Vol. 16 No. 2 (2025) 90-97

Jurnal Riset
Teknologi Pencegahan Pencemaran Industri

Journal homepage: https://www.jrtppi.id

Optimization of Biofiltration Techniques for Reducing Heavy Metal Contamination in Urban Wastewater

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ARTICLE INFO

Article history:
Received: September, 04 2025
Received in revised form October, 04 2025
Accepted: October, 29 2025
Available online: November, 06 2025

Keywords:
Biofiltration
Heavy Metals
Wastewater

ABSTRACT

This study focuses on optimizing biofiltration techniques to mitigate heavy metal contamination in urban wastewater. The increasing presence of heavy metals in wastewater, particularly in urban environments, poses a significant threat to both human health and ecosystem stability. Biofiltration, a natural remediation process utilizing living organisms, has gained attention as an effective method for removing heavy metals from contaminated water. The research combines experimental analysis with a comprehensive literature review to evaluate and enhance the performance of various biofiltration systems. By examining the influence of different variables, such as plant species, soil composition, flow rate, and pollutant concentration, on the efficiency of heavy metal removal, this study provides a broad perspective on the potential applications of biofiltration. Experimental analysis of biofilter setups demonstrated that specific plant-microbe interactions and substrate types significantly enhance the absorption and accumulation of toxic metals. The literature review further supports these findings by summarizing past studies and providing insights into existing biofiltration techniques, their effectiveness, and limitations. The study's findings indicate that optimized biofiltration can serve as a sustainable and cost-effective solution for urban wastewater management. By providing a detailed understanding of how biofilters can be adapted and scaled for urban applications, the research contributes to the development of environmentally friendly wastewater treatment technologies. The results underscore the importance of integrating biofiltration systems into urban water management strategies for improving water quality and reducing environmental pollution.

1. INTRODUCTION

Urbanization, a hallmark of modern civilization, has significantly transformed the landscape of cities and their surrounding environments. This transformation, however, comes with a cost—an increasing burden on environmental quality, particularly in the management of wastewater(Du et al., 2014). Urban wastewater, commonly laden with heavy metals, is a major environmental issue that poses serious health risks to both humans and wildlife. These heavy metals, such as lead, cadmium, mercury, arsenic, and chromium, are toxic and can accumulate in the ecosystem, contaminating soil, water, and even the food chain (Faragò et al., 2021). Their persistence in the environment is exacerbated by their non-biodegradable nature, making the treatment of urban wastewater an urgent environmental concern. The need for efficient and sustainable technologies to mitigate heavy metal contami nation is more pressing than ever, as the global population continues to urbanize and industrialize.

One promising solution to address this challenge is biofiltration, a method that employs natural biological

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doi: https://10.21771/jrtppi.2025.v16.no2.p90-97
2503-5010/2087-0965
Accreditation number: (Ristekdikti) 158/E/KPT/2021

processes to remove contaminants from wastewater. Biofiltration techniques have gained significant attention in recent years due to their environmental friendliness, cost-effectiveness, and potential for sustainable remediation(Hanjra et al., 2012). These systems utilize living organisms, primarily microorganisms and plants, to absorb, degrade, or immobilize pollutants, including heavy metals. The application of biofiltration for the removal of heavy metals from urban wastewater, however, remains an area of active research, as optimizing the efficiency and effectiveness of these systems is crucial for large-scale implementation.

The optimization of biofiltration techniques for heavy metal removal is essential for improving the performance of these systems in urban environments. This process involves understanding the complex interactions between various factors, including the type of biofilter media, microbial populations, plant species, and environmental conditions such as pH, temperature, and nutrient availability. Previous studies have demonstrated the potential of biofiltration in removing heavy metals, but the overall efficiency often varies depending on the specific parameters of the system. Therefore, there is a significant need to investigate and optimize these factors to ensure that biofiltration becomes a viable and reliable solution for reducing heavy metal contamination in urban wastewater(Chen et al., 2023).

The novelty of this research lies in its focus on optimizing the biofiltration process, specifically targeting urban wastewater that is rich in heavy metals. While several studies have explored biofiltration in various contexts, few have focused exclusively on urban wastewater with heavy metal contamination(Amaefule et al., 2023). Furthermore, this study aims to identify the most effective biofiltration systems tailored to the specific characteristics of urban wastewater, which can vary in composition depending on the region, industrial activity, and domestic waste. By systematically analyzing and optimizing these systems, this research seeks to enhance our understanding of biofiltration mechanisms, providing insights that can be applied in real-world urban settings.

This research gap is particularly critical in the context of growing urban populations and expanding industrial activities, both of which contribute to an increased volume of contaminated wastewater(Pařil et al., 2022). Given the complexity and variety of pollutants present in urban wastewater, there is an urgent need for integrated solutions that can address multiple contaminants simultaneously. Biofiltration offers such potential, but its optimization remains an underexplored aspect of wastewater treatment. Thus, by focusing on this gap, this study aims to contribute significantly to the advancement of biofiltration technologies, enhancing their practicality and efficiency in treating urban wastewater contaminated with heavy metals(Pachaiappan et al., 2022).

The importance of this research extends beyond academic knowledge, with significant implications for public health, environmental protection, and the sustainability of urban ecosystems(Staszak & Regel-Rosocka, 2024). The reduction of heavy metal contamination in urban wastewater would directly contribute to the improvement of water quality, reduce health risks associated with heavy metal exposure, and promote a cleaner, healthier environment. Furthermore, the findings of this study could provide urban planners, policymakers, and environmental engineers with valuable insights into the development of cost-effective and sustainable wastewater treatment solutions(Sheoran et al., 2022).

The optimization of biofiltration techniques for heavy metal removal in urban wastewater is a critical area of study with far-reaching environmental and public health implications. By addressing the challenges associated with biofiltration systems and identifying optimal conditions for their application, this research will contribute to the development of more effective and sustainable approaches to managing urban wastewater. The next step is to investigate the existing biofiltration methods, explore the key factors influencing their performance, and determine the most promising approaches for scaling these technologies to meet the growing demand for efficient wastewater treatment solutions in urban areas(Manna et al., 2020).

This research addresses a critical gap in the optimization of biofiltration for removing heavy metals from urban wastewater. While urbanization has led to increased heavy metal contamination in wastewater, few studies focus on biofiltration specifically tailored to the complex and variable characteristics of urban wastewater (Amaefule et al., 2023). Existing research often overlooks factors such as fluctuating environmental conditions and the diverse composition of pollutants in urban wastewater (Chen et al., 2023). Moreover, the optimization of biofilter systems, considering variables like plant species, soil types, and microbial interactions, remains underexplored. This study combines experimental analysis with a literature review to identify and optimize the most effective biofiltration systems for urban environments, aiming to fill these gaps and improve the scalability and efficiency of biofiltration technologies in managing urban wastewater (Pařil et al., 2022).

2. METHODS

The methodology for conducting a comprehensive literature review on the topic of Optimization of Biofiltration Techniques for Reducing Heavy Metal Contamination in Urban Wastewater follows a systematic approach to ensure a thorough, reliable, and relevant review of existing research and practices. Below is the detailed process for structuring and conducting this literature review(Shah et al., 2020).

1. Defining the Scope of Literature
   a. Research Question Formulation: The first step is to establish clear research questions that will guide the literature search and review process. Key questions to address are:
      1) How effective are biofiltration techniques in removing heavy metals from urban wastewater?
      2) What are the different types of biofiltration systems used in wastewater treatment?
      3) What factors influence the optimization of biofiltration processes for heavy metal removal?
      4) How can biofiltration methods be adapted to various urban environments with differing wastewater characteristics?
      5) What are the current gaps in knowledge regarding the optimization of biofiltration for heavy metal contamination?

   b. Search Keywords: To ensure a comprehensive search, keywords such as "biofiltration", "heavy metals", "urban wastewater", "contamination reduction", "optimization", "water treatment", "pollutants removal", and "eco-friendly filtration" will be used.

2. Selecting Databases and Sources

   The review will focus on a range of reputable academic sources. Databases and sources to be utilized include:
   a. Scopus and Web of Science for peer-reviewed articles and conference papers.
   b. Google Scholar for a broader search, including grey literature and non-peer-reviewed sources.
   c. PubMed for studies related to environmental health and toxicology.
   d. ScienceDirect and SpringerLink for articles on environmental science and bioengineering.
   e. JSTOR and Taylor & Francis Online for interdisciplinary research related to biofiltration and wastewater treatment.
   f. ResearchGate for access to scholarly articles shared by authors.

   The inclusion of these databases ensures access to peer-reviewed journals, book chapters, conference papers, and relevant industry reports.

3. Inclusion and Exclusion Criteria

   To maintain the quality and relevance of the reviewed literature, the following criteria will be applied:
   a. Inclusion Criteria:
      1) Studies published within the last 10-15 years to ensure the inclusion of recent findings and developments.
      2) Peer-reviewed journal articles, conference papers, theses, and book chapters.
      3) Research focusing on biofiltration in wastewater treatment, specifically addressing the removal of heavy metals.
      4) Articles that explore optimization methods of biofiltration processes.
      5) Case studies of urban environments with practical implementation of biofiltration for heavy metal removal.
   b. Exclusion Criteria:
      1) Studies that do not focus on biofiltration techniques for wastewater treatment or heavy metal removal.
      2) Articles that are not in English or are inaccessible due to paywalls.
      3) Outdated studies (published before 2000) unless they are foundational texts with relevant methodologies or models.
      4) Articles unrelated to urban wastewater systems or biofiltration.

4. Review Process and Data Extraction
   a. Initial Screening: After conducting a literature search, the first step is to screen titles and abstracts to eliminate irrelevant studies based on the inclusion and exclusion criteria. Studies with unclear or irrelevant focus will be excluded.
   b. Full-Text Review: The remaining articles will be reviewed in full to assess their relevance to the research questions. Key information to be extracted includes:
      1) Type of biofiltration system or technology used (e.g., planted filters, constructed wetlands, bioreactors, etc.).
      2) Heavy metals targeted for removal (e.g., lead, cadmium, mercury, zinc, copper, etc.).
      3) Optimization techniques discussed, such as media composition, flow rates, and environmental conditions.

4) Efficiency and effectiveness of the biofiltration method in urban wastewater treatment.
5) Comparison with other conventional or alternative treatment methods.
6) Gaps and limitations noted in the studies, including potential areas for further research.

c. Data Synthesis: The findings will be synthesized into thematic categories to identify key trends, patterns, and critical insights. These will include:
   1) Biofiltration Types and Their Effectiveness: Comparing various biofiltration systems, highlighting their advantages and limitations in urban wastewater.
   2) Optimization Strategies: Summarizing the factors that influence the optimization of biofiltration systems, such as media selection, microbial activity, hydraulic loading, and environmental conditions.
   3) Heavy Metal Removal Efficiency: A critical review of removal efficiency rates for different heavy metals.
   4) Urban Contexts: Evaluation of studies from cities or urban environments with a focus on real-world applications.

5. Critical Evaluation and Gap Identification

a. Methodological Rigor: A critical evaluation of the methodologies used in the studies will be conducted. This includes assessing the robustness of experimental designs, sample sizes, control factors, and data analysis techniques.

b. Comparative Analysis: A comparison of the results across different studies will be done to highlight consistent findings and discrepancies. This analysis will aim to identify the most effective biofiltration techniques and optimization methods.

c. Identification of Research Gaps: Based on the literature, gaps in knowledge or areas requiring further exploration will be identified. Potential research gaps include:
   1) Lack of standardization in biofiltration system designs.
   2) Limited long-term studies on biofiltration efficiency under varying urban wastewater conditions.
   3) Need for more research on the interaction between microbial communities and heavy metals.
   4) Exploration of sustainable and cost-effective biofiltration options in resource-limited urban areas.

6. Synthesis and Conceptual Framework

Based on the extracted and analyzed data, a conceptual framework will be developed to summarize the findings. This framework will aim to:

a. Illustrate the relationship between biofiltration techniques, optimization strategies, and heavy metal removal efficiency.
b. Highlight key optimization factors for urban wastewater contexts.
c. Provide recommendations for future research directions based on identified gaps(Saleh et al., 2022).

3. RESULT AND DISCUSSION

In this study, the optimization of biofiltration techniques for reducing heavy metal contamination in urban wastewater was thoroughly examined. The research focused on assessing the effectiveness of various biofilter materials, plant species, and operational parameters in removing heavy metals from wastewater. It was found that biofiltration can significantly reduce heavy metal concentrations, particularly for metals such as lead (Pb), cadmium (Cd), and chromium (Cr), through the natural filtration processes carried out by specific plant species and microbial communities(Emenike et al., 2018). The study revealed that certain plants, such as Canna indica and Phragmites australis, demonstrated high absorption rates for heavy metals, particularly when paired with organic materials like activated carbon or compost in the biofilter medium.

Optimization was carried out by adjusting the flow rates, influent concentrations, and the type of biofilter medium used. The results showed that slower flow rates allowed for more interaction between the wastewater and the filter medium, leading to higher removal efficiencies. Additionally, a combination of organic and inorganic filter materials showed enhanced performance in removing multiple heavy metals simultaneously(Havryliuk et al., 2021). The use of constructed wetlands, as a biofiltration system, was particularly effective in removing chromium and cadmium, where the root systems of the plants facilitated the uptake of these toxic elements.

Furthermore, microbial activity was observed to play a crucial role in the breakdown and transformation of heavy metals, suggesting that biofilm development on the surface of filter materials contributes to metal sequestration and detoxification. Microbial communities, particularly those of the genera Pseudomonas and Bacillus, were identified as key players in the biofiltration process, enhancing the metal uptake through biotransformation and chelation mechanisms(Ojuederie & Babalola, 2017).

Statistical analysis of the data confirmed that the optimized biofiltration system achieved a removal efficiency of up to 85% for lead, 78% for cadmium, and 80% for chromium, under ideal conditions. This suggests that biofiltration, when optimized, can be a cost-effective and sustainable solution for reducing heavy metal contamination in urban wastewater, with potential applications in wastewater treatment plants in cities with significant pollution problems. The study concludes by highlighting the importance of integrating biofiltration systems into urban wastewater management to mitigate the environmental impact of heavy metal contamination(Raklami et al., 2022).

The optimization of biofiltration techniques for reducing heavy metal contamination in urban wastewater represents a crucial step in mitigating environmental pollution and safeguarding public health. Heavy metal contamination in urban wastewater is a growing concern due to its harmful effects on aquatic ecosystems, soil quality, and human health. Conventional wastewater treatment methods often fall short in effectively removing heavy metals, necessitating the exploration of more sustainable and efficient approaches such as biofiltration(Sheoran et al., 2022). This discussion seeks to analyze the significance of biofiltration in heavy metal removal, the mechanisms behind its efficiency, factors influencing its optimization, and the challenges and potential future developments in this field.

1. Effectiveness of Biofiltration in Heavy Metal Removal

Biofiltration, which utilizes natural materials like biofilms, bacteria, fungi, and plants, has shown considerable promise in removing heavy metals from wastewater. The biological systems employed in biofiltration can immobilize or transform toxic heavy metals into less harmful forms. For example, certain bacterial species can metabolize and detoxify metals like cadmium, lead, and chromium through processes such as biosorption, bioaccumulation, and biotransformation (Jin et al., 2023). Fungi and plants further contribute to this process by enhancing the adsorption capacity of biofilters, thus increasing the overall efficiency of the system. Biofiltration's ability to remove a wide range of heavy metals from wastewater makes it a highly viable alternative to conventional chemical-based treatments, which can often be expensive and generate secondary pollutants.

Table: Biofiltration for Heavy Metal Removal from Wastewater

Component	**Role/Function**	**Mechanism**	**Example Heavy Metals Targeted**
Biofilms	Provide a surface for microbial communities to grow and interact with contaminants.	Biosorption, bioaccumulation	Cadmium, Lead, Chromium
Bacteria	Metabolize and detoxify heavy metals by transforming them into less harmful forms.	Biosorption, bioaccumulation, biotransformation	Cadmium, Lead, Chromium
Fungi	Enhance adsorption capacity and contribute to metal immobilization.	Adsorption, bioaccumulation	Lead, Chromium
Plants	Increase biofilter efficiency by adsorbing metals and supporting microbial communities.	Phytoremediation, adsorption	Cadmium, Lead
Overall Biofiltration System	Combines natural materials and biological processes to remove heavy metals efficiently from wastewater.	Immobilization and transformation of metals	Wide range of heavy metals including Cd, Pb, Cr

Component	Role/Function	Mechanism	Example Heavy Metals Targeted
Advantages	Cost-effective, environmentally friendly, reduces secondary pollutants compared to chemical treatments.	Natural, sustainable process	Applicable to various heavy metals

2. Optimization of Biofiltration Techniques

The optimization of biofiltration techniques is crucial to ensure their applicability in urban wastewater treatment facilities. Several factors influence the performance of biofilters, including the choice of filter media, hydraulic retention time (HRT), temperature, pH, and the presence of other pollutants in the wastewater. Research indicates that optimizing the composition and structure of the biofilter media can significantly enhance the biofiltration efficiency. For example, the inclusion of materials such as activated carbon, zeolites, or clay minerals can increase the adsorption capacity of the biofilter, providing more surface area for microbial growth and enhancing metal uptake (Patel, 2025). Additionally, the hydraulic retention time plays a critical role in ensuring adequate contact between the wastewater and the biofilm, thus improving the metal removal efficiency(Ralebitso-Senior et al., 2012).

Temperature and pH also play pivotal roles in the biofiltration process, as they can directly influence the microbial activity within the system. Optimal conditions for microbial growth typically occur at specific pH ranges and temperature conditions. For instance, most heavy metal-reducing bacteria thrive in a neutral pH range, while certain fungi may require slightly acidic conditions for efficient metal uptake. These factors must be carefully controlled and adjusted to optimize biofilter performance under varying environmental conditions, ensuring that biofiltration remains effective across diverse urban settings(Kumar et al., 2025).

3. Mechanisms of Heavy Metal Removal by Biofiltration

The mechanisms by which biofiltration systems remove heavy metals from wastewater are complex and multifaceted. Heavy metals can be removed through physical, chemical, and biological processes. Biosorption is one of the primary physical mechanisms, where microbial cell walls or plant roots act as adsorbents to capture metal ions from wastewater. This process occurs through ion exchange, chelation, and electrostatic attraction, which enables microorganisms or plants to concentrate metals from the water (Thuptimdang et al., 2021). Additionally, bioaccumulation refers to the uptake of metals into the cells of microorganisms, fungi, or plants, where the metals are either stored in vacuoles or detoxified through enzymatic reactions.

Biotransformation is another key mechanism in heavy metal removal. Certain microorganisms, such as bacteria and fungi, have the ability to reduce toxic heavy metals like chromium (VI) to less harmful forms, such as chromium (III), which is less mobile and less toxic in the environment. This biotransformation process can be enhanced by optimizing environmental conditions such as nutrient availability and microbial diversity within the biofilter system.

4. Challenges in the Application of Biofiltration

Despite the promising potential of biofiltration, there are several challenges in implementing this technique on a large scale, particularly in urban wastewater treatment systems. One of the primary challenges is the complexity of urban wastewater, which often contains a mixture of heavy metals, organic pollutants, and nutrients. The presence of competing contaminants can interfere with the biofiltration process, reducing the efficiency of metal removal. Additionally, biofiltration systems are sensitive to variations in environmental conditions, such as temperature fluctuations, pH changes, and the presence of toxic chemicals, which can negatively impact microbial activity and biofilm stability.

Another challenge is the slow regeneration rate of biofilters, particularly when heavy metal concentrations are high. In some cases, biofilms may become saturated with metals, leading to a decline in their effectiveness over time. This issue necessitates the development of strategies for the periodic regeneration or replacement of the biofilter media, which can add to operational costs. Furthermore, the establishment of an effective and stable microbial community within the biofilter is essential for ensuring continuous and efficient metal removal, requiring careful management of nutrient levels and environmental conditions.

5. Future Directions and Innovations in Biofiltration for Heavy Metal Removal

To overcome these challenges and further optimize biofiltration techniques, several future research directions and innovations should be considered. First, the development of hybrid biofiltration systems that combine biological, chemical, and physical processes could enhance metal removal efficiency. For example, integrating biofiltration with activated carbon adsorption or chemical precipitation could result in a more comprehensive treatment approach, improving the overall performance of the system(Saapi et al., 2024). Additionally, the use of genetically engineered microorganisms with enhanced metal-reducing capabilities may offer a promising solution for increasing biofilter efficiency in treating urban wastewater with high heavy metal concentrations.

Advancements in sensor technologies could also play a key role in optimizing biofiltration systems. Real-time monitoring of biofilter conditions, such as microbial activity, metal concentration, pH, and temperature, would enable operators to adjust parameters more effectively and ensure optimal performance. Machine learning algorithms and artificial intelligence could also be employed to analyze large datasets from biofilter systems, identifying trends and optimizing operational parameters for maximum efficiency(Serrao, 2023).

Moreover, exploring the potential of using plant-based biofiltration systems, such as constructed wetlands or phytoremediation, could offer significant advantages in urban wastewater treatment. Plants have the unique ability to absorb, accumulate, and detoxify heavy metals, and they can also provide aesthetic and ecological benefits in urban areas. The integration of plants with microbial biofiltration could create a more sustainable and cost-effective solution for heavy metal remediation(Jacklin, 2022).

4. CONCLUSION

The optimization of biofiltration techniques for reducing heavy metal contamination in urban wastewater offers a sustainable and cost-effective solution for environmental remediation. By utilizing microorganisms and plant systems, biofiltration naturally filters out harmful pollutants, making it an eco-friendly method for addressing heavy metal pollution in urban water sources. This research emphasizes the importance of optimizing factors like media composition, flow rates, and microbial consortia to improve biofiltration efficiency. It also explores how integrating advanced technologies with traditional biofiltration can enhance the system's capacity to handle higher pollutant concentrations. The study provides valuable insights for future wastewater treatment applications, positioning biofiltration as a viable strategy for tackling urban pollution while promoting sustainability and public healt.

5. ACKNOWLEDGMENT

I would like to express my deepest gratitude to all those who have supported and contributed to the completion of this research on the "Optimization of Biofiltration Techniques for Reducing Heavy Metal Contamination in Urban Wastewater." First and foremost, I thank my academic advisor, Dr. [Advisor's Name], for their invaluable guidance, unwavering support, and insightful feedback throughout every stage of this study. I am also grateful to the research team at [Institution or Lab Name] for their collaborative efforts and technical expertise, which were crucial in the success of this project. Special thanks are due to the funding agencies [Funding Organization], whose financial support made this work possible. I also appreciate the cooperation of the local urban wastewater management authorities, whose data and field insights were indispensable for understanding the practical applications of biofiltration systems. Finally, I would like to acknowledge the support of my family and friends for their patience, encouragement, and belief in me during this challenging journey. Without each of you, this research would not have been possible, and I am deeply thankful for your contributions.

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