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Mangrove Biofiltration as A Green Biotechnology for Wastewater Remediation: Targeting DO, BOD, COD, Phosphate, Detergent Mbas, and Ammonia

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Abstract: This Wastewater treatment plants are essential for reducing pollution before wastewater is discharged, but conventional systems often fail to achieve effective pollutant removal. This study aimed to measure the effectiveness of mangrove powder in treating industrial wastewater before it is discharged into the environment to improve wastewater quality. Samples were taken at two points: after conventional wastewater treatment and after treatment with mangrove biofiltration. The biofiltration system was designed to address the limitations of conventional treatment, particularly in reducing BOD_5, COD, phosphate, MBAS, and increasing dissolved oxygen (DO). Sampling was carried out using a one liter sterile sample bottle. Sampling was carried out using a 1-liter sterile sample bottle. Sampling was carried out at one point with four repetitions. Parameters analyzed included TSS, pH, DO, BOD_5, COD, nitrate, nitrite, ammonia, phosphate, sulfate, and MBAS detergent. Mangrove biofiltration achieved reductions in TSS (55.26%), COD (99.35%), nitrate (100%), BOD_5 (99.15%), phosphate (96.67%), sulfate (99.55%), nitrite (100%), ammonia (90.00%), and MBAS (100%), while DO increased by 47.37% and pH remained stable. These improvements indicate the mangrove biofilter's capacity to adsorb and biologically degrade organic matter and pollutants, enhancing wastewater quality to meet reuse standards. The results of the study show the potential of mangrove-based biofiltration as a solution for waste treatment units using mangrove biofiltration to reduce the concentration of DO, BOD, COD, phospat, Detergen MBAS, and Ammonis in industrial waste before being discharged into the environment.

Keywords: Ammonia, biofiltration, detergent MBAS, mangrove powder, phosphate.

Introduction

Wastewater Industrial production processes produce waste containing organic materials and nutrients, requiring adequate wastewater treatment units or wastewater treatment plants (Z. Zhao et al., 2023). All industries are generally equipped with primary wastewater treatment plants (WWTPs). The various media and techniques used to decompose waste depend on the level of waste and the ultimate disposal target. (X. Liu et al., 2024) The challenge lies in the effectiveness of these wastewater treatment plants, which treat industrial wastewater before it is released into the environment (Asheghmoalla & Mehrvar, 2024).

The wastewater treatment plant used is a basic wastewater treatment plant that functions to channel all waste from the production process into wastewater (Campanati et al., 2022). The process that occurs in wastewater involves reducing waste containing various pollutants to a certain concentration that is safe for discharge into the environment (Hiep et al., 2023). Water treated with conventional waste sometimes has limitations in reducing major pollutants so that some parameters are not optimally decomposed by the wastewater treatment unit. The type of pollutant produced depends on the type of process carried out. In general, pollutants that are often used as indicators are such as biological oxygen demand (BOD), chemical oxygen demand (COD), phosphate, Dissolved Oxygen and MBAS (M. Liu et al., 2024). The target is that all parameters can reach acceptable quality standard thresholds before being discharged into the environment (Fagnant et al., 2018).

Another possible solution to improve the quality of conventional wastewater treatment plants is the implementation of ecological filtration systems, such as biofiltration based on natural materials, including mangroves, which offer a good solution to increase wastewater treatment efficiency (Saili et al., 2022). Mangroves are known for their phytoremediation capabilities, especially in reducing organic loads and increasing oxygen in aquatic systems (Kumar et al., 2021. This study examines the comparative properties of conventional wastewater treatment systems and systems using mangrove biofiltration in treating industrial wastewater (H. M. Ahmed et al., 2024). Measurements were conducted at treatment points using conventional treatment compared to treatment using mangroves as biofiltration.

The urgency of this research lies in the preliminary study results, which showed that initial tests of conventional wastewater treatment did not reduce all parameters to meet quality standards. Several environmental quality indicators exceeded the standard values, namely dissolved oxygen, BOD, phosphorus, and MBAS detergent (M. Liu et al., 2024). These parameters are crucial indicators for assessing the effectiveness of wastewater treatment before discharge into the environment. The importance of this research is to evaluate the effectiveness of mangrove-based biofiltration in industrial wastewater management for the treatment of wastewater that has been discharged from conventional treatment units.

Materials And Methods

This study uses a field-scale experimental approach by designing a hybrid wastewater treatment system integrating mangrove biofiltration with ultrafiltration. The system consists of three biofiltration ponds, each measuring 4 m × 2 m × 1.5 m, arranged in series . The processing unit consists of three reactor ponds. The first pond serves as the initial reservoir, containing only waste. The second pond is equipped with mangrove powder in sacks. The third pond stores the results of the processing unit with mangroves. The design is designed to ensure a contact time of 4 hours to ensure complete removal of contaminants from the waste.(Fagnant et al., 2018). The system is designed to handle industrial wastewater flows ranging from 93 to 229 m^3 per day, which pass through the mangrove biofilter ponds before entering a 25-micron membrane ultrafiltration unit for advanced purification (A. M. Ahmed & Kareem, n.d.). Water samples are collected before and after treatment for laboratory analysis of chemical and physical parameters, focusing on key indicators such as DO, BOD_5, COD, phosphate, and MBAS detergent (Abd Wahid et al., 2021). The data are then tabulated to evaluate and compare pollutant removal efficiencies

Results And Discussion

Based on the research methodology described earlier, an initial analysis was carried out on the effluent produced by the conventional wastewater treatment system as a baseline comparison. Samples were collected after treatment in the conventional waste water and analyzed in the laboratory for 11 water quality parameters. The results of the chemical and physical parameter measurements of the conventional WWTP effluent are presented in Table 1. These data serve as reference values for evaluating the performance of the mangrove biofiltration system designed in this study.

The data in the table shows that laboratory results for effluent from conventional wastewater output showed several parameters exceeding the wastewater quality standard threshold. The parameters that increased included biochemical oxygen demand (BOD_5) at 26.95 mg/L, COD at 27.63 mg/L, phosphate at 15.04 mg/dL, and detergent content of MBAS at 0.06 mg/L (12). In conventional wastewater, ammonia (NH_3-N) reached 0.283 mg/L. In contrast, the dissolved oxygen (DO) level of 0.19 mg/L is still within the standard range, but the results do not reflect good water quality limits (Kusuma et al., n.d.-a).

Table 1. Reference values for evaluating the performance of the mangrove biofiltration system

No	Parameter	Unit	WWTS Conventional
1	TSS	mg/L	4
2	pH	-	8.87
3	DO	mg/L	0,19
4	COD	mg/L	27.63
5	Nitrate (NO3)	mg/L	2,45
6	BOD5	mg/L	26.95
7	Phosphate (PO4)	mg/L	15,04
8	Sulfate (SO4)	mg/L	22,00
9	Nitrite (NO2)	mg/L	0,09
10	Ammonia (NH3-N)	mg/L	0,283
11	Detergen MBAS	mg/l	0,06

The table shows the results after the wastewater passed through mangrove biofiltration using a multistage system with a retention time of 4 hours. The results from the mangrove biofiltration demonstrate changes in the effluent output from the conventional system. The effluent concentration results after the wastewater passed through the mangrove biofiltration system are shown in Table 2.

Table 2. Industrial Wastewater Quality After Mangrove Biofiltration

No	Parameter	Unit	After mangrove
1	TSS	mg/L	0,5
2	pH	-	7,31
3	DO	mg/L	6,45
4	COD	mg/L	9.50
5	Nitrate (NO3)	mg/L	2,40
6	BOD5	mg/L	4,90
7	Phosphate (PO4)	mg/L	1.10
8	Sulfate (SO4)	mg/L	0,10
9	Nitrite (NO2)	mg/L	0,09
10	Ammonia (NH3-N)	mg/L	0,02
11	Detergen MBAS		0,02

After implementing mangrove biofiltration using mangrove powder in sacks with a retention time of 4 hours, the first reactor served as a reservoir. The second reactor contained mangrove powder in sacks, positioned so that water could be filtered by the mangrove dust. The retention period for the mangrove powder was 4 hours. The third reactor served as a reservoir after the water from the reactor containing the mangrove powder in sacks was released.

The data in the following table shows the percentage decrease and increase in the process after using mangrove powder as a biofilter. The table shows the results after wastewater passed through mangrove biofiltration using a multistage system with a retention time of 4 hours. The results of mangrove biofiltration indicate changes in effluent output compared to the conventional system. The effluent concentration after wastewater passed through the mangrove biofiltration system is indicated by the percentage decrease and increase.

Tabel 3. Fluctuation of waste samples with Mangrove Biofiltration

No	Parameter	Decline (%)
1	TSS	55,26%
2	pH	0,00%
3	DO	-47,37% (increase)
4	COD	99,35%
5	Nitrate (NO3)	100,00%
6	BOD5	99,15%
7	Phosphate (PO4)	100,00%
8	Sulfate (SO4)	99,55%
9	Nitrite (NO2)	100,00%
10	Ammonia (NH3-N)	90,00%
11	Detergent MBAS	100,00%

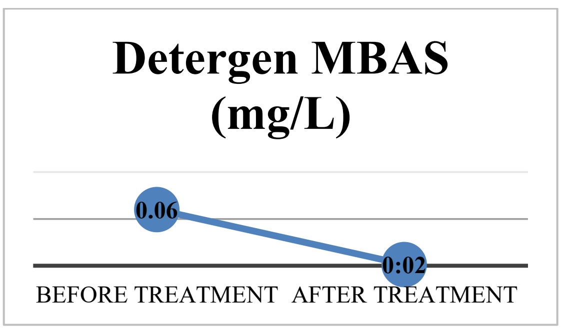

Figure 1. Changes in MBAS detergent before and after mangrove biofiltration

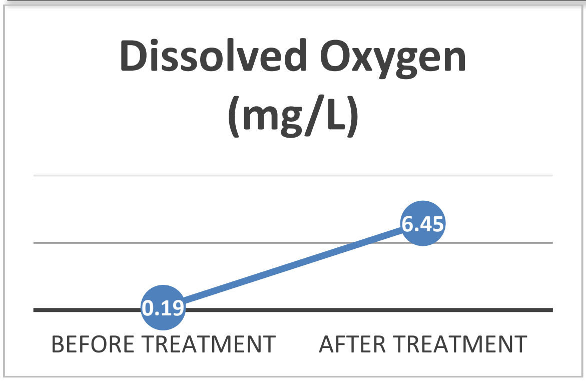

Figure 2. Changes in DO detergent before and after mangrove biofiltration

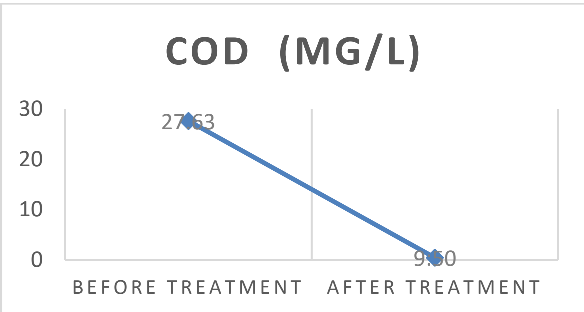

Figure 3. Changes in COD detergent before and after mangrove biofiltration

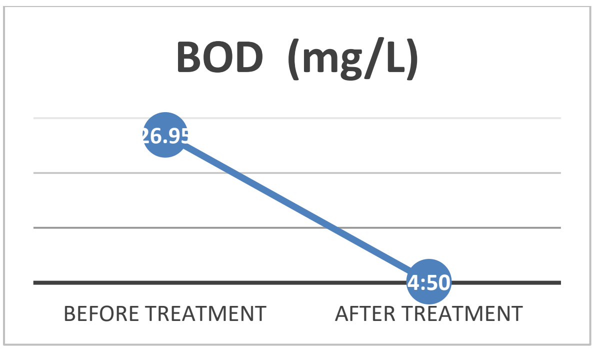

Figure 4. Changes in BOD detergent before and after mangrove biofiltration

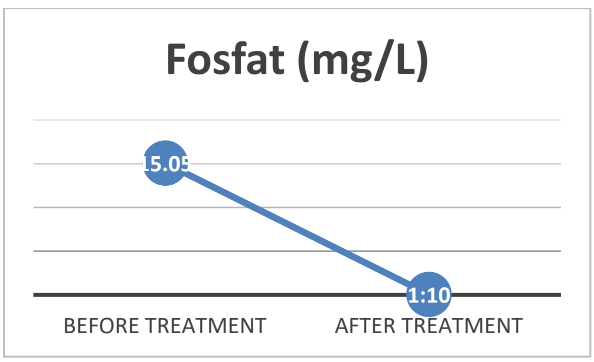

Figure 5. Changes in Fosfat detergent before and after mangrove biofiltration

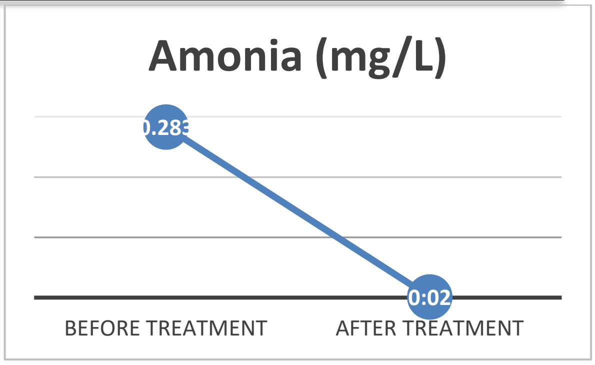

Figure 5. Changes in Fosfat detergent before and after mangrove biofiltration

Figure 6. Design flow of WWTP with mangrove biofiltration

Discussion

Measurements of the effectiveness of various effluent concentrations were conducted at two points: after the conventional wastewater treatment plant and after the mangrove biofiltration plant. Each sampling point was replicated four times after the wastewater treatment plant and after the mangrove biofiltration (Sganzerla et al., 2023). The conventional wastewater treatment plant system uses sand, coconut fiber, and gravel as filtration media, while the mangrove biofiltration system used mangrove powder in sacks placed in the wastewater treatment unit (Kim et al., 2024). This approach allows for a clear comparison of the pollutant reduction efficiency between the traditional filtration method and the mangrove-based biofiltration system(Verâne et al., 2020).

The results of the study showed the use of mangrove biofiltration implemented in sacks as a wastewater treatment system. The initial concept of industrial waste processing used conventional

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industrial waste processing. The initial modification of conventional waste processing to modification with mangrove biofiltration in sacks can improve waste quality. Several main parameters such as DO, BOD_5, COD, phosphate, MBAS detergent, and ammonia (NH_3-N)(Lasisi et al., 2023). Improving waste quality with the use of a mangrove biofiltration system functions as an effective wastewater filtration(Xu et al., 2024). Dissolved oxygen (DO) levels increased from 0.19 mg/L to 6.45 mg/L. The increase in dissolved oxygen levels after treatment indicates an improvement in aerobic conditions in the biofiltration process. The increase in Dissolved Oxygen levels from 0.19 mg/L to 6.45 mg/L can occur because mangroves function as a biofilter thereby reducing organic pollutants which ultimately increase DO values.

The use of Reducing organic matter and pollutants reduces the value of biological oxygen demand (BOD). This decrease in BOD load is in line with the increase in DO values in wastewater. The use of mangroves in this modified wastewater treatment plant causes microbes to grow around the mangroves, resulting in increased dissolved oxygen (DO) levels. The structural design of the building in the wastewater treatment plant and the layout of the mangroves in the mangrove treatment plant are designed in such a way that they have a cross-sectional design to increase water circulation and gas exchange (passive aeration). The retention or waiting period in this study was 4 hours in the treatment plant. During the waiting period, the process that occurs is that the tannin content of the mangrove powder helps to settle waste and solids and maximizes the biofiltration process in breaking down all pollutants and increasing oxygen (Rehman et al., 2021).

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The structural design of the building in the wastewater treatment plant and the layout of the mangroves in the mangrove treatment plant are designed in such a way that they have a cross-sectional design to increase water circulation and gas exchange (passive aeration) (Idris et al., 2024). The retention or waiting period in this study was 4 hours in the treatment plant (Rehman et al., 2021). During the waiting period, the process that occurs is that the tannin content of the mangrove powder helps to settle waste and solids and maximizes the biofiltration process in breaking down all pollutants and increasing oxygen(Maura et al., 2023).

The BOD parameter in the mangrove biofiltration unit showed a reduction from 26.95 mg/L to 4.90 mg/L—This reduction was influenced by the role of mangrove powder wrapped in sacks, which have a fine pore structure and high lignocellulose content (Xu et al., 2024). The reduction in BOD and COD values by various processes in mangrove biofiltration is inversely proportional to the increase in dissolved oxygen values. The increase in dissolved oxygen in various processes will decompose the BOD and COD values in the waste. The presence of microorganisms and a retention time process of 4 hours allows larger particles to settle by gravity, while dissolved compounds are decomposed through microbial activity (Kawan et al., 2022).

Vegetative biofilters are effective in reducing BOD through microbial metabolism and filtration. Other studies have shown that the activity of mangrove powder in sacks reduces BOD by more than 60% in domestic wastewater. The decomposition process in waste is also influenced by retention time (Roy et al., 2021). The efficiency of pollutant reduction with a longer retention time (4 hours) indicates significant effectiveness. This is in line with other studies that effectiveness can be increased with longer retention times. The reduction in BOD and COD in this study supports findings that indicate that mangrove biofiltration and microbial degradation in the treatment unit significantly reduce pollutant loads.

Microorganisms in wastewater during the filtration process will stick to the surface powder of mangrove powder. Microbes will multiply and produce EPS (extracellular polymeric substances). Microbes finally form biofilms on the surface of the mangrove. This condition is supported by the pore structure in sacks and mnggroves so that wastewater can enter and form biofilm. The presence of this biofilm is able to medgradate pollutants in wastewater. In addition, the presence of aerobic minrobes in biofilm also increases dissolved oxygen. The decrease in ammonia levels from 0.65 mg/L to 0.23 mg/L in biofiltration is adsorption-biosorption and microbial colonization in mangrove powder media. Mangrove powder in sacks has a lignocellulose structure with negatively charged functional groups (–OH, –COOH, and $–OCH_3$) so that it is able to bind ammonium ions (NH_4^+) through electrostatic interactions and ion exchange, making it a natural biosorbent (D. Zhao et al., 2021).

Decreased ammonia levels from 0.65 mg/l to 0.23 mg/l in biofiltration are adsorption-biosorption and microbial colonization in mangrove powder media. Mangrove powder in a sack has a lignocellulose and negative charge (-OH, -COOH, and $-och_3$ structure so that it can bind to ammonium ions (NH_4^+) through electrostatic interactions and ion exchange, making it natural biosorbents (24). Microorganisms in wastewater during the filtration process will stick to the surface of the mangrove powder. Microbes will multiply and produce EPS (extracellular polymers). Microbes eventually form biofilm on the surface of the mangrove. This condition is supported by the structure of pores in sacks and planting holes so that wastewater can enter and form biofilm (D. Zhao et al., 2021). The existence of this biofilm is able to degrade pollutants in wastewater. Microorganisms in wastewater during the filtration process will attach to the surface of the mangrove powder.

This condition is supported by the structure of pores in sacks and planting holes so that wastewater can enter and form biofilm. In connection with the presence of ammonia the presence of nitrosomonas and nitrobacter bacteria facilitates nitrification. In a more anoxic media layer, partial denitrification occurs which reduces the accumulation of nitrates. (Zhang et al., 2024) Decreased ammonia does not only occur due to chemical adsorption, but also microbial activity associated with the media. The mechanism of physical absorption occurs through ammonia molecules attached to the surface of mangroves through hydrogen bonds, and electrostatic interactions with functional groups (-OH, -COOH, $-och_3$).

The biosorption process begins with dissolved ammonia in wastewater will accumulate on the surface of the powdered media. The nitrification process begins when water and mangrove content attach to mangrove powder and form biofilm. This process can reduce ammonia and increase efficiency by struggling with waste concentration is higher than effectiveness with the use of conventional waste treatment systems (Loh et al., 2021). Data shows a significant increase in all parameters observed after biofiltration based on mangrove biofiltration in the train, especially at the level of organic material (BOD5, COD), ammonia, and DO (Adjovu et al., 2023).

The use of mangrove powder in phosphate reduction can occur because absorption by OH and COOH groups will form precipitation with Ca, Mg, and Fe. Biological accumulation also occurs by phosphate-accumulating microbes (PAOs) (Kusuma et al., n.d.-b). Another mechanism for phosphate absorption by mangrove powder is also enhanced by the presence of microbial biofilms on its surface. Phosphate accumulator microbes (PAOs) can store phosphate in the form of intracellular polyphosphates, thereby reducing phosphate concentrations in wastewater. Lignocellulosic compounds in mangrove fibers support microbial growth by providing a growth surface and additional nutrients. The combination of metal ion precipitation and PAO activity can reduce phosphate by more than 70%, in line with findings on the use of biomass-based substrates such as mangrove powder, which work synergistically through chemical and biological mechanisms (Senzanje et al., 2023; Zairinayati & Shatriadi, 2019).

The decrease in the concentration of MBAS detergent by mangrove powder in sacks as biofiltration occurs through chemical and biological mechanisms. lignocellulose and tannins in mangrove powder in sacks. The bond has a hydroxyl group (–OH), carboxyl (–COOH)

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will bind to the negatively charged sulfonate group ($-SO_3^-$) Anionic surfactants such as linear alkyl benzene sulfonate (LAS) produce an adsorption process. In addition, tannins in mangrove powder have the ability as polyphenols so that they act as natural biocoagulants that are able to make detergent molecules to form large flocs that are easy to settle.

Microbes such as pseudomonas and Bacillus can grow on mangrove powder so that they produce alkyl sulfonate mono-oxygenase enzymes to break the alkyl-sulfonate bonds in surfactants into simple compounds such as CO_2, H_2O, and sulfate (Hashmat et al., 2024). Both of these methods are capable of reducing MBAS levels, reducing foam, and increasing clarity, thus optimizing oxygen diffusion into the system and increasing DO levels (29). These results are consistent with research on mangrove biofiltration and artificial wetland systems, which show that a decrease in surfactant correlates positively with an increase in dissolved oxygen, although several studies at very high surfactant concentrations found the opposite, where aerobic microbial activity was inhibited, resulting in a decrease in DO. (Makała et al., 2023)

Overall, the results of the study using a modified conventional wastewater treatment unit compared to the use of mangroves as biofiltration. The use of mangroves as a filtration material in this finding uses mangrove powder in sacks. The results of the study compare the results of research using conventional wastewater treatment units with those using mangroves (Mentari et al., 2022). The design used in the study with conventional treatment units and with mangrove biofiltration uses the same pond or reactor design (Hussain et al., 2024). The findings of nature-based treatment systems such as mangrove powder filters in sacks have shown high efficiency compared to the use of conventional treatment units (Hossain et al., 2022).

The use of mangroves as biofiltration mangroves operates through a combination of physical, chemical, and biological mechanisms, including adsorption by lignocellulose in mangrove powder, sedimentation of suspended particles, ion exchange, biosorption of heavy metals, formation of organic-metal complexes, and microbial degradation facilitated by the root surface or filter media as their habitat (Hamisi et al., 2022). Mangroves are also able to form biofilms so that the nitrification-denitrification process to remove ammonia and nitrate, as well as the absorption of phosphate through binding with metal cations in the sediment (Verâne et al., 2020). This mangrove process can increase oxygen and purify the water because oxygen can penetrate the water's surface. Wastewater treatment units using mangroves can reduce organic load.

Filtration units using mangroves make mangrove biofiltration a sustainable, cost-effective, and efficient alternative to complement existing wastewater treatment infrastructure (Toprak et al., 2022). Statistical test results showed that mangrove biofiltration effectively reduced TSS (87.5%), COD (65.6%), BOD_5 (81.8%), phosphate (92.7%), sulfate (99.5%), ammonia (92.9%), and MBAS detergent (66.7%). Furthermore, DO levels increased sharply from 0.19 mg/L to 6.45 mg/L, indicating a significant improvement in dissolved oxygen quality, while pH became more neutral and nitrate levels remained relatively stable.

Conclusions

The integration of mangrove-based biofiltration into conventional IPAL systems significantly enhances the removal efficiency of critical pollutants in AMDK industrial wastewater. This method improved dissolved oxygen levels and reduced organic and nitrogenous loads, including BOD, COD, and NH3-N. The results support further application and scaling of this ecological treatment approach in sustainable water management strategies for industrial facilities.

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