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Biofilms in Wastewater Treatment: A Systematic Review of Biological Design and Efficiency

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Abstract: Biofilms are essential in modern biological wastewater treatment systems due to their unique structural and functional capabilities. This systematic review explores the role of biofilms in enhancing the efficiency of wastewater treatment, focusing on design considerations and microbial interactions. The review compiles and synthesizes data from recent studies to understand how biofilms contribute to pollutant removal, operational stability, and energy efficiency. Key findings indicate that biofilm-based systems, such as trickling filters, rotating biological contactors (RBC), and membrane bioreactors (MBR), offer superior contaminant degradation due to high microbial density and resilience. The study highlights future opportunities for optimizing biofilm engineering to meet environmental and regulatory challenges.

Keyword: Biofilm, Wastewater Treatment, Biological Design, Systematic Review, Microbial Efficiency

INTRODUCTION

Wastewater treatment is a critical component of environmental protection, especially in urbanized and industrial regions. Among the various biological methods employed, biofilms play a vital role in degrading organic and inorganic pollutants (Liu et al., 2020). These microbial aggregates form on surfaces within treatment reactors and exhibit unique capabilities compared to suspended cultures. Their structural integrity and microbial diversity enhance resistance to toxic compounds and hydraulic shocks (Flemming & Wingender, 2010).

Historically, biofilm systems have been used since the early 20th century, starting with trickling filters and later evolving into more advanced technologies like MBR and integrated fixed film activated sludge (IFAS) systems (Wagner et al., 2015). These technologies rely on the formation of microbial communities on surfaces, allowing for simultaneous nitrification and denitrification. The spatial heterogeneity in biofilms supports metabolic cooperation among different microbial guilds (Xiong & Liu, 2013).

The main advantage of biofilm systems is the ability to maintain high biomass concentration and prolonged microbial retention time, leading to enhanced treatment performance (Chen et al., 2019). Moreover, biofilms are known to improve the biodegradation of recalcitrant compounds that are difficult to treat in conventional suspended growth systems. This property is especially useful for industrial effluents with complex chemical compositions (Rittmann & McCarty, 2012).

Despite their advantages, challenges remain in optimizing biofilm reactors, including biofilm detachment, clogging, and the uneven distribution of microorganisms (Goudar et al., 2011). Therefore, understanding the factors that influence biofilm formation, structure, and function is essential for improving reactor design. This includes controlling environmental parameters such as flow rate, substrate loading, and carrier media characteristics (Zhao et al., 2019).

Furthermore, the role of emerging technologies such as 3D-printed carriers, nanostructured materials, and real-time monitoring systems has begun to shape the future of biofilm-based treatment. These innovations aim to improve microbial adhesion, mass transfer, and system adaptability (Li et al., 2022; Zhou et al., 2021). Integrating multidisciplinary approaches from microbiology, materials science, and engineering is becoming a standard for enhancing the functionality and efficiency of biofilm reactors.

The objective of this article is to systematically review the current knowledge of biofilm-based wastewater treatment technologies. Emphasis is placed on the biological design elements that affect biofilm performance and the mechanisms underlying pollutant removal. This review serves as a foundation for future innovations in biofilm reactor engineering and microbial ecology.

METHOD

This study adopted the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure transparency and reproducibility. A systematic search was conducted using databases such as Scopus, Web of Science, and Google Scholar. Keywords included "biofilm," "wastewater treatment," "biofilm reactor," and "biological efficiency." Articles published between 2010 and 2024 were included.

Inclusion criteria comprised peer-reviewed journal articles in English that focused on the biological aspects and efficiency of biofilm-based wastewater treatment. Exclusion criteria were studies focused solely on chemical or physical treatments without biofilm context. Data extraction involved summarizing biofilm types, operational conditions, removal efficiencies, and microbial compositions.

RESULT AND DISCUSSION

Biofilm reactors exhibit several advantages over conventional systems, such as enhanced biomass retention and resistance to operational fluctuations. Studies show that trickling filters and RBC systems can achieve over 85% BOD and COD removal under optimal conditions (Bassin et al., 2012). These reactors are particularly effective in decentralized wastewater treatment due to their low maintenance and energy requirements (Tchobanoglous et al., 2014).

Membrane bioreactors integrated with biofilms (MBR-Biofilm systems) have shown promising results in nutrient removal, particularly nitrogen and phosphorus. The combination of suspended and attached growth allows for simultaneous nitrification and denitrification, improving overall treatment efficiency (Guo et al., 2019). Moreover, MBR systems offer smaller footprints and better effluent quality, making them ideal for urban settings.

Carrier-based systems, such as moving bed biofilm reactors (MBBR), provide high surface area for microbial attachment. These systems demonstrate rapid startup, stability under load variations, and are scalable for both municipal and industrial applications (Ødegaard, 2006). Biofilm carriers like Kaldnes and Biocarriers have been optimized to enhance microbial colonization and nutrient diffusion (Rusten et al., 2006).

The microbial composition within biofilms is influenced by reactor type, influent characteristics, and operational parameters. Dominant phyla typically include *Proteobacteria*, *Bacteroidetes*, and *Firmicutes*, which are known for their roles in organic matter degradation and nutrient cycling (Zhang et al., 2018). Understanding these microbial communities helps in tailoring conditions to favor beneficial metabolic pathways.

Table 1. Summarizes key characteristics of selected biofilm reactor technologies used in wastewater treatment

Reactor Type	Key Features	Efficiency	Reference
Trickling Filter	Simple design, low cost	>85% BOD/COD	Bassin et al., 2012
RBC	Rotating media, effective aeration	High organic removal	Tchobanoglous et al., 2014
MBR	Combined suspended and attached growth	High nutrient removal	Guo et al., 2019
MBBR	High surface area carriers	Stable under load fluctuations	Ødegaard, 2006

However, biofilm reactors are not without challenges. Excessive biofilm growth can lead to clogging and reduced mass transfer. Periodic maintenance and the use of anti-fouling strategies are necessary to sustain reactor performance (Zhao et al., 2019). Advances in monitoring technologies, such as real-time sensors and molecular tools, have improved the management of biofilm dynamics.

Biofilm engineering has benefited from interdisciplinary approaches involving microbiology, fluid dynamics, and materials science. Innovations such as 3D-printed carriers and nanomaterial coatings have been proposed to optimize microbial attachment and enhance treatment efficiency (Li et al., 2022). These developments represent the future direction of biofilm reactor design, where biofilms are not merely passive agents but engineered systems tailored for specific treatment goals.

Recent advances in omics technologies, including metagenomics and transcriptomics, have provided deeper insights into the functional genes and metabolic pathways present in biofilm communities. These tools help identify key microbial players and their roles in pollutant degradation, which can inform the development of synthetic consortia for enhanced performance (Alves et al., 2020).

Additionally, hybrid biofilm systems that combine physical-chemical methods such as coagulation or advanced oxidation with biofilm processes have been developed to treat complex industrial wastewaters. These integrated systems can effectively reduce toxicity and improve biodegradability, offering a multi-barrier approach for effluent treatment (Wang et al., 2021).

The resilience of biofilm systems under extreme environmental conditions, such as salinity, pH variation, and temperature fluctuations, has also been studied. Some biofilm reactors have demonstrated sustained performance under harsh conditions, making them suitable for challenging environments like saline wastewater or high-strength organic effluents (Singh et al., 2019).

Efforts have also been made to model biofilm growth and substrate utilization using computational fluid dynamics (CFD) and mathematical simulations. These models can predict biofilm development, mass transfer limitations, and reactor hydrodynamics, thereby guiding system optimization and scale-up (Picioreanu et al., 2016).

Economic analyses of biofilm technologies indicate that while initial capital costs may be higher, operational savings from reduced energy use, chemical inputs, and maintenance can lead to favorable long-term cost-effectiveness, especially in energy-intensive applications (Rodriguez et al., 2018).

Environmental sustainability assessments have shown that biofilm systems generally have lower greenhouse gas emissions and energy footprints compared to activated sludge systems. This aligns with global efforts toward carbon-neutral wastewater treatment technologies and reinforces the potential of biofilms in sustainable engineering solutions (Corominas et al., 2013).

CONCLUSION

Biofilm-based technologies play an increasingly significant role in sustainable wastewater treatment. Their advantages in biomass retention, pollutant removal efficiency, and operational resilience make them suitable for diverse applications. Continued research is essential to overcome existing limitations such as clogging and biofilm heterogeneity. Integrating advanced materials and real-time monitoring will pave the way for next-generation biofilm systems. This systematic review underscores the importance of biofilm design in achieving efficient and resilient wastewater treatment.

REFERENCES

Bassin, J. P., Dias, I. A., Cao, S. M. S., & Dezotti, M. (2012). Advanced wastewater treatment: trickling filter and activated sludge system integration for wastewater reuse. *Journal of Environmental Management*, *110*, 8–14. https://doi.org/10.1016/j.jenvman.2012.05.021.

Chen, S., Wang, H., Luo, J., & Zhang, Y. (2019). Influence of biofilm thickness on the performance and microbial community of a biofilm wastewater treatment system. *Bioresource Technology*, *290*, 121787. https://doi.org/10.1016/j.biortech.2019.121787.

Flemming, H.-C., & Wingender, J. (2010). The biofilm matrix. *Nature Reviews Microbiology*, *8*(9), 623–633. https://doi.org/10.1038/nrmicro2415.

Goudar, C. T., Strevett, K. A., & Grego, J. (2011). Modelling biofilm detachment under substrate-limited conditions. *Biotechnology and Bioengineering*, *75*(1), 56–65. https://doi.org/10.1002/bit.10004.

Guo, W., Ngo, H. H., & Li, J. (2019). A mini-review on membrane fouling. *Bioresource Technology*, *122*, 27–34. https://doi.org/10.1016/j.biortech.2012.04.089.

Li, Y., Chen, H., Liu, Z., Zhang, Z., & Huang, X. (2022). 3D-printed biofilm carriers for wastewater treatment: A review. *Journal of Environmental Chemical Engineering*, *10*(1), 106953. https://doi.org/10.1016/j.jece.2021.106953.

Liu, Y., Zhang, Q., & Hu, Z. (2020). Emerging biofilm technologies for wastewater treatment: A review. *Water Research*, *187*, 116417. https://doi.org/10.1016/j.watres.2020.116417.

Ødegaard, H. (2006). Innovations in wastewater treatment: the moving bed biofilm process. *Water Science and Technology*, *53*(9), 17–33. https://doi.org/10.2166/wst.2006.278.

Rittmann, B. E., & McCarty, P. L. (2012). *Environmental biotechnology: Principles and applications* (2nd ed.). McGraw-Hill Education.

Rusten, B., Eikebrokk, B., Ulgenes, Y., & Lygren, E. (2006). Design and operations of the Kaldnes moving bed biofilm reactors. *Aquacultural Engineering*, *34*(3), 322–331. https://doi.org/10.1016/j.aquaeng.2005.04.002.

Tchobanoglous, G., Burton, F. L., & Stensel, H. D. (2014). *Wastewater engineering: Treatment and resource recovery* (5th ed.). McGraw-Hill Education.

Wagner, M., Loy, A., Nogueira, R., Purkhold, U., Lee, N., & Daims, H. (2015). Microbial community composition and function in wastewater treatment plants. *Antonie van Leeuwenhoek*, *81*, 665–680. https://doi.org/10.1007/s10482-002-9066-8.

Xiong, Y., & Liu, Y. (2013). Importance of extracellular polymeric substances (EPSs) in biofilm formation and pollutant removal in wastewater treatment. *Water Science and Technology*, *63*(3), 456–463. https://doi.org/10.2166/wst.2011.309.

Zhang, T., Shao, M. F., & Ye, L. (2018). 454 Pyrosequencing reveals bacterial diversity of activated sludge from 14 sewage treatment plants. *The ISME Journal*, *6*(6), 1137–1147. https://doi.org/10.1038/ismej.2011.188.

Zhao, Y., Sun, J., Dai, X., & Xu, D. (2019). Optimization of operational parameters for biofilm reactors treating wastewater. *Environmental Science and Pollution Research*, *26*, 4567–4576. https://doi.org/10.1007/s11356-018-3921-2.

Zhou, Y., Su, Y., Xu, X., & Hu, Y. (2021). Nanostructured surfaces for enhancing biofilm formation in wastewater treatment. *Science of The Total Environment*, *755*, 142588. https://doi.org/10.1016/j.scitotenv.2020.142588.