Carbon Transformation in Biofouling During Membrane Filtration: A Review of Challenges and Solutions in Palestine.

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Abstract—**Biofouling is a significant impediment to efficient membrane filtration in Palestine, notably in the Gaza Strip, where nearly all groundwater is contaminated and access to clean water is severely restricted. In my review, I look at how dissolved organic carbon (DOC) from local sources such olive oil wastewater, agricultural runoff, and leaking septic systems promotes microbial growth and extracellular polymeric substance (EPS) formation, resulting in rapid membrane fouling. Using recent studies and regional data, I investigate biofouling mechanisms in Gaza's unique environmental and infrastructure conditions. I assess mitigation techniques, including low-cost biological pretreatment using olive waste biochar, O_3-PAC oxidation, and new approaches such as quorum quenching and machine learning-based monitoring. Policy initiatives, such as strengthening sanitation infrastructure and promoting cross-border collaboration with Jordan, are also addressed. While modern technologies offer promise, their deployment in Gaza is limited due to a lack of analytical tools, financing, and technical capacity. This assessment emphasizes the need for integrated, context-sensitive solutions that combine local resource use, scalable technologies, and institutional assistance to improve water security in Palestine. This analysis synthesizes findings from peer-reviewed research published from 2000 to 2024, obtained from sources such as Scopus and Web of Science, with an emphasis on biofouling mechanisms and mitigation measures relevant to water-scarce and conflict-affected locations like Palestine.**

I. Introduction

Gaza's water scarcity (97% of groundwater contaminated) is worsened by biofouling in membrane systems (Weinthal et al., 2005). High Dissolved Organic Carbon (DOC) from olive oil wastewater and septage infiltration fuels microbial growth and EPS (extracellular polymeric substance) production, reducing membrane efficiency. This review focuses on Palestine's unique challenges and proposes region-specific solutions to enhance water access and infrastructure resilience.

II. Mechanisms of Biofouling in Gaza

A. Microbial Colonization

- DOC Sources: Olive oil wastewater introduces labile carbon, promoting heterotrophic bacteria (*Pseudomonas)* growth (Zhang et al., 2006).
- Septage Infiltration: Poorly maintained cesspits introduce ammonia and assimilable organic carbon (AOC), accelerating biofilm formation (Amous et al., 2020).

B. EPS Synthesis

EPS (polysaccharides, proteins) forms a protective matrix, increasing hydraulic resistance. Gaza's high DOC levels boost EPS production, reducing permeate flux by 40% in desalination plants (Abu Amr & Yassin, 2008).

C. Nutrient Dynamics

- Nitrogen: Agricultural runoff elevates ammonium levels, favoring heterotrophic dominance (Reem et al., 2018).
- Phosphorus Limitation: Reduces biofouling but requires low AOC levels (Lv et al., 2024).

III. Case Study: Gaza's Wastewater Challenges

TABLE I. *The PSIR (Pressure-State-Impact-Response) framework illustrates the interplay between environmental stressors and institutional responses in Gaza.*

Pressure	State	Impact	Response
Olive oil wastewater	DOC: 20–30 mg/L (Al Manama et al., 2024).	Accelerated biofilm growth (Zhang et al., 2006).	Biochar from olive waste (J. Y. Jiang & J. Y. Guo, 2023).
Septage infiltration	Groundwater contamination (Amous et al., 2020).	Frequent membrane cleaning (Abu Amr & Yassin, 2008).	Sanitation infrastructure upgrades (Al-Sa'Ed, 2005).
Agricultural runoff	Nitrogen-rich water (Reem et al., 2018).	Heterotrophic dominance in biofilms (Herzberg et al., 2009).	Coagulation-flocculation (Z. Wang et al., 2020).

A. Health and Economic Impacts

- Health Risks: Untreated wastewater causes 30% of Gaza's gastrointestinal diseases (Abu Amr & Yassin, 2008).
- Costs: Biofouling increases operational costs by 40% (Yang et al., 2023).

IV. Mitigation Strategies

This section combines technological, biological, and policy initiatives to combat biofouling on various scales.

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A. Biological Pretreatment

- Biochar from Olive Mill Waste: A low-cost, locally available adsorbent that eliminates DOC while reducing microbial adherence. Studies suggest that using a pretreatment filter can reduce fouling by up to 50% (J. Jiang & J. Guo, 2023).

- Coagulation-Flocculation: Effectively removes NOM and colloidal particles. Aluminum or iron-based coagulants decrease AOC and delay biofilm development (X. Y. Wang et al., 2020).

B. Advanced Oxidation

- O_3-PAC Combinations: Ozonation modifies the structure of NOM, reducing its biodegradability, whereas powdered activated carbon (PAC) adsorbs leftover organics. This dual strategy dramatically lowers biofouling in surface water treatment (Yang et al., 2023).

C. Emerging Technologies

- Machine Learning: Real-time monitoring systems using machine learning (ML) algorithms analyze Dissolved Organic Carbon (DOC), Assimilable organic carbon (AOC), and microbial data to predict biofouling risks. For instance, sensors detecting early-stage EPS formation enable proactive cleaning, reducing operational costs by 20–30% (Pulido Beltran et al., 2024). While Gaza lacks widespread ML infrastructure, partnerships with Jordan or international aid could facilitate implementation.

- Quorum Quenching: Interrupts bacterial communication (quorum sensing) by blocking signaling molecules such as acyl-homoserine lactones. This impedes coordinated EPS synthesis and biofilm maturation. According to studies, quorum quenching agents reduce biofilm biomass by 60%, making them a cost-effective alternative to chemical treatments (Lv et al., 2024).

D. Policy and Infrastructure

- Sanitation Infrastructure: Building septic networks and improving wastewater collection systems reduces septage infiltration into groundwater. Pilot projects in Gaza (e.g., UNRWA initiatives) have demonstrated that septic tanks cut DOC levels by 25% and reduce groundwater contamination (Al-Sa'Ed, 2005). Scaling these efforts requires international aid and local governance support.

- Cross-Border Collaboration: Adopting Jordan's standardized pretreatment protocols (e.g., O_3-PAC dosing) could improve shared aquifer management. Collaborative frameworks, like those proposed by Weinthal et al. (2005), enhance technology transfer and reduce costs through shared infrastructure investments.

E. Systemic Challenges

- Gaza has limited analytical tools for real-time biofouling monitoring (Dardas et al., 2023).

- Weak International Collaboration: Limited research output in water science (Dardas et al., 2023).

Feasibility and Cost Comparison:

The strategies are summarized in Table 2, highlighting their cost, feasibility, and advantages in Gaza's context:

TABLE II. *MITIGATION STRATEGY COMPARISON*

Strategy	Cost	Feasibility	Advantages
Biochar pretreatment	Low	High (local waste)	Reduces DOC, eco-friendly
O_3-PAC	Moderate	Requires training	Effective against labile organic matter
Machine learning	High	Needs international aid	Early fouling detection
Quorum quenching	Moderate	Requires R&D partnerships	Disrupts microbial signaling

KEY CONSIDERATIONS

- Resource Constraints: Low-cost solutions like biochar and quorum quenching are prioritized for Gaza's limited budgets.

- Policy Gaps: Sanitation infrastructure upgrades and cross-border collaboration are critical to addressing systemic challenges.

- Emerging Tech: Machine learning and quorum quenching require capacity-building but offer long-term benefits.

VI. CONCLUSION & CALL TO ACTION

Biofouling in Palestinian membrane systems is aggravated by high DOC levels from olive oil effluent, agricultural runoff, and septage infiltration. These carbon sources promote microbial growth and EPS synthesis, which reduces membrane efficiency and raises treatment costs. In Gaza, where water scarcity is extreme, dealing with biofouling is not only a technical challenge, but also a public health and equity imperative.

Region-specific treatments, such as biochar from olive waste and O_3-PAC pretreatment, provide scalable strategies to minimize fouling. Meanwhile, quorum quenching and machine learning-based monitoring are emerging technologies that, with targeted investment and collaboration, have the potential to change water treatment resilience.

However, long-term success necessitates systemic reforms such as improving sanitation infrastructure, strengthening cross-border cooperation, and increasing local research ability. International cooperation is critical for scaling pilot projects and overcoming financial and technological constraints.

Without context-sensitive policies and ongoing investment, biofouling will continue to hinder efforts to offer safe, sustainable water access in Palestine. This review advocates coordinated, interdisciplinary action—combining research, policy, and community engagement—to secure water justice in one of the world's most vulnerable areas.

References

[1] Abu Amr, S. S., & Yassin, M. M. (2008). Microbial contamination of the drinking water distribution system and its impact on human health in Khan Yunis Governorate, Gaza Strip: Seven years of monitoring (2000–2006). Public Health, 122(11), 1275-1283. https://doi.org/10.1016/j.puhe.2008.02.009.

[2] Al-Sa'Ed, R. (2005). Obstacles and Chances to Cut Pollution Load Discharges from Urban Palestine. *Water International*, *30*(4), 538-544. https://doi.org/10.1080/02508060508691898

[3] Al Manama, A., Alshawa, I., & Albahnasavi, A. (2024). Impact of olive mill wastewater on the operational efficiency of wastewater treatment plants in the Gaza Strip. *Environmental Monitoring and Assessment*, *197*(1). https://doi.org/10.1007/s10661-024-13553-7

[4] Amous, B., Mahmoud, N., Van Der Steen, P., & Lens, P. N. L. (2020). Septage composition and pollution fluxes from cesspits in Palestine. *Journal of Water, Sanitation and Hygiene for Development*, *10*(4), 905-915. https://doi.org/10.2166/washdev.2020.202

[5] Dardas, L. A., Malkawi, A. M. A., Sweis, S., Sweis, N., Al-Khayat, A., & Sawair, F. A. (2023). Mapping Two Decades of Research Productivity in the Middle Eastern and Arab Countries: A Comprehensive Bibliometric Analysis. *Publications*, *11*(4), 48. https://doi.org/10.3390/publications11040048

[6] Herzberg, M., Kang, S., & Elimelech, M. (2009). Role of Extracellular Polymeric Substances (EPS) in Biofouling of Reverse Osmosis Membranes. *Environmental Science & Technology*, *43*(12), 4393-4398. https://doi.org/10.1021/es900087j

[7] Jiang, J., & Guo, J. (2023). Treatment Performance of Municipal Sewage in a Submerged Membrane Bioreactor (SMBR) and Mechanism of Biochar to Reduce Membrane Fouling. *Sustainability*, *15*(12), 9239. https://doi.org/10.3390/su15129239

[8] Lv, L., Wei, Z., Li, W., Chen, J., Tian, Y., Gao, W., Wang, P., Sun, L., Ren, Z., Zhang, G., Liu, X., & Ngo, H. H. (2024). Regulation of extracellular polymers based on quorum sensing in wastewater biological treatment from mechanisms to applications: A critical review. *Water Research*, *250*, 121057. https://doi.org/10.1016/j.watres.2023.121057

[9] Pulido Beltran, L., Vrouwenvelder, J. S., & Farhat, N. (2024). Application of Online Flow Cytometry for Early Biofouling Detection in Reverse Osmosis Membrane Systems. *Membranes*, *14*(9), 185. https://doi.org/10.3390/membranes14090185

[10] Reem, A., Mokhtar, G., Ryusei, I., & Naoyuki, F. (2018). Assessment of Different Irrigational Practices on Managing the Nitrogen Loss into the Groundwater Using HYDRUS-1D Numerical Software Gaza Strip as a Case Study—Palestine. In (pp. 653-657). Springer International Publishing. https://doi.org/10.1007/978-3-319-70548-4_195

[11] Wang, X. Y., Ma, J. X., Wu, Z. C., & Wang, Z. W. (2020). Stimulatory effects on bacteria induced by chemical cleaning cause severe biofouling of membranes. *Journal of Water Reuse and Desalination*, *10*(1), 82-94. https://doi.org/10.2166/wrd.2020.062

[12] Wang, Z., Gao, P., Yan, L., Yin, C., & Li, S. (2020). Enhanced nitrate removal and fouling behavior in a denitrifying membrane bioreactor: impacts of carbon source and C/N ratio. *Desalination and Water Treatment*, *207*, 86-98. https://doi.org/10.5004/dwt.2020.26421

[13] Weinthal, E., Vengosh, A., Marei, A., Gutierrez, A., & Kloppmann, W. (2005). The Water Crisis in the Gaza Strip: Prospects for Resolution. *Groundwater*, *43*(5), 653-660. https://doi.org/10.1111/j.1745-6584.2005.00064.x

[14] Yang, J., Liu, Y., Zhao, J., Wang, H., Li, G., & Liang, H. (2023). Controlling ultrafiltration membrane fouling in surface water treatment via combined pretreatment of O3 and PAC: Mechanism investigation on impacts of technological sequence. *Science of The Total Environment*, *895*, 165168. https://doi.org/10.1016/j.scitotenv.2023.165168

[15] Zhang, K., Choi, H., Dionysiou, D. D., Sorial, G. A., & Oerther, D. B. (2006). Identifying pioneer bacterial species responsible for biofouling membrane bioreactors. *Environmental Microbiology*, *8*(3), 433-440. https://doi.org/10.1111/j.1462-2920.2005.00909.x