MEMBRANE BIOREACTOR TECHNOLOGY AS AN INNOVATIVE SOLUTION FOR SUSTAINABLE WASTEWATER TREATMENT

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Abstract. *This article elucidates the fundamental principles of MBR systems, provides an in-depth analysis of bioreactor characteristics, and comprehensively examines the membrane separation process. Membrane fouling, the main barrier to large-scale MBR adoption, is explored in detail, along with the most advanced contemporary mitigation strategies. A selection of novel MBR configurations and their benefits is also summarized. To promote broader and more cost-effective implementation of MBR technology, existing challenges and prospective research directions are proposed.*

Keywords: *membrane system, wastewater treatment, MBR adoption, biological treatment, membrane separation, membrane fouling*

Introduction. The development of submerged membrane configurations in the 1990s marked a significant breakthrough, dramatically reducing energy consumption and operational costs compared to earlier side-stream designs [1]. This innovation catalyzed the rapid expansion of MBR applications in both municipal and industrial wastewater treatment [2]. Today, MBR systems can operate at higher mixed liquor suspended solids concentrations than conventional processes, reducing reactor volumes while maintaining superior treatment performance [3,4].

Despite these advances, membrane fouling remains the primary operational challenge in MBR systems, leading to increased transmembrane pressure, reduced permeate flux, and higher maintenance requirements [5,6]. Ongoing research focuses on developing fouling mitigation strategies, including membrane surface modifications, optimized aeration patterns, and advanced cleaning protocols [7,8].

The operating conditions of a bioreactor exert a profound influence on key microbial characteristics, including cell size, the abundance of negatively acting filamentous microorganisms (which, in conventional activated sludge (CAS) systems, are notorious for causing sludge bulking, poor settleability in secondary clarifiers, and subsequent carry-over of solids into the effluent, ultimately leading to clogging of downstream mechanical filters), and overall microbial growth rates.

Figure 1. Filamentous bacteria observed as elongated, thread-like microbial structures within activated sludge systems.

Conversely, microbial community activity affects MBR performance in two critical and interrelated ways:

1. the extent of pollutant removal and the final quality of the treated effluent;
2. the rate and nature of membrane fouling.

Therefore, a deep understanding of the core principles of biological treatment encompassing microbial physiology and ecology, metabolic pathways, microbial stoichiometry, and reaction kinetics within the bioreactor — is indispensable for determining optimal operating regimes and for the successful design and scale-up of full-scale MBR plants.

The composition and structure of the microbial community within a single MBR facility differ from those in other facilities, and even within one plant, microbial populations evolve over time. This variability stems primarily from the inherent traits of microorganisms in engineered environmental systems (including MBRs) and the influences exerted by the influent wastewater entering the bioreactor. Nevertheless, by meticulously adjusting operational parameters and reactor design, it is feasible to selectively enrich specific microbial taxa within the bioreactor.

Although the types and functional roles of microorganisms in CAS and MBR bioreactors are essentially the same, their physiological and ecological characteristics differ markedly. These differences arise primarily from the distinctly longer solids retention time (SRT) and significantly higher biomass concentrations maintained in MBR systems, which lead to the following consequences:

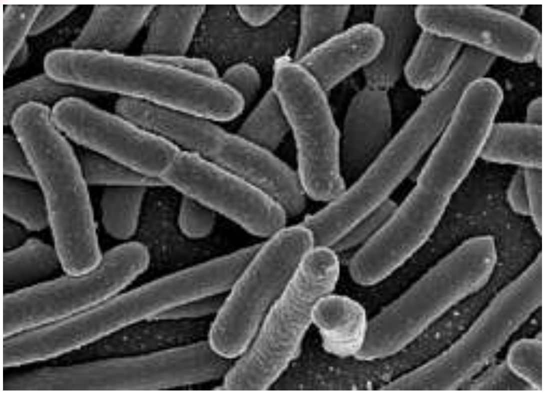
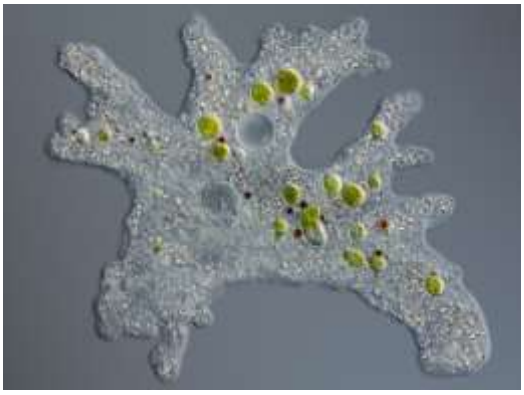

Figure 2. Representative morphology of Escherichia coli, a facultative anaerobic bacterium classified within the phylum Proteobacteria.

Figure 3. Amoebae identified as free-living protozoa contributing to the trophic dynamics of wastewater treatment microbial communities.

The microbial community in a bioreactor typically comprises five major groups: bacteria (predominantly Proteobacteria), unicellular protozoa (Amoebae, Flagellates, Free-swimming and Stalked Ciliates), metazoa (Rotifers, Nematodes, Tardigrades), filamentous bacteria, algae, and fungi. Nevertheless, more than 90 % of the microorganisms present in activated sludge are bacteria. Most bacteria occur as pairs, chains, or clusters (flocs), although solitary cells are also common. Their remarkable physiological versatility enables them to utilize a wide variety of substances as energy sources, electron donors, electron acceptors, and carbon sources. This metabolic flexibility is highly advantageous for the removal of diverse organic and inorganic pollutants and for the targeted degradation of specific recalcitrant compounds.

Microorganisms exhibit a strong tendency to adhere to surfaces, which leads to biofilm formation. Biofilm cells are embedded in a self-produced matrix of extracellular polymeric substances (EPS), primarily composed of polysaccharides, proteins, lipids, and nucleic acids. The high content of proteins and carbohydrates in EPS confers strong adhesive properties to the biofilm. This adhesion constitutes one of the principal drawbacks of MBR systems. To prevent excessive accumulation of biofilm on membrane fibers and to ensure uninterrupted biological treatment, coarse-bubble aeration (air scouring) is continuously or intermittently applied beneath the membrane modules, thereby mechanically dislodging attached biofilms and maintaining permeate flux.

Membrane fouling remains the primary limitation to widespread MBR adoption, increasing TMP, reducing flux, and necessitating frequent cleaning or membrane replacement, which elevates operational costs.

Foulants are materials that deposit on or within the membrane, reducing performance. They are commonly categorized into four groups:

Biofouling: Involves living microorganisms (bacteria, fungi, algae) that colonize the membrane surface, forming biofilms. These block pores and create a resistant layer. Biofouling is exacerbated by extracellular polymeric substances (EPS) and soluble microbial products (SMP), which act as "glue" for attachment.

Inorganic (Precipitative) Fouling: Results from precipitation of scales (e.g., calcium carbonate, magnesium sulfate, struvite) due to supersaturation, often triggered by high pH or hardness in the feedwater. This is less common in submerged MBRs but prevalent in systems treating hard or industrial wastewater.

Organic (Adsorptive) Fouling: Caused by adsorption of soluble organics such as oils, polymers, hydrocarbons, cationic surfactants, proteins, and polysaccharides. SMP and EPS from microbial metabolism are major contributors, leading to gel layer formation and irreversible fouling.

Particulate/Colloidal (Solids Accumulation) Fouling: Involves deposition of sludge flocs, colloids, and suspended solids between fibers or on the surface, forming a cake layer. This is the dominant reversible fouling type in MBRs, often accounting for 70-80% of total resistance

References

[1] Yamamoto K, Hiasa M, Mahmood T, Matsuo T. Direct solid-liquid separation using hollow fiber membrane in an activated sludge aeration tank. Water Science and Technology, 1989, 21(4-5), 43-54. DOI: 10.2166/wst.1989.0209

[2] Judd S, Judd C. The MBR Book: Principles and Applications of Membrane Bioreactors for Water and Wastewater Treatment. 2nd Edition, Butterworth-Heinemann, Oxford, 2011. DOI: 10.1016/B978-1-85617-481-7.00001

[3] Lin H, Gao W, Meng F, et al. Membrane bioreactors for industrial wastewater treatment: A critical review. Critical Reviews in Environmental Science and Technology, 2012, 42(7), 677-740. DOI: 10.1080/10643389.2010.526494

[4] Kraume M, Drews A. Membrane bioreactors in waste water treatment – Status and trends. Chemical Engineering & Technology, 2010, 33(8), 1251-1259. DOI: 10.1002/ceat.201000104

[5] Meng F, Zhang S, Oh Y, Zhou Z, Shin HS, Chae SR. Fouling in membrane bioreactors: An updated review. Water Research, 2017, 114, 151-180. DOI: 10.1016/j.watres.2017.02.006

[6] Liao BQ, Kraemer JT, Bagley DM. Anaerobic membrane bioreactors: Applications and research directions. Critical Reviews in Environmental Science and Technology, 2006, 36(6), 489-530. DOI: 10.1080/10643380600678146

[7] Wang Z, Wu Z, Tang S. Characterization of dissolved organic matter in a submerged membrane bioreactor by using three-dimensional excitation and emission matrix fluorescence spectroscopy. Water Research, 2009, 43(6), 1533-1540. DOI: 10.1016/j.watres.2008.12.033

[8] Le-Clech P, Chen V, Fane TAG. Fouling in membrane bioreactors used in wastewater treatment. Journal of Membrane Science, 2006, 284(1-2), 17-53. DOI: 10.1016/j.memsci.2006.08.019