

LABORATORY-SCALE REACTORS EMPLOYING MOVING BED BIOFILM REACTOR (MBBR) TECHNOLOGY: A COMPREHENSIVE REVIEW

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ABSTRACT – Moving bed biofilm reactor (MBBR) technology has emerged as a highly efficient and robust process for biological wastewater treatment, offering advantages such as compact reactor footprint, enhanced biomass retention, and resistance to loading fluctuations. This review provides a comprehensive overview of the application of MBBR technology in laboratory-scale reactors, highlighting its underlying principles and comparing it to traditional suspended and attached growth systems. Emphasis is placed on design considerations, operational parameters, and performance evaluation in terms of pollutant removal efficiency and process stability. Moreover, the paper discusses the latest advancements and future perspectives concerning new carrier media materials, hybrid reactor configurations, and potential for full-scale implementation. The findings underscore the adaptability and effectiveness of MBBR technology in achieving superior treatment performance, making it an attractive option for researchers and practitioners seeking to address a wide array of wastewater challenges.

Keywords: MBBR, Biofilm, Wastewater, Treatment, Carriers.

INTRODUCTION

The growing global concern over water quality has prompted significant research and development of advanced wastewater treatment processes. Biological treatment systems are critical components of modern wastewater treatment plants, as they effectively remove organic pollutants, nutrients, and other contaminants through microbial metabolism. Traditional biological treatment processes can be broadly classified into suspended-growth systems, such as activated sludge processes, and attached-growth systems, such as trickling filters and rotating biological contactors. More recently, hybrid or combined systems have also gained attention [1-5]. Among these, moving bed biofilm reactor (MBBR) technology has garnered considerable interest owing to its compact design, high treatment efficiency, and robust performance under variable loading rates [6].

The MBBR process was originally developed in Norway during the late 1980s and early 1990s. Since then, numerous full-scale installations, as well as laboratory- and pilot-scale

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studies, have confirmed the technology's potential for removing organic matter, nitrogen, and other pollutants. The distinctive feature of MBBR is the presence of carrier elements in the reactor that facilitate biofilm growth, leading to improved biomass retention and treatment effectiveness [2,7]. This paper aims to provide a comprehensive review of laboratory-scale MBBR reactors, elucidating the key design and operational parameters, summarizing performance data from various studies, and discussing emerging trends and future perspectives related to the technology.

OVERVIEW OF MBBR TECHNOLOGY

MBBR technology is based on the principle of biofilm formation on specially designed carrier materials (often referred to as "media" or "carriers") that are continuously mixed throughout the reactor (Figure 1). The carriers, typically made of polyethylene or polypropylene, provide a protected surface area where microbial communities can attach and form biofilms. Aeration or mechanical mixing ensures that these carriers remain in constant motion, thereby enhancing contact between the wastewater and the biofilm. The result is a system combining the advantages of suspended growth (direct contact with contaminants) and attached growth (high biomass concentrations and resilience to shock loads) [8-11].



Figure 1 Example of an aerobic MBBR reactor with biomass growth clearly visible on the carrier surface [12]

MBBRs can operate with a significantly lower sludge age and higher organic loading rates than traditional activated sludge systems, leading to smaller reactor volumes. The biomass grows predominantly on the carrier surfaces, allowing for better retention and reduced washout. This feature also eliminates or reduces the need for a separate clarification step, a critical element in many conventional wastewater treatment processes. In addition, MBBR systems often exhibit greater stability when subjected to varying influent characteristics, pH fluctuations, and toxic shocks [9, 12-14].

In laboratory setups, MBBR technology is commonly deployed in cylindrical reactors made of glass or acrylic. The choice of carrier material is typically based on factors such as surface area-to-volume ratio, durability, and the ability to promote adequate biofilm growth. Aeration systems are designed to provide both oxygen supply and mixing to ensure the carriers remain well-suspended [15].

LABORATORY-SCALE MBBR REACTORS

Laboratory-scale MBBR reactors serve as an essential step before transitioning to pilot or full-scale implementations. They allow researchers to investigate fundamental aspects of MBBR performance under controlled conditions, including the influence of various operating parameters, carrier design, and wastewater compositions. Additionally, these smaller systems facilitate the rapid assessment of novel carrier materials, advanced process configurations, and new operational strategies [16].

The design of laboratory-scale MBBR systems typically involves a transparent vessel, which enables visual observation and documentation of biofilm growth on carrier surfaces. The carriers are placed inside the reactor at a defined fill fraction (ranging from 20% to 70% of the total reactor volume, depending on the intended loading). Continuous or intermittent aeration is provided through diffusers located at the bottom of the reactor to maintain dissolved oxygen concentrations sufficient for the microorganisms and to ensure the carriers stay in suspension. Depending on the nature of the study, the system can be operated under batch or continuous-flow conditions [17]. The feed composition may range from synthetic wastewater (with precise carbon, nitrogen, and phosphorus levels) to real municipal or industrial wastewater, depending on the specific research objectives.

One of the challenges in laboratory-scale MBBR experiments is accurately simulating real operating conditions, such as diurnal variations in influent characteristics or fluctuations in loading. Researchers often incorporate programmable logic controllers (PLCs) or automated control systems that can adjust influent flow rates or nutrient concentrations over time to address these issues. Another challenge lies in scaling up results. Because the hydrodynamics, oxygen transfer efficiency, and biofilm characteristics might differ in larger systems, careful attention should be paid to dimensionless parameters and similarity criteria during the design and interpretation of laboratory-scale experiments [18].

OPERATIONAL PARAMETERS IN MBBR SYSTEMS

Operational parameters play a significant role in determining the efficiency and stability of MBBR systems. One key parameter is the hydraulic retention time (HRT), which influences the contact time between the wastewater and the biofilm. In laboratory setups, HRTs can range from a few hours to more than a day, depending on the study's objectives and the desired removal efficiency [3].

Organic loading rate (OLR) is another critical parameter, reflecting the mass of biodegradable matter introduced per unit volume of reactor per day. Laboratory-scale studies typically explore a wide range of OLR values to understand how the system reacts to different pollutant loads. The balance between OLR and the available biomass (i.e., carrier fill fraction and microbial growth) is crucial to ensure that the system can handle the incoming load without risking overload or biomass washout.

Dissolved oxygen (DO) concentration is also essential, particularly for aerobic processes aimed at removing organic matter and nitrogenous compounds through nitrification. In well-aerated MBBR systems, DO levels are generally maintained above 2

mg/L, but this can vary based on the reactor's specific design and the target pollutants. Laboratory studies often employ oxygen probes and controllers to keep the DO within the desired range. Additionally, the mixing intensity, commonly measured by air flow rate in aerobic MBBR systems, determines the movement of carriers, the shear forces on the biofilm, and the overall oxygen transfer efficiency [19].

Temperature can significantly affect microbial activity and growth, especially for nitrifying bacteria, which have a narrower optimal temperature range. Laboratory reactors usually maintain a constant temperature using thermostatic baths or heating jackets to eliminate fluctuations that could confound experimental results. pH is another factor influencing microbial metabolism. Typically, MBBR systems are maintained at a near-neutral pH of around 7 to 8, although certain specialized processes (e.g., partial nitrification) might require different pH ranges [13].

PERFORMANCE OF MBBR IN LABORATORY REACTORS

In laboratory-scale investigations, MBBR systems have consistently demonstrated high removal efficiencies for chemical oxygen demand (COD) and biochemical oxygen demand (BOD). Removal rates above 85% are common, depending on the organic loading rate and carrier fill fraction. Successful nitrogen removal has also been reported in numerous studies, particularly when the MBBR system is combined with anoxic zones or operates in sequential aerobic–anoxic modes for nitrification-denitrification. Phosphorus removal, however, often requires additional treatment steps, such as chemical precipitation or the incorporation of enhanced biological phosphorus removal processes [2,3,16].

One of the most notable advantages of MBBR technology is its resilience to fluctuating load conditions. Laboratory experiments indicate that MBBR reactors can absorb sudden increases in organic or toxic loading with minimal impact on overall performance. This robustness is attributed to the stable biofilm communities established on the carriers, which can withstand short-term disturbances more effectively compared to conventional suspended-growth systems.

Researchers have also investigated the use of innovative carrier materials, including those made from biodegradable polymers or modified surfaces with immobilized nanoparticles to enhance biofilm formation or target specific pollutants such as heavy metals or recalcitrant organic compounds. These laboratory-based studies demonstrate the adaptability of MBBR technology to different wastewater streams, from municipal sewage to high-strength industrial effluents [20].

FUTURE PERSPECTIVES

Future developments in laboratory-scale MBBR research are expected to focus on hybrid configurations that combine MBBR with other advanced treatment processes, such as membrane filtration, electrochemical processes, or advanced oxidation. These integrated systems have the potential to expand the range of treatable pollutants and further improve the overall water quality. Additionally, the application of novel carrier

media with tailored surface properties, higher surface area-to-volume ratios, and enhanced mechanical robustness remains a topic of ongoing investigation.

The increasing adoption of digital technologies and process modeling tools offers another promising direction. Advanced process simulations and real-time monitoring technologies can help researchers optimize operational parameters, reduce energy consumption, and predict system responses under dynamic conditions [21,22]. Machine learning techniques may also be employed to identify complex relationships between operating variables and treatment performance in laboratory MBBR reactors, ultimately leading to more robust and efficient full-scale processes.

CONCLUSION

Moving bed biofilm reactor technology has proven to be a reliable and efficient approach for wastewater treatment in laboratory-scale studies. Its capacity to maintain high biomass concentrations, tolerate fluctuating loads, and adapt to various wastewater characteristics has led to wide acceptance and continuous development. Laboratory-scale MBBR reactors provide valuable insight into the fundamental interactions between biofilms, carriers, and wastewater, informing the design and operation of larger systems. Key research directions include optimizing carrier materials, exploring hybrid configurations with other advanced processes, and employing modeling and real-time monitoring strategies to enhance system performance. As water quality regulations tighten and environmental challenges persist, MBBR technology will likely remain at the forefront of innovation in biological wastewater treatment.

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