Navigating Pharmaceutical Contamination: The Role of Constructed Wetlands in Mitigating Emerging Aquatic Pollutants

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Abstract

Widespread pharmaceutical use leads to the contamination of surface waters through urban wastewater, hospital effluents, and agricultural runoff. Classified as contaminants of emerging concern (CECs), pharmaceuticals disrupt aquatic ecosystems by altering microbial communities, fostering antibiotic resistance, and threatening biodiversity. Their molecular stability, designed to withstand human metabolic processes, complicates degradation in conventional wastewater treatment plants. Constructed wetlands (CWs) offer a promising alternative for mitigating pharmaceutical pollution by employing natural processes to filter and degrade these compounds. This paper explores the mechanisms of pharmaceutical removal in CWs, focusing on environmental variables such as pH, temperature, and hydraulic retention time (HRT), while addressing current challenges and opportunities for advancing CW performance.

Introduction to Pharmaceuticals as Contaminants of Emerging Concern

Pharmaceuticals in aquatic environments are a growing concern due to their persistent nature and disruptive effects (Luo et al., 2014). Introduced through urban wastewater, hospital effluents, and agricultural runoff, these contaminants alter microbial communities, foster antibiotic resistance, and jeopardize biodiversity. Certain pharmaceuticals, such as endocrine-disrupting compounds (EDCs), interfere with hormonal systems, causing significant ecological impacts, including reproductive anomalies in aquatic organisms. The inability of conventional wastewater treatment plants (WWTPs) to adequately remove these compounds underscores the need for innovative approaches like constructed wetlands.

Overview of Constructed Wetlands

Constructed wetlands (CWs) mimic natural wetland processes to treat wastewater (Matamoros et al., 2017). Characterized by vegetated systems with shallow basins, CWs utilize substrates and root zones to filter and degrade contaminants through physical, chemical, and biological processes. Unlike conventional WWTPs, CWs incorporate photodegradation, biodegradation, and sorption mechanisms, making them uniquely suited for pharmaceutical removal. This section explores the basic design and functioning of CWs, emphasizing their advantages and limitations in addressing pharmaceutical contamination.

Factors Affecting Pharmaceutical Removal in Constructed Wetlands

Pharmaceutical removal in constructed wetlands is influenced by a combination of physicochemical properties, environmental variables, and microbial processes. The solid-water distribution coefficient (Kd) determines how pharmaceuticals partition between water and sediment. High Kd values result in sludge retention but may lead to accumulation in sediments, necessitating regular sediment management. The octanol-water partition coefficient (Kow) and Henry's law constants also play critical roles. Compounds with low logKow values (<2.5) remain highly mobile, while those with high values (>4) adhere to substrates, reducing bioavailability. Similarly, pKa values dictate mobility based on pH, as weakly acidic pharmaceuticals like ibuprofen exhibit increased solubility in higher pH environments, complicating removal efforts.

Environmental variables such as temperature and hydraulic retention time (HRT) significantly impact pharmaceutical degradation (Frascaroli et al., 2021). Seasonal temperature changes affect microbial activity, with colder months reducing biodegradation rates. CWs can integrate design features to insulate root zones and promote anaerobic processes during winter. Extended HRTs enhance pharmaceutical interaction with microbial communities, increasing degradation efficiency.

Microbial processes and redox conditions further contribute to pharmaceutical breakdown. Microbial biofilms create environments that support both aerobic and anaerobic conditions, facilitating degradation (Tafti et al., 2024). Cometabolism, where microbes degrade pharmaceuticals incidentally while metabolizing primary energy sources, addresses persistent compounds effectively. Hybrid CW designs, combining subsurface flow and open-water elements, address seasonal variations by leveraging both anaerobic and photodegradation processes.

Opportunities and Needs into the Future

Incorporating innovative materials and designs can enhance CW performance. Adding biochar and modified substrates with high sorption capacity improves retention and degradation of low-sorption pharmaceuticals. Advanced models simulating biofilm dynamics and sediment interactions can optimize CW performance for specific contaminants.

Upstream interventions, such as regulating pharmaceutical discharge, are critical for reducing contamination at its source (Okoye et al., 2022). Integrating CWs with green infrastructure initiatives offers scalable solutions for long-term ecosystem protection. However, addressing highly mobile and persistent pharmaceuticals may require advanced technologies, including granular activated carbon or ion exchange systems, alongside CWs. Continuous monitoring of environmental variables, such as light availability, oxygen levels, and temperature, ensures year-round efficiency.

Conclusion

Pharmaceutical pollution poses a significant threat to aquatic ecosystems, necessitating innovative and sustainable management solutions. Constructed wetlands provide an effective approach by utilizing natural processes for pharmaceutical removal. However, their success relies on thoughtful design, optimization of key factors such as HRT and microbial biofilms, and integration with upstream source control measures. By aligning these efforts, we can address the systemic challenges posed by emerging contaminants and safeguard the integrity of aquatic ecosystems.

References

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