operational parameters. • Operationally complex.
Algae harvesting	P	• Less land requirement • Can achieve P content up to 3.4% of dry biomass weight.	• Requires post-processing. • Pathogens and micropollutants are a concern. • Lack of information on potential effects of allelochemicals and/or cyanotoxins.
Electrochemical	P	• Economical. • Continuous cation dosing. • Can use pH shifting for direct P recovery.	• Co-precipitation of $CaCO_3$. • Energy requirement Is inversely proportional to wastewater conductivity.
IEX /Adsorption	N	• Can meet very low N discharge limits. • Operationally simple. • Can withstand shock loadings.	• Mainly used more for N removal than recovery. • Limited adsorption/ desorption capacity and resin life. • Adsorption capacity impaired by competing ions. • Requires a lot of chemicals.
Electrochemical	N	• N can be concentrated to reduce chemical and operational costs in post-recovery steps.	• Reaction time limited by anode pH. • N recovery requires stripping and absorption into an acid solution.
Bioelectrochemical	N	• Can generate energy. • Concentrate N in cathode compartment for post-recovery. • Eliminate chemical pH adjustment.	• Sensitive to pH, influent toxicity, and substrate loading. • N recovery requires stripping and absorption into an acid solution.
Struvite precipitation	N	• Lower evaporative losses.	• High operational costs due to chemical requirement.
Stripping and absorption	N	• Easy installation and simple operation. • Energy requirement is economical.	• Require pH adjustment. • Typically used for high strength wastewater. • Energy requirement for stripping is inversely proportional to influent NH_3 concentration.

Source: Modified from Perera *et al.* (2019).

independent control of HRT and solids retention time (SRT). Despite their advantage over conventional algal systems, the relative complexity derived from the operation and maintenance of the additional membrane separation process of MPBR systems is a key challenge to implementation (Luo *et al.*, 2018).

15.4 NUTRIENT RECOVERY FROM DIFFERENT WASTEWATERS

15.4.1 Urine

Although urine constitutes less than 1% volume of total wastewater, it adds up to 50%–80% of the nutrient load in WWTPs. However, urine could be a potential cheap substitute for chemical fertilizers. Direct application of urine as fertilizer has been discouraged due to various hygienic pitfalls, thus driving researchers to explore alternative nutrient recovery methods. Urine source separation with P recovery as struvite had lower life cycle environmental impacts than P removal during wastewater treatment combined with synthetic fertilizer production, even when accounting for the new infrastructure required for urine source separation (Wu *et al.*, 2022a, 2022b).

15.4.2 Anaerobic digestate

There is a focus on nutrient recovery technologies from anaerobic digestate (AnD) (Table 15.2). AnD is normally rich in NPK and also contains stabilized carbon, magnesium, calcium, zinc, manganese, sulphur, heavy metals, and so on (Table 15.3). The resultant digestate is widely applied as manure onto farmlands.

Substrates for anaerobic digestion process include food waste; agro residues; fish farm sludge; catering waste; waste activated sludge and vegetable waste; cattle manure; and cow dung and pig slurry (Kuusik *et al.*, 2017; Sheets *et al.*, 2015; Tampio *et al.*, 2016; Walsh *et al.*, 2018; Xia & Murphy, 2016).

15.4.3 Domestic wastewater

Domestic wastewater consists of blackwater (water used to flush toilet and human faeces), greywater (water from showers, laundries, dishwashers, and tubs), and yellow water (human urine). Lately, research has focused on recovering nutrients from domestic wastewater, due to the abundant presence of N and P in it. Various technologies adopted for nutrient recovery from domestic wastewater are summarized in Table 15.4.

Table 15.2 Digestate characteristics.

S. No.	Characteristics	Unit	Range
	pH	–	7.1–8.9
	Moisture	%	65.8–98.6
	Organic matter	% of total solids	12.3–81.5
	Carbon content	g/kg TS	300–452
	Nitrogen content	g/kg	3.5–157
	Ammoniacal nitrogen	g/kg	1.5–108
	Phosphorus content	g/kg	0.06–66
	Potassium content	g/kg	0.02–100
	Calcium	g/kg	3–10
	Sulphur	g/kg	6–10
	Magnesium	g/kg	10–52

Source: Modified from Selvaraj and Velvizhi (2021).

Table 15.3 Nutrient recovery technologies from anaerobic digestate.

Process	Performance Outcome	References
Ammonia stripping	93.3%–99.9% of ammonia recovery	Ukwuani and Tao (2016)
Ammonia stripping and struvite crystallization	Ammonia – 80%–90% and phosphorus – 90%–94% recovery	Hidalgo *et al.* (2016)
Membrane filtration	4.7–6.1 kg phosphorus/ton; 6–9.7 kg total nitrogen/ton	Gienau *et al.* (2018)
Membrane system	71.6% ammonia recovery	Rivera *et al.* (2021)
Electrodialysis + struvite precipitation	95.8%–100%,ammonia and 86.1%–94.4% phosphate	Wang *et al.* (2015)

Table 15.4 Nutrient recovery technologies from domestic wastewater.

Wastewater	Recovery Method	N Recovery (%)	P Recovery (%)	References
Domestic wastewater	Struvite precipitation	–	87	Mehta *et al.* (2015)
Municipal wastewater	Adsorption with natural adsorbents	100	93	Bhattacharya *et al.* (2018)
Semiconductor wastewater	Struvite precipitation	98	70	Kim *et al.* (2009)
Cola beverage	Struvite precipitation	–	97	Foletto *et al.* (2013)

Table 15.5 Nutrient recovery technologies from agricultural wastewater.

Wastewater	Process	Performance Outcome	References
Swine wastewater	Biofocculant prepared from anaerobic sludge	54.5% ammonia recovery	Guo *et al.* (2018)
Swine wastewater	Modified zeolite + biofloculant	85.8% ammonia recovery	Guo *et al.* (2018)
Aquaculture wastewater	Using a thermally treated gastropod shell	99% P recovery	Oladoja *et al.* (2015)
Digested swine wastewater	Ammonia stripping with struvite precipitation	88.03% Ammonia and 96.07% total phosphorus recovery	Cao *et al.* (2019)

15.4.4 Agriculture

Among farm-based wastes, nutrients have been recovered successfully from dairy manure, poultry manure, swine manure, cattle urine, aquaculture wastewater, abattoir wastewater, and so on (Kataki *et al.*, 2016). Various technologies adopted for nutrient recovery from agriculture wastewater is summarized in Table 15.5.

15.5 ECONOMIC VIABILITY OF THE NUTRIENT RECOVERY PROCESS

In 1000 m^3 of domestic wastewater, chemical precipitation yields 33.8 kg struvite, while micro-algae results in 299.1 kg (dry powder). Energy consumption was lowest for the fuel cells at 216.2 kWh/1000 m^3, while microalgae used the highest energy at 943.3 kWh/1000 m^3. Cost-saving analysis showed that microalgae as a nutrient recovery choice was the most economic than the rest (Gowd *et al.*, 2022). Only a few industries, such as Ostara, Colsen Water & Environment and Algalwheel have implemented pilot systems on nutrient recovery across the world. In a few cases, nutrient recovery can reduce the maintenance costs by generating revenue (Egle *et al.*, 2016; Van der Hoek *et al.*, 2016). In Europe, the cost of phosphate recovery was economical (€2–3 (≈ US$2.22–3.33)/kg·P as compared to phosphate removal (Ashley *et al.*, 2009). Additionally, effluent quality has a significant impact (De Vrieze *et al.*, 2019; Etter *et al.*, 2011; Sánchez, 2020; Ye *et al.*, 2020). However, in many cases, the commercial viability of the product remains a challenge.

On a large scale, biological phosphorus removal combined with chemical and electrochemical struvite precipitation and chemical precipitation alone can be recommended for centralized plants. Whereas for onsite and packaged treatment plants, electrochemical and chemical precipitation, and IEX may be adapted. For nitrogen recovery, struvite precipitation and acid absorption following separation by gas stripping or gas permeable membrane have an edge over other methods. Electrochemical precipitation of struvite and calcium phosphate is preferred to minimize the chemical addition (Morales *et al.*, 2013; Perera *et al.*, 2019; Wei *et al.*, 2018).

15.6 CHALLENGES AND FUTURE PERSPECTIVES

The need for nutrient recovery is urgent due to the expensive process of ammonium production and the quick depletion of phosphate-based rocks (Sartorius *et al.*, 2012; Ye *et al.*, 2018). But the main problems are contamination, high operational costs, low value of end products, and end-user perception of recovered nutrients made from waste (Verstraete *et al.*, 2016). To overcome technology bottlenecks, successful business models are needed to transform economic returns into commercial successes, and policy and education strategies must be implemented to make nutrient recovery socially acceptable (Ye *et al.*, 2020).

15.7 SUMMARY

In wastewater treatment, nutrient recovery is crucial for reducing pollution and environmental harm and for improving sustainability. The selection of nutrient recovery technology plays an important role. Struvite and microalgae are the most frequently recovered products that are highly recommended as an alternative to fertilizers. But compared to commercially available fertilizers, the recovered nutrient-rich product is still expensive. In future, even if the economic returns are insufficient, considering the sustainable development goals (SDGs) and its environmental benefits and discharge norms stipulated by regulators, nutrient recovery from wastewater streams will become mandatory.

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