# Bio-membrane based integrated systems for nitrogen recovery in wastewater treatment: Current applications and future perspectives

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**Abstract**

Nitrogen removal is crucial in wastewater treatment process as excessive nitrogen content could result in eutrophication and degradation of aquatic ecosystems. Moreover, to satisfy the fast-growing need of fertilizers due to an increase in human population, recovering nitrogen from wastewater is of the most sustainable approach. Currently, the membrane technique integrated with biological processes namely bio-membrane based integrated system (BMIS) is a promising technology for recovering nitrogen from wastewater, including osmotic membrane bioreactors, bioelectrochemical systems and membrane photobioreactors. In this review study, the nitrogen recovery in different BMHSs, the role of operational parameters and the nitrogen recovery mechanism were discussed. Apart from this, the implementation of nitrogen recovery at pilot- and full-scale was summarized. Perspectives on the major challenges and recommendations of the BMIS for the nitrogen recovery in wastewater treatment were proposed, in which the integrated technologies and more scale-up studies regarding nitrogen recovery by the BMISs were also highlighted and recommended.

**Keywords:** Nitrogen recovery; Ammonium recovery; Bio-membrane based integrated systems; Wastewater

## 1. Introduction

Nitrogen (N) is one of the most important nutrients in the biosphere due to its important role in biological synthesis, including nucleic acids, proteins and other cell constituents (Madigan et al., 2012). For nearly a century, N has played an important role in the synthesis of fertilizers for food production, especially given its indispensable role in sustaining agricultural yields, which is fixed when adopting the full-scale Haber-Bosch process. The Haber-Bosch process when implemented in industry is energy-intensive, in which 35–50 MJ/kg·N or 28–30 GJ/t are required to produce reactive nitrogen in agriculture (Kirova-Yordanova, 2004; Yan et al., 2018). However, 1.6 tons of carbon dioxide are emitted during the industrial nitrogen production process (Beckinghausen et al., 2020). Moreover, 949 $m^3$ of natural gas is needed to generate 1 ton of anhydrous $NH_3$ fertilizer, which also occupies 87% of total energy requirements in the production of fertilizer (Beckinghausen et al., 2020). In their study, Swaminathan and Sukalac (2004) commented that 1–2% of global energy is being allocated to produce nitrogen fertilizers. Currently, the world's booming human population and activity have challenged the sustainable supply of nitrogen-based fertilizers (Beckinghausen et al., 2020). Therefore, these increasing fertilizer demands coupled with environmental costs suggest a need for alternative methods for the production of agricultural nitrogen.

It should be noted that most nitrogen used in agriculture is lost to the aquatic environment and the atmosphere, and only 17% is consumed by humans through crops or livestock. For this reason, large fluxes of reactive nitrogen which ultimately end up in water bodies, results in various environmental issues. These include, for example, atmospherically active gases that contribute to global warming, groundwater contamination, toxic algae blooms and eutrophication. Overall, the natural nitrogen cycle has been significantly altered by anthropogenic activity, so it is of great importance to mitigate these deleterious impacts. Full-scale applications of nitrogen removal have been widely studied using advanced wastewater treatments in order to prevent eutrophication through various techniques, including nitrification-denitrification, aerobic nitrification-denitrification, partial nitritation and anaerobic ammonium oxidation, otherwise known as Anammox (Ali and Okabe, 2015; Du et al., 2014; Mukarunyana et al., 2018; Wang et al., 2021). By applying these bio-techniques, reactive nitrogen can be removed through microbial consumption and released into the atmosphere through the conversion of ammonium to gaseous nitrogen. However, more than 50% of total energy requirements are allocated to wastewater treatments for the removal of organics and nitrogen (Nowak, 2003). At the same time, greenhouse gases and nitrous oxide ($N_2O$) can be generated during the nitrogen removal processes, which contributes to global warming, especially given a carbon footprint basis under specific circumstances (Law et al., 2012). More importantly, the exact causes, pathways and mechanisms of $N_2O$ production during the nitrogen removal process are not fully understood. Due to the challenges in the nitrogen removal process on an industrial-scale, research has shifted the balance in favor of nitrogen recovery processes in wastewater treatment plants. Besides, reusing nitrogen from wastewater could offset the energy consumption for industrial nitrogen production.

The main aim of nitrogen recovery is to exploit the ammonia and/or ammonium from wastewater to directly/indirectly produce fertilizer, cultivate microalgae for the subsequent use in the biogas/biofuels industry and serve as food sources for animals/humans (Ekasari and Maryam, 2012; Lee et al., 2020a; Li et al., 2021; Matassa et al., 2015; Thorin et al., 2018; Walsh et al., 2012; Wuang et al., 2016). It is not wise to blindly accept all the final-end products achieved in the nitrogen recovery process because such products may potentially contain a large amount of metal and other contaminants. On this basis, it is necessary to separate foreign substances from nitrogen before implementing the recovery process, which has the potential to obtain a viable fertilizer supplement that is consistent and safe to use. In addition to this, the nitrogen content in wastewater is often diluted despite the high volume of wastewater, so a step to achieve concentration of this resource is essential to help reduce energy consumption and increase economic feasibility. Given the membrane technology being implemented with minimal energy input and no additional chemicals needed, its use would be particularly beneficial in the recovery of nitrogen, including the function of separation and enrichment. Simultaneously, the bioprocess should also be incorporated into the nitrogen recovery processes and treatments. This is not only because the bioprocess can remove organics and some metals to further reduce the risk of membrane fouling, but also transform organic nitrogen into ammonia nitrogen to enrich nitrogen.

In this review, we outlined the recent state-of-the-art developments of bio-membrane based integrated systems (BMISs) for nitrogen recovery from the liquid phase such as reject water and sludge dewatering filtrate at wastewater treatment, considering the recent development in integrated technologies, membrane applications, operational schemes and system configurations. This review also highlighted the current applications of nitrogen at full-scale, which is rarely reported in other similar reviews. Considering the merits and demerits of the existing technologies, we provided an outlook on pressing issues and future directions of the recovery of nitrogen. We also aim to promote more full-scale applications and inspire further relevant research for nitrogen recovery for sustainable development.

## 2. Current applications of bio-membrane based integrated systems for nitrogen recovery in wastewater treatment

### 2.1. Osmotic membrane bioreactors

Osmotic membrane bioreactors (OMBRs) are formed by integrating bio-processes with forward osmosis (FO) membrane (Cornelissen et al., 2008; Viet et al., 2019). Compared to traditional MBRs that utilize microfiltration (MF) or ultrafiltration (UF), OMBRs have a number of salient advantages, including higher water quality, capable of reversible foulant, lower membrane fouling potential and energy requirements (Ab Hamid et al., 2020; Wang et al., 2016b; Xue et al., 2016; Yu et al., 2017). The possible reason for this is that FO operates at ambient temperature and very low or no hydraulic pressure (Coday et al., 2014). More specifically, the use of osmotic pressure in the OMBR enhances the removal of contaminants and makes washing away the fouling layer easier, which reduces the costs of cleaning and increases permeate flux (Viet et al., 2019).

In the OMBRs, the FO membrane can reject ammonium, leading to its accumulation in the feed side (Xie et al., 2014). Thus, OMBR has recently been proposed for the recovery of ammonium in wastewater treatments. In the study by Qiu and Ting (2014), over 97% of ammonium ions in the influent was found to be enriched within the bioreactor as well as phosphate and magnesium ions despite partial ammonium consumed for microbial growth. This offers approximately 80% ammonium which can be recovered by subsequent struvite precipitation through the adjustment of the pH between 8.0–9.5. There was no requirement for magnesium input in the study because: firstly, $Mg^{2+}$ ions can be rejected and then enriched in the bioreactor; and secondly, $MgCl_2$ was served as the draw solution, thus providing $Mg^{2+}$ ions for struvite formation due to the reverse draw flux of the FO process.

Apart from this, the UF or MF membrane could also be applied in the feed side of OMBRs to extract the ammonium rejected using the FO membrane to the penetrant, which makes the small concentration of contaminants in the penetrant (Holloway et al., 2015; Qiu et al., 2015) (Fig. 1).

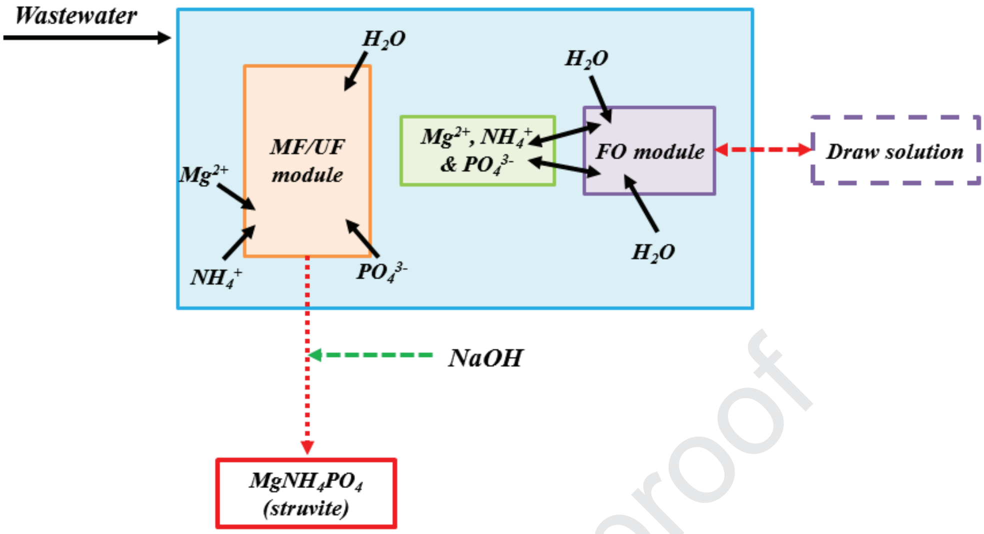


**Figure 1.** Schematic of the osmotic membrane bioreactor (OMBR) integrated system for ammonium recovery

In this scenario the UF/MF membrane functions parallel with the FO membrane, which improves the recovery system's technical feasibility as well as economic sustainability. Furthermore, adding a fixed bed biofilm to the feed side of OMBR could achieve enhanced removal of suspended solids and thereby reduce the risk of the FO membrane fouling (Qiu et al., 2016). The integration of reverse osmosis (RO)/ membrane distillation (MD) membrane with OMBRs has great potential to recover water from the draw solution, making the draw solute reusable and enhancing the applicability of the OMBR for the ammonium recovery (Chang et al., 2017; Luo et al., 2016). Table 1 summarizes the factors affecting the OMBR performance regarding the nitrogen recovery from waste streams.

**Table 1** Factors affecting the nitrogen recovery by OMBRs

| Parameters | Summary | Reference |
|---|---|---|
| Membrane type | ✓ The FO membrane with smaller membrane thickness and higher density active layer could more effectively accumulate the ammonium ions. | Yan et al. (2018) |
| pH value | ✓ The solution pH can determine the ammonium species and high pH adversely affects the ammonium recovery. | |
| Sludge retention time (SRT) | ✓ The optimal SRT of OMBR is different and dependent on operation conditions and membrane property.<br>✓ Higher SRT facilitates the mitigation of membrane fouling in OMBR. | Viet et al. (2019)<br>Yang et al. (2019) |
| Temperature | ✓ High temperature may impede reverse solute flux of the magnesium ions and thereby impede the ammonium recovery through struvite precipitation. | Feng et al. (2018b) |



**2.2 Bioelectrochemical system**

The bioelectrochemical system (BES) typically has two chambers which are separated by a cation-exchange membrane (CEM). In BES, chemical energy is converted to electrical energy through catalyzed reactions at the anode chamber by electrochemically active bacteria (Arredondo et al., 2015; Feng et al., 2018a; Sun et al., 2019). More specifically, organics are anaerobically oxidized by heterotrophic microorganisms, donating electrons transferred to the anode. Then, the electrons would be transported through an external resistor to the cathode and subsequently reduced by electron acceptors such as air, which completes the electrical_circuit. Microbial fuel cells (MFC) and microbial electrolysis cells (MEC) are the two primary types of BES and the favorability of the thermodynamic reaction is the main difference between them. MFCs use a thermodynamically favorable reaction in the anode chamber, so electrical energy could be recovered while reducing oxygen. Moreover, the cathode reaction in MECs is thermodynamically unfavorable, which requires extra electric energy being required to operate the system (Wu and Modin, 2013). The recovery of energy in the form of hydrogen or electricity production improves the market potential while applying BES to recover ammonium. The electricity generated in the BES could alleviate the fouling of the CEM (Wang et al., 2013) despite the fact that membrane fouling is still a problem (Ge et al., 2015).

To maintain neutral electrical charge of a BES, cations in the anolyte migrate across the CEM to the catholyte, which is responsible for the pH gradient and membrane potential (Kuntke et al., 2018; Rahimi et al., 2020). As a result of this process, the zones localized the anode and cathode provide acid and alkaline environments, respectively (Mohan et al., 2014). Besides, the reduction of oxygen in the cathode compartment generates hydroxyl ions. It is, therefore, favorable for ammonia/ammonium to be recovered by stripping and/or chemical precipitation (Cheng et al., 2013). Ammonium enriched in the cathode chamber arrives there due to being transported by the CEM from the anolyte to the catholyte. The electrical_field drives the ammonia/ammonium migration across the CEM, which is only affected by the current density. In contrast, ammonium diffusion caused by the ammonium concentration gradient between the anolyte and catholyte would reach an equilibrium. Even though the ammonium transport is beneficial for N recovery, concentration gradients of cations other than $H^+$ and pH gradients could result in possible loss of CEM and thereby influence the BES performance (Sleutels et al., 2017).

Kuntke et al. (2012) discovered the ammonium recovery from urine through air stripping in a single-chamber MFC at a rate of 3.29 g·N/d·m$^2$ (*vs.* membrane surface area) at a current density of 0.50 $A/m^2$ (*vs.* membrane surface area). The volatile ammonia could be adsorbed by an acid solution for further use as raw materials in industry and fertilizers in agriculture. This research has achieved a positive energy balance of 3.46 kJ·g/N, which means more energy was produced than required for the recovery of ammonium. Furthermore ammonium recovery can also be done with simultaneous phosphate recovery via struvite precipitation (Arredondo et al., 2015) (Fig. 2).

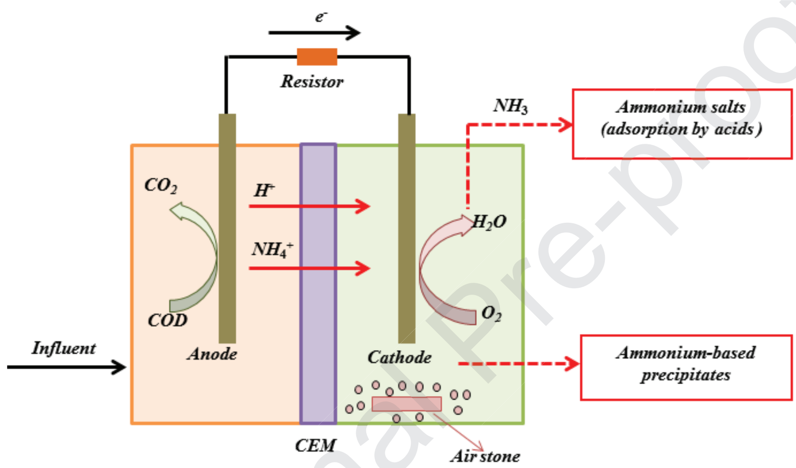


**Figure 2.** Schematic of the BES for ammonium recovery (adapted from Ngo et al., 2020)

Wu and Modin (2013) found the changes in the catholyte pH were proportional to the current of the BES, but the shift of ammonium to ammonia required additional power being supplied. The overall energy consumption in the BES was about half the energy needed for ammonia production through the industrial Haber-Bosch process. Ye et al. (2019b) proposed a double-chamber microbial fuel cell (MFC) to recover ammonium from domestic wastewater. In their study, struvite formed in the cathode chamber and ammonium was thus successfully recycled.

Many other studies have also confirmed the ammonium recovery via chemical precipitation in BES (Almatouq and Babatunde, 2018; Hirooka and Ichihashi, 2013; Ichihashi and Hirooka, 2012; Santoro et al., 2013; Wang et al., 2019). In a scale-up MEC (0.5 $m^2$), 59 ± 31% of total ammonia-nitrogen was recovered in the form of ammonium sulphate solution while treating urine for 6 months with an applied voltage of 0.5 V (Zamora et al., 2017). The ammonium recovery in the system required an energy input of 4.9 ± 1.0 MJ kg/N, which is lower than the energy cost of fixation using the Haber-Bosch method, i.e. approximately 45 MJ kg/N (Maurer et al., 2003).

In more recent years, the BES has been modified and developed to improve the recovery of nitrogen, such as submersible microbial desalination cell (SMDC) (Chen et al., 2015; Wu and Modin, 2013; Zhang and Angelidaki, 2015). Zhang and Angelidaki (2015) placed the MDC in an anaerobic digestion process to recover ammonium by hydrolysis, in which 88% of ammonium was recovered from the reactor (2400 to 280 mg·N/L). No extra power supply was needed in the system except for the air supply. The factors influencing the nitrogen recovery efficiency in the BES are shown in Table 2.

**Table 2** Factors affecting the nitrogen recovery in BESs

| **Parameters** | **Summary** | **Reference** |
|---|---|---|
| Nitrogen loading rate | ✓ Increasing nitrogen loading rate may compromise the nitrogen recovery due to its negative effects on cation/electron transfer.<br>✓ The optimum recovery rate is different for each study. | Ye et al. (2019a)<br>Merino-Jimenez et al. (2017)<br>Mahmoudi et al. (2020) |
| Current density | ✓ Ammonia recovery is tightly coupled to current, and, therefore, systems with applied energy show higher ammonia recovery. | Kuntke et al. (2018) |
| pH value | ✓ The pH values affect the species of ammonium. | |
| Cathode materials | ✓ Cathode electrode can be classified into abiotic electrode and biological electrode.<br>✓ Carbon and graphite are the most popular materials for bio-cathodes and bio-anodes, respectively, which is attributed to their low costs and being suitable for growing electrochemically active biofilms.<br>✓ Biological electrodes are promising to be used in the BES because they are inexpensive and also possess sustainable properties. | Rozendal et al. (2008)<br>Clauwaert et al. (2007b)<br>Gregory et al. (2004)<br>Clauwaert et al. (2007a) |

### 2.3. Membrane photobioreactor

Phototrophic systems can utilize energy stored in the sunlight to curtail the amount of nitrogen in wastewater treatment. Microalgae is one primary class of phototrophic organisms in freshwater and marine systems that grow relatively quickly and can adapt to harsh conditions. Photobioreactor (PBR) is used to cultivate microalgae in current biological wastewater treatments to perform oxygenic photosynthesis (Delgadillo-Mirquez et al., 2016; Lu et al., 2021; Sood et al., 2015), followed by organic wastes being decomposed into simple inorganic nutrients through using bacterial populations. It can grow photo-autotrophically with only water as the electron donor (oxygenic photosynthesis) in constant and diurnal light (Gardner-Dale et al., 2017; Madigan et al., 2012; Sturm and Lamer, 2011; Whitton et al., 2016). Solid separation, however, is the biggest challenge in the PBR (Cuellar-Bermudez et al., 2017; Gonçalves et al., 2017) since the settlement capacity of most microalgae is too poor to make solids separation difficult (Barros et al., 2015; Cai et al., 2013). The combination of membrane technology with PBR (i.e., membrane photobioreactor, MPBR) would be a solution to improve the accumulation and growth of biomass within the bioreactor due to decoupling SRT from HRT (Lee et al., 2020b; Zhang et al., 2020). Thus, MPBRs have more compact reactor footprints and less energy-intensive solids separation when compared to conventional PBRs or ponds (Abouhend et al., 2018). Compared to conventional wastewater treatment such as activated sludge process, the MPBR is more environmentally friendly.

In MPBR, the fast growth of microalgae requires a substantial amount of phosphorus and nitrogen, which can be effectively provided from wastewaters (Fig. 3). Besides, the biomass and bioactivity of microalgae in MPBR could be maintained by controlling operational parameters such as temperature and aeration, the frequency of light, power, spectral composition and the source of nutrients and water (Baral et al., 2020; Liao et al., 2018).

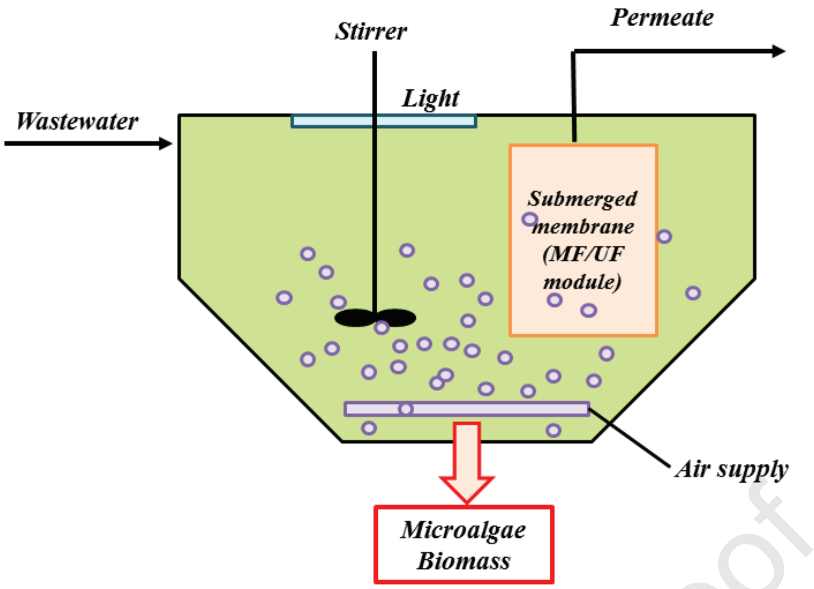


**Figure 3.** Schematic diagram of microalgae membrane photobioreactor (adapted from Kumar et al., 2020).

Ammonia can be assimilated with microalgae for conversion into biomass rather than being released into the atmosphere as the $N_2$ gas, which does not require additional organic carbon. In this scenario, nitrite and nitrate in aquatic environments should be reduced to ammonium only before their assimilation and transportation into microalgae (Rahimi et al., 2020). The possible reason for this is that nitrite and nitrate are relatively stable inorganic forms of nitrogen in waters. A two-step process catalyzed using microalgae is used for reducing nitrite and nitrate, as shown in Eqs. (1) and (2) (Barsanti and Gualtieri, 2014). Thus, ammonification and assimilatory reduction of nitrite to ammonium determine the nitrogen recovery capacity of microalgae:

$$NO_3^- + 2H^+ + 2e^- \rightarrow NO_2^- + H_2O \quad (1)$$

$$NO_2^- + 8H^+ + 6e^- \rightarrow NH_4^+ + 2H_2O \quad (2)$$

At full-scale wastewater treatment, microalgae are cultivated through the suspended- and immobilized-cell systems. The nitrogen to phosphorus molar (N/P) ratio affects the production of microalgal biomass and Choi and Lee (2015) suggested that the N/P ratio should be in the 5-30 range, making the nitrogen and phosphorus sufficient for such microalgae growth. Various wastewater sources such as dairy manure, swine and municipal wastewater are suitable for growth of microalgae with the appropriate N/P molar ratios (Gonçalves et al., 2017). Nitrogen taken up by microalgal biomass is highly promising in being converted for value-adding products such as for the production of pharmaceuticals, animal feed, food, biofuels, fertilizers and various high-valued bioproducts without generating any harmful by-products (Jankowska et al., 2017; Ruiz-Martinez et al., 2012; Xin et al., 2010). To enhance the microalgae growth for nitrogen recovery, it is important to control several principle parameters such as temperature and solution pH (Table 3).

330 **Table 3** Factors affecting the nitrogen recovery by microalgae

| Parameters | Summary | Reference |
|---|---|---|
| Temperature | ✓ High temperature leads to ammonium volatilization, thus impeding the ammonium uptake by microalgae.<br>✓ Temperature affects the growth of microalgae and solubility of $CO_2$, in which high temperature results in the emission of volatile $CO_2$.<br>✓ The optimal temperature for microalgae growth is dependent on the microbial community.<br>✓ An appropriate increase in temperature improves metabolic activity as well as microalgal growth.<br>✓ Decreasing temperature adversely affects the nitrate uptake by microalgae while the ammonium recovery is not affected. | Gonçalves et al. (2017)<br>Xin et al. (2011)<br>Reay et al. (1999) |
| pH value | ✓ The alkaline environment favors the ammonium conversion to volatile ammonia and thereby reduces the amount of ammonium uptake by microalgae.<br>✓ The pH value affects the hydrolysis of $CO_2$, where conversion to bicarbonate would occur with increasing pH; simultaneously, $CO_2$ enrichment and buffering can prevent the harmful effect of pH increase on growth and nitrogen recovery. | Gonçalves et al. (2017)<br>Taziki et al. (2015) |
| Light | ✓ Light, both in quality (wavelength) and quantity can affect the microalgae growth and nitrogen removal efficiency.<br>✓ Dark condition is economical for applying microalgae at wastewater treatment, so microalgae that can adapt to such dark condition is suggested to effectively take up nitrogen. | Ogbonna et al. (2000) |

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## 3. Case studies

Although nitrogen recovery using BMISs is preferred over nitrogen removal in current wastewater treatment, there are still many challenges facing nitrogen recovery processes (Ye et al., 2018). Most current studies on this are conducted in lab-scale experiments, with only a few being of pilot- or full-scale (Table 4). For instance, Viruela et al. (2018) utilized a 2.2-$m^3$-MPBR in parallel to recover ammonium from an AnMBR effluent at full-scale sewage treatment with two commercial-scale hollow-fiber UF membrane modules applied (PURON® Koch Membrane Systems, 0.03 μm pore size). In this scenario, up to 7.68 mg·N/L·d could be recovered with the simultaneous production of 66 mg·VSS/L·d. It was clear that the integrated AnMBR and MPBR system consumed less energy and the environmental footprints of the wastewater treatment was smaller. Overall, this combination improves the recovery system's sustainability and feasibility in terms of technical and economic aspects.

346 **Table 4** Pilot- and full-scale application of nitrogen recovery through BMISs

| **Wastewater source** | **Configuration** | **Capacity** | **Efficiency** | **Reference** |
|---|---|---|---|---|
| Anaerobically digested dairy farm sludge from an organic dairy farm located in North Wales | MBR | Two 100 L vessels with cross-flow microfiltration MF (0.20 µm pore size and 0.22 $m^2$ membrane area) | 68.9% of $NH_3$-N recovered | Gerardo et al. (2013) |
| Anaerobically treated sewage from Carraixet wastewater treatment plant in Spain | MPBR | Two treatment lines and each line has two 0.62 $m^3$ and hollow-fibre ultrafiltration membrane unit (, 0.03 µm pore size, 31 $m^2$ total filtering area). | Nutrient recovery rate at 7.68 mg·N/L·d | Viruela et al. (2018) |
| Effluent from a pilot-scale AnMBR located at Valle de Guerra (La Laguna, Canary Islands, Spain) | MPBR | A tubular photobioreactor of 32 L and a membrane tank of 9 L equipped with PVDF ultrafiltration hollow-fibres with 0.04 µm rated pore diameter | 39% of nitrogen recovered | González et al. (2017) |
| Effluent from an AnMBR plant fed by the primary settler effluent of the Carraixet wastewater treatment plant in Spain | MPBR | A PBR working volume of 230 L and membrane tank has a total working volume of 14 L and a filtration area of 3.4 $m^2$ | Nitrogen recovery rate at 19.7 ± 3.3 mg·N/L·d | González-Camejo et al. (2020) |
| Wastewater derived from red meat processing facilities in | AnMBR | 200 L stainless steel reactor and a 0.9 $m^2$ submerged hollow fibre membrane | 90% of ammonium recovered as $NH_3$ | Jensen (2015) |

| | | | | |
|---|---|---|---|---|
| Queensland, Australia | | | | |
| Wastewater from Swiss municipal wastewater treatment plants | MEC | a shared/common anolyte chamber of 168 L and a stack of 32 MEC units with cathodes of 40 mL each. | Being recovered as struvite | Blatter et al. (2020) |
| pig slurry collected from the slurry pits of a swine farm located at León (Spain). | MEC | 8/16 L per chamber. | Accumulation in catholyte 15.3 g·N/ d·$m^2$ and recovered by struvite | San-Martín et al. (2019) |

## 4. Future Perspectives

It is important to eliminate nitrogen from wastewater as high nitrogen concentrations pose serious risks to the environment. Recently, nitrogen recovery has been proved to possess higher market value and application potential. Therefore, the recovery of nitrogen has been of great concern in wastewater management. To date, the BMISs have become promising technology for nitrogen recovery. The possible points to consider in future research for the nitrogen recovery via BMISs are as follows:

1) Membrane fouling is still a big challenge existing in the BMIS for the recovery of nitrogen, which could decrease the filtration efficiency as well as the lifetime of the membrane. Due to the unique characteristics of microalgae, microalgal environment may aggravate membrane fouling potential compared to the biological sludge environment (Xu et al., 2014). Efficient cleaning strategies have been developed to mitigate the membrane fouling. For example, the fouling in OMBRs could be mitigated by optimization of operating parameters, decreasing salinity in mixed liquor and physical and chemical cleaning (Wang et al., 2016a). However, the management of membrane fouling is expensive and requires a lot of energy and chemicals being used. Factors affecting membrane fouling include membrane properties, sludge characteristics and operational conditions (Song et al., 2018). Therefore, an understanding of membrane fouling including its effects and characteristics is necessary. More significantly, the further development of using membrane is urgent in the mitigation of membrane fouling.

2) The nitrogen recovery process should consider the final product. Fig. 4 illustrates the various end products obtained through nitrogen recovery techniques. Furthermore, research should consider the actual market for these fertilizer products

where there is potential to establish better relationships between farmers and local wastewater treatment plants, especially given the smaller scale of the recovery system as compares to the global mineral fertilizer industry.

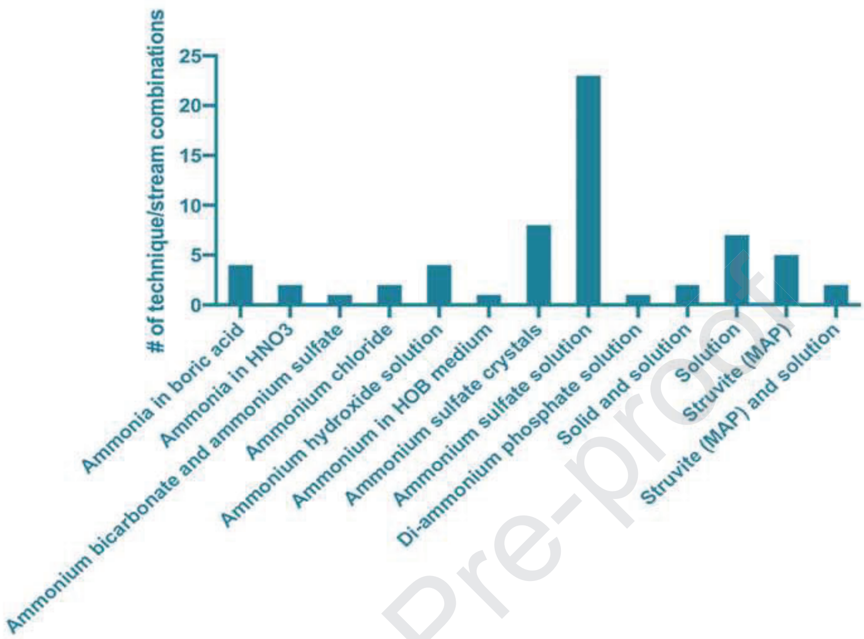


**Figure 4.** Final products achieved in the nitrogen recovery process (adapted from Beckinghausen et al., 2020)

3) In the BMIS for the recovery of nitrogen, the uncertainty of microbial activity needs more attention, such as substrate consumption via competing metabolic processes, unwanted biomass growth and incomplete biodegradation of substrates, which can hinder the system's performance (Pandey et al., 2016). Therefore, economic analysis may be the best solution to determine the most appropriate techniques for nitrogen recovery using different techniques at different locations, especially given the fact there is not one single answer to the question of nitrogen recovery (Ahmed et al., 2019). Apart from this, it is important to avoid or reduce the occurrence potential of nitrification, denitrification and other biological nitrogen removal process to maximize the recovery of nitrogen.

4) Future research should consider the pilot-scale and even full-scale application of BMISs while applying them in treating real nitrogen-rich waste streams. This is despite the fact that scaling-up the BES reactor volume from lab-scale reactors to larger volumes with less internal resistance is still a challenge.

5) More optimization studies of BMISs for the nitrogen recovery are needed. These include, for instance: the effects of assembling communities; electrode materials; fluctuating nutrient levels; internal resistance and reactor configuration. They are all necessary to be understood while applying BES to recover nitrogen. Moreover, the ammonium ion enrichment and transport for membrane processes, overcoming process upsets from these contaminants and competing ions need more research efforts in the future (Nancharaiah et al., 2016).

6) A combination of technologies will be necessary to minimize energy consumption and maximize nitrogen recovery efficiencies (Yan et al., 2018; Ye et al., 2018). In particular, the integration of BES and FO-based system should be given priority due to their low energy input and membrane fouling (Ye et al., 2020). For example, Qin et al. (2016) utilized the BES-FO integrated system to recover ammonium while treating landfill leachate. In this scenario, 65.7% of ammonium could be recovered simultaneously with a 51% water recovery.

7) A conflict between energy recovery and ammonium recovery does exist with BES (Kelly and He, 2014). High current density indeed enhances the pH elevation of catholyte as well as the subsequent ammonium recovery, but the energy recovery is seriously affected. Therefore, further research should consider developing the BES configuration if it is expected to have simultaneous and effective recovery of ammonium and energy. Multiple BES modules constitute a choice because the recovery of ammonium and energy could be obtained in separate units (Zhang et al.,

2013).

## 5. Conclusion

Research has begun to shift its focus to nitrogen recovery rather than removing nitrogen from waste streams. In the context of treatment plants with low nutrient limits, the nitrogen enrichment applying membrane technology is more desirable for further recovery. Applications of the BMIS for nitrogen recovery for wastewater were successfully reviewed in this work. Key knowledge gaps that need future research efforts were found to be: (1) in-depth mechanistic insights on the membrane fouling and its effective solution in the recovery system; (2) selection of appropriate final products; (3) more comprehensive understanding of microbial activity; (4) optimization of these nitrogen recovery techniques from lab-scale to pilot/full-scale; (5) more studies on the hybridization of the BMIS for nitrogen recovery and (6) cost-efficiency evaluation.

Acknowledgement

This research was supported by 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), Republic of Korea (No. 20183020141270 and No. 20194110300040).

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