STATE OF THE ART OF WETLANDS SYSTEMS FOR THE TREATMENT OF EFFLUENTS FROM LANDFILLS

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Abstract

Landfill leachate is an effluent with a high polluting load, characterized by high concentrations of persistent organic matter, ammonia and heavy metals. Conventional treatment of these wastes involves high energy and operational costs, demanding more sustainable alternatives. This paper presents a state-of-the-art review on the use of Constructed Wetlands (CW) as a Nature-Based Solution for leachate treatment. The methodology consisted of a systematic literature review across scientific databases, covering studies published in the last years. The results indicated a significant growth in publications in recent years, with a higher concentration starting in 2021. Journal analysis highlighted Science of the Total Environment, Ecological Engineering, and Journal of Environmental Management. The most recurrent keywords indicated a focus on wastewater treatment and the use of constructed wetlands for leachate treatment, in addition to a growing interest in the removal of emerging contaminants and the understanding of microbiological processes involved in the efficiency of these systems. It is concluded that CW systems represent a consolidated, low-cost technology for the post-treatment or complementary treatment of landfills, although challenges such as the acute toxicity of raw leachate still require integrated pre-treatment strategies.

Keywords: Nature-Based Solutions, Leachate Treatment, Green Infrastructure, Phytoremediation, Sustainability.

INTRODUCTION

Population growth, combined with consumption-driven lifestyles, has significantly intensified the generation of municipal solid waste (MSW). In Brazil, solid waste generation in 2023 was approximately 81 million tons, equivalent to more than 221 thousand tons of waste generated daily (ABREMA, 2024).

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Solid waste management in Brazil is governed by Law No. 12,305/2010, which established the National Solid Waste Policy (PNRS) and sets forth a strict order of priority for management, beginning with non-generation and proceeding successively through reduction, reuse, recycling, and treatment. According to this legal framework, sanitary landfills remain the predominant method of environmentally adequate final disposal and must be used exclusively for receiving residual waste, that is, waste for which all possibilities of technical or economic recovery have been exhausted. By mandating the elimination of open dumps, the legislation imposes the challenge of managing the environmental impacts arising from the confinement of these materials, highlighting the need for effective systems for treating the leachate generated at this final stage of the production chain. Sanitary landfills are the main alternative for the disposal of municipal and industrial solid waste worldwide (Yang et al., 2023).

Leachate generated in municipal solid waste landfills represents a serious environmental challenge, causing ecological and public health impacts (Bakhshoodeh et al., 2020; El-Saadony et al., 2023). This effluent generally contains high concentrations of pollutants and toxic compounds, requiring proper treatment before discharge. It is characterized by high concentrations of organic matter, heavy metals, nitrogen, phosphorus, and salts, and presents pH values ranging from acidic to neutral, depending on the age of the landfill (Bakhshoodeh et al., 2020).

With regard to water pollution control, CONAMA Resolutions No. 357/2005 and No. 430/2011 establish the parameters and maximum limits for the discharge of effluents into water bodies. Whereas the former classifies fresh, brackish, and saline waters according to their predominant uses, the latter specifies restrictive conditions for the disposal of complex effluents, such as landfill leachate. Among the main challenges imposed by these regulations is the removal of high concentrations of ammoniacal nitrogen and organic matter (expressed as BOD5 and COD), requiring treatment systems capable of operating with high biological stability.

In recent years, several technologies have been investigated for leachate treatment, including advanced oxidation processes, membrane filtration, and biological systems with high potential for reducing water contamination. Among these technologies, Nature-Based Solutions (NbS) stand out, presenting themselves as an economical alternative, simple to construct and operate, with low energy consumption, while also providing long-term treatment efficiency and additional environmental benefits such as landscape integration and ecosystem services (Von Sperling; Sezerino, 2018).

In this context, different approaches may be applied, such as natural and constructed wetlands (Almeida, 2025). Wetlands, or constructed wetlands, are a low-technology approach used for the controlled and optimized treatment of contaminated water, inspired by the natural processes occurring in natural wetlands. In this system, contaminant removal takes place through the combined action of plants, microorganisms, and substrate components, making it possible to reduce compound concentrations to levels that are safe for the biota/aquatic environment (Almeida, 2025). In this case, plants play primarily an indirect role in contaminant removal, as they help create suitable conditions for pollutant removal. Their only direct effect is the uptake of nutrients and heavy metals (Bakhshoodeh et al., 2020).

The use of technologies such as Constructed Wetlands contributes to compliance with the PNRS (Law 12,305/2010) and CONAMA Resolutions 357 and 430 by ensuring that leachate treatment meets the required discharge standards before returning to the environment, thereby promoting the sustainability of final disposal. In light of the above, this study aims to carry out a literature review on the application of constructed wetlands in the treatment of landfill leachate.

METHODOLOGY

The present study was characterized as a literature review developed on the basis of previously published research, consisting mainly of scientific articles. This study was based on the analysis of scientific publications indexed in English in the Science Direct (Elsevier) database. The article search was carried out using the keywords “wetland” and “landfill leachate”, employing double quotation marks (“ ”)

at the beginning and end of each term, as well as the Boolean operator AND between the words, in order to restrict the results to studies that simultaneously addressed both themes.

Data collection was conducted in August 2025, considering all publications available in the database up to the time of the search. After the initial identification of documents, a screening process was performed based on the eligibility criteria defined for the study, excluding duplicate documents and those not directly related to the research topic.

After the article search had been completed, the data were processed using the bibliometrix package, available in the RStudio software (version 2025.05.1 Build 513). This tool enabled the organization and analysis of the bibliographic information extracted from the database, allowing quantitative analyses of the scientific output related to the theme.

Based on this analysis, the following results were extracted and organized: distribution of articles by year of publication, journals with the greatest number of publications on the topic, and most frequent keywords. For this study, only scientific articles and review articles were considered, and these criteria were applied as selection filters.

RESULTS AND DISCUSSION

The temporal evolution of publications on the use of wetlands in leachate treatment, presented in Figure 1, reveals a growing scientific field. Of the 1,962 studies identified, a significant concentration of works can be observed from the year 2021 onward, which demonstrates the consolidation of this technology as a strategic alternative in the face of contemporary sanitation challenges.

Regarding the nature of the documents, the predominance of experimental studies (70%), conducted at scales ranging from laboratory to full scale, demonstrates the practical and applied character of research in the area. Complementarily, the expressive share of review articles (30%) indicates an effort by the academic community to synthesize treatment mechanisms and the advances achieved. It is worth

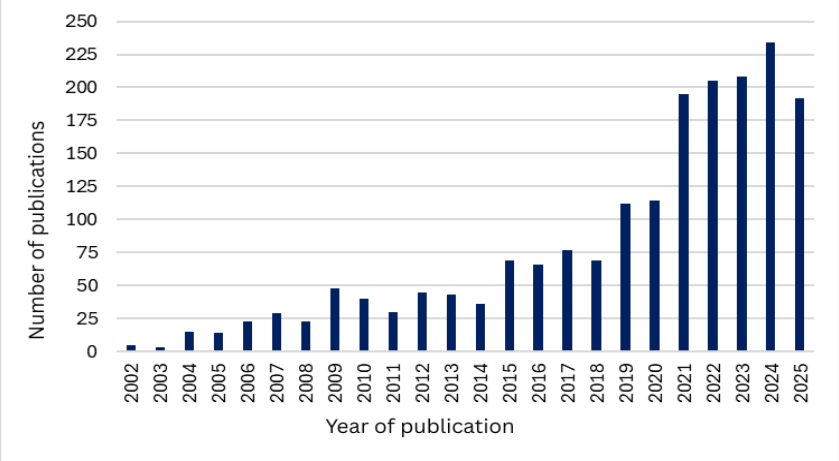
noting that the 2025 data comprise publications recorded up to August, maintaining the trend of high productivity observed in previous years.

Another point that may explain the increase in publications in more recent years is related to the growth of environmental concerns associated with the management of landfill leachate. Leachate has a high organic load, contains recalcitrant compounds, and presents potential toxicity, which makes its treatment a challenge for conventional technologies. In this context, systems based on constructed wetlands have been widely investigated because of their low energy consumption, operational simplicity, and capacity for integration with natural pollutant-removal processes, factors that contribute to the growing scientific interest in this area.

In addition, the advancement of research may also be associated with the search for more sustainable and nature-based solutions for the treatment of complex effluents. Constructed wetlands have been widely investigated because they combine physical, chemical, and biological processes, involving the joint action of substrates, macrophyte plants, and microbial communities in contaminant removal. Thus, the growth of publications over time reflects not only the expansion of academic interest, but also the recognition of this technology as a promising alternative within environmentally sustainable treatment strategies.

Figure 1

Temporal evolution of the number of publications on wetlands and leachate (up to August 2025).



Source: Authors

The analysis of the number of publications by journal (Figure 2) shows that the highest concentration of studies is found in the journal Science of the Total Environment (227 publications), demonstrating the broad insertion of the topic in a prominent multidisciplinary journal in the environmental field. In addition, journals such as Ecological Engineering (115), Journal of Environmental Management (114), and Chemosphere (103) reinforce the prominence of the theme in the context of ecological engineering, environmental management, and chemical pollution. This diversity of publication suggests that the research is not restricted only to water treatment, but also engages with pollution mitigation practices, environmental conservation, and sustainable development.

At an intermediate scale of recurrence, journals such as Waste Management (49) and Journal of Cleaner Production (46) also demonstrate the association with waste management and cleaner production practices, areas that complement environmental studies by addressing sustainability in industrial processes. On the other hand, journals such as Ecotoxicology and Environmental Safety (19) and Process Safety and Environmental Protection (19) presented a smaller number of publications, indicating that aspects related to environmental toxicology and industrial process safety have less representation in the scope analyzed.

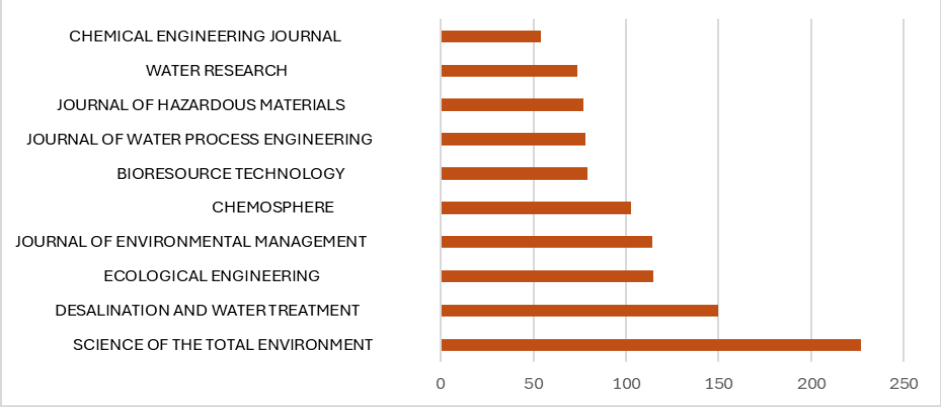
The distribution of publications among different journals highlights the interdisciplinary nature of the research related to the topic. The simultaneous presence of journals focused on environmental engineering, waste management, cleaner production, and environmental risk assessment indicates that the studies are not limited solely to technological treatment approaches, but also incorporate perspectives related to sustainable resource management, pollution prevention, and the assessment of environmental impacts. Thus, the distribution of publications across different journals demonstrates the interdisciplinary character of the theme, which involves environmental engineering, waste management, and water pollution control.

Another relevant aspect is that the concentration of articles in high-impact journals in the environmental field suggests that the theme has aroused growing interest in the international scientific community. Journals such as Science of the Total Environment, Chemosphere, and Journal of Environmental Management are recognized for publishing research related to pollutant assessment, treatment technologies, and environmental management, which indicates that the studies analyzed are situated within a consolidated and highly visible context of scientific discussion. This also suggests that the research developed in this area directly contributes to the advancement of knowledge on pollution control and the protection of water resources.

Additionally, the presence of journals focused on sustainability and waste management reinforces the trend toward integration among different strategies for mitigating environmental impacts. This convergence points to an increasingly systemic approach in environmental research, in which treatment technologies are assessed not only for their technical efficiency, but also for their contribution to sustainable practices and the circular economy. In this sense, the diversity of journals identified reflects the expansion of scientific discussions on environmentally responsible solutions, highlighting the importance of multidisciplinary approaches for addressing the challenges associated with pollution and natural resource management.

Figure 2

Main journals that published articles on the topic up to August 2025 (n = 1962 articles), considering the records extracted from the Science Direct database.



Source: Authors.

The analysis of keywords, represented in Figure 3, shows that the most recurrent terms are related to wastewater treatment, with wastewater treatment and wastewater standing out, which demonstrates the relevance of the subject in the scientific literature. Next appear landfill leachate and constructed wetlands, confirming the importance of constructed wetlands as a sustainable technology for the management of landfill leachate. Terms linked to remediation strategies were also frequent, such as phytoremediation, adsorption, and bioremediation, reinforcing the diversity of approaches studied. In addition, the presence of words such as heavy metals, microplastics, emerging contaminants, and nitrogen indicates that studies have encompassed both classical contaminants and so-called emerging contaminants. Finally, terms such as microbial community, anammox, and nitrogen removal highlight the relevance of microbiological processes for explaining and improving the efficiency of wetlands in effluent treatment.

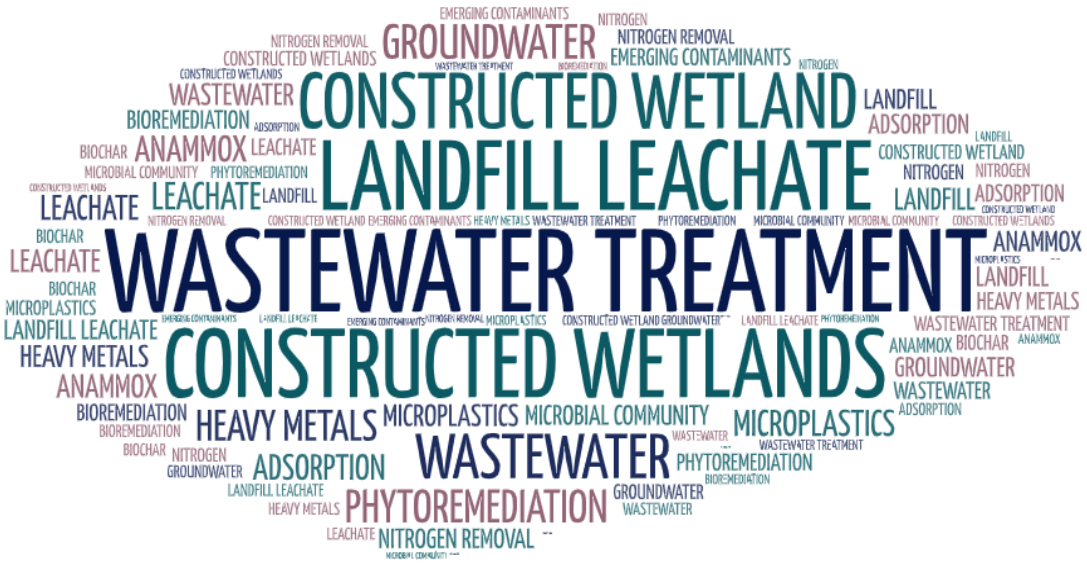
Furthermore, the diversity of terms observed in the keywords suggests that studies on constructed wetlands for leachate treatment have addressed different dimensions of the treatment process. While some studies focus on the efficiency of removing specific pollutants, others investigate the mechanisms involved in purification, including interactions among plants, substrates, and microbial communities. This multiplicity of approaches demonstrates that the field of research is not limited merely to the assessment of system performance, but also seeks to understand the ecological and biochemical processes that underpin the functioning of these technologies.

Another relevant aspect is the presence of terms related to emerging contaminants, such as microplastics and emerging contaminants, which indicates a recent trend in the literature to expand the scope of investigation beyond the pollutants traditionally monitored. This movement reflects growing concern about compounds that exhibit environmental persistence, potential toxicity, and difficulty of removal by conventional technologies. In this sense, constructed wetlands have been investigated not only as an alternative for the removal of organic matter and nutrients, but also as systems capable of contributing to the mitigation of new types of pollutants present in complex effluents.

Additionally, the recurrence of terms associated with microbiological processes, such as microbial community and anammox, highlights the growing interest in understanding the role of microbial communities in treatment efficiency. These microorganisms are essential to processes such as nitrification, denitrification, and biological nitrogen removal, which directly influence the performance of wetlands. Thus, the prominence of these keywords indicates a trend toward deeper research at the microbiological and molecular levels, seeking to optimize the operation of these systems and expand their application in the treatment of highly complex effluents.

Figure 3

Word cloud of the most frequent keywords in articles on the topic. The size of each word indicates its frequency of occurrence.



Source: Authors

As a synthesis, the results obtained from the bibliometric analysis indicate that research on the use of constructed wetlands for the treatment of landfill leachate shows consistent growth and recent consolidation in the scientific literature. The temporal evolution of publications demonstrates the increasing interest of the academic community, especially in recent years, while the distribution of articles among prominent journals in the environmental field demonstrates the relevance of the theme in different

areas related to pollution control and water resource management. At the same time, the analysis of keywords reveals the diversity of approaches investigated, including remediation strategies, nutrient removal, the study of microbial communities, and the evaluation of emerging contaminants. Taken together, these results highlight the multidisciplinary nature of the theme and reinforce the role of constructed wetlands as a promising and widely investigated alternative for the sustainable treatment of leachate.

CONCLUSIONS

The study demonstrated the growth of research on the use of wetlands in the treatment of landfill leachate. The data indicate that global interest in this field has intensified, reflected in a significant increase in the rate of scientific publications in recent years.

Based on the analysis of journals and keywords, it can be concluded that constructed wetlands stand out as a promising alternative for the treatment of landfill leachate, frequently being associated with research on wastewater treatment, phytoremediation, removal of heavy metals, and emerging pollutants. The bibliographic analysis shows that the theme is interdisciplinary in nature and of growing relevance, reinforcing its potential as a sustainable, low-cost, and effective solution for effluent management and the protection of water resources.

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