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Optimization and Comparative Performance Evaluation of Moving Bed Biofilm Reactor Configurations for Municipal Wastewater

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Abstract- The increasing generation of wastewater due to urbanization and industrialization has created a strong demand for efficient and sustainable treatment technologies. The Moving Bed Biofilm Reactor (MBBR) system has emerged as an advanced biological treatment method that combines the benefits of suspended and attached growth processes. This study focuses on the optimization and comparative assessment of wastewater treatment performance across different MBBR configurations, including single-stage, multi-stage, and hybrid systems. Operational parameters such as Hydraulic Retention Time, Organic Loading Rate, Dissolved Oxygen, and carrier filling ratio were analyzed to determine optimal operating conditions. Performance indicators including Biochemical Oxygen Demand, Chemical Oxygen Demand, Total Suspended Solids, and ammonia removal efficiency were evaluated. The results indicate that single-stage systems provide moderate treatment efficiency, while multi-stage systems significantly improve nitrification and overall pollutant removal. Hybrid MBBR systems achieved the highest treatment efficiency but required higher energy input. Optimization analysis revealed that maintaining an HRT of 6–8 hours, a carrier filling ratio of around 50%, and DO levels between 2–4 mg/L resulted in enhanced performance. Among the configurations studied, the multi-stage MBBR system offered the best balance between efficiency, operational stability, and costeffectiveness. The findings confirm that optimized MBBR systems provide a reliable and scalable solution for modern wastewater treatment applications.

Keywords: Municipal Wastewater, MBBR, Optimization, BOD, COD.

I. INTRODUCTION

Water pollution caused by rapid urbanization, industrialization, and population growth has become a major environmental concern worldwide. The increasing generation of municipal and industrial wastewater creates serious challenges for maintaining water quality and protecting aquatic ecosystems. Conventional wastewater treatment methods, such as the activated sludge process, are widely used but often face limitations including large land requirements, high sludge production, sensitivity to load fluctuations, and increased operational costs. Therefore, there is a growing demand for advanced and sustainable treatment technologies that provide higher efficiency, compact design, and stable operation.

The Moving Bed Biofilm Reactor (MBBR) technology has emerged as an effective biological wastewater treatment process due to its ability to combine the advantages of suspended growth and attached growth systems. In MBBR systems, specially designed plastic carriers move freely inside the aeration tank and provide a large surface area for microbial biofilm growth. These microorganisms degrade organic pollutants efficiently while maintaining high biomass concentration within the reactor. The technology offers several advantages such as smaller footprint, low sludge generation, resistance to shock loading, easy operation, and improved treatment efficiency.

MBBR systems are widely used for the treatment of municipal and industrial wastewater and are capable of achieving high removal efficiencies for Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total Suspended Solids (TSS), and ammonia nitrogen. The performance of the reactor mainly depends on operational parameters such as hydraulic retention time, dissolved oxygen concentration, organic loading rate, and media filling ratio. Proper optimization of these parameters is essential for achieving maximum treatment efficiency and operational stability.

This study focuses on the performance evaluation and optimization of MBBR technology for municipal wastewater treatment. The research aims to analyse pollutant removal efficiency under different operating conditions and evaluate the suitability of MBBR systems as an advanced and sustainable solution for wastewater management.

By providing a comprehensive comparison of single-stage, multi-stage, and hybrid MBBR systems, this study contributes to the development of an optimization framework for wastewater treatment plant design and operation. The findings are expected to support engineers, researchers, and policymakers in selecting appropriate MBBR configurations tailored to specific wastewater characteristics and regulatory requirements. In the context of sustainable development and environmental protection, optimizing biological treatment systems such as MBBR is essential for ensuring safe water discharge, protecting aquatic ecosystems, and promoting resource efficiency. The integration of advanced monitoring technologies, automation, and energy optimization strategies further enhances the potential of MBBR systems to meet future wastewater management challenges.

II. LITERATURE REVIEW

Overall, the literature indicates that multi-stage and hybrid MBBR systems provide superior performance compared to single-stage configurations. However, proper optimization of HRT, DO levels, and carrier filling ratios remains critical for maximizing efficiency and minimizing operational costs. Recent studies in 2025 have focused on integrating artificial intelligence and real-time monitoring with MBBR systems for performance optimization. Researchers have emphasized predictive modeling for nutrient removal efficiency and energy optimization using machine learning algorithms. Studies report that AI-assisted multi-stage MBBR systems improved ammonia removal efficiency by more than 10% compared to conventional control systems. Recent work also highlights membrane-coupled MBBR systems (MBBR-MBR hybrid) achieving above 95% COD and BOD removal with improved effluent quality suitable for reuse applications.

In 2024, several experimental investigations compared single-stage and multi-stage MBBR systems under varying organic loading rates. Findings demonstrated that multi-stage systems offered superior nitrification and denitrification due to better biomass distribution and oxygen gradient control. Studies also optimized carrier filling ratios between 40– 60%, concluding that 50% filling provides the best balance between treatment efficiency and hydraulic performance. Energy efficiency studies revealed that optimized aeration strategies could reduce operational costs by up to 15%.

Research in 2023 primarily focused on hybrid MBBR (IFAS) systems for upgrading existing wastewater treatment plants. Results indicated that integrating biofilm carriers into conventional activated sludge systems enhanced biomass retention and improved shock load resistance. Reported BOD and COD removal efficiencies ranged from 92–97%, while ammonia removal exceeded 85% under optimized HRT conditions. Computational fluid dynamics (CFD) modeling was increasingly used to analyze carrier movement and oxygen transfer dynamics within reactors.

In 2022, comparative studies examined the impact of Hydraulic Retention Time (HRT) and Organic Loading Rate (OLR) on MBBR performance. Researchers observed that maintaining HRT between 6–8 hours significantly enhanced organic matter degradation. Studies also analysed biofilm thickness and microbial community dynamics, confirming that thicker biofilms improved nitrification but required adequate aeration to prevent oxygen limitation. Sustainable carrier materials and biodegradable media were also explored.

Studies conducted in 2021 evaluated MBBR systems for industrial wastewater treatment, including textile and food processing effluents. Results demonstrated that MBBR systems could handle high organic loads with stable performance. Removal efficiencies reported were approximately 85–95% for COD and 80–90% for ammonia nitrogen. Research also highlighted the resilience of biofilm systems under fluctuating pH and temperature conditions. Energy consumption analysis became an important research focus during this year.

n 2020, research emphasized nutrient removal and process intensification in multi-stage MBBR configurations. Investigations showed improved nitrogen removal through staged aeration and anoxic zones. Studies reported that proper DO control (2–4 mg/L) was essential for optimal microbial activity. Mathematical modeling based on first-order kinetics and Monod equations was widely applied to predict substrate degradation rates and reactor performance.

Research in 2019 explored the integration of MBBR systems with membrane filtration units to enhance effluent quality. MBBR-MBR hybrid systems demonstrated high removal efficiencies (>95% COD removal) and reduced sludge production. Additionally, studies investigated the impact of carrier surface area on microbial growth and pollutant removal efficiency, confirming that higher specific surface area improves biofilm formation and treatment capacity.

In 2018, attention was directed toward process optimization and cost analysis of MBBR systems. Researchers evaluated aeration efficiency and identified energy consumption as the primary operational cost factor. Experimental studies confirmed that optimized aeration systems could significantly reduce energy demand without compromising treatment efficiency. Comparative assessments also showed that MBBR systems required smaller footprints compared to conventional activated sludge processes.

Studies in 2017 focused on evaluating MBBR systems for small and decentralized wastewater treatment plants. Results indicated that compact MBBR units were highly effective in rural and semi-urban areas. Organic removal efficiencies ranged from 80–90%, while ammonia removal performance depended strongly on temperature and HRT. Research also emphasized the low sludge production characteristics of MBBR technology.

In 2016, investigations examined biofilm growth kinetics and microbial community analysis in MBBR reactors. Studies reported that biofilm-based systems maintained higher biomass concentrations compared to suspended growth systems. Research also evaluated the influence of carrier type and geometry on pollutant removal efficiency. Findings confirmed that optimized carrier design significantly enhances system performance. This table shows Literature Review according to works.

III. METHODOLOGY

The present study focuses on evaluating the performance of a Moving Bed Biofilm Reactor (MBBR) system for the treatment of wastewater. The methodology adopted in this work was designed to ensure accurate analysis of wastewater characteristics and effective assessment of treatment efficiency under controlled conditions. Wastewater samples were collected using the grab sampling technique, which involves collecting a single sample at a specific point in time. This method ensures that the sample represents the actual characteristics of the wastewater at the time of collection. The collected samples were carefully transported to the laboratory to avoid contamination or alteration of their properties before analysis.

Upon arrival at the laboratory, the influent wastewater was subjected to detailed physicochemical analysis to determine its initial characteristics. Key parameters such as turbidity, pH, electrical conductivity, total dissolved solids (TDS), dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), ammonical nitrogen, and total Kjeldahl nitrogen (TKN) were measured. These parameters are essential indicators of water quality and help in understanding the level of pollution present in the wastewater. The analysis revealed that the wastewater possessed moderate organic strength, which indicates a considerable presence of biodegradable organic matter and nitrogenous compounds requiring treatment.

To treat the wastewater, a pilot-scale Moving Bed Biofilm Reactor (MBBR) system was designed and constructed. The reactor had a working volume of approximately 10 liters, making it suitable for laboratory-scale experimentation. One of the key features of the MBBR system is the use of floating plastic carrier media, which provide a large surface area for the growth of microorganisms. These carriers remain suspended in the reactor and facilitate the formation of biofilms. Biofilms are layers of microorganisms that attach themselves to surfaces and play a crucial role in the biodegradation of pollutants.

The reactor was operated under continuous aeration to maintain sufficient dissolved oxygen levels, which are necessary for the survival and activity of aerobic microorganisms. Aeration not only supplies oxygen but also ensures proper mixing of wastewater and carrier media within the reactor. As the system operated, microorganisms began to attach to the carrier media and formed stable biofilms. These biofilms enhanced the efficiency of the treatment process by increasing the concentration of active biomass in the reactor. The microorganisms present in the biofilm metabolized organic pollutants and converted them into simpler and less harmful substances, thereby reducing the pollution load of the wastewater.

The performance of the MBBR system was evaluated by comparing the concentrations of key parameters in the influent and effluent samples. Special emphasis was given to the removal efficiency of biochemical oxygen demand (BOD), chemical oxygen demand (COD), and ammonical nitrogen, as these are critical indicators of organic and nitrogen pollution. The results showed a significant improvement in water quality after treatment. The influent wastewater initially exhibited a BOD value of 28.8 mg/L and a COD value of 86.4 mg/L, indicating moderate levels of organic pollution. Additionally, the presence of ammonical nitrogen at a concentration of 27.39 mg/L highlighted the need for effective nitrogen removal processes.

After treatment in the MBBR reactor, the effluent showed a remarkable reduction in pollutant concentrations. The BOD value decreased from 28.8 mg/L to 4 mg/L, indicating efficient removal of biodegradable organic matter. Similarly, the COD value was reduced from 86.4 mg/L to 14 mg/L, demonstrating the reactor's capability to eliminate both biodegradable and non-biodegradable organic substances. The concentration of ammonical nitrogen was also significantly reduced from 27.39 mg/L to 5 mg/L, which confirms the effectiveness of the biological processes in converting nitrogenous compounds into less harmful forms. This reduction is primarily attributed to the activity of nitrifying bacteria present in the biofilm, which convert ammonia into nitrites and nitrates.

The observed reduction in BOD and COD values clearly indicates that the MBBR system is highly efficient in degrading organic pollutants. The presence of biofilm on the carrier media enhances microbial activity and provides a stable environment for the growth of microorganisms, resulting in improved treatment performance. The continuous aeration ensures that sufficient oxygen is available for aerobic degradation processes, further contributing to the efficiency of the system. Moreover, the reduction in ammonical nitrogen demonstrates that the reactor is capable of handling nitrogenous pollutants effectively, which is an important requirement for wastewater treatment.

Figure:1 System A Conventional

Figure:2 System B Two Stage

IV. RESULTS AND COMPARATIVE ANALYSIS

Config.	BOD Removal	COD Removal	Ammonia Removal	Stability	Energy Requirement
Single Stage	85–90%	80–85%	65–70%	Moderate	Low
Two-Stage	92–96%	88–92%	80–88%	High	Moderate
Hybrid MBBR	94–98%	90–95%	85–92%	Very High	High

V. CONCLUSION

The study demonstrates that the Moving Bed Biofilm Reactor (MBBR) system is an effective and reliable technology for wastewater treatment. The use of carrier media for biofilm development significantly enhances microbial activity and improves the overall efficiency of the treatment process. The results obtained in this study confirm that the MBBR system can achieve substantial removal of organic and nitrogenous pollutants, making it suitable for sustainable wastewater management. The system offers several advantages, including compact design, high treatment efficiency, and ease of operation, which make it an attractive option for both small-scale and large-scale wastewater treatment applications. Therefore, the implementation of MBBR technology can contribute significantly to environmental protection and the sustainable management of water resource. That optimization of operational parameters significantly enhances MBBR performance. Among the evaluated configurations, multi-stage MBBR systems offer the best balance between treatment efficiency and operational cost. Hybrid systems achieve the highest removal efficiencies but involve increased energy consumption. Proper optimization of HRT, DO levels, and carrier filling ratio is essential for maximizing system efficiency. The optimized MBBR system is a reliable and sustainable solution for modern wastewater treatment applications.

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