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Extraction of Landfill Leachate via Reverse Osmosis, Microfiltration, Ultrafiltration and Nanofiltration: A Meta-Data Analysis

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ABSTRACT

Landfill leachate is a complex environmental concern due to its composition of organic pollutants, inorganic salts, ammonia, nitrogen, and heavy metals. Proper treatment is critical to prevent soil and groundwater contamination. This study conducts a meta-data analysis of advanced filtration techniques-reverse osmosis (RO), microfiltration (MF), ultrafiltration (UF), and nanofiltration (NF)-for landfill leachate extraction. A systematic review of studies published from 2020 to 2024 was performed which leads to the identification of eight relevant articles. The removal efficiencies of the various methods varied significantly, with RO showing the highest performance at 99%, followed by NF at 89.8%, UF at 61%, and MF at 25%. Despite the high efficacy of RO, limitations such as high energy consumption, membrane fouling, and waste concentrate production were noted. NF and UF also demonstrated good performance but faced challenges with specific pollutants and operational efficiency. MF, while less effective, could be useful in pre-treatment stages. The study suggests that further advancements including the integration of multiple treatment technologies are necessary to enhance performance and reduce environmental impacts. Future research should address the limitations of current methods to ensure more sustainable landfill leachate management.

1. Introduction

Landfill leachate is a significant environmental worldwide concern that pose risks to ecosystems, water resources, and human health. It is a complex organic pollutant product created during the sanitary landfilling process known as landfill leachate [1]. As a special type of wastewater produced in landfills, leachate is mainly composed of organic pollutants, inorganic salts, ammonia, nitrogen, and heavy metals and features high pollutants, complex composition, and large fluctuations in water quality and volume [2]. Such composition makes landfill leachate highly variable and challenging to manage [1,2]. Improper handling of landfill leachate can lead to soil and groundwater contamination, exacerbating pollution and spreading diseases [3]. Therefore, its capture and treatment are essential components of sustainable solid waste management [4].

Various treatment methods have been explored to address the challenges posed by landfill leachate. Advanced filtration techniques such as reverse osmosis, microfiltration, ultrafiltration, and nanofiltration have gained significant attention due to their ability to target specific pollutants and improve water quality. These techniques are known for their capacity to reduce chemical oxygen demand (COD), biochemical oxygen demand (BOD), and heavy metals, among other contaminants. However, their environmental implications, such as energy consumption, sludge generation, and potential residual pollutants, require further investigation [5]. Recent innovative studies had also shown the potential of integrating biological, chemical, and physical methods to enhance landfill leachate treatment. These includes the use of microorganisms, electrochemical processes, and natural coagulants, to address the limitations of traditional methods [6,7]. For instance, the application of algae in leachate treatment has demonstrated dual benefits such as water quality improvement and biomass generation for biofuel production [6].

Despite the growing body of research to address landfill leachate, there is a need for a comprehensive analysis of the efficiency and environmental impacts of these advanced filtration techniques. This study aims to bridge that gap by conducting a meta-analysis of reverse osmosis, microfiltration, ultrafiltration, and nanofiltration technologies for landfill leachate treatment. By systematically synthesizing findings from various studies, this research provides valuable insights into the effectiveness and environmental implications of these filtration methods that can contribute to the development of sustainable waste management practices.

2. Experimental Methods

This study employs a meta-data analysis that involved a systematic and thorough literature search to ensure the inclusion of relevant studies on landfill leachate extraction using advanced filtration techniques such as reverse osmosis, microfiltration, ultrafiltration, and nanofiltration. The search was conducted using specific keywords, namely "Landfill Leachate Extraction" along with the terms "Reverse Osmosis, Microfiltration, Ultrafiltration, and Nanofiltration," in the Google Scholar database. To enhance the comprehensiveness of the search, the bibliographies of already identified articles were also reviewed to uncover additional relevant studies that might not have appeared in the initial search results. The systematic approach aimed to include high-quality and relevant studies which were subsequently synthesized to provide reliable insights into the efficiency and environmental implications of these advanced filtration techniques. This methodological framework ensures that the analysis is both rigorous and relevant to recent challenges in sustainable waste management practices.

Fig. 1 depicts the systematic steps involved in conducting this meta-analysis on landfill leachate extraction using advanced filtration techniques. The process begins with Step 1 (Identification Stage), where a comprehensive literature search is conducted using specific keywords, such as "Landfill Leachate Extraction," "Reverse Osmosis," "Microfiltration," "Ultrafiltration," and "Nanofiltration," in databases like Google Scholar. Additionally, the bibliographies of identified articles are reviewed to locate additional studies that may have been overlooked in the initial search.

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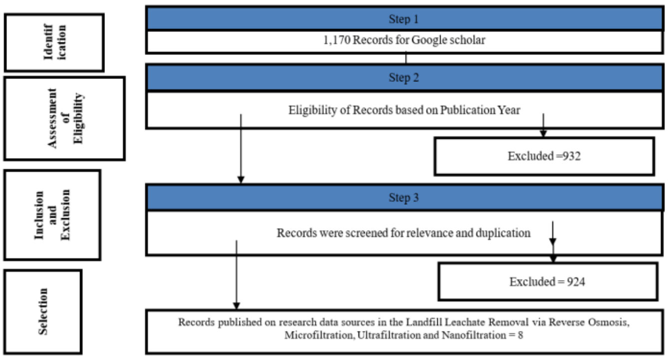

Fig. 1 Stepwise process of meta-analysis methodology

This step aims to compile as many potentially relevant articles as possible for further evaluation. A total of 1,170 studies were retrieved that are relevant with the search keywords in the google scholar. Next step involves screening by assessing the identified articles to ensure they meet the initial inclusion criteria. Articles published between 2020 and 2024 are selected to ensure the analysis focuses on recent studies and advancements in the field. Irrelevant, duplicate, or non-peer-reviewed articles are excluded to maintain the quality and relevance of the meta-analysis. This step alone removed 932 out of 1170 of the retrieved studies.

Following this, step 3 which is about eligibility is carried out to evaluate the screened articles based on more specific criteria. This involves determining whether the studies provide sufficient data on landfill leachate extraction and the performance of the filtration techniques under investigation. Articles that do not align with the study's objectives or lack relevant data are excluded. Only those with robust methodologies and significant findings are included in the final analysis. This further removed 924 out of 932 retrieved studies. Finally, Step 4 which talks about synthesizing the findings from the remaining (8) eligible studies. The data from these studies are systematically analyzed to evaluate the effectiveness of reverse osmosis, microfiltration, ultrafiltration, and nanofiltration techniques for landfill leachate treatment. This step provides valuable insights into the efficiency and environmental implications of these methods, contributing to the broader understanding of sustainable waste management practices. This systematic approach ensures transparency, replicability, and rigor in the research process.

Table 1 Summary of relevant studies for meta-analysis on the extraction of landfill leachate via reverse osmosis, microfiltration, ultrafiltration and nanofiltration

No.	Title	Ref.	Leachate Component	Treatment Used	Removal Efficiency	Limitation/s
1	A comprehensive review of landfill leachate treatment technologies.	[8]	Dissolved Salts and Micro-organism	Reverse Osmosis	99%	High Energy, generate concentrated waste stream
			Heavy Metals	Nanofiltration	99.2%	Less Effective for monovalent ions, produce waste concentrate
			Suspended Solids, bacteria and viruses	Ultrafiltration	90%	Limited in removing dissolved ions and small molecules
2	Treatment of stabilized landfill leachate in an integrated adsorption–fine-ultrafiltration system	[9]	Organic Compounds	Ultrafiltration	46.7%	Low organics removal efficiency
3	Recent advances in municipal landfill leachate: A review focusing on its characteristics, treatment, and toxicity assessment	[10]	Organic Compounds (COD)	Reverse Osmosis	97%	Fouling and high energy consumption
			Organic Compounds (COD)	Ultrafiltration	52%	-
4	Nanofiltration applied to the landfill leachate treatment and preliminary cost estimation.	[11]	Organic Compounds (ultraviolet quenching substances)	Nanofiltration	98%	Impact on Co-treatment, Higher energy and material costs
5	Distribution and removal characteristics of microplastics in different processes of the leachate treatment system	[12]	Suspended Solids (Micro-plastic)	Ultrafiltration	75%	Can accumulate in sludge
6	Revisiting Microplastics in Landfill Leachate: Unnoticed Tiny Microplastics and Their Fate in Treatment Works	[13]	Suspended Solids (Micro-plastic)	Reverse Osmosis	99%	Tiny microplastics could also generate and released from membrane treatment systems
7.	Nanofiltration and reverse osmosis processes for the removal of micro-pollutants.	[14]	Micro-pollutants	Nanofiltration	77%	Low performance on a small group of micro-pollutants
			Micro-pollutants	Reverse Osmosis	98%	Low performance on a small group of micro-pollutants
8.	Perspectives on technology for landfill leachate treatment	[15]	Organic Compounds (colloids and suspended matter, COD)	Microfiltration	25%	It cannot be used alone. Served as pre-filtration procedure.
				Ultrafiltration	40%	Strongly dependant on the material type of membrane
				Nanofiltration	85%	Low retention of the monovalent ions
				Reverse osmosis	98%	Membrane fouling

3. Results and Discussion

This section presents a comprehensive evaluation of the efficiency of these advanced extraction methods such as reverse osmosis, microfiltration, ultrafiltration, and nanofiltration based on the eight studies analyzed in this meta-analysis. The result of the eight relevant studies is scrutinized and the findings are presented in the preceding sub-section. Table 1 presents the various studies on landfill leachate treatment technologies that focuses on the leachate components, treatments used, removal efficiency, and limitations. The table also provides the overview of eight relevant studies included in the meta-analysis that presents the efficiency of different treatment technologies for landfill leachate extraction. Several components of leachate are identified, including dissolved salts, microorganisms, heavy metals, suspended solids, bacteria, viruses, organic compounds, and microplastics. Different treatment technologies such as reverse osmosis (RO), nanofiltration (NF), ultrafiltration (UF), and microfiltration (MF) are employed, with varying levels of removal efficiency.

For instance, Wang & Quia [8] explored the use of RO, NF, and UF for the removal of dissolved salts, microorganisms, heavy metals, and suspended solids. The highest efficiency, 99%, was achieved using RO for dissolved salts and microorganisms. Though, some limitations such as high energy consumption and the generation of concentrated waste streams were observed. Treatments such as NF and UF were used for heavy metals and suspended solids, with NF achieving a 99.2% removal efficiency for heavy metals, though it was less effective for monovalent ions and generated waste concentrates. UF, with a 90% removal efficiency, was limited in removing dissolved ions and small molecules. Other studies, such as Kulikowski et al. [9] demonstrated lower removal efficiencies, such as 46.7% for organic compounds using UF. This highlights a limitation in organic removal efficiency. In contrast, Lou et al. [10] found RO to be effective for removing organic compounds (97%) but noted issues with fouling and high energy consumption.

On the other hand, the treatment of microplastics was also a prominent topic, with studies by Zhang et al. [12] and Sun et al. [13] showing that UF and RO technologies were effective in removing suspended microplastics, with RO achieving up to 99% removal. However, microplastics could accumulate in sludge or potentially be released back into the environment after membrane treatment. While studies like those of Song et al. [14], focused on micro-pollutants. They showed that while RO and NF had

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significant removal efficiencies (98% for RO and 77% for NF), they still had limitations in performance for certain micro-pollutants. Similarly, Peng [15] provided an overview of various filtration methods where UF achieved a modest 40% removal efficiency, and RO performed at 98% efficiency, but was hindered by membrane fouling.

In summary, the results pinpoint the effectiveness of membrane-based technologies like RO, NF, and UF for leachate treatment, with RO generally showing the highest removal efficiencies. However, these methods are often constrained by factors such as energy consumption, fouling, waste concentrate production, and limitations in handling certain pollutants. Therefore, further advancements and integration of treatment methods may be necessary to improve efficiency and reduce environmental impacts.

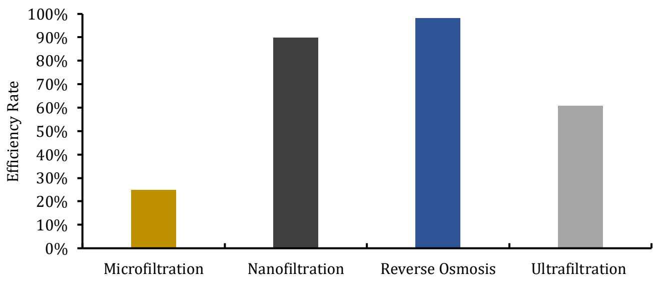

Fig. 2 Comparison of removal efficiency among membrane technologies for landfill leachate extraction

Fig. 2 illustrates the different efficiency removal rate of different advanced membrane technologies in extracting landfill leachate. It shows that they vary which reflects their different capabilities in removing contaminants. Microfiltration shows the lowest removal efficiency at just 25% which indicates that it is not highly effective in treating leachate on its own. This low performance may be attributed to its limited ability to filter smaller particles, which restricts its application as a primary treatment method. On the other hand, Nanofiltration achieves a significantly higher removal efficiency of 89.8%. This makes it much more effective in treating leachate. Nanofiltration is particularly efficient for removing larger contaminants and divalent ions, though it may not be as effective for monovalent ions or smaller molecules.

Reverse Osmosis is the most effective membrane technology, with a removal efficiency of 98%. This suggests that it is capable of removing a wide range of contaminants, including dissolved salts, organic compounds, and other pollutants. Its high removal rate makes it a preferred choice for comprehensive leachate treatment, although it comes with challenges such as high energy consumption and membrane fouling. Finally, Ultrafiltration falls between the other technologies, with a removal efficiency of 61%. This moderate performance indicates that while ultrafiltration can remove some contaminants, it is less effective than reverse osmosis or nanofiltration, particularly when it comes to smaller dissolved ions or particles.

In summary, while Reverse Osmosis offers the highest efficiency, it also comes with higher operational costs. Nanofiltration provides a good balance between performance and cost, while Ultrafiltration and Microfiltration offer limited benefits for leachate treatment but may be useful in pre-treatment stages or for specific types of contaminants. This can be confirmed in the result presented in Table 1.

Table 2 One-way ANOVA on the comparison of efficiency removal rate among membrane technologies

Source	SS	df	MS	F	P-value	Conclusion
Membrane Technologies	0.69	3	0.230	11.98	0.0009*	Significantly Different
Error	0.21	11	0.019			
Total	0.90	14	0.064			

Multiple Comparison Test using Bonferroni

Row Mean – Col Mean	Microfiltration	Nanofiltration	Reverse Osmosis
Nanofiltration	0.648, p = 0.009*	-	-
Reverse Osmosis	0.732, p = 0.003*	0.084, p = 1.0	-
Ultrafiltration	0.357, p = 0.228	-0.291, p = 0.058	-0.746, p = 0.008*

Table 2 presents the result of one-way analysis of variance to investigate the significant difference in the efficiency removal rate of different advanced technologies for landfill leachate extraction. It shows that the membrane technologies for landfill leachate extraction reveals significant differences in their effectiveness. The results of the F-test indicate a highly significant variation among the four membrane technologies, with a p-value of 0.0009. This confirms that not all treatments membrane technologies are equally effective in removing landfill leachate. The Bonferroni multiple comparison test further shows the specific differences between pairs of technologies. Notably, reverse osmosis (RO) and microfiltration (MF) show a significant difference in performance, with a mean difference of 0.732 and a p-value of 0.003. This indicates that RO outperforms MF in leachate treatment. Similarly, nanofiltration (NF) and microfiltration also show a significant difference, with a mean difference of 0.648 and a p-value of 0.009. This also suggests that NF is more effective than MF. However, there is no significant difference between Reverse Osmosis and Nanofiltration, with a mean difference of 0.084 and a p-value of 1.0. This shows that these two technologies perform similarly. The comparison between ultrafiltration (UF) and microfiltration also does not reveal any significant difference (p-value = 0.228) which shows that both are similar in their leachate treatment capabilities. On the other hand, ultrafiltration and reverse osmosis show a significant performance gap, with UF being less effective than RO (mean difference of -0.746, p-value of 0.008).

These findings suggest that, while reverse osmosis and nanofiltration are generally more effective in removing contaminants from landfill leachate, microfiltration and ultrafiltration tend to perform less efficiently. specifically, Reverse Osmosis proves to be the most efficient in comparison to other technologies, particularly in removing a broad range of contaminants. Whereas, nanofiltration is shown to be slightly less effective but still provides significant removal efficiency. These results highlight the importance of selecting the appropriate membrane technology based on the specific treatment needs and the types of contaminants present in the leachate. Further improvements and optimizations in these technologies may be necessary to increase efficiency, reduce costs, and mitigate limitations such as fouling and energy consumption.

4. Conclusion

Landfill leachate represents a significant environmental challenge that encapsulates the complexity of modern waste management. This paper investigates eight studies about the efficiency of membrane technologies for landfill leachate extraction. It reveals a notable difference in their effectiveness. Reverse osmosis (RO) emerges as the most efficient technology, with removal efficiencies reaching up to 99%. It proves highly effective for removing contaminants such as dissolved salts, microorganisms, and organic compounds.

However, it is associated with challenges, such as high energy consumption, membrane fouling, and the generation of concentrated waste streams. Nanofiltration (NF) also demonstrates a strong performance with an 89.8% removal efficiency, particularly for larger contaminants and divalent ions. Yet, it has limitations in removing monovalent ions and smaller molecules. Ultrafiltration (UF) and microfiltration (MF) show much lower removal efficiencies, with UF at 61% and MF at only 25%. Although these methods are less efficient, they can serve as useful pre-treatment steps or be used to address specific contaminants, such as microplastics.

Given the variations in the effectiveness of the membrane technologies, it is recommended that future studies focus on improving the performance of the technologies that show limitations, such as ultrafiltration and microfiltration. Research should explore ways to mitigate the issues of membrane fouling, reduce energy consumption, and address the challenges related to waste concentrate generation.

Additionally, combining different treatment technologies, such as integrating reverse osmosis with nanofiltration or ultrafiltration, may offer a more comprehensive approach to landfill leachate treatment, improving efficiency and reducing operational costs. Municipalities and industries should carefully assess the specific contaminants present in the leachate and select the most suitable membrane technology, taking into account the treatment objectives, cost-effectiveness, and environmental impact. Optimizing existing technologies and exploring novel treatment methods will be essential to ensure more sustainable and efficient landfill leachate management in the future.

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