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Microscale Processes, Macroscale Solutions: Biofilms in Sustainable Water Filtration

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The increasing global demand for safe drinking water emphasizes the importance of energy-efficient and sustainable treatment technologies such as slow sand filtration (SSF). Central to SSF's efficacy is the bioactive layer, or Schmutzdecke (SD), which facilitates particle removal through biological and physical processes. This study bridges microscale insights into biofilm dynamics with macroscale filtration performance, advancing our understanding of SSF optimization.

The research investigates the impact of operational parameters, such as sand grain size and material, on SD development and SSF performance. Fine-grain sand filters were found to promote faster SD formation, enhancing microbial activity and particle retention. A key finding was the role of the protein-to-carbohydrate ratio within the SD as a critical indicator of Escherichia coli removal efficiency. To uncover the mechanisms underlying particle removal, microfluidic experiments with realistic pore structures were conducted using 1.5 µm fluorescent particles and biofilms of varying maturity. Advanced fluorescent microscopy and confocal laser scanning microscopy enabled direct observation of biofilm growth, particle transport, and removal mechanisms at pore-scale resolution.

The results demonstrated that biofilm growth significantly alters porous media properties, including pore size distribution, hydraulic conductivity, and effective porosity. As biofilm matured, preferential flow paths emerged in the porous media, increasing particle velocities from 4.58 mm/s in clean conditions to 7.4 mm/s in bio-clogged conditions. This hydrodynamic shift created isolated zones and enhanced straining mechanisms, resulting in over 50-fold reduction in hydraulic conductivity and a decrease in effective porosity from 36% to 9%. Consequently, the fraction of permanently attached particles increased significantly, improving log10 removal efficiency of the sand [1].

At the macroscale, these findings align with observed improvements in SSF performance under mature SD conditions. The study highlights that biofilm-induced surface roughness and pore structure modifications enhance particle retention by developing low-velocity zones favourable to attachment. Furthermore, increased tortuosity due to biofilm growth redirected flow through preferential paths, amplifying particle capture efficiency.

This research provides a comprehensive framework for understanding the interplay between biofilm development and filtration performance across scales. By elucidating the mechanisms driving particle removal in SSF systems, it offers actionable insights for optimizing operational parameters to ensure safe drinking water production while maintaining filter longevity.

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References

[1] Samari-Kermani, M., de Vries, E. T., Schijven, J. F., & Raoof, A. (2024). A closer look at the role of biofilms in water filtration: Bridging microscopic insights with system performance. Journal of Water Process Engineering, 67, 106104. https://doi.org/10.1016/j.jwpe.2024.106104

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