VNU Journal of Science: Earth and Environmental Sciences, Vol. 40, No. 2 (2024) 1-12

VNU Journal of Science: Earth and Environmental Sciences

Journal homepage: https://js.vnu.edu.vn/EES

Review Article

Recent Advanced Biological Wastewater Treatment Technologies

Le Linh Thy[1], Nguyen Huu Viet[2], Bui Xuan Thanh[2,*]

[1]*University of Medicine and Pharmacy at Ho Chi Minh City (UMP),*
217 Hong Bang, District 5, Ho Chi Minh City, Vietnam
[2]*Ho Chi Minh City University of Technology (HCMUT), Vietnam National University Ho Chi Minh,*
268 Ly Thuong Kiet, District 10, Ho Chi Minh City, Vietnam

Received 03 June 2024
Revised 07 June 2024; Accepted 24 June 2024

Abstract: Conventional wastewater treatment approaches such as activated sludge processes often rely on energy-intensive and resource-demanding processes. However, emerging technologies offer promising solutions to improve the sustainability of wastewater management. This review examines three innovative technologies, including anaerobic membrane bioreactor (AnMBR), partial nitritation/anammox (PN/A), and microalgae-based processes, and their potential advantages over traditional methods. AnMBR combine membrane filtration with anaerobic biological treatment, enabling high-quality effluent, reduced sludge production, and a compact footprint. The PN/A is a two-step biological process that can achieve efficient nitrogen removal with lower aeration requirements. Microalgae-based systems leverage photosynthetic organisms to remove nutrients and organic matter while generating biomass for potential resource recovery. Each alternative technology has strengths and limitations that must be carefully evaluated based on the site-specific factors, such as wastewater characteristics, treatment objectives, and local conditions. Continued research and technological development is necessary to address the remaining technical and economic barriers impeding their wider adoption. Integrating multiple alternative technologies in a treatment train can help optimize overall performance by leveraging the complementary advantages of different processes. This holistic approach can advance the sustainable wastewater management, promoting resource efficiency, energy savings, and environmental protection.

Keywords: Anaerobic membrane bioreactor; Microalgae-based processes; Partial nitritation/anammox; Sustainability development; Wastewater treatment.

---

[*] Corresponding author.
E-mail address: bxthanh@hcmut.edu.vn

https://doi.org/10.25073/2588-1094/vnuees.5144

1. Introduction

Wastewater is produced as a byproduct of countless human activities, from domestic and industrial processes to agricultural operations. As global populations grow and economic development accelerates, the volume of wastewater generated worldwide has increased dramatically. Water pollution has long been a critical challenge, posing significant environmental, ecosystem, and human health threats such as contamination of drinking water. Over the years, various wastewater treatment, reuse, recycling, and resource recovery technologies have been developed to address this issue. A major concern is the substantial energy consumption of wastewater treatment plants (WWTPs). Electric energy demand accounts for about 90% of their total energy consumption [1]. It has been estimated that WWTPs are responsible for 1% of European countries' total national electricity consumption [2]. For each WWTP, electric energy accounts for 25–40% of total operating costs, of which 50 to 60% are connected to sludge treatment [3]. Beyond their significant energy demands, WWTPs also directly generate huge quantities of greenhouse gas (GHG) emissions and sludge during the various treatment processes. These byproducts of wastewater treatment pose environmental challenges that must be addressed. Therefore, addressing the energy consumption, GHG emissions, and sludge management associated with WWTPs will improve water infrastructure's sustainability and minimize human activities' overall environmental impact.

The research focusing on water environmental protection has recently undergone a notable shift. The emphasis has gradually transitioned from well-established conventional technologies towards more eco-friendly, cost-effective, and sustainable approaches, collectively known as "green technologies". These emerging solutions offer outstanding advantages and have gained significant attention for pollution control, especially in water and wastewater remediation. Several practical green treatment processes have been proposed and applied, including membrane bioreactors, partial nitritation/anammox (PN/A), and algae-based systems [1, 4]. These technologies harness innovative approaches to improve environmental compatibility, enhance resource and energy efficiency, enable resource recovery, and reduce operational costs compared to conventional systems. While conventional wastewater treatment methods have been widely adopted, the growing emphasis on sustainable green technologies represents an important shift in the research and development landscape. This transition holds immense promise for addressing water pollution challenges in a more environmentally responsible and resource-conscious manner. This review lays the groundwork for a more in-depth exploration of these challenges and potential remedies for sustainable wastewater treatment.

2. Conventional Activated Sludge Process

The activated sludge process (ASP) is a widely used biological treatment technique that utilizes aerobic microorganisms to break down organic matter and remove nutrients like nitrogen and phosphorus from wastewater. This technique involves aerating a mixed liquor containing wastewater and suspended biomass (activated sludge) to facilitate the growth and activity of the microorganisms. While effective at treating wastewater, this conventional approach has several environmental drawbacks. The ASP requires significant energy inputs, primarily for aeration to maintain the microorganisms and for sludge pumping. This high energy demand contributes to the overall energy footprint of WWTPs utilizing this method [5]. Besides, the biological processes in the ASP can generate methane and nitrous oxide, both major greenhouse gases (GHG). Conventional ASP generates large quantities of excess sludge that require further handling and disposal. This sludge contains concentrated contaminants and can pose environmental risks if not managed properly. Improper management of the excess sludge produced can also result in additional GHG emissions during storage, transport, and disposal [6].

The conventional approach typically does not focus on recovering valuable resources (e.g. nutrients and energy) from wastewater and sludge. Therefore, opportunities for a more circular economy approach are often missed. To address these environmental drawbacks, a growing focus is on developing and implementing more sustainable alternative treatment technologies, such as anaerobic digestion, membrane bioreactors, and integrated resource recovery systems. These approaches aim to reduce energy consumption, minimize GHG emissions, improve sludge management, and enable the recovery of resources from wastewater.

3. Recent Wastewater Treatment Technologies

The generation of nitrous oxide (N_2O) during the nitrification step of the conventional nitrification-denitrification process is an important environmental concern that requires careful management. Therefore, some alternative technologies were applied to mitigate the production of this potent greenhouse gas.

3.1. Anaerobic Membrane Bioreactor (AnMBR)

3.1.1. AnMBR for Wastewater Treatment

There has been a growing trend in applying AnMBR technology for wastewater treatment across various sectors in recent years. AnMBR is similar to MBR but operates under anaerobic conditions, utilizing anaerobic microorganisms to treat the wastewater. The anaerobic biological processes in AnMBR systems convert organic matter into biogas, primarily methane, which can be used for energy generation. The membrane component in AnMBR systems serves the same purpose as in MBR, separating the treated effluent from the anaerobic biomass [7].

The growing trend in AnMBR applications is driven by the technology's ability to address the increasing demand for sustainable, energy-efficient, and resource-recovery-oriented wastewater treatment solutions. Anaerobic digestion is a highly energy-efficient process that generates biogas. This biogas can be used as a renewable energy source to power the treatment plant or sold as fuel, reducing the wastewater treatment system's overall energy consumption and carbon footprint [8]. The anaerobic digestion process in the AnMBR can effectively recover nutrients, such as nitrogen and phosphorus, from the wastewater. These nutrients can be extracted and recycled to soil, contributing to a more circular economy and reducing the need for synthetic fertilizers [9]. Compared to conventional aerobic wastewater treatment, AnMBR generates significantly less sludge, reducing sludge disposal costs and environmental impact. Furthermore, the AnMBR's membrane filtration component produces high-quality, disinfected effluent that can be safely reused for various purposes, such as irrigation, industrial processes, or groundwater recharge [10], reducing the demand for freshwater resources.

3.1.2. Application of AnMBR

Municipalities are increasingly adopting AnMBRs to treat domestic or municipal wastewater. The technology offers benefits such as energy recovery, reduced sludge production, and a smaller footprint compared to conventional aerobic systems [11]. Several full-scale municipal AnMBR plants have been commissioned in countries like Spain, China, and the Netherlands.

A semi-industrial-scale AnMBR plant was used to treat sulfate-rich, high-loaded municipal wastewater as a pre-treatment step of a full-scale WWTP in Spain [12]. The organic loading rate (OLR) ranged between 0.6±0.2 and 1.2±0.4 kg COD/$m^3 \cdot d$. The plant mainly consists of a 40 m^3 anaerobic reactor connected to three ultrafiltration membrane tanks (PURON®). The results showed an average COD removal of above 87%. The methane yields varied from 74 to 170 L CH_4/kg COD and wasting sludge production was reduced by 8% and 42% compared to conventional activated sludge systems.

Moreover, the submerged and external AnMBR system for removing COD and BOD from real and synthetic municipal wastewater was reported. Kong et al., [13] investigated the treatment of real municipal wastewater in a pilot-scale submerged AnMBR. The reactor was equipped with 12 groups of hollow-fiber membrane units. The experiment was conducted for seven months under 25 °C and HRT of 6 h, respectively. The treatment capacity was equal to 20 m^3/day. The COD and BOD removal efficiency was over 90% and 95%, respectively. AnMBRs are well-suited for treating high-strength industrial wastewater from sectors like food and beverage, pulp and paper, and chemical processing. The ability to recover energy through biogas makes AnMBRs attractive for industrial applications. Many companies are retrofitting aerobic treatment plants with AnMBR systems to improve efficiency and reduce operating costs.

The high organic load and fluctuating characteristics of food and beverage industry wastewater make the AnMBR an ideal solution, as it can effectively handle these challenges while producing high-quality effluent. Sawadogo et al., [14] used an AnMBR coupled with an external nanofiltration (NF) system to treat wastewater from the beverage industry. The COD load varied from 0.8 to 5.7 g COD/L.d. The AnMBR provided over 99% turbidity removal, while the COD removal efficiency was 94%. NF resulted in almost complete rejection of most ions, with removal rates above 90%. The biogas produced was estimated at 0.21 L biogas/g $COD_{removed}$.

Another example is a pilot-scale AnMBR, which provides excellent biomass retention and was operated to investigate its treatment performance for vinasse from Baker's yeast industries at mesophilic conditions [15]. This study investigated that COD removal varied between 48% and 92% under volumetric load up to 10 kg COD m^3/d. A specific methane production of 0.37 m^3 CH_4/kg COD was achieved. A tubular UF membrane module was applied to treat high COD concentrations up to 18000 mg/L of the AnMBR permeate. The concentrate of the membrane was sent back to the reactor together with the recirculation flow. These results showed that the pilot system could be utilized in designing and operating full-scale AnMBRs for high-strength industrial effluents.

In short, these examples showcase the versatility and adaptability of AnMBR technology in addressing various industrial sectors' diverse wastewater treatment needs. As industries strive to enhance their environmental sustainability and resource efficiency, adopting AnMBR systems is expected to continue growing, driving the transition towards more sustainable industrial wastewater management practices.

3.2. Partial Nitritation/Anammox Process

3.2.1. Partial Nitritation/Anammox – Based Processes for Sustainable Development

The generation of nitrous oxide (N_2O) during the nitrification step of the conventional nitrification-denitrification process is an important environmental concern that requires careful management. Therefore, some alternative technologies, such as the PN/A process, were applied to mitigate the production of this potent greenhouse gas. The PN/A process is a promising alternative to conventional nitrification-denitrification, offering significant potential for more sustainable wastewater treatment [16]. In the PN/A process, the first step is partial nitritation (PN), where ammonia-oxidizing bacteria (AOB) convert a portion of the influent ammonia to nitrite. The second step involves the anammox bacteria, which can directly convert the remaining ammonia and the produced nitrite into nitrogen gas without needing an external carbon source [17]. This two-step process is more energy-efficient than the conventional nitrification-denitrification approach, which requires complete nitrification followed by heterotrophic denitrification [18, 19].

The PN/A process is more sustainable than conventional nitrogen removal due to several factors, such as energy requirements, organic carbon demand, and reduced sludge production. Importantly, the PN/A process significantly reduces energy-intensive aeration requirements compared to conventional nitrification, leading to substantial operational cost savings and a smaller carbon footprint. The PN/A process can reduce energy-intensive aeration requirements by approximately 60% compared to full nitrification [20], offering a promising economic outlook.

Besides, anammox bacteria can directly convert nitrite and ammonium to nitrogen gas without needing an external organic carbon source. Due to the slower growth rate of the anammox bacteria (18-132 days) [21] compared to conventional nitrifying and denitrifying bacteria, thus the PN/A process generates less excess sludge. The PN/A process can reduce excess sludge production by approximately 80% compared to the conventional nitrification-denitrification approach. This reduction in sludge production leads to lower costs and environmental impacts associated with sludge handling and disposal [22].

Additionally, integrating the PN/A process with resource recovery technologies, such as those that focus on producing bioenergy (e.g. biogas) or recovering nutrients (e.g. struvite) from the process, can further enhance the sustainability of wastewater treatment systems. The PN/A process can be coupled with an anaerobic digestion system to generate biogas, producing renewable energy (e.g. heat, electricity) for the treatment plant. Integrating the PN/A process with energy recovery systems can lead to a net-zero or net-positive energy balance for the wastewater treatment facility [23].

A combination of biofilm development and the PN/A process can effectively retain the slow-growing anammox bacteria [19, 24]. The membrane's high biomass concentration and physical separation help maintain the desired microbial balance and prevent biomass washout. Some MBR-based PN/A systems have been implemented in various locations, such as the Sluisjesdijk WWTP in Rotterdam, Netherlands. A single-stage PN/A process successfully started-up by using porous polyurethane hydrogel carriers to treat low-strength wastewater for two months [24]. Fluorescence in situ hybridization analysis indicated that AOB were located at the outer layers of carriers, while anammox bacteria consortia proliferated in the inner layers. The results showed that Candidatus Kuenenia's growth rate was 0.08 d^{-1}. This study provides novel insights into PN/A biofilm formation on the porous polyurethane hydrogel carrier.

Overall, the PN/A process not only demonstrates significant potential for sustainable development in wastewater treatment but also offers a beacon of hope for our environment. By reducing aeration requirements, eliminating the need for external organic carbon, and generating less excess sludge, the PN/A process presents a more energy-efficient and environmentally friendly alternative to the conventional nitrification-denitrification approach.

3.2.2. Reactor Configurations for PN/A Process

Several common reactor configurations, such as sequential batch reactors (SBRs), membrane bioreactors (MBRs), and up-flow anaerobic sludge blanket (UASB) reactors, are used to implement the PN/A process in wastewater treatment plants. SBRs are one of the most common reactor types used for the PN/A process. SBR's cycle, with distinct phases of filling, reaction, settling, and decanting, allows for the effective control of the microbial communities and process parameters [25]. Examples of PN/A-based SBR systems include the DEMON (Deammonification) process and the SHARON-Anammox process [26].

Moreover, MBR-based PN/A systems offer unique features. For instance, they can retain slow-growing anammox bacteria in the PN/A process. This is made possible by the physical separation provided by the membrane, which retains the slow-growth anammox bacteria within the reactor, preventing their washout and maintaining the necessary biomass concentration for the PN/A process. The membrane separation also creates distinct compartments between the aerobic and anaerobic zones within the MBR system. In the aerobic zone, a partial nitritation reaction occurs and is maintained on the membrane surface or in the mixed liquor. Simultaneously, the anammox reaction can occur in an anaerobic zone, established in the sludge bed or within the membrane pores. This unique spatial separation of the nitritation and anammox processes helps optimize the operating conditions for each step, setting MBR-based PN/A systems apart from other technologies.

MBR-based PN/A systems have been successfully implemented in various locations, serving as a testament to their effectiveness. For instance, the Sluisjesdijk WWTP in Rotterdam, Netherlands, stands as an excellent illustration of a successful MBR-based PN/A system implementation. Another noteworthy case is Yun et al., [27], who applied two novel umbrella-shaped membrane modules to construct a two-stage PN/A process. This study achieved the best nitrogen-removing effect, demonstrating the potential of this technology for the treatment of nitrogen-rich wastewater. The cell densities of AOB and anammox bacteria were 58.32×10^{12} and 28.39×10^{12} copies, respectively, further highlighting the advantages of MBRs' physical separation and biomass retention capabilities.

The Continuous Stirred-Tank Reactor (CSTR) is a versatile reactor configuration used for the PN/A process. The CSTR provides a well-mixed, homogeneous environment [28] that precisely controls key operational parameters such as pH, temperature, dissolved oxygen, and hydraulic retention time (HRT). The CSTR configuration enables the simultaneous occurrence of the PN/A steps within the same reactor, optimizing the overall nitrogen removal efficiency [19]. The CSTR design is not only efficient but also easily scalable, making it suitable for treating larger volumes of wastewater or influent streams. In a typical CSTR setup for PN/A, the reactor is operated under carefully controlled conditions to favor the growth of the desired AOB and anammox bacteria. This includes maintaining a low dissolved oxygen concentration, a suitable pH range, and an optimal HRT to balance the growth rates of the two microbial groups.

The CSTR configuration has found widespread use in various wastewater treatment applications, including municipal and industrial wastewater treatment. The PN/A process, when implemented with a CSTR, has proven its effectiveness in achieving efficient nitrogen removal while significantly reducing operational costs and energy consumption compared to traditional nitrification-denitrification processes. Le et al., [19] used a CSTR to treat synthetic low-strength wastewater under intermittent aeration conditions. This study achieved over 80% nitrogen removal at the nitrogen loading rate of 0.12–0.16 $kgN/m^3.d$. The biomass was efficiently retained using fiber carriers with a specific activity of anammox bacteria that was 1.5 times higher than that of AOB. These reactor configurations, along with their specific design and operational features, have been successfully implemented in full-scale PN/A-based wastewater treatment plants, demonstrating the flexibility and adaptability of this sustainable technology.

3.3. Algae Based Processes

3.3.1. Sources of Microalgae

Microalgae can be cultivated in various wastewater sources, including municipal, industrial, and agricultural, making them a versatile solution for various applications. The cultivation systems can be tailored to local conditions, resource availability, and specific treatment or resource recovery needs, enhancing the scalability and deployment potential. Various microalgae strains have been successfully used in wastewater treatment applications. For example, *Chlorella vulgaris* and *Chlorella sorokiniana* are the most widely studied microalgae for wastewater treatment. They are known for their high nutrient removal efficiency, particularly for nitrogen and phosphorus [28]. *Chlorella* species are robust and can tolerate a wide range of environmental conditions [28, 29]. *Scenedesmus obliquus* and *Scenedesmus dimorphus* are commonly used in wastewater treatment. They have demonstrated effective removal of organic matter, nitrogen, and phosphorus from various types of wastewaters. *Scenedesmus* species are relatively fast-growing and can form dense cultures [30, 31]. *Spirulina* is a cyanobacterium with high nutritional value and potential for wastewater treatment. It has performed well in removing nutrients, heavy metals, and organic pollutants from wastewater. Spirulina can tolerate high pH and saline conditions, making it suitable for various wastewater sources [32].

3.3.2. Algae Based Processes

In sustainable development, the potential of microalgae-based wastewater treatment has attracted attention worldwide. This innovative approach promises to achieve zero emissions by seamlessly integrating wastewater treatment and resource recovery. Microalgae, as photosynthetic organisms, demonstrate their prowess by efficiently utilizing carbon dioxide (CO_2) as a carbon source for their growth and biomass production. CO_2, a byproduct of various wastewater treatment processes such as aerobic biological treatment and anaerobic digestion, can be harnessed and transformed into microalgal biomass by incorporating microalgae into wastewater treatment systems [33]. Moreover, microalgae play a crucial role in our ecosystem by effectively removing nutrients like nitrogen and phosphorus from wastewater through biological assimilation. This not only aids in the efficient treatment of wastewater but also serves as a powerful tool in preventing eutrophication in receiving water bodies, a pressing environmental concern [34]. Furthermore, the versatility of microalgae biomass is truly remarkable. It can be harnessed for biofuel production, paving the way for a more sustainable energy future. Additionally, it can be used to create a myriad of other valuable co-products, opening up a world of possibilities for resource recovery.

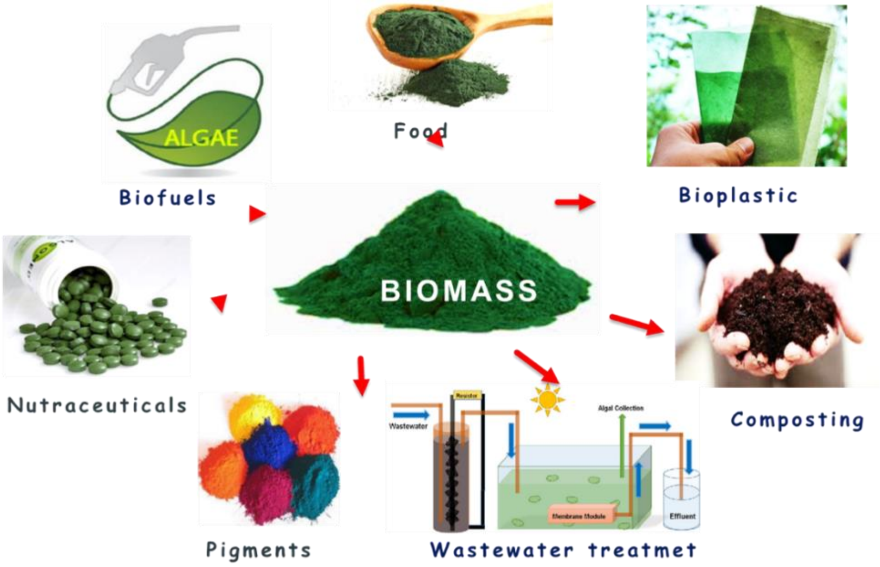

Figure 1. Valued-added products from microalgae biomass.

Moreover, in terms of the circular economy, this symbiotic relationship can lead to more than just advantages. Activated sludge microorganisms can foster a mutually beneficial relationship with co-culture microalgae, potentially boosting their growth and increasing their biomass yield. This co-culture biomass can then be harvested and processed to recover valuable resources, such as biofuels, biofertilizers, and high-value biochemicals (Figure 1). The diverse range of products derived from the biomass, including biofuels, animal feed, soil amendments, and specialty chemicals, can maximize economic value generation. Importantly, the residual byproducts or waste streams from the processing and conversion of the co-culture biomass can be further integrated into other processes, such as biogas production or nutrient recovery, creating a reassuring closed-loop system.

3.3.3. Configurations of Microalgae-Based Process for Wastewater Treatment

Some typical microalgae-based reactor configurations, such as high-rate algal ponds (HRAPs) and integrated algal ponding systems (IAPS), are used to treat wastewater. HRAPs are shallow, mixed, open-air ponds that mimic natural algal ecosystems. They offer a cost-effective and scalable solution for wastewater treatment and biomass production. HRAPs can be coupled with secondary treatment systems for enhanced performance [35]. IAPS combines multiple pond systems, including maturation ponds, high-rate algal ponds, and settling ponds. This integrated approach allows efficient nutrient removal, biomass harvesting, and resource recovery [36]. An IAPS was conducted in the study of Dube et al., [36] in South Africa. In this study, the IAPS is supplied continuously with municipal sewage and comprises a primary facultative pond containing a cylindrical in-pond digester. Each component's design capacity and unit volume is 500 p.e. per day. The results showed that the formation of a microalgal–bacteria floc and settle ability together with biomass removal from algal settling ponds (ASPs) is shown to reduce total suspended solids (TSS) from above 50 mg/L to 20 mg/L. Thus, the production of readily settleable biomass coupled with the removal of settled biomass from ASP ensures that the final effluent TSS remains below the general limit of 25 mg/L and yields an effluent suitable for irrigation or discharge.

Recently, photobioreactors (PBRs) are another common process configuration, which can be designed as open, closed, or hybrid systems. These systems showcase their versatility and adaptability to different wastewater treatment needs. They can achieve high biomass productivity and nutrient removal rates. The integration of co-culture microalgae and activated sludge in a photobioreactor system has emerged as a promising approach. This innovative method offers potential opportunities for a circular economy approach to wastewater treatment, instilling hope for more sustainable practices in the field.

In the microalgae-bacteria co-culture reactor, microalgae will use light as their energy source and CO_2 as their carbon supply while simultaneously producing oxygen and biomass. In contrast, bacteria will use oxygen as an electron acceptor and organic carbon as an energy source to respire aerobically, releasing CO_2 and water. Below are examples of these two processes' simplified reactions:

$$Photosynthesis: 6CO_2 + 6H_2O + light \rightarrow C_6H_{12}O_6 + 6O_2$$

$$Aerobic\ respiration: C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + heat$$

The oxygen required for aerobic respiration is created throughout photosynthesis. Carbon dioxide is required for photosynthesis and is created by aerobic respiration. Bacteria and microalgae have a symbiotic relationship because they supply each other with essential chemical components. This is why a photobioreactor with a co-culture needs less energy for aeration [34, 37]. Co-culture using microalgae-activated sludge in PBRs was investigated for wastewater treatment performance [38]. The results found that removing nutrients and COD from natural lighting conditions were only 10% and 13% lower than artificial lighting, respectively. The total energy consumption of natural lighting was over two times less than that of artificial lighting at 0.294 kWh/L. It reveals that natural lighting systems significantly cut energy costs compared to artificial lighting (~60%). As a practical viewpoint on energy aspects and treatment performance, a natural lighting PBR system would be a sustainable option for microalgae-activated sludge co-culture systems treating wastewater. The mentioned information indicated that the co-culture photobioreactor system could help reduce conventional wastewater treatment's energy and resource demands, leading to cost savings and improved economic viability. Furthermore, the interactions between microalgae and bacteria depend on the species and environmental conditions. Bacteria can promote or inhibit algae growth by producing growth factors or mycotoxins, while algae can also inhibit or promote bacterial growth by producing exotoxins or growth factors. Therefore, properly controlling culture conditions is key to creating a favorable environment for both microorganisms in the symbiotic system [38].

In short, the microalgae-based process presents a comprehensive solution to achieving zero emissions by combining wastewater treatment, carbon capture, and the production of valuable co-products [39]. The integration of wastewater treatment and microalgae cultivation promotes a sustainable and holistic approach to resource management. It not only minimizes waste and reduces environmental impact but also plays a crucial role in the circular economy. Importantly, microalgae-based systems can significantly contribute to addressing urgent environmental challenges such as water scarcity, nutrient pollution, and fossil fuel dependence, while simultaneously generating valuable products and resources.

4. Conclusions

The future of wastewater treatment holds immense promise as we integrate innovative technologies that not only enhance efficiency and resource recovery but also align with sustainability principles. Anaerobic membrane bioreactors (AnMBRs) offer more than just a promising alternative to conventional aerobic treatment. They leverage anaerobic digestion to produce biogas while minimizing energy demands. With the added advantage of membrane filtration, AnMBRs can achieve high-quality effluent while recovering valuable resources like water and nutrients, significantly contributing to the circular economy. Microalgae-based processes, on the other hand, harness microalgae's inherent capabilities to remove nutrients, recover water, and even generate biofuels or valuable biomass. These natural solutions enhance wastewater treatment and create opportunities for sustainable resource production. However, it's important to note that the scalability of these processes may be challenging, particularly in large-scale applications. The PN/A process, facilitated by advanced technologies like membrane bioreactors (MBRs), represents a significant advancement in biological nutrient removal. The spatial segregation and biomass retention offered by MBRs optimize the operating conditions for the PN/A reactions, leading to enhanced performance and reduced energy consumption.

Integrating these innovative technologies within the wastewater treatment sector is instrumental and pivotal in driving sustainable development by prioritizing energy efficiency, resource recovery, and holistic management approaches. In the future, wastewater will no longer be viewed as a waste stream but as a valuable resource to be harnessed for the benefit of our communities and the planet.

Acknowledgements

This research is funded by Vietnam National University Ho Chi Minh (VNU-HCM) under grant number B2024-20-03.

References

[1] H. Guven, R. K. Dereli, H. Ozgun, M. E. Ersahin, I. Ozturk, Towards Sustainable and Energy Efficient Municipal Wastewater Treatment by Up-Concentration of Organics, Progress in Energy and Combustion Science, Vol. 70, 2019, pp. 145-168, https://doi.org/10.1016/j.pecs.2018.10.002.

[2] S. D. Fraia, N. Massarotti, L. Vanoli, A Novel Energy Assessment of Urban Wastewater

Treatment Plants, Energy Conversion and Management, Vol. 163, 2018, pp. 304-313, https://doi.org/10.1016/j.enconman.2018.02.058.

[3] L. Castellet, M. M. Senante, Efficiency Assessment of Wastewater Treatment Plants: A Data Envelopment Analysis Approach Integrating Technical, Economic, and Environmental Issues, Journal of Environmental Management, Vol. 167, 2016, pp. 160-166, https://doi.org/10.1016/j.jenvman.2015.11.037.

[4] A. Abbew, A. A. Amadu, S. Qiu, P. Champagne, I. Adebayo, P.O. Anifowose, S. Ge, Understanding the Influence of Free Nitrous Acid on Microalgal-Bacterial Consortium in Wastewater Treatment: A Critical Review, Bioresource Technology, Vol. 363, 2022, pp. 127916, https://doi.org/10.1016/j.biortech.2022.127916.

[5] Y. Gu, Y. Li, F. Yuan, Q. Yang, Optimization and Control Strategies of Aeration in WWTPs: A Review, Journal of Cleaner Production, Vol. 418, 2023, pp. 138008, https://doi.org/10.1016/j.jclepro.2023.138008.

[6] B. Wu, X. Dai, X. Chai, Critical Review on Dewatering of Sewage Sludge: Influential Mechanism, Conditioning Technologies and Implications to Sludge Re-Utilizations, Water Research, Vol. 180, 2020, pp. 115912, https://doi.org/10.1016/j.watres.2020.115912.

[7] M. A. Musa, S. Idrus, H. C. Man, N. N. N. Daud, Wastewater Treatment and Biogas Recovery Using Anaerobic Membrane Bioreactors (AnMBRs): Strategies and Achievements, Energies, Vol. 11, 2018, pp. 1675, https://doi.org/10.3390/en11071675.

[8] Z. K. Lim, T. Liu, M. Zheng, M. Rattier, J. Keller, Z. J. Yuan, J. Guo, S. Hu, Membrane Reciprocation As Energy-Efficient Fouling Control with High Biogas Recovery in A Pilot-Scale Anaerobic Membrane Bioreactor, Resources, Conservation and Recycling, Vol. 190, 2023, pp. 106849, https://doi.org/10.1016/j.resconrec.2022.106849.

[9] Y. Ye, H. H. Ngo, W. Guo, S. W. Chang, D. D. Nguyen, S. Varjani, Q. Liu, X. T. Bui, N. B. Hoang, Bio-membrane Integrated Systems for Nitrogen Recovery from Wastewater in Circular Bioeconomy, Chemosphere, Vol. 289, 2022, pp. 133175, https://doi.org/10.1016/j.chemosphere.2021.133175.

[10] Y. Huang, P. Jeffrey, M. Pidou, Municipal Wastewater Treatment with Anaerobic Membrane Bioreactors for Non-Potable Reuse: A Review, Critical Reviews in Environmental Science and Technology, Vol. 54, 2024, pp. 817-839, https://doi.org/10.1080/10643389.2023.2279886.

[11] A. Aslam, S. J. Khan, H. M. A. Shahzad, Anaerobic Membrane Bioreactors (Anmbrs) for Municipal Wastewater Treatment-Potential Benefits, Constraints, and Future Perspectives: An Updated Review, Science of the Total Environment, Vol. 802, 2022, pp. 149612, https://doi.org/10.1016/j.scitotenv.2021.149612.

[12] Á. Robles, A. J. Benítez, J. B. Giménez, F. Durán, J. Ribes, J. Serralta, J. Ferrer, F. Rogalla, A. Seco, A Semi-Industrial Scale Anmbr for Municipal Wastewater Treatment at Ambient Temperature: Performance of the Biological Process, Water Research, Vol. 215, 2022, pp. 118249, https://doi.org/10.1016/j.watres.2022.118249.

[13] Z. Kong, J. Wu, C. Rong, T. Wang, L. Li, Z. Luo, J. Ji, T. Hanaoka, S. Sakemi, M. Ito, S. Kobayashi, M. Kobayashi, Y. Qin, Y. Li, Large Pilot-Scale Submerged Anaerobic Membrane Bioreactor for the Treatment of Municipal Wastewater and Biogas Production at 25 °C, Bioresource Technology, Vol. 319, 2021, pp. 124123, https://doi.org/10.1016/j.biortech.2020.124123.

[14] B. Sawadogo, Y. Konaté, A. W. Nouhou Moussa, G. Lesage, F. Zaviska, M. Heran, H. Karambiri, Anaerobic Membrane Bioreactor Coupled with Nanofiltration Applied to the Treatment of Beverage Industry Wastewater Under Soudano-Sahelian Climatic Conditions, Journal of Membrane Science and Research, Vol. 8, 2022, https://doi.org/10.22079/jmsr.2022.545078.1521.

[15] M. Turker, R. K. Dereli, Long Term Performance of A Pilot Scale Anaerobic Membrane Bioreactor Treating Beet Molasses Based Industrial Wastewater. Journal of Environmental Management, Vol. 278, 2021, pp. 111403, https://doi.org/10.1016/j.jenvman.2020.111403.

[16] H. E. A. Hazmi, G. K. Hassan, M. Maktabifard, D. Grubba, J. Majtacz, J. Mąkinia, Integrating Conventional Nitrogen Removal with Anammox in Wastewater Treatment Systems: Microbial Metabolism, Sustainability and Challenges. Environmental Research, Vol. 215, 2022, pp. 114432, https://doi.org/10.1016/j.envres.2022.114432,

[17] L. T. Le, B. T. Dang, X. T. Bui, D. Jahng, Anammox-An Energy-Efficient Nitrogen Removal Process In Wastewater Treatment, in: X. T. Bui, D. D. Nguyen, P. Ashok (Eds.), Current Developments in Biotechnology and Bioengineering, 2021, pp. 503-527, https://doi.org/10.1016/B978-0-323-99874-1.00004-X.

[18] J. Li, J. Li, Y. Peng, S. Wang, L. Zhang, S. Yang, S. Li, Insight Into the Impacts of Organics on Anammox and Their Potential Linking to System Performance of Sewage Partial Nitrification-Anammox (PN/A): A Critical Review, Bioresource Technology, Vol. 300, 2020, pp. 122655, https://doi.org/10.1016/j.biortech.2019.122655.

[19] L. T. Le, L. D. Nghiem, X. T. Bui, D. Jahng, Improve Nitrogen Removal of the Biofilm Single-Stage PN/A Process by Optimizing the Intermittent Aeration Strategy, Environmental Technology & Innovation, Vol. 30, 2023, pp. 103078, https://doi.org/10.1016/j.eti.2023.103078.

[20] S. Mishra, V. Singh, L. Cheng, A. Hussain, B. Ormeci, Nitrogen Removal from Wastewater: A Comprehensive Review of Biological Nitrogen Removal Processes, Critical Operation Parameters and Bioreactor Design, Journal of Environmental Chemical Engineering, Vol. 10, 2022, pp. 107387, https://doi.org/10.1016/j.jece.2022.107387.

[21] M. Laureni, D. G. I. Weissbrodt, O. S. Robin, J. L. Nielsen, E. Morgenroth, A. Joss, Activity and Growth of Anammox Biomass on Aerobically Pre-treated Municipal Wastewater, Water Research, Vol. 80, 2015, pp. 325-336, https://doi.org/10.1016/j.watres.2015.04.026.

[22] W. Wang, D. Li, S. Li, H. Zeng, J. Zhang, Research on Partial Nitritation and Anaerobic Ammonium Oxidation Process, IntechOpen, 2024, https://doi.org/10.5772/intechopen.112708.

[23] Z. Kong, Y. Xue, Y. Zhang, T. Hao, H. Chen, J. Sun, Y. Pan, D. Li, Y. Li, Y. Huang, Insights Into the Carbon Neutrality for the Treatment Process Engineering of Municipal Wastewater by Anaerobic Membrane Bioreactor Integrated with Partial Nitritation-Anammox: CO_2 Reduction and Energy Recovery, Journal of Water Process Engineering, Vol. 49, 2022, pp. 102996, https://doi.org/10.1016/j.jwpe.2022.102996.

[24] W. Liu, H. Zhou, W. Zhao, C. Wang, Q. Wang, J. Wang, P. Wu, Y. Shen, X. Ji, D. Yang, Rapid Initiation of A Single-Stage Partial Nitritation-Anammox Process Treating Low-Strength Ammonia Wastewater: Novel Insights Into Biofilm Development on Porous Polyurethane Hydrogel Carrier, Bioresource Technology, Vol. 357, 2022, pp. 127344, https://doi.org/10.1016/j.biortech.2022.127344.

[25] G. K. Azeez, F. Y. A. Jaberi, S. A. Ahmed, A. A. Hussain, Sequencing batch Reactor (SBR) Technology in Wastewater Treatment: A Mini-Review, AIP Conf. Proc., Vol. 2806, 2023, pp. 030014, https://doi.org/10.1063/5.0163432.

[26] P. Izadi, A. Eldyasti, Towards Mainstream Deammonification: Comprehensive Review on Potential Mainstream Applications and Developed Sidestream Technologies, Journal of Environmental Management, Vol. 279, 2021, pp. 111615, https://doi.org/10.1016/j.jenvman.2020.111615.

[27] H. Yun, T. Wang, H. Meng, Using an Innovative Umbrella-Shape Membrane Module to Improve MBR for PN-ANAMMOX Process, Environ Sci Pollut Res, Vol. 30, 2023, pp. 27730-27742, https://doi.org/10.1007/s11356-022-24166-3.

[28] H. S. Yun, Y. S. Kim, H. S. Yoon, Characterization of Chlorella sorokiniana and Chlorella Vulgaris Fatty Acid Components Under A Wide Range of Light Intensity and Growth Temperature for Their Use As Biological Resources, Heliyon, Vol. 23, 2020, pp. e04447, https://doi.org/10.1016/j.heliyon.2020.e04447.

[29] T. N. D. Cao, H. Mukhtar, L. T. Le, D. P. H. Tran, M. T. T. Ngo, M. N. Pham, T. K. Q. Vo, X. T. Bui, Roles of Microalgae-Based Biofertilizer in Sustainability of Green Agriculture and Food-Water-Energy Security Nexus, Science of the Total Environment, Vol. 870, 2023, pp. 161927, https://doi.org/10.1016/j.scitotenv.2023.161927.

[30] S. N. Badar, M, Mohammad, Z. Emdadi, Z. Yaakob, Algae and Their Growth Requirements For Bioenergy: a Review, Biofuels, Vol. 12, 2018, pp. 307-325, https://doi.org/10.1080/17597269.2018.1472978.

[31] K. E. Ogbonna, J. C. Ogbonna, O. U. Njoku, K. Yamada, I. Suzuki, Effect of Organic Carbon Sources on Growth, Lipid Production and Fatty Acid Profile in Mixotrophic Culture of Scenedesmus Dimorphus (Turpin) Kützing, The Microbe, Vol. 3, 2024, pp. 100064, https://doi.org/10.1016/j.microb.2024.100064.

[32] H. R. Lim, K. S. Khoo, K. W, Chew, C. Chang, H. S. H. Munawaroh, P. S. Kumar, N. D. Huy, P. L. Show, Perspective of Spirulina Culture with Wastewater Into A Sustainable Circular Bioeconomy, Environmental Pollution, Vol. 284, 2021, pp. 117492, https://doi.org/10.1016/j.envpol.2021.117492.

[33] R. K. Goswami, S. Mehariya, O. P. Karthikeyan, V. K. Gupta, P. Verma, Multifaceted Application of Microalgal Biomass Integrated with Carbon Dioxide Reduction and Wastewater Remediation: A Flexible Concept for Sustainable Environment, Journal of Cleaner Production, Vol. 339, 2022, pp. 130654, https://doi.org/10.1016/j.jclepro.2022.130654.

[34] A. Fallahi, F. Rezvani, H. Asgharnejad, E. K. Nazloo, N. Hajinajaf, B. Higgins, Interactions of Microalgae-Bacteria Consortia for Nutrient Removal from Wastewater: A Review, Chemosphere, Vol. 272, 2021, pp. 129878, https://doi.org/10.1016/j.chemosphere.2021.129878.

[35] N. Kumar, N. S. Geetansh, C. Himani, S. Kirti, T. Saurabh, V. Pooja, S. Gaurav, Microalgae in Wastewater Treatment and Biofuel Production: Recent Advances, Challenges, and Future Prospects, In: Kumar, V. Thakur, I. S. (eds) Omics Insights in Environmental Bioremediation, Springer, Singapore, 2022, pp. 237-271, https://doi.org/10.1007/978-981-19-4320-1_11.

[36] A. Dube, A. K. Cowan, Algal Settling Ponds Contribute to Final Effluent Quality of Integrated Algal Pond Systems for Municipal Sewage Treatment, Water and Environment Journal, Vol. 37, 2023, pp. 232-241, https://doi.org/10.1111/wej.12831.

[37] L. Aditya, T. M. I. Mahlia, L. N. Nguyen, H. P. Vu, L. D. Nghiem, Microalgae-Bacteria Consortium for Wastewater Treatment and Biomass Production, Sci. Total Environ, Vol. 838, 2022, https://doi.org/10.1016/j.scitotenv.2022.155871.

[38] T. T. D. Nguyen, X. T. Bui, T. Nguyen, H. H. Ngo, K. Y. A. Lin, C. Lin, L. T. Le, B. T. Dang, M. Bui, S. Varjani, Co-Culture of Microalgae-Activated Sludge in Sequencing Batch Photobioreactor Systems: Effects of Natural and Artificial Lighting on Wastewater Treatment, Bioresource Technology, Vol. 343, 2021, pp. 126091, https://doi.org/10.1016/j.biortech.2021.126091

[39] O. Emmanuel, Rozina, T. C. Ezeji, Utilization of Biomass-Based Resources for Biofuel Production: A Mitigating Approach Towards Zero Emission, Sustain. Chem. One World, Vol. 2, 2024, 100007. https://doi.org/10.1016/j.scowo.2024.100007.