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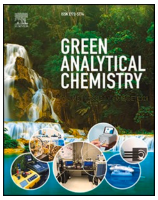

Green chemistry treatment of seafood processing wastewater using pilot scale Anaerobic Membrane Bioreactor (AnMBR) in a realtime mode

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ABSTRACT

The seafood processing industry's growing revenue heightens the urgency of treating wastewater rich in harmful pollutants. Addressing this challenge, Anaerobic Membrane Bioreactor (AnMBR) technology emerges as a green and sustainable solution by integrating activated sludge microorganisms and nano-pore membranes without using chemicals. This study hypothesizes that a pilot-scale AnMBR system can effectively treat seafood processing wastewater while achieving compliance with stringent discharge standards. A 0.5 m^3/day pilot AnMBR was constructed and operated for two months in a seafood factory to evaluate pollutant removal and operational stability. The system achieved high pollutant removal efficiencies: 99.63 ± 0.14 % Total Suspended Solids (TSS), 61.04 ± 7.77 % Chemical Oxygen Demand (COD), 32.02 ± 17.42 % Total Diluted Solids (TDS), 13.30 ± 4.17 % Total Nitrogen (TN), and 11.12 ± 2.46 % Total Phosphorus (TP), with favorable sludge parameters (SVI: 20, MLSS: 11.5 g/L) and stable operation (TMP: 0.66 bar, flux: 18.2 L/m^2·h). These results meet two national seafood wastewater discharge standards, highlighting AnMBR's potential for large-scale applications in the industry. These outcomes obtained at the pilot-scale level meet two national parameters discharge standard which applies specifically to seafood processing wastewater. It underscores the significant potential of AnMBR technology for widespread adoption in treating real-time wastewater generated by the seafood industry.

1. Introduction

Seafood processing is a vital and rapidly growing industry worldwide. By 2018, global farmed seafood production had reached a record high of 82.1 million tonnes, with Asia as the dominant producer [1]. However, it also generates large amounts of wastewater containing numerous toxic and polluting substances. These substances originate from various processing stages, including soaking compounds, phosphorus, and other organic materials, resulting in wastewater with high concentrations of diverse components. The pH of seafood processing wastewater depends on several factors, such as the water source, products, salts, and chemicals used during processing [2] that can be degraded due to lipid oxidation, enzymes, and microbes [3]. In addition, It is important to adapt the processes to the special requirements that easily spoiled products as fish have [4]. Also, the wastewater quality varies depending on the fish, the processes, the water, and the additives [5]. In seafood processing wastewater, salt is generated during the processes of washing, marinating, and preserving seafood products. The functions of salt include: ensuring microflora, improving sensory attributes, mainly color, taste (salty) and texture as well as acting as a binder and emulsifier [6]. It is well established that 1.5–2.0 % NaCl enhances the sensory appeal of canned or processed seafood products [7], with TDS values ranging from 3 to 8.5 g/L. Additionally, oils and fats are generated during fish canning and fish processing operations [8]. Fat, oil, and grease (FOG) should be removed from wastewater because they often float on the water surface, disrupting oxygen exchange into the water [9]. Additionally, seafood processing generates significant amounts of organic matter from raw materials, with most of the

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biochemical oxygen demand (BOD_5) typically originating from retained water during the slaughter process [10]. The fish canning industry produces wastewater with high concentrations of organic pollutants, ranging from 10,000 to 50,000 mg/L [11]. Nitrogen in seafood wastewater exists in both organic and inorganic forms, often combined with carbon, hydrogen, and oxygen. Most nitrogen is organic, derived from proteins that consist of 20 amino acids, each containing an amine and an acid group, and constitute 15–20 % of the wet weight of fish and marine invertebrates [12]. High ammonia concentrations are sometimes observed due to the high blood and mucus content in the wastewater stream. Phosphorus is partially derived from fish but can also be introduced through processing and cleaning products [13].

Wastewater from seafood processing can have harmful effects on the environment and human health if not properly treated before discharge, due to its high organic content and potential presence of pathogens. To achieve optimal efficiency in treating seafood processing wastewater, it is essential to analyze the components and properties of the wastewater, establish suitable treatment methods, and ensure compliance with output standards for seafood processing wastewater. Numerous methods are employed for removing contaminants from seafood processing wastewater. Physico-chemical treatments utilize both physical and chemical processes, including pH adjustment (neutralization), coagulation, flocculation, chemical precipitation, chemical oxidation, and dissolved air flotation (DAF) [14]. DAF can be integrated with other treatments to enhance output quality or combined with coagulants and flocculants, achieving up to 50 % removal of TSS and 80 % removal of fats, oils, and grease (FOG) [15]. Membrane technologies, leveraging nanoscale porous structures, are also applicable for seafood wastewater treatment [16]. For example, ceramic ultrafiltration (UF) membranes used in treating herring processing brine demonstrated reductions in COD, TSS, and nitrogen levels [17]. The study recorded retention rates of up to 42 % for COD and 95 % for TSS. However, membrane fouling remains a significant challenge due to the high levels of suspended solids and organic matter in seafood wastewater. A potential solution is to utilize backwash mechanisms to mitigate fouling [18]. To deal with eutrophication, biochar is one of potential to solve the issues due to its special structure and ability to absorb the nutrients, biochar promotes the growth of specific microbes that outcompete algae for nutrients, reducing algal biomass and the risk of harmful blooms [19]. For treating PFAS, one of toxic contaminant that could harm people, highly efficient nanocomposite materials could effectively remove PFAS from water. UiO-66-NH_2/GO/ PVA composite also demonstrated high reusability, maintaining substantial PFOA removal efficiency across multiple cycles with 9.904 mg/g, optimal reduction occurring at approximately pH 5 [20]. For antiobiotic could be found in some seafood like shrimp, photocatalytic activation of persulfate has recently been considered an effective and environmentally friendly approach for antibiotic decomposition, The results confirmed that CuFe-layered double hydroxide/ graphene oxide exhibited excellent performance for the persulfate activation with a trimethoprim removal efficiency of 90.8 % under UV-light irradiation [21]. Another popular treatment method is biological treatment, which is advantageous for being cost-effective, non-toxic, clean, and eco-friendly. The activated sludge biological treatment process is commonly used in seafood wastewater treatment due to its high organic matter removal efficiency. However, its efficiency in removing other contaminants is relatively low, achieving only 15–50 % removal of organic nitrogen and 10–20 % removal of phosphorus [22]. Employing anaerobic treatment first, followed by aerobic treatment, is an optimal approach for treating fish effluents. A combination of up-flow anaerobic sludge blanket reactors (UASBR), anaerobic filters (AF), and anaerobic fluidized bed reactors (AFBR) can generate biogas while achieving up to 90 % removal of organic substances [11]. However, these methods often require significant energy consumption, particularly those involving continuous aeration to maintain high dissolved oxygen levels. This leads to increased operational costs and a larger environmental footprint for the treatment process. The efficient operation of these systems also demands a high level of expertise and access to well-equipped laboratories [23], which can pose challenges in regions with limited resources. Additionally, while these methods are effective in treating wastewater, they produce a substantial amount of sludge, which creates environmental disposal challenges [24]. Moreover, the use of chemicals in some treatment processes can result in secondary pollution, further complicating wastewater treatment [25].

Anaerobic Membrane Bioreactors (AnMBRs) have demonstrated significant potential in wastewater treatment by integrating anaerobic processes with membrane filtration [26]. In recent years, AnMBR for municipal wastewater treatment is increasingly being researched as a cost-effective alternative to produce nutrient rich, solids free effluents with a high degree of pathogen removal, while occupying a small footprint [27]. AnMBRs achieved similar COD removal and methane yield as CSTRs but with higher OLRs and reduced hydraulic retention times (HRT) [28]. The use of membranes for biomass separation can enable the long sludge retention times (SRTs) needed to compensate for the low growth rates of anaerobic organisms while also producing solids-free wastewater [29]. It also exhibiting the ability to remove >98 % of influent COD in a single step [30]. This high efficiency is further enhanced by the production of substantial volumes of high-quality biogas through the anaerobic digestion of waste, which can serve as a renewable energy source, thereby improving the sustainability of the system [29]. In terms of effluent quality, AnMBRs outperform traditional commercial systems, producing superior quality effluent and demonstrating a longer membrane life cycle [31]. Additionally, their compact design requires less floor space compared to conventional systems and offers the added benefit of energy recovery from sewage [32]. AnMBRs can also be combined with the anoxic-oxic process to form the anaerobic-anoxic-oxic (A_2O) process, which increases treatment efficiency, minimizes CO_2 emissions [33], and treats harmful organic compounds such as N, N-dimethylformamide (DMF) [34], … These attributes collectively highlight the advantages of AnMBRs in wastewater treatment, particularly in applications where space and energy efficiency are critical. In this study, a pilot-scale AnMBR system with a capacity of 0.5 m^3/day was installed for the first time directly at a seafood processing factory in Vung Tau City, Vietnam. The system underwent a two-month operation period, with the first month dedicated to stabilizing its performance. Subsequently, the system operated daily to assess real-time performance, including hydraulic retention time (HRT) and organic loading rate (OLR). Throughout operation, samples were collected daily from the equalization tank and output for analysis of removal efficiency in the laboratory. Parameters such as TSS, COD, TN, TP, as well as sludge characteristics including SVI and MLSS were examined. The primary objective of the study was to evaluate the AnMBR system's effectiveness in removing organic and inorganic pollutants, particularly optimizing biomass separation, enhancing sustainability, maintaining long sludge retention times for anaerobic microorganisms, and producing superior effluent quality. The findings of this research provide a robust foundation for testing AnMBR technology on a practical scale, particularly in the context of seafood processing wastewater treatment.

2. Materials and methodology

2.1. Experimental pilot-model

The AnMBR system, which utilizes microorganisms from activated granular sludge sourced from the company's existing wastewater treatment system, employs a two-tank setup to manage seafood processing wastewater in this study, as shown in Fig. 1.

Wastewater is supplied by a submersible pump from the existing wastewater treatment system's equalization tank into the system's input wastewater tank, from where it is pumped into the anaerobic tank using a Lotus Pumps HT-75 24 V 1.8 L/min pump (China). The wastewater then enters the anaerobic tank, which has a height of 1500 mm and a

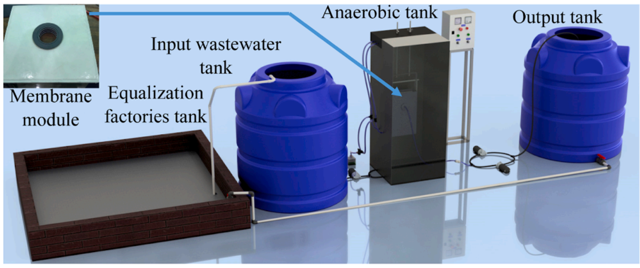


Fig. 1. AnMBR system for seafood processing wastewater treatment.

bottom measuring 600 × 600 mm, made of stainless steel 304 from Hoa Phat Steel Company (Vietnam). The tank's volume is 0.5 m^3 and contains a flat sheet membrane submerged to act as a filter. The flat sheet membrane, MANN+HUMMEL module NADIR UP150P (Germany), is made from polyethersulfone (PES) with an average membrane pore size of 0.1 μm and a surface area of 1 m^2. The combination of the anaerobic biological tank and the membrane filter ensures efficient sludge retention, mitigating biomass reduction. The membrane module is connected to Lotus Pumps HT-75 pumps, which operate on a 9-minute suction and 1-minute backwash cycle to minimize fouling [18]. Pressure gauge measurements update the membrane transmembrane pressure (TMP) every 5 min. The system operates automatically, with continuous monitoring of input and output values.

Operational details involve a continuous 60-day operation with varying hydraulic retention time (HRT) modes to assess contaminant removal effectiveness. Initially set at 24 h, the HRT gradually decreases over time. HRT plays an important role in AnMBR performance, as its values can vary depending on feed characteristics, system hydraulics, slurry properties, and other factors. HRT values can range from as low as 1 hour to as high as 30 days [35]. The conditions and operating modes of the model are described in detail in Table 1.

The study used seafood processing wastewater from Baseafood Company in Vung Tau City, which was rich in COD, organic nitrogen, and phosphorus, as shown in Table 2 below:

Wastewater sample is collected at 8:00 a.m. each morning from the system's input equalization tank and output tank to ensure uniformity of wastewater properties. The samples are then transported to the laboratory on the same day to minimize any potential changes in the physicochemical properties of the samples.

2.2. Analytical methods

Analytical methods are referenced in SMEWW 2017 Standard Methods for the Examination of Wastewater, the analyzed physical-chemical parameter are: COD, TN, NO_3^-, NO_2^-, NH_4^+, and TP [36]. COD was measured using closed reflux method using $K_2Cr_2O_7$ oxidation. TN was measured using Shimadzu TN 5000A analyser. NO_3^-, NO_2^-, NH_4^+ and TN were analyzed using ion chromatography Metrohm 940 Professional Vario, Switzerland. TDS was determined by Multiparameter Hanna HI9829–01,042, Italy. While determine TSS used the different between the mass of dry filter paper before and after filtration as in Eq.1 below [36]:

Table 1
Conditions and operating modes of AnMBR system.

Phase	HRT(h)	V (L)	OLR (mg/L.day)	Time (day)
1	24	500	1.200	15
2	12	500	2.400	15
3	10	500	2.880	15
4	8	500	3.600	15

Table 2
Average parameter of wastewater entering the AnMBR system.

No.	Parameters	Unit	Value
1	pH	–	5.5 – 8.0
2	TDS	g/l	2.46 – 5.89
3	TSS	mg/l	125 - 240
5	COD	mg/l	750 – 1750
6	TP	mg/l	28 - 40.6
7	TN	mg/l	149 - 300
8	NH_4^+	mg/l	3.5 – 5.53
9	NO_3^-	mg/l	4.39 – 4.88
10	NO_2^-	mg/l	3.5 – 6.2

$$TSS\left(\frac{mg}{L}\right) = \frac{Dry\ weight\ of\ residue\ and\ filter,\ g - \ dry\ weight\ of\ filter\ alone, g}{sample\ volume,\ mL} \tag{1}$$

Regarding biological sludge parameter MLSS, SVI)are often used. While MLSS are the concentration of suspended solids in mixed liquor, usually expressed in grams per liter, SVI is a very important indicator that determines the control or rate of desludging on how much sludge is to be returned to the anaerobic basin and how much to take it out from the system. The Eq.2 and Eq..3 which used for calculated MLSS and SVI are shown below [37]:

$$MLSS\left(\frac{mg}{L}\right) = \frac{(M_1 - M_0)\ \times\ 100}{V} \tag{2}$$

- MLSS: Mixed liquor suspended solids (mg/L).
- M_1: Weight of paper sample with biomass (g).
- M_0: Weight of paper sample without biomass (g).
- V: Sample volume (ml).

$$SVI = \frac{SV30\ \times\ 1000}{MLSS} \tag{3}$$

- SVI: Sludge Volume Index, mL/g
- SV30: Volume of settled solids in one-liter graduated transparent measuring cylinder after 30 min settling period, mL/L.

3. Results and discussion

3.1. Sludge index

After a short period of adaptation to the backflow, the particles continued to grow, and the TSS fraction increased over time. The MLSS value increased steadily from 10.5 g/L to 11.5 g/L and continued to rise. The MLSS range was around 2.5–9.0 g/L for high-strength synthetic wastewater [38], and about 10.3 g/L for non-azo textile wastewater [39]. The sludge volume index (SVI) decreased on the 20th day because the sludge had not fully adapted to the treatment tank environment, but it increased rapidly in the following period. The initial decrease in SVI, followed by a rapid increase, suggests that the activated sludge in the anaerobic biological reactor adapted quickly. The results show that the SVI value posed a potential risk of pin-floc occurrence ($SVI < 100$ mg/L), but with the concentration of seafood processing wastewater fluctuating continuously, stabilizing the biomass concentration at a low level helped limit overload during daily sludge storage [40]. Moreover, the sludge granules were a key factor in the start-up and stability of the AnMBR [41]. The microbial community's stability under varying operational conditions is another concern, necessitating detailed profiling using metagenomic tools to identify key functional species and optimize reactor conditions as shown in Fig. 2.

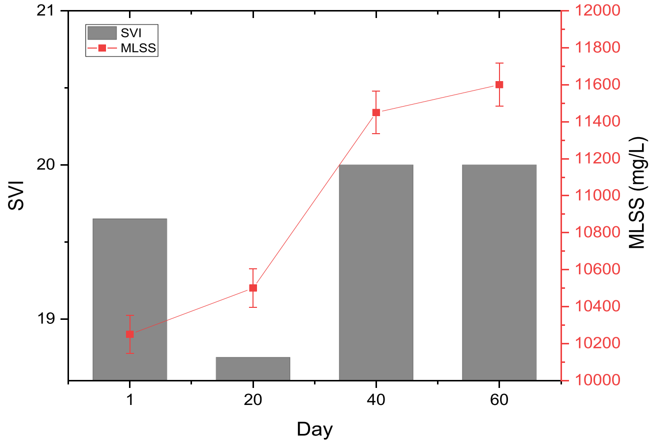


Fig. 2. Sludge index in AnMBR system including SVI and MLSS.

3.2. Pollutant removal efficiency

3.2.1. Total solids

Total Solids (TS) is a critical parameter in wastewater management and refers to the total amount of solids present in a water sample. It includes both TSS and TDS. TDS in wastewater refers to the total amount of mobile charged ions, including minerals, salts, or metals, dissolved in a given volume of water [36]. During the first phase of the process, the TDS began at a level of 3 g/L and increased to 5 g/L by the end of the phase. The output during this phase fluctuated between 1.8 g/L and 3.5 g/L. In the subsequent phase, the input TDS reached a peak of 6 g/L, while the output remained relatively low at 2 g/L. For the remaining phases, the input TDS oscillated between 5.0 and 5.5 g/L before decreasing to 2.5 g/L. The average efficiency of TDS removal throughout the process was approximately 32.02 ± 17.42 %. The lower efficiency could potentially be attributed to the membrane in the system becoming clogged or fouled [42]. Addressing this requires investigating fouling mechanisms and implementing mitigation strategies such as improved cleaning protocols, pretreatment optimization, or using membranes with higher selectivity for dissolved solids.

The TSS concentration of wastewater has been reported to be the main factor affecting clogging [43]. An increase in particle concentration leads to an increase in the convection flow of solids towards the membrane surface and enhanced fouling formation. The data presented in Fig. 3 indicates that the influent concentration fluctuated significantly, ranging from 100 to 250 mg/L with no discernible pattern on a daily basis. Despite these variations, the system consistently demonstrated a high treatment efficiency, achieving a removal rate of over 99 %, as evidenced by effluent concentrations consistently below 1 mg/L.

In other AnMBR trials, TSS removal efficiency reach 99.2 % [29], Ozgun et al. found that AnMBR systems removed 98–99.5 % of TSS, while conventional systems struggled with fluctuating removal rates, especially during peak load periods [27]. Although the results of the system are still low, when the output is still low, previous studies have only tested on urban wastewater or have low pollution concentrations and are more stable than seafood processing wastewater. Therefore, the fact that the study achieved such efficiency at the beginning is a positive sign and a premise for the future.

3.2.2. Chemical oxygen demand

The organic substances in the wastewater are biodegraded by anaerobic bacteria. These bacteria break down the organic substances to generate energy and build their cell structures. Additionally, the membrane separates the treated effluent from the activated sludge, effectively removing landfill leachate [44] and dissolved organic matter [45]. COD parameter values before and after treatment during the 60-day operating period are shown in Fig. 4. The surveyed COD content ranged from 1000 mg/L to 1500 mg/L, with results after treatment ranging from 200 to 500 mg/L. The input COD fluctuated quite a bit; however, the output COD was treated to a relatively low concentration. COD removal efficiency ranged from 50 % to 80 %, with an average value of 59.91 ± 6.96 %. In comparison with other studies, COD

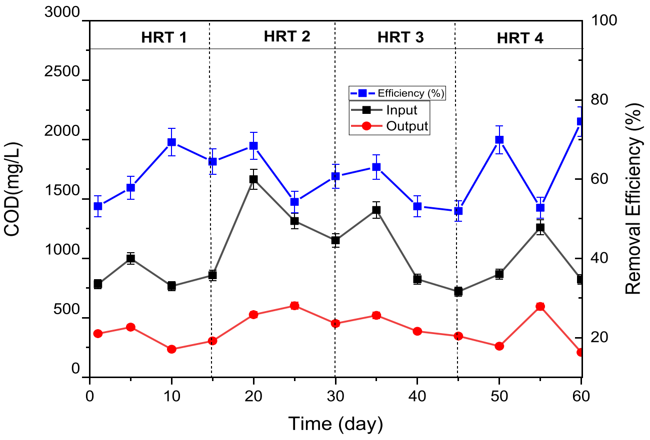


Fig. 4. COD removal efficiency.

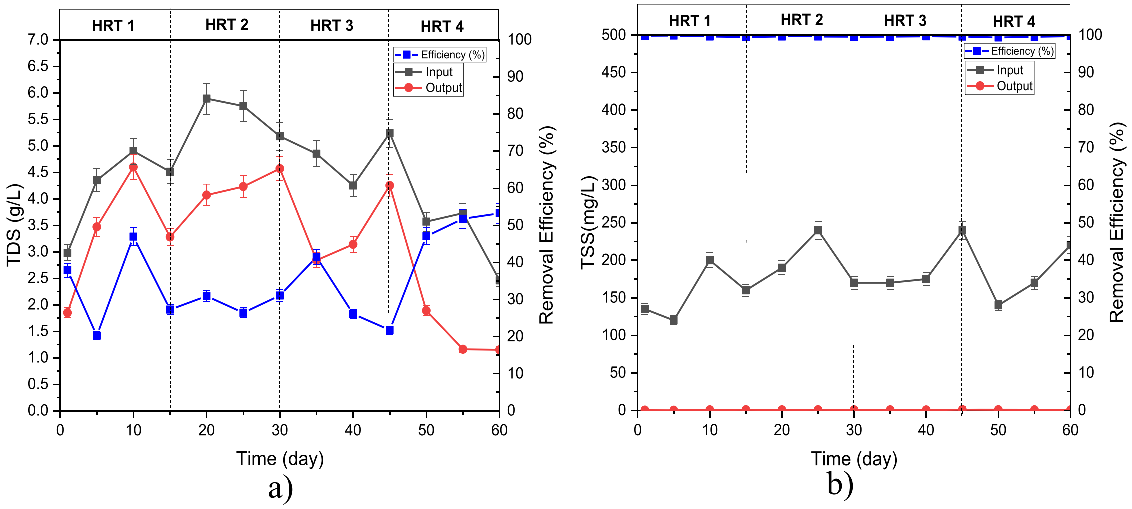


Fig. 3. Removal efficiency of: a) TDS; b) TSS.

removal efficiency was 65.9–88.8 % for liquor condensate wastewater with an integrated ceramic membrane AnBB-MBR system [46], while lower than 75 % was achieved with the ceramic integrated AnMBR system [47]. In studies using UF filters, when tested with the AnMBR system with an integrated 0.05 μm filter membrane, the removal efficiency was 45 % [48], or 61.3 % when treating wastewater from landfill leachates with a PVDF UF membrane [49]. There are several reasons that may explain the lower COD removal efficiency in this study. However, the high load of seafood processing wastewater must be the main factor, as it increases the likelihood of membrane fouling. This fouling reduces the system's ability to effectively separate and degrade pollutants, limiting microbial contact with the substrate and decreasing the overall efficiency of COD removal.

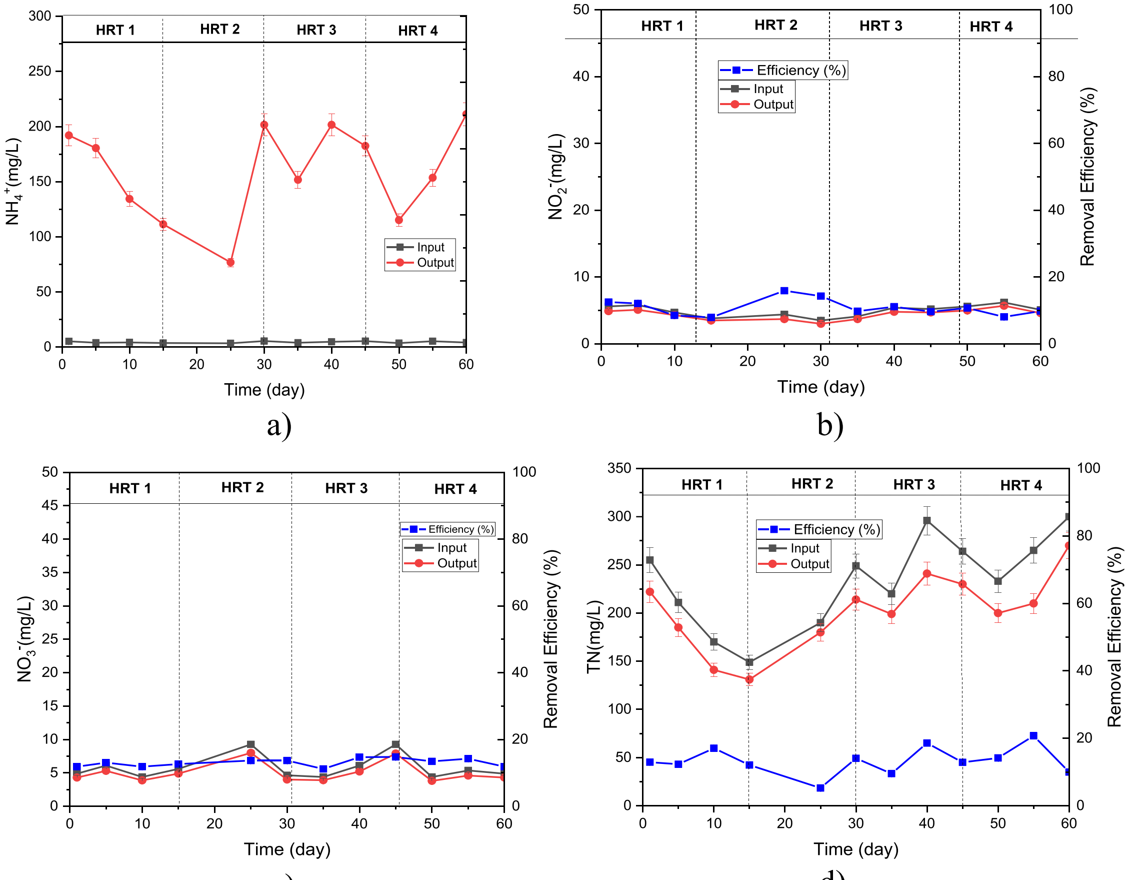
3.2.3. Nitrogen compounds

Nitrogen removal primarily occurs through several key processes. First, ammonification breaks down organic nitrogen compounds, such as proteins and amino acids, into ammonium (NH_4^+) by anaerobic microorganisms. Although denitrification can occur when nitrate (NO_3^-) is present and used as an electron acceptor, the anaerobic environment typically limits this process, as nitrification (the oxidation of ammonia to nitrate) requires oxygen, resulting in incomplete denitrification. Additionally, some ammonium (NH_4^+) is assimilated by biomass, where it is used for microbial growth, though this process is also limited under anaerobic conditions. Finally, ammonia stripping can occur at higher pH levels, where ammonia (NH_3) volatilizes and is removed from the system as a gas. The overall denitrification reaction can be represented as follows (Eq. (4)) [50]:

$$5NO_3^- + 12H^+ + 6e^- \rightarrow 2.5N_2 + 6H_2O \tag{4}$$

In more detail, Fig. 5 illustrates the transformation of TN into NH_4^+, NO_3^-, and NO_2^- through the denitrification process. The NH_4^+ concentration, which constitutes a significant percentage of the TN, oscillates between 3.5 and 5.525 mg/L, with the output ranging from around 40 to 110 mg/L. This can be explained by the transformation of organic nitrogen into ammonium in the anaerobic environment [51]. In the case of NO_2^-, the input concentration ranges from 3.5 to 6.2 mg/L, while the output fluctuates between 3 and 5.7 mg/L. The removal efficiency for NO_2^- is not consistent, as NO_2^- can be converted to N_2 during the denitrification process, resulting in an overall efficiency of about 10.85 ± 2.37 %. For NO_3^-, the difference between the input and output values is approximately 10 mg/L. However, due to the lower value range (fluctuating between 1 and 2 mg/L), the average removal efficiency stands at 13.08 ± 1.16 %. When examining the HRT phases, performance fluctuates with each phase. This can be attributed to the dynamics of nitrogen metabolism.

The input TN value ranges from 149 to 300 mg/L, while the output is around 201.92 mg/L. The daily efficiency also witnesses fluctuations. This can be explained by the variation in the concentration of input wastewater, which makes it difficult for the microorganisms in granular sludge to adapt. Additionally, the AnMBR treatment process is anaerobic, so the amount of oxygen is limited, affecting the growth of biological bacteria and also limiting the denitrification process, where the transformation of nitrogen occurs, starting from ammonia to nitrate, nitrite, and nitrogen. Specific bacteria, such as *Nitrobacter, Yeast*, and *Bacillus subtilis*, were used to achieve an efficiency of 81.53 % [52]. When compared to previous studies, the TN removal efficiency of around 37.32 ± 6.69 % is higher than that of an AnMBR system with a PVDF UF tubular membrane used to treat lab-made wastewater, which had an efficiency of 16.5 % [53]. A study by J. Li et al. showed that a



a)

b)

c)

d)

Fig. 5. Removal efficiency of: a) NH_4^+, b) NO_2^-, c) NO_3^- d) TN.

combined anaerobic baffled reactor–membrane bioreactor process achieved average removal rates of 79 % for TN [54]. In addition, Z. Sun et al. reported 68.5 % TN removal in municipal wastewater [55]. However, as seafood wastewater contains large amounts of suspended solids and organic matter, the treatment efficiency is considered acceptable. Elevated ammonium levels post-treatment highlight inefficiencies in degradation pathways. Incorporating an aerobic polishing step or promoting ammonium-oxidizing processes, such as anammox, could enhance removal.

3.2.4. *Total phosphorus*

Phosphorus removal in AnMBR is typically achieved through the process of enhanced biological phosphorus removal (EBPR). This involves the uptake of phosphate (PO_4^{3-}) by polyphosphate-accumulating organisms (PAOs) under alternating anaerobic and aerobic conditions. During the anaerobic phase, PAOs take up volatile fatty acids (VFAs) and release stored phosphate into the medium. In the subsequent aerobic phase, they take up phosphate from the medium and store it intracellularly as polyphosphate. The chemical equation for aerobic phosphate uptake is described in Eq. 5 [56]:

$$H_2O + ATP \rightarrow ADP + HPO_4^{2-} + H^+ \tag{5}$$

In Fig. 6, the input values range from 28 to 40.6 mg/L, while the output ranges from 23.94 to 35 mg/L. Similarly, the TP treatment efficiency of the system is about 11.12 ± 2.46 %, compared with 38.94 % in another report [52]. The reasons for this trend are similar to those observed in total nitrogen treatment, with factors such as the limited oxygen supply and the slow kinetic processes involved in phosphorus treatment [57]. Additionally, the research was conducted under real conditions with high and difficult-to-control pollutant discharges in the input wastewater on consecutive days, making it challenging for microorganisms to adapt. For example, in HRT 2, the input wastewater concentration gradually increased, leading to a steady decrease in treatment efficiency, which continued even at the end of HRT 4. In comparison to certain studies, alternative strategies for reducing chemical usage in phosphorus removal have been explored, including enhanced biological phosphorus removal [58]. Notably, biopolymers like hydrogel and adsorbent substances such as ferric-calcium-based biochar have demonstrated considerable potential [59]. These methods have achieved approximately 60 % or higher efficiency in phosphorus removal [60]. Therefore, it can be seen that the method of applying AnMBR alone in this direct wastewater process does not give a really high efficiency. However, this is just a premise to be able to upgrade the efficiency for future studies. In addition, the current process does not use any chemical compounds in the treatment process, so it can be called "Green chemistry treatment" which is very friendly and towards sustainable development. In the future, a post-treatment stage based on an advanced aerobic/anaerobic (A/O) process or coagulation should be added in the system. This stage will utilize a combination of aerobic and anaerobic conditions or coagulation to optimize phosphorus removal performance. This is particularly useful for lowering the total phosphorus concentration in the effluent to meet strict environmental standards as shown in Fig. 7.

3.3. *Membrane properties*

3.3.1. *Flux*

Flux, which indicates the quantity of wastewater that passes through a specific area of a filter, is crucial for assessing the applicability of a filter in treating wastewater with high levels of suspended solids and organics [61]. Initially, the flow rate was 19 L/m^2.h, but it consistently decreased in the subsequent days to 17.4 L/m^2.h. Membrane cleaning was performed to maintain operation, and a similar decreasing trend in flux was observed, reaching 17.4 L/m^2.h on the 40th day. The final observed flux was 18 L/m^2.h, with an average of approximately 18.2 ± 0.41 L/m^2.h. When compared with the study of J. Zhou [62], the flux value continuously decreased from 32 L/m^2.h to approximately 15 L/m^2.h when applied to treat high-strength wastewater. It is evident that the flux and TMP trends are similar due to the significant amount of organic pollutants and biofouling in the seafood processing wastewater, which block the membrane's pore size and highlight the importance of the backwash mechanism. Through the chart above, it can be seen that the maintenance and cleaning of the filter membrane plays an important role in maintaining the treatment efficiency of the system. Going into more detail, when the Flux value continuously decreases for 5–6 days, the membrane must be backwashed and cleaned with low concentration NaClO chemical to ensure that the pores of the filter membrane are not blocked by wastewater. This can help the filter membrane relieve pressure in addition to the backwash cycle of 9 min of filtration and 1 min of backwash. Helps the system operate continuously for a long time as shown in Fig. 8.

3.3.2. *Transmembrane pressure (TMP)*

The transmembrane pressure (TMP) value represents the resistance to flow due to membrane surface 'fouling' and membrane channel 'clogging'. It can be observed that the TMP value increases rapidly from 0.6 on the first day to 0.65 on the fifth day, reaching a peak of 0.7 on the twelfth day. At this point, membrane cleaning must be performed due to concerns about reduced efficiency and potential damage to the filter membrane. After cleaning the membrane using the backwash mechanism and NaOCl 1 % if the fouling is too thick [63], NaOCl is effective for cleaning biological and organic fouling in membranes due to its strong oxidizing and biocidal properties [64]. It breaks down organic molecules like proteins and fats, while also killing biofilm-forming microorganisms. It disrupts the extracellular polymeric substances (EPS) in biofilms, facilitating easier removal. However, NaOCl must be used carefully to

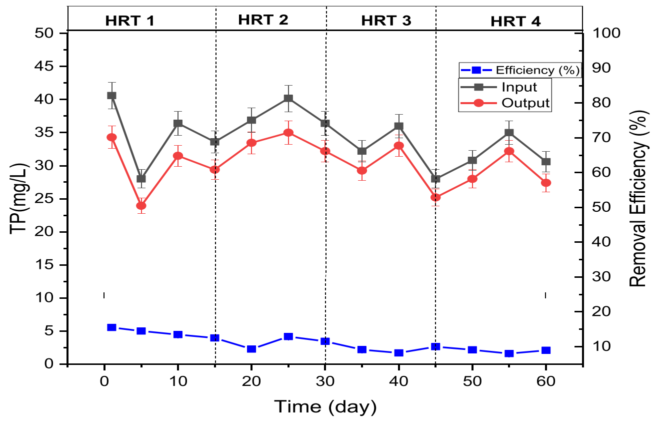


Fig. 6. TP removal efficiency.

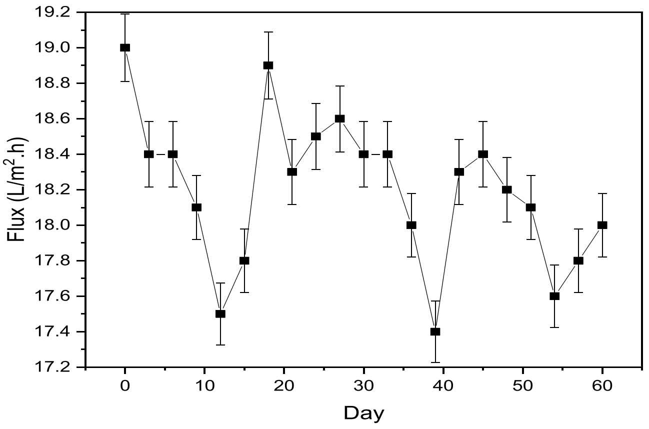


Fig. 7. Flux value of flat sheet membrane.

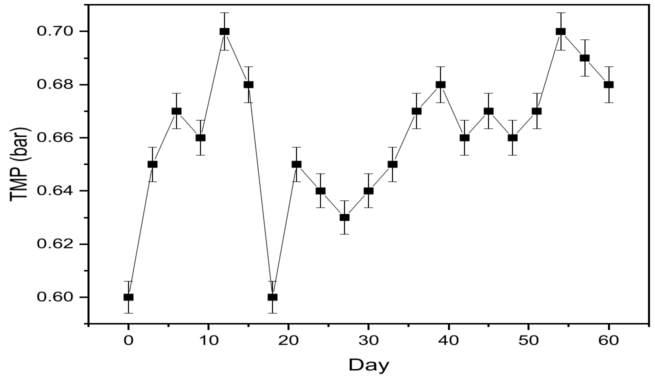


Fig. 8. TMP value of flat sheet membrane.

avoid damaging sensitive membrane materials. After cleaning, the TMP value returns to 0.6 and continues to increase but remains unstable, reaching 0.68 on the fourteenth day. Towards the end of the cycle, it can be seen that after cleaning the membrane, the TMP value does not return to 0.6 but hovers around 0.66 bar This can be explained by the high concentration of wastewater, causing dirt particles to become stuck in the filter pores of the membrane. In summary, the average TMP value achieved by the filter membrane is 0.66 ± 0.02 bar R. Fox et al. reported that the TMP increased continuously from 0.02 bar to 0.8 bar; however, due to testing only on low-strength wastewater, the pressure returned to 0.01 bar after backwashing at the end of the cycle. Therefore, the pressure achieved in this study is consistent with operating conditions, and further testing is needed to limit membrane clogging [65]. Similar to the flux value, the TMP value also needs to be continuously surveyed to be able to evaluate the quality of the filter membrane. When the TMP value is high for a long time, the filter membrane needs to be cleaned similar to the flux value to lower the TMP value to a safe value. Avoid tearing the filter membrane, which greatly affects the efficiency of wastewater treatment as shown in Table 3.

3.4. Comparing output effluent with Vietnamese national discharge standard for seafood processing wastewater

The performance of the AnMBR system will be compared against the established output Vietnamese discharge standards for pollution parameters in seafood processing wastewater, as outlined in QCVN 11-MT:2015/BTNMT, Column B. These standards specifically apply to wastewater discharged into water sources that are not used for domestic water supply purposes.

The AnMBR system exhibited a removal efficiency of 32.02 % for TDS, yielding an average output concentration of 3.12 g/L. In the case of TSS, the system demonstrated a commendable removal efficiency of 99.63 %, reducing the concentration to an average of 0.67 mg/L, which is well within the prescribed limit of 100 mg/L. The removal efficiency for TP was recorded at 11.12 %, with an average output concentration of 29.58 mg/L, slightly higher than the standard limit of 20 mg/L.

In addition, the removal of COD was 61.04 %, with an average output concentration of 404.88 mg/L, which exceeds the standard limit of 150 mg/L. This indicates a potential area for improvement, as previous studies have shown that AnMBR systems can achieve higher COD removal efficiencies with integrated pre-treatment strategies [66]. Furthermore, the removal efficiency for TN was 13.30 %, with an average output concentration of 201.92 mg/L, surpassing the standard limit of 60 mg/L. The removal efficiencies for Nitrate (NO_3^-) and Nitrite (NO_2^-) were 13.03 % and 10.85 %, respectively, with average output concentrations of 5 mg/L and 4.41 mg/L. However, the system was not effective in treating NH_4^+.

The study's omission of biogas recovery, a key advantage of anaerobic systems, limits its sustainability analysis. Future research should focus on strategies to maximize biogas yield, such as co-digestion, optimizing organic loading rates, and integrating energy recovery systems. This would enhance the system's overall efficiency and economic viability.

3.5. Conclusion

In conclusion, the research highlights the critical influence of pH, nitrogen concentration, and various wastewater indicators on biological treatment processes, particularly in the context of Basefood seafood processing factory. The findings demonstrate promising removal efficiencies for TSS and COD, with TSS removal reaching approximately 99 %, but show poor efficiency for organic contaminants, including TN, TP, NH_4^+, NO_3^-, and NO_2^-. Additionally, operational conditions of the membrane, including a flux of around 18.2 L/m^2·h and a TMP of 0.66 bar, should be considered.

However, challenges such as microorganism adaptation in real-time wastewater, energy costs, gas recovery, and the treatment efficiency of nitrogen and phosphorus content highlight areas for further research and improvement. Addressing these challenges will be crucial for transforming AnMBR technology into an energy-efficient system. Monitoring additional indicators, such as sludge particle size and gas production, will be essential for a more accurate assessment of system performance.

Factors like HRT, dissolved methane recovery membranes, and the interplay of sulfides, pH, alkalinity, ammonia, and long-chain fatty acids must be carefully considered to overcome current limitations. The

Table 3
Compare Efficiency of AnMBR system with Vietnam standard for treated seafood wastewater for discharging into environment.

No.		Unit	Input range (mg/L)	This study		Vietnam standard for treated seafood wastewater for discharging into environment (QCVN 11-MT:2015/BTNMT. Column B
				Average output	Removal Efficiency (%)	
1.	TDS	g/l	2.46 – 5.89	4.44	32.02	–
2.	TSS	mg/l	120 - 240	0.67	99.63	100
3.	COD	mg/l	750 – 1750	404.88	61.04	150
4.	TP	mg/l	28 – 40.6	30.26	11.12	20
5.	TN	mg/l	149 - 300	201.92	13.3	60
6.	NH_4^+	mg/l	3.5 – 5.525	83	–	20
7.	NO_2^-	mg/l	3.5 – 6.2	4.41	10.85	–
8.	NO_3^-	mg/l	4.39 – 9.27	5	13.08	–

findings provide a strong foundation for further exploration and eventual full-scale implementation of AnMBR technology, offering promise for sustainable and efficient wastewater management practices within the seafood processing sector. The system could meet two parameter requirements of Vietnam's output discharge standard for seafood wastewater (Column B). As wastewater treatment technologies continue to evolve, ongoing research and advancements in AnMBR hold promise for enhancing overall efficiency and sustainability in industrial wastewater treatment.

CRediT authorship contribution statement

Tran Thi Thai Hang: Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Vien Vinh Phat:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Nguyen Anh Dao:** Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Huynh Hieu Hanh:** Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Nguyen Nhat Thoai:** Formal analysis, Data curation, Conceptualization. **Pham Tien Hung:** Formal analysis, Data curation, Conceptualization. **Dao Van Tri:** Software, Resources, Project administration, Data curation. **Tran Le Luu:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Tran Hung Thuan:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition. **Nguyen Van Tuyen:** Supervision, Project administration, Formal analysis, Conceptualization. **Chu Xuan Quang:** Resources, Project administration, Methodology, Conceptualization. **Maria Francesca Vigile:** Supervision, Project administration, Methodology, Conceptualization. **Alfredo Cassano:** Supervision, Project administration, Conceptualization. **Francesco Galiano:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Alberto Figoli:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The Authors have no interests to declare. There are no conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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Data availability

Data will be made available on request.

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