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Review Paper

Modern Filtration Technologies for Nutrient Removal from Domestic Wastewaters: A Review

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Abstract

Nitrogen and phosphorus are essential for the growth and vitality of living organisms; hence they are called nutrients. However, the discharge of nutrient-rich waste streams into aquatic ecosystems leads to eutrophication. Therefore, nutrient removal from wastewater is critical to meet strict nutrient discharge standards. In general, the management of water and wastewater resources is essential to achieve sustainable development. Today, with the progress of urbanization, the necessity to remove nutrients from domestic wastewater that threaten human health is strongly felt. Therefore, it is necessary to develop current methods in addition to using previous methods in nutrient removal to be economically viable and also to increase the efficiency of the system. Due to the presence of nutrients such as nitrogen and phosphorus, domestic wastewater causes the rapid growth of all kinds of algae after being discharged into the water and finally ends in the phenomenon of enrichment. As a result, it is necessary to reduce the amount of phosphorus and nitrogen as much as possible before discharging the wastewater into water sources. Therefore, in this study, a new perspective of modern filtration technologies in the removal of phosphorus and nitrogen is given. It is necessary to explain that most of the following methods are relatively new methods that are converted into methods with higher efficiency and lower costs for domestic wastewater treatment by combining or modifying the main process.

Introduction

The global water consumption has doubled in the recent decades (Van Vliet et al., 2017). Currently, humanity has endangered by water-related issues, which are increasing due to population growth, rapid urbanization and the growing crisis of climate change (Koop and van Leeuwen, 2017). Wastewater is produced as the result of various agricultural, domestic and industrial operations, and in addition to inorganic and organic chemicals that are released into the atmosphere, it contains human-made pollutants and nutrients (Patwardhan, 2017; Le et al., 2021; Mofijur et al., 2021). If these pollutions are not properly treated, they lead to the destruction of the environment and pose risks to human health (Prosser and Sibley, 2015). Therefore, wastewater management and treatment are one of the main programs in many parts of the world to prevent threats to water quality and availability (Abdel-Raouf et al., 2012). Many countries have focused on improving domestic wastewater treatment technologies, especially regarding the reduction of phosphorus (P) and

nitrogen (N) in wastewater effluents (Connor et al., 2017).

In order to achieve a more sustainable society, it is necessary to rethink the approach to dealing with waste; however, it can also lead to some opportunities. On the other hand, it is necessary to produce clean energy and move towards a carbon-free future. In particular, there is a growing interest in the development of new renewable energy technologies that, unlike solar or wind energy, produce a predictable and stable amount of energy regardless of the weather. For example, Statkraft's prototype osmotic power plant in Tofte, Norway, was the world's first osmotic or salinity gradient power generation plant (Skilhagen et al., 2008; Statkraft, 2013). However, implementing resource recovery technologies is a challenge. Because in the past, wastewater treatment plants were designed and built in a centralized manner with the sole purpose of reducing the pollutant load. To move from pollution removal to recovery sources, existing treatment facilities must be redesigned and modified with the help of governments, scientific institutions, private stakeholders and end users (Kehrein et al., 2020). In addition, socio-economic challenges caused by the past and future of the country's political and socio-economic situation are also a big obstacle (Montwedi et al., 2021).

The presence of nutrients (phosphorus and nitrogen) in wastewater can be a challenge or an opportunity (Eslamian, 2016). The discharge of nutrients from wastewater into the environment can contaminate land and water and cause eutrophication in natural surface water environments, which can lead to algal blooms and other environmental challenges (Dube et al., 2016; Vu et al., 2019).The findings show that while nutrients are essential for healthy ecosystems, there is a link between nutrient overload and harmful algal blooms (HABs) (Heisler et al., 2008, United States Environmental Protection Agency, 2015). Consequently, strict rules have been established in many countries to protect aquatic ecosystems and human health (Jafarinejad, 2019a; Jafarinejad and Jiang, 2019; United States Environmental Protection Agency, 2009; Liu et al., 2011 and Xue et al., 2015).

In the current decade, the concept of nutrient removal/recovery has been used as a sustainable solution to develop and design a variety of modern wastewater treatment technologies to recover nutrients from waste streams and is one of the high-priority research areas (Xue et al., 2015). On the other hand, forward osmosis (FO) membrane technology has grown significantly in the past decade, but application in wastewater treatment has been slower due to some specific limitations. In this study, nutrient removal processes, FO membrane technology, main factors affecting FO process performance, water source for nutrient recovery, previous studies on FO membrane process for nutrient removal/recovery from wastewater and sludge, membrane fouling, and recent developments in FO membranes for nutrient removal/recovery are briefly and critically reviewed. Then, proposed possible schemes for applying the FO process in conventional wastewater treatment plants (WWTPs) were theoretically presented. Finally, based on the gaps identified in the region, the challenges ahead, future prospects and conclusions were discussed.

Aims and Objectives

In this study, different types of modern nutrient removal filtration technologies will be introduced and assessed. With regards to the global water and energy crisis, and on the other hand the global warming and intensive climate change, the most cost-effective methods will be of higher attention and consideration in this study. In other words, high energy-consuming methods are disregarded in this review paper. Details of each method and technology will be discussed and at the end, it is expected to have a comprehensive comparison between the methods and distinguish which method would perform better in each unique situation.

Modern Nutrient Removal Technologies

Modern nutrient removal technologies combine treatment steps with judicious design and create conditions to enable a high degree of nutrient removal and differ from

conventional nutrient removal technologies in several ways (Anjali and Sabumon, 2024; Do et al., 2020; Rene et al., 2020). Recently, emerging nutrient removal technologies, including phosphorus and nitrogen removal exclusively have been developed to enhance nutrient removal efficiency and save energy and operating cost, such as simultaneous nitrification/denitrification (SND), anaerobic oxidation of ammonium (anammox), single reactor for ammonia removal with high activity from nitrite (SHARON) etc. (Ahn, 2006; Andalib, 2011; Shammas and Wang, 2010; Lee et al., 2021, Kwak et al., 2020). Each of the aforementioned methods will be discussed in the following sub-sections.

Simultaneous Nitrification/Denitrification SND)

Simultaneous nitrification, denitrification and phosphorus removal (SNDPR) process has elicited significant attention for high-efficient and low-cost simultaneous nitrogen and phosphorus removal (Chen et al., 2024; Takeda et al., 2025; Wu et al., 2023 and Kwak et al., 2020) Besides relying on conventional phosphorus-accumulating organisms (PAOs) and denitrifying microbes, slow-growing and autotrophic nitrifying bacteria, and heterotrophic nitrifying PAOs (DNPAOs) and glycogen-accumulating organisms (DGAOs and enriched in nitrophores) can also contribute to nitrogen removal (He et al., 2016; Sun et al., 2024; Yang et al., 2016; Roy et al., 2021, Zhao et al., 2018).

The simultaneous nitrification, denitrification and phosphorus removal (SNDPR) system has attracted much attention due to its economy and efficiency (Wu et al., 2023). The main functional microorganisms in the SNDPR system include ammonia-oxidizing bacteria (AOB), nitrite-oxidizing bacteria (NOB), glycogen-accumulating organisms (GAOs), glycogen-accumulating organisms (DGAOs), polyphosphate-accumulating organisms (PAOs), polyphosphate-accumulating organisms (DPAOs), and ordinary heterotrophic denitrifying organisms (OHOs) (Rosas-Echeverría et al., 2023; Carvalho et al., 2007, Wang et al., 2020).

The SNDPR process is usually operated with anaerobic/microaerobic (A/MO) or anaerobic/microaerobic/anoxic (A/MO/A) operation mode and combines simultaneous nitrification (SND) with enhanced biological phosphorus removal (EBPR). A single reactor during the anaerobic period, DGAOs, PAOs and DPAOs store simple organic substances such as low-chain fatty acids in water in the form of poly-β-hydroxy alkenoate (PHA) in the cell, meanwhile, PAOs and DPAOs They can break down and release intracellular polyphosphate and phosphorus into the environment (De Kreuk et al., 2005; Freitas et al., 2005). Under aerobic conditions, AOB and NOB oxidize ammonia nitrogen and nitrogen to nitrate nitrogen, respectively. DGAOs carry out the denitrification process by degrading intracellular PHA, in addition, PAOs/DPAOs use oxygen/nitrite as electron acceptors and absorb excess phosphorus (Rubio-Rincón et al., 2017; He et al., 2018., Freitas et al., 2005). Nitrate and nitrite removal depends on DGAOs and DPAOs, and phosphorus removal by PAOs and DPAOs is more than absorption and discharge of phosphorus-rich residual sludge.

Anaerobic Oxidation of Ammonium (Anammox)

With the increasing development of urbanization, the total amount of wastewater discharge continues to increase (Yu et al., 2019). For example, the wastewater discharge of China reached 69.97 billion tons in 2017 (Normative Documents on the Guidance of Prices, 2017). By the end of 2018, more than 5000 municipal wastewater treatment plants have been built in China (Qu et al., 2019). In particular, a large amount of municipal wastewater containing ammonium is typically discharged after treatment, thus intensifying the eutrophication of water bodies and damaging the ecological environment (Qiu, 2021; Wang et al., 2022 , Chen et al., 2021a). Therefore, an efficient and stable reduction of the effluent concentration of ammonia nitrogen is very important for the control of eutrophication (Ma et al., 2020). By far, the conventional biological nitrogen removal (BNR) from wastewater mainly relies on two independent processes including nitrification

and denitrification. With regards to these processes, ammonia nitrogen in municipal wastewater is finally converted to dinitrogen (N2) and discharged into the atmosphere under the synergistic action of multiple microorganisms (Faraji et al., 2017; Pourmohammad et al., 2020; Li et al., 2024; Singh et al., 2025, Chen et al., 2021b). Unfortunately, the BNR process has come under increasing criticism because it is considered economically and environmentally unsustainable in terms of energy consumption, sludge production, and greenhouse gas emissions (Zhang et al., 2019, Zhan et al., 2020).

To cope with such engineering challenges, people have begun to devote themselves to research on the autotrophic anaerobic ammonium oxidation (anammox) process, which is a process in which nitrite and ammonium are simultaneously converted into dinitrogen through the function of anammox bacteria, taking nitrite as the electron acceptor and ammonium as the electron donor (Yan et al., 2024 , Van de Graaf et al., 1996). At the end of the 20th century, new biological nitrogen removal technologies based on the principle of anammox have been rapidly developed. For example, the partial nitrification-anammox (PN-AMX) as a complete autotrophic process has been employed to achieve nitrification and anammox in the reactor and thus result in nitrogen removal through the synergistic action of ammonium oxidizing bacteria (AOB) and anammox bacteria (Jafarinejad, 2019b; Liu et al., 2017; Ma et al., 2015, Ma et al., 2016).

Up to now, more than 110 anammox plants have been established in full-scale applications worldwide, most of which are used for treating high ammonium wastewater with low C/N and high temperatures (Ma et al., 2016). Nevertheless, when PN-AMX is applied to mainstream municipal wastewater treatment, the concentration of free ammonia (FA) and free nitrous acid (FNA) is low that cannot effectively inhibit the activity of nitrite-oxidizing bacteria (NOB), leading to the gradual decrease of the accumulation rate of $NO_2^- - N$ and even a poor nitrogen removal rate (Mao et al., 2017). Moreover, as the total nitrogen (TN) concentration in municipal wastewater is low (20-75 mg L^{-1}), containing organic matter, and the temperature might fluctuate greatly (below 10°C in winter), it is made difficult to remove nitrogen using the PN-AMX process. In summary, the unstable accumulation of nitrite has been the bottleneck of PN-AMX in mainstream municipal wastewater treatment (Wang et al., 2016).

Single Reactor for Ammonia Removal with High Activity from Nitrite (SHARON)

The SHARON filtration process is a partial nitrification process where the ammonia is oxidized to nitrite (Wei et al., 2017; Wang et al., 2016., Ganigué et al., 2009) The study conducted by Liang (2007) determined the optimal conditions to acquire constant SHARON process for leachate treatment in a bench-scale fixed bed biofilm reactor. The results showed that both dissolved oxygen and ammonium volumetric loading rate had effects on the SHARON process. In the SHARON process, rejection water from dewatering of digested sludge is treated for N-removal. It concerns a highly active process operating without sludge retention (Guan, 2024). The single tank reactor is intermittently aerated. Due to differences in growth rate nitrite oxidizers are washed out of the system while ammonia oxidizers can be maintained, resulting in N-removal over nitrite (Mulder et al., 2001).

Previously, before the SHARON process was developed, a broad range of process factors such as: pH, DO, temperature, NH_4, HNO_2 and other inhibitors have been tested to achieve nitrification/denitrification with nitrite as intermediate. Most of them initiated the formation of nitrite but could not prevent the formation of nitrate after longer periods. It seemed probable that all these process factors were not successful for full-scale application. The SHARON process is the first successful technique by which nitrification/denitrification with nitrite as intermediate under stable process conditions was achieved (Mulder et al., 2001).

The SHARON filtration process has been described in detail by Hellinga et al. (1998).

This process (patented) distinguishes itself from other biological wastewater treatment processes by a complete absence of sludge retention. Growth and washout of sludge are in equilibrium. The process has the following characteristics.

• Developed for biological nitrogen removal over nitrite in concentrated wastewater.

• Due to high temperatures (30–40 ºC) fast growing micro-organisms will develop in the reactor. The aerobic retention time may be limited to 1 day.

• Micro-organisms show high activity; however, the Ks value is rather high. As a result, effluent concentrations will be several tens of milligrams. The effluent concentration is independent of the influent concentration, the removal efficiency increases with higher inlet concentrations. In case of WWTP Dokhaven (NH_4–N>1 g/l) this results in removal efficiencies of over 90%.

• Nitrite oxidation can be prevented since at higher temperatures the NO2-oxidizing bacteria grow slower than the NH_4-oxidisers (Hunik et al., 1993). In a system without biomass retention (SRT=HRT) it is simple to limit the SRT in such a way that ammonium will be oxidised and nitrite will not be oxidised. Ammonia removal over nitrite instead of over nitrate has the following advantages:

• Oxidation to nitrite requires only 75% of the aeration energy.

• Denitrification starting with nitrite requires only 60% of the BOD addition.

• pH control is very important, due to the high concentrations and to high reaction rates.

The biocarbonate in the anaerobic effluent and the denitrification process compensate the acidifying effect of the nitrification. Both will take 50% of the alkalinity requirement. In the process however, the CO2 stripping needs to be sufficient to allow full use of the biocarbonate.

• Heat production is significant due to the high inlet concentrations. This had to be considered in the process design.

• As the process functions without sludge retention there is no influence of the presence of suspended solids in the reject water, for example, due to temporary malfunction of the sludge dewatering.

• Simple single reactor (CSTR) system required.

Conclusion

The current review paper provides an overview of major nutrients, their environmental and health effects, and their sources. With many distinct advantages, including operational simplicity, cost-effectiveness, extensive energy efficiency, and minimal need for pH control, SND is a desirable alternative for nutrient removal from domestic wastewater. Phosphorus removal denitrification appears to be a very promising process that leads to significant energy savings, less sludge production, improved efficiency, and reduced carbon source requirements, thus, it can effectively use limited carbon resources used in domestic sewage The incorporation of DPAOs in a SND process is recommended to realize DPAO mediated denitrification in a simultaneous nitrification–denitrification-phosphorus removal (SNDPR) system. It is also recommended that the coupling of archaeal ammonium oxidation-anammox-modified denitrifying phosphorous removal processes to intensify nitrogen removal and phosphorous recovery from low carbon/nitrogen wastewater in mainstream application with no external carbon source addition (Rouzitalab et al., 2020).

Recommendations

Drawing from the key insights of this review, the following recommendations aim to support researchers, engineers, and policymakers in advancing nutrient removal technologies in domestic wastewater treatment systems:

Move from Lab to Field

Many of the innovative technologies discussed such as SND, Anammox, SHARON, and forward osmosis have shown great promise in the lab. However, their real potential lies in how they perform at pilot and full-scale levels. More field-based studies are needed to evaluate their reliability, cost, and long-term

performance under actual operational conditions.

Think Beyond Removal, Focus on Recovery

Instead of just removing nutrients, future systems should aim to recover and reuse them. Nitrogen and phosphorus, for example, can be turned into valuable fertilizers(Volpin et al., 2018). Technologies like struvite precipitation and FO-based nutrient capture should be refined to support circular and sustainable practices.

Make Energy Efficiency a Priority

As energy costs and environmental concerns grow, it's important to prioritize low-energy, low-input solutions. Processes that pair biological nutrient removal with energy recovery (like anaerobic digestion) can make treatment plants more self-sufficient and eco-friendlier.

Bring in Smart Technology

Incorporating real-time sensors, automated monitoring, and AI-driven decision tools could help treatment plants react more quickly and operate more efficiently. Smart systems can also support predictive maintenance and early warning for process disruptions.

Tackle Membrane Fouling Head-On

Forward osmosis has great potential, but membrane fouling is still a big challenge. Developing better membrane materials with antifouling properties and finding practical cleaning solutions should be a research priority.

Evaluate the Bigger Picture

Life cycle assessments (LCAs) and techno-economic analyses (TEAs) are essential. These tools can help determine the true environmental and economic impacts of new technologies, guiding smarter investments and long-term planning.

Support Small-Scale, Localized Systems

In many rural or underserved areas, large centralized systems aren't feasible. Modular, decentralized treatment units that use these filtration technologies could offer effective, affordable solutions especially if tailored to local conditions.

Align with Policy and Institutional Frameworks

For these technologies to take off, supportive policies and funding mechanisms are crucial. Governments should revise discharge standards, incentivize innovation, and provide financial and technical support for transitioning to more advanced and sustainable treatment options.

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Authors' contribution

First Author: Saeid Eslamian, Led the research and manuscript preparation.

Second Author: Mousa Maleki, Provided analytical support and contributed to manuscript revisions.

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