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Harnessing Microalgae Photobioreactors to Address Rising Sludge and Fouling Challenges in Membrane Bioreactors

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Abstract. This study explored the application of microalgal engineering in a photobioreactor to mitigate rising sludge and fouling issues in a Wastewater Treatment Plant (WWTP). By introducing microalgae into the activated sludge of a Moving Bed Biofilm Reactor (MBBR), this study aimed to enhance the dissolved oxygen content within the MBBR, which was a critical factor for optimizing the reduction of Chemical Oxygen Demand (COD) and Biochemical Oxygen Demand (BOD) in wastewater. During the microalgae cultivation phase, *Chlorella* sp. was cultured with adding nutrients, including urea and TSP. Upon reaching a sufficient Mixed Liquor Suspended Solids (MLSS) concentration, microalgae were inoculated into the MBBR. The research results demonstrated an improvement in the quality of the effluent and a reduction in rising sludge within the clarifier, coinciding with an increase in dissolved oxygen content exceeding 2 mg/L. Cost-benefit analysis revealed a significant reduction in WWTP operational costs, primarily due to the discontinuation of two blowers that were previously operated. This study encourages the utilization of microalgae in MBBRs as a potential solution to reduce operational costs in the wastewater treatment industry.

Keywords: Fouling, MBBR, Microalgae, Photobioreactor, Rising Sludge, Wastewater

INTRODUCTION

Wastewater treatment is a critical component of environmental conservation and human health. Effective removal of organic matter and nutrients is a fundamental requirement in wastewater treatment processes to safeguard water resources and aquatic ecosystems. Conventional methods, such as the widely used Conventional

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Activated Sludge (CAS) process (Wang *et al.*, 2022), have traditionally been used for this purpose. However, these conventional processes often struggle to eliminate micropollutants from wastewater efficiently, leading to adverse consequences for aquatic life and public health (Edefell *et al.*, 2021; Muharja *et al.*, 2022).

Microalgae-based technology has emerged as a promising and sustainable alternative for wastewater treatment (Abdelfattah *et al.*, 2023). Microalgae offer the advantage of biotreatment while simultaneously producing biomass that can be harnessed for various applications, thereby contributing to reduced greenhouse gas emissions (Chai *et al.*, 2021; Hussain *et al.*, 2021; Muharja *et al.*, 2020). Nonetheless, the nutrient removal efficiency of microalgae-based systems, particularly concerning parameters such as biochemical oxygen demand (BOD), chemical oxygen demand (COD), total phosphorus (TP), and phosphate (PO_4-P), often falls short of the efficiency achieved by conventional methods (Sinn *et al.*, 2023).

To address these limitations and confront the challenges of wastewater treatment, the Moving Bed Biofilm Reactor (MBBR) has emerged as a highly promising biological treatment technology that surpasses the performance of CAS (Chandran *et al.*, 2023; Pilli *et al.*, 2020). MBBR systems foster the growth of biofilms or microorganisms on carriers, leading to enhanced biodegradation (Liang *et al.*, 2021; Masmoudi Jabri *et al.*, 2019). MBBR has demonstrated potential for reducing COD, BOD_5, and nutrient pollutants. Nonetheless, MBBR systems encounter challenges, such as rising sludge during denitrification, where sludge particles adhere to nitrogen gas bubbles and rise to the surface (An *et al.*, 2022), and membrane fouling, a process in which particles, microorganisms, organic substances, or inorganic compounds accumulate on or adhere to membrane surfaces, reducing filtration efficiency (Kovacs *et al.*, 2022).

In wastewater treatment, microalgae photobioreactors (MPBR) have gained significant attention in recent research. These systems provide a sustainable and efficient method for remediating wastewater while facilitating nutrient recovery (Goh *et al.*, 2022). MPBR harnesses the photosynthetic abilities of microalgae to eliminate contaminants and organic matter from wastewater, thereby enhancing water quality (Leyva-díaz *et al.*, 2022). Incorporating microalgae in PBRs has been acknowledged for its potential in nutrient removal, especially in scenarios where heavy metals like Zn, Cu, and As could affect microbial communities and nutrient removal efficiency (Collao *et al.*, 2022). On the other hand, the integration of co-culture systems involving bacteria and microalgae has shown promising results. These systems leverage the synergistic interactions between microalgae and bacteria to enhance nutrient removal and treatment efficiency. Co-culturing microalgae with bacteria has been demonstrated to lead to higher nutrient removal rates, particularly nitrogen and phosphorus, which are crucial components in wastewater treatment (Santo *et al.*, 2022). Therefore, this finding leads to potential co-culture systems in MPBR and MBBR.

This study investigated the integration of microalgal photobioreactors (MPBRs) to address these challenges and enhance the performance of MBBRs. Microalgae, known for their rapid growth and photosynthetic capabilities, can effectively extract nutrients, such as phosphorus and nitrogen, from wastewater (Wang *et al.*, 2023). The incorporation of MPBRs into MBBRs has the potential to harness the bioenergy contained within microalgae, offering a more efficient and sustainable approach to wastewater treatment (Alimny *et al.*, 2019; Muharja *et al.*, 2017).

The primary objective of this study was to evaluate the efficacy of microalgal photobioreactors in addressing rising sludge and membrane fouling issues in MBBRs, ultimately improving the overall wastewater treatment performance. Additionally, this study aimed to identify the key factors influencing the efficiency of microalgal technology in wastewater treatment and assess its impact on energy consumption. In doing so, this study was expected to contribute to developing environmentally friendly and sustainable wastewater treatment practices. The significance of this study lies in its potential to advance wastewater treatment practices, contribute to environmental sustainability, and provide valuable insights for future research in this field.

MATERIALS AND METHODS

Materials

The materials used in this study included *Chlorella sp.*, sodium hydroxide (99%, Merck), aluminum sulfate (99%, Merck), potassium dichromate (99%, Merck), sulfuric acid (98.5%, Merck), mercury(II) sulfate (99%, Merck), silver sulfate (99%, Merck), sulfamic acid (99%, Merck), potassium hydrogen phthalate (99%, Merck), sodium fluoride anhydrous (99%, Merck), sodium 2-(para-sulfophenylazo)-1,8-dihydroxy-3,6-naphthalene disulfonate (99%, Merck), zirconium(IV) oxide chloride octahydrate (99%, Merck), sodium arsenite (99%, Merck), hydrochloric acid (37%, Merck), ethanol (70%, Onemed), urea (99%, Merck), and sodium phosphate (99%, Merck).

Experimental Set Up

This study performed a rising sludge and fouling test using a Moving Bed Biofilm Reactor-Membrane Bioreactor (MBBR-MBR). The experimental setup, shown in Figure 1, had a flow rate capacity of 100 L/day, a hydraulic retention time of 6 hours, and an organic loading rate of 3.2 kgCOD/m^3/day. Dissolved oxygen (DO) in the MBBR was controlled within the 2-4 mgO_2/L range.

In designing the incorporation of microalgae into the activated sludge in the MBBR, 1000 mg/L of microalgae was added to 3000 mg/L of activated sludge. The percentage of microalgae-to-activated sludge was set at 1-5%. The required amount of microalgae to be added to the MBBR tank, with WWTP capacity of 100 L/day, was 0.025 L, with a MLSS of 1000 mg/L, as formulated in Eq. (1).

Evaluation of DO, COD Removal, and Rising Sludge in the MBBR Process

In this study, the evaluations of DO and COD removal were conducted in an MBBR. First, wastewater of COD concentration of 800 mg/L was fed into the MBBR. During the operation, the blower was disabled for 300 minutes. DO and COD levels were analyzed every 30 minutes. DO was measured using a digital DO meter, and COD analysis was conducted according to Standard Nasional Indonesia (SNI) 6989.02:2019. The equation used to calculate the efficiency of COD removal is shown in Eq. 2.

$$\text{Eff. of COD removal} = \frac{(C_f - C_p)}{C_f} \times 100\% \quad (2)$$

Where Cf and Cp are the feed and permeate concentrations, respectively.

$$V\ Microalgae = \frac{The\ nutrient\ requirements\ of\ microalgae\ \left(\frac{kg}{day}\right)}{The\ density\ of\ microalgae\ in\ water\ \left(\frac{kg}{m^3}\right)} \quad (1)$$

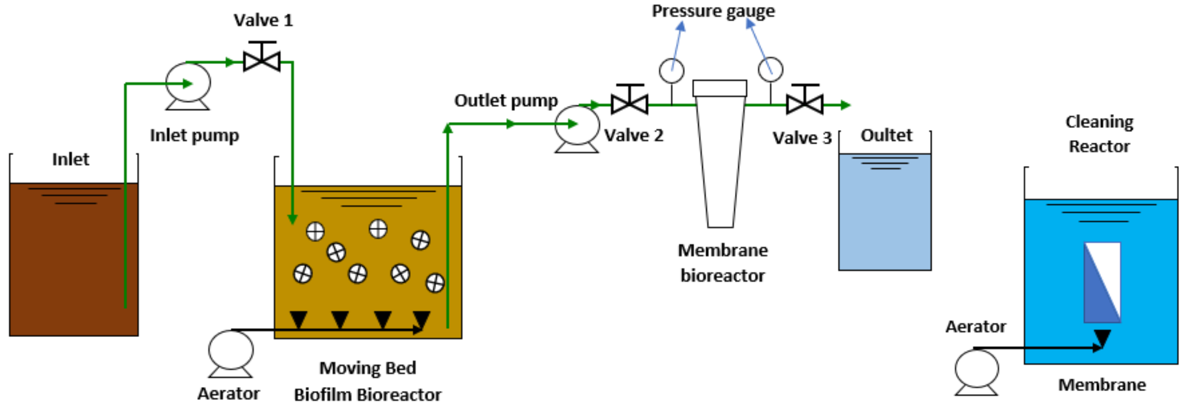

Fig. 1: The experimental set-up

Following that, every day for 9 days, DO levels were analyzed, and TSS from the settling steps after the biological process in the MBBR was measured. TSS was analyzed to assess rising sludge. The TSS analysis was conducted according to Standard Nasional Indonesia (SNI) 06-6989.3-2004.

Permeate Flux and Fouling Evaluation in MBR

In this study, permeate flux tests were conducted three times. The first test involved measuring permeate flux with pure water. The second test followed the study conducted by Rachman *et al.* (2024); however, in this study, microalgae were added to the activated sludge at a ratio of 1:3. The third test was similar to the first. The equation for calculating permeate flux performance is provided in Eq. 3.

$$J = \frac{V}{A \times t} \quad (3)$$

Where V is the permeate volume (liters), A is the membrane area (m^2), and t is the filtration time (hours) (Darmayanti *et al.*, 2023). To evaluate membrane fouling, the flux recovery ratio (FRR), reversible fouling ratio (RFR), and irreversible fouling ratio (IFR) were calculated using Eq. (4), (5), and (6), respectively.

$$FRR = \frac{J_{w1}}{J_{w2}} \times 100\% \quad (4)$$

$$RFR = \frac{J_{w2} - J}{J_{w1}} \times 100\% \quad (5)$$

$$IFR = \frac{J_{w1} - J_{w2}}{J_{w1}} \times 100\% \quad (6)$$

Where J_{w1} is the water flux in the first step (L/h·m^2), J_{w2} is the water flux in the third step (L/h·m^2), and J is the wastewater flux in the second step (L/h·m^2) (Darmayanti *et al.*, 2023; Rachman *et al.*, 2024).

RESULTS AND DISCUSSION

Chlorella sp. Growth Curve

Figure 2 displays the concentration of Mixed Liquor Suspended Solids (MLSS) of *Chlorella* sp. microalgae in the cultivation tank. Based on Figure 2, optimal microalgae growth occurs on days 25 and 30, reaching

1,300 mg/L MLSS of microalgae. The increase in *Chlorella* sp. microalgae was directly proportional to the MLSS concentration. When microalgae come into contact with wastewater, they efficiently utilize organic matter for growth. Microalgae require sufficient time to reproduce and meet nutrient requirements. These findings align with the research conducted by Wang *et al.* (2020), which states that the relative stability of the MLSS increase is due to the balance between the symbiotic growth of algae-bacteria and mineral accumulation. The decrease in MLSS microalgae on day 26 can be influenced by the death phase and/or a limited nutrient supply. This aligns with the study conducted by Zou *et al.* (2022), which indicated that the MLSS increased gradually during the first 22 days. On the 23rd day, microalgae began to die and decompose, leading to a decrease in the MLSS content.

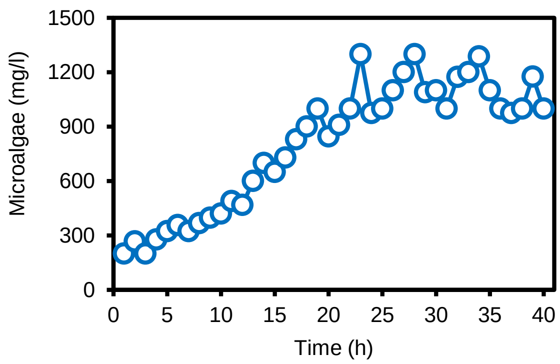

Fig. 2: Concentration of Mixed Liquor Suspended Solids (MLSS) of microalgae

Impact of Microalgae Addition on Organic Pollutant Biodegradation

Figure 3a illustrates the analysis of Dissolved Oxygen (DO) before and after the microalgae addition. The DO analysis results before the microalgae addition indicated a concentration of 1.6 mg/L, which accumulated to 14.55 mg/L on the last day. After adding microalgae, the DO values reached 5.9 mg/L, accumulating to 53.3 mg/L on the final day. This indicated that microalgae increased DO levels as microalgae produced oxygen gas through photosynthesis. The increased DO concentration aided the efficiency of activated sludge in reducing BOD and COD. The results aligned with the quality of the effluent, which appeared cloudy before microalgae addition and became clear after the addition of microalgae. The rise in DO levels was attributed to the release of photosynthetic oxygen by microalgae, with an increase rate of 0.75 mg/L, 0.5 mg/L, and 1.13 mg/L per day (Otondo *et al.*, 2018). According to previous research, adding microalgae increases dissolved oxygen during the daytime due to microalgae photosynthesis, which releases oxygen (Huang *et al.*, 2022; Kaur Nagi *et al.*, 2021).

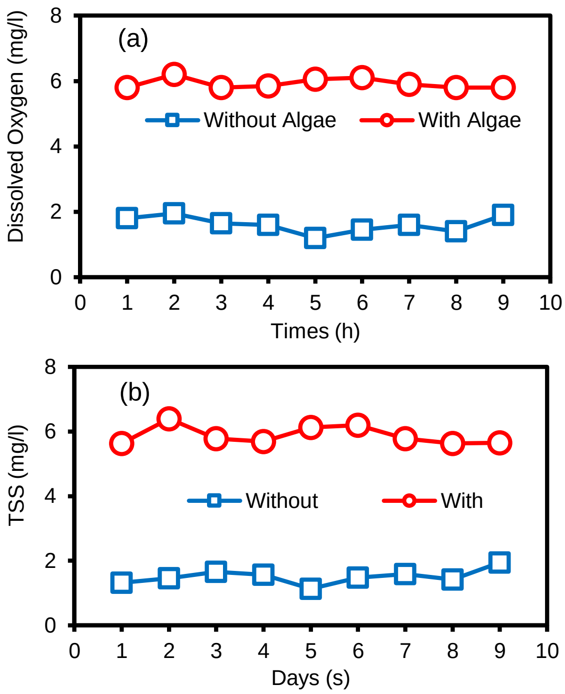

Fig. 3: Analysis of Dissolved Oxygen (DO) (a), and Total Suspended Solid (TSS) (b) before and after microalgae addition

Figure 3b presents the analysis of rising sludge in the clarifier, with Total Suspended Solids (TSS) outlet measurements. Based on

Figure 3b, the amount of TSS or sludge particles settling in the clarifier tank increased with the microalgae addition. Before microalgae addition, the TSS value was 1.5 mg/L, and after microalgae addition, the TSS value in the clarifier tank rose to 5.87 mg/L. The increase in TSS in the clarifier tank was attributed to the activity of microalgae, which release polysaccharides responsible for bio-flocculation, leading to TSS sedimentation (Dlangamandla *et al.*, 2023). The sedimentation process in the clarifier tank caused an increase in TSS in the clarifier tank, but decreased TSS in the wastewater from 2.85 mg/L to 1.29 mg/L. Our findings are consistent with those of the previous studies. Huang *et al.*, (2022) reported that adding microalgae in wastewater treatment increased the TSS to a very high value of 451.61 mg/L by the 12th week. Another study, as mentioned by Sutherland *et al.* (2020), also noted that adding microalgae increased TSS, with the highest value of 168±34 mg/L (Sutherland *et al.*, 2020).

Wastewater Treatment Performance Without Aeration

Figure 4a shows the COD quality before and after microalgae addition, and blower downtime measurements. According to Figure 4a, the highest COD reduction was achieved with a 5% microalgae concentration, resulting in 98.875% efficiency with a 30-minute blower downtime. The increased COD reduction efficiency correlates with higher oxygen levels due to the increased microalgae concentration. Microalgae photosynthesis releases oxygen, which aids the development of aerobic bacteria, thus reducing COD levels.

Moreover, as the microalgae concentration increased, the impact of the blower downtime on COD reduction became less significant. This is because the oxygen the microalgae supplies is sufficient for bacterial metabolism. Our research findings align with those of previous studies that have reported that under non-aeration conditions, microalgae can generate extra oxygen via photosynthesis to support heterotrophic growth. As a result, microalgae can absorb the carbon dioxide produced as a carbon source. This anticipated symbiotic relationship offers benefits in gas exchange and oxygen utilization, ultimately boosting the efficiency of Chemical Oxygen Demand (COD) removal (Fan *et al.*, 2021b, 2021a; Zhang *et al.*, 2018).

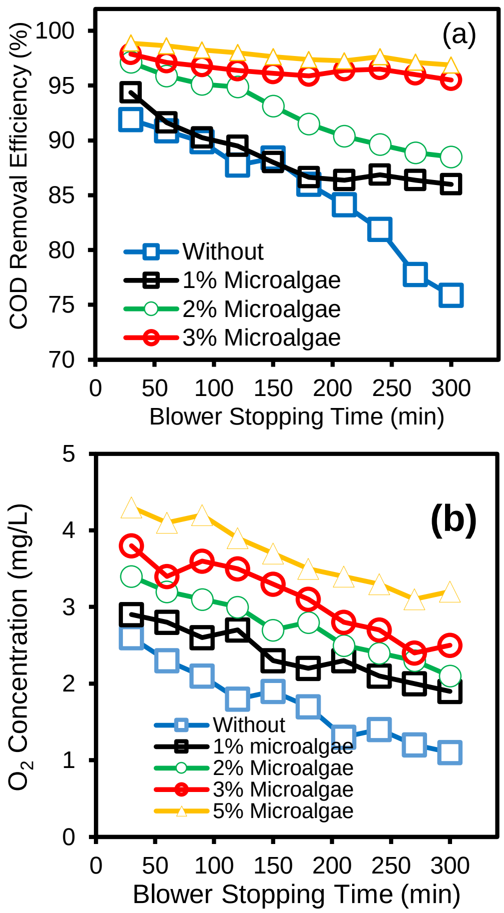

Fig. 4: Analysis of COD removal efficiency (a), and dissolved O_2 in outlet (b) before and after microalgae addition

The dissolved oxygen concentration in the outlet before and after the addition of microalgae is shown in Figure 4b. The highest oxygen concentration was obtained with 5% microalgae variation and a 30-minute blower downtime, measuring 4.3 mg/L. The lowest oxygen concentration was obtained with no microalgae variation and a 300-minute blower downtime, measuring 1.1 mg/L. This indicates that higher microalgae concentrations result in increased oxygen levels, primarily because of the photosynthetic activity of the microalgae (Fu et al., 2021).

The blower downtime also affected the oxygen concentration, as the blower is one of the devices responsible for oxygen production. The longer the blower was off, the lower the oxygen concentration, as the oxygen production source shifted to microalgae photosynthesis without blower assistance. In the studies conducted by Masojídek *et al.* (2021) and Prasad *et al.* (2021), it was mentioned that a decrease in CO_2 accompanies the increase in oxygen concentration during the photosynthesis process. This can be explained by the photosynthesis reaction itself, where microalgae utilize carbon dioxide (CO_2) as a substrate to form sugars and oxygen through photosynthesis. In wastewater treatment processes, CO_2 can be generated through the oxidation of COD, which is highly advantageous for reducing COD levels and increasing O_2 concentrations.

Fouling Evaluation

The fouling study in this study was conducted by evaluating the flux recovery and irreversible fouling ratios, as shown in Figure 5. Figure 5(a) depicts that the treatment without microalgae addition resulted in a lower FRR compared to the treatment with 1-5% microalgae addition. However, IRR in the treatment without microalgae addition increased, as shown in Fig. 5(b). This phenomenon indicated that microalgae contribute to reducing fouling on the membrane surface. According to Huang *et al.* (2015), adding microalgae in activated sludge can reduce the concentration of extracellular polymeric substances (EPS) by 25%. As Olk *et al.* (2019) noted, EPS is a major cause of irreversible fouling on membrane surfaces. Therefore, the more microalgae added to the activated sludge, the greater the reduction in EPS.

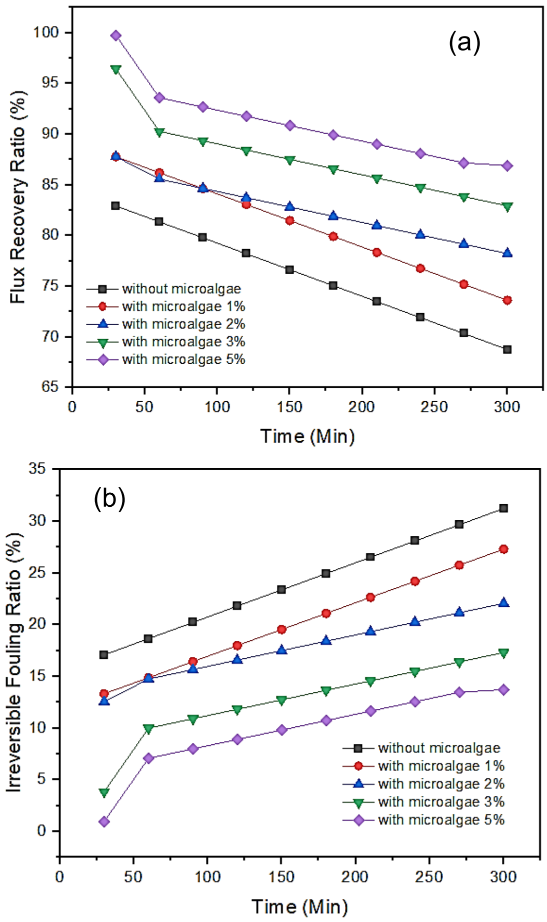

Fig. 5: Time course of FRR (a), and IRR (b) with addition of microalgae

Reaction Processes in MBBR

Figure 6 illustrates the reaction processes within the MBBR. First, a biodegradation process outside the biofilm media, requires oxygen to degrade pollutants, such as COD and BOD (Saini *et al.*, 2023). Second and third, nitrification and denitrification processes occur (Huynh *et al.*, 2023).

Nitrification is the oxidation of free ammonia (NH_4^+) into nitrite and nitrate with the assistance of *Nitrobacter sp.* and *Nitrosomonas sp.*, along with oxygen. Denitrification is the reduction of nitrite and nitrate to nitrous oxide and nitrogen gas, facilitated by *Bacillus sp.*, *Pseudomonas sp.*, and *Clostridium sp.* bacteria, without the need for oxygen (James and Vijayanandan, 2023).

In the MBBR, the biofilm media has a large surface area, resulting in enhanced nitrification and denitrification processes and competition for oxygen consumption between the COD and BOD degradation processes and nitrification processes. A limited supply of oxygen for the COD and BOD degradation reduces their performance, leading to suboptimal reductions in COD and BOD levels beyond the treated water quality standards (Wang *et al.*, 2014).

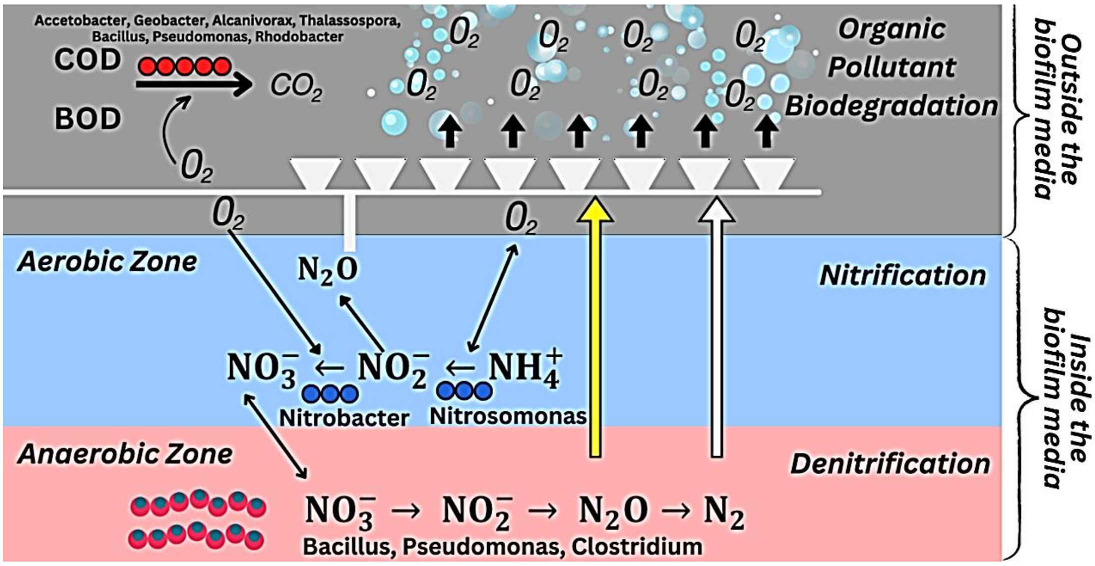

Fig. 6: Reaction mechanism in MBBR with the addition of microalgae

Table 1. Operational cost of 0.1 m^3/day capacity

Operational Cost without Microalgae					
Electrical	**Power (watt)**	**Operate (hours/day)**	**Consume (KWh/day)**	**Price (USD/KWh)**	**Total (USD)**
Aerator for MBBR	8	24	0.192	0.094	0.018
Aerator for membrane cleaning	8	24	0.192	0.094	0.018
Intake pump	125	24	3	0.094	0.28
Membrane pump	200	24	4.8	0.094	0.45
Chemical	**Dosage (mg/L)**	**Capacity (m^3/day)**	**Consume (kg/day)**	**Price (USD/Kg)**	**Total (USD)**
Natrium hypochlorite	100	0.1	0.01	1.88	0.019
Total Price (USD/day)					**0.79**
Operational Cost (USD/m^3)					**7.89**
Operational Cost with Microalgae 5%					

Electrical	Power (watt)	Operate (hours/day)	Consume (KWh/day)	Price (USD/KWh)	Total (USD)
Aerator for MBBR	8	12	0.096	0.094	0.0090
Aerator for membrane cleaning	8	6	0.048	0.094	0.0045
Intake pump	125	24	3	0.094	0.28
Membrane pump	200	24	4.8	0.094	0.45
Chemical	**Dosage (mg/L)**	**Capacity (m^3/day)**	**Consume (kg/day)**	**Price (USD/Kg)**	**Total (USD)**
Natrium hypochlorite	30	0.1	0.003	1.88	0.0056
Total Price (USD/day)					**0.75**
Operational Cost (USD/m^3)					**7.53**

Economic Analysis of Operational Costs

The operational cost analysis in this study was conducted on a WWTP with a capacity of 0.1 m^3/day. Compared operational costs were compared between treatments without microalgae addition and with 5% microalgae addition. Table 1 presents the comparison between these two treatments. The components included in the operational cost analysis cover only equipment's electricity consumption and membrane cleaning chemicals' consumption.

The key difference between the two treatments lies in the operating hours of the aerator for the MBBR. In the treatment without microalgae addition, the aerator operated for 24 hours, whereas, with the addition of microalgae, it operated for only 12 hours. This is because microalgae can naturally substitute the blower operation by supplying oxygen. Additionally, the operating hours of the aerator for membrane-cleaning differed. In the treatment without microalgae addition, the aerator operated for 24 hours, while in the treatment with microalgae addition, the blower operated for only 6 hours. This was due to microalgae's ability to reduce the EPS concentration in activated sludge, thereby decreasing the fouling ratio, as shown in Figure 6.

Furthermore, the consumption of membrane cleaning chemicals, specifically sodium hypochlorite (NaOCl), was also considered. In the treatment without microalgae (Muharja *et al.*, 2023), the required concentration of NaOCl was 100 mg/L, whereas, in the treatment with microalgae addition, only 30 mg/L of NaOCl was needed. This is because the chemical concentration for membrane cleaning does not need to be as high, given that the IFR values, as presented in Figure 6, are lower than the treatment without microalgae addition.

The total operational cost per m^3 was calculated to be USD 7.89 for the treatment without microalgae and USD 7.53 for the treatment with microalgae addition, resulting in a difference of USD 0.36 per m^3.

CONCLUSIONS

This study evaluated the impact of microalgae addition on wastewater treatment performance in a membrane bioreactor system. The results revealed that the inclusion of microalgae not only enhanced the biodegradation of organic pollutants but significantly improved the efficiency of COD and BOD reduction by increasing dissolved oxygen levels through photosynthesis. Furthermore, adding microalgae was shown to mitigate membrane fouling by reducing extracellular polymeric substances, leading to a lower irreversible fouling ratio. A notable finding is the potential of microalgae to substitute for mechanical aeration, thereby reducing energy consumption. This substitution was reflected in the economic analysis, where operational costs were reduced by USD 0.36 per m^3 adding microalgae. These findings highlight the prospects for integrating microalgae into wastewater treatment systems, offering a more sustainable and cost-effective approach. While the study confirmed the benefits of microalgae addition, future research should explore these systems' long-term stability and the process's scalability for larger wastewater treatment facilities. Further investigation into optimizing microalgae concentrations and evaluating the economic feasibility of different configurations could enhance the practical application of this technology.

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