JOURNAL OF
HYDRO-METEOROLOGY

Review Article

Application of ozone technology in leachate treatment for sustainable development: A brief review

Luu Thi Cuc[1], Hoang Van Hung[2], Van Huu Tap[3]*

[1] Lao Cai Campus, Thai Nguyen University; luuthicuc@tnu.edu.vn; cuc41mta@gmail.com
[2] Thai Nguyen University; hoangvanhung@tnu.edu.vn
[3] Center for Advanced Technology Development, Thai Nguyen University; tapvh@tnus.edu.vn; vanhuutap@gmail.com

*Corresponding author: tapvh@tnus.edu.vn; Tel.: +84– 983465086

Received: 17 January 2025; Accepted: 17 March 2025; Published: 8 June 2025

Abstract: This paper provides an overview of ozone technology in leachate treatment, including its characteristics, sources, treatment efficiency, and challenges. The research elucidates the efficacy of ozone-based methodologies in eliminating pollutants, such as chemical oxygen demand (COD) and ammonium nitrogen (NH_4^+-N), from leachate, attaining removal rates of up to 99.8% for COD and 91.14% for NH_4^+-N under optimized experimental conditions. Nevertheless, significant drawbacks persist, encompassing elevated energy consumption, the possible generation of deleterious byproducts (e.g., bromates and aldehydes), and compliance with regulatory frameworks. This review further delineates recent progress in ozone-mediated leachate treatment and delineates critical obstacles to its future application, with a particular focus on Vietnam. In this context, Vietnam produces approximately 4.3 million tons of municipal solid waste annually, of which over 70% is consigned to landfills, yet the resultant leachate remains insufficiently managed, contributing to environmental degradation. The investigation adopts a methodical framework, incorporating data analysis, consolidation of results, and a comparative assessment of literature spanning 2014 to 2025. The outcomes serve as a valuable resource for researchers and policymakers interested in leachate management and ozone technology applications, offering a clear foundation and direction for future investigations.

Key words: Ozone technology; Leachate; Characteristics; Challenges; Wastewater treatment.

1. Introduction

The remediation of organic contamination in leachate represents a pressing global environmental challenge, attributable to its intricate composition and the inherent threats it poses to ecosystems and human well-being. Leachate, a heavily contaminated fluid, emerges from the infiltration of precipitation through landfill waste. It is characterized by elevated levels of organic compounds, ammonia, heavy metals, and recalcitrant organic pollutants. When inadequately addressed, leachate can precipitate significant pollution of soil and aquatic resources, thereby endangering both human health and ecological integrity [1]. Various methods, including biological treatment processes, chemical sedimentation, adsorption, and membrane filtration, are applicable for leachate treatment [2]. A study [3] analyzed the effectiveness of conventional treatment methods and found that they vary in pollutant removal efficiency. Research [4] revealed that, the application of chemical, electrochemical, and physical techniques for leachate treatment surpasses biological methods in efficacy, though these approaches incur higher expenses. The study [5] performed a comparative evaluation of prevalent leachate treatment method encompassing recycling, biological processes, chemical oxidation, chemical precipitation, coagulation, and membrane filtration and determined that isolated recycling or biological treatments frequently prove inadequate, particularly for leachate laden with heavy metals. Conversely, a combined biological-physical-chemical strategy markedly improves treatment performance. Chemical oxidation employing potent oxidants such as ozone (O_3) accelerates the breakdown of persistent organic contaminants, thereby shortening treatment duration and enhancing the economic viability of biological methods. Nonetheless, the substantial energy demands of emission-dependent technologies, including ultrasonic systems, ozonation units, and ultraviolet lamps, considerably elevate the overall cost of treatment.

In Vietnam, the management of landfill leachate has emerged as an increasingly critical issue, driven by accelerated urban development and deficiencies in waste management infrastructure. Numerous landfills across the nation release untreated or insufficiently processed leachate into the surrounding environment, resulting in water contamination and heightened risks to public health. A 2023 assessment from the Ministry of Natural Resources and Environment indicates that Vietnam produces around 4.3 million tons of municipal solid waste each year, with more than 70% being directed to landfills. A significant proportion of these facilities lack adequate leachate treatment mechanisms, thereby exacerbating groundwater pollution [6].

Ozone technology is a promising technology trend that is most proposed for mineralization of organic pollutants through the reactivity of active elements (typically OH^*). Ozone, a powerful oxidizing agent, facilitates the breakdown of recalcitrant organic contaminants [1]. Ozone can cure leachate effluent using ozone and ozone + UV. The effectiveness of this technology in treating leachate has been confirmed. However, the predicted efficiency in removing COD and ozone consumption, as well as the influence of UV radiation, suggest alterations in their patterns [7]. Research conducted by [8] published in 2020, demonstrated that ozonation effectively removed color (87.5%), COD (99.8%), and NH_4^+-N (91.14%) from leachate at optimized conditions. However, the economic feasibility and regulatory challenges for widespread adoption of this technology, particularly in developing countries like Vietnam, remain major concerns.

2. Materials and Methods

2.1. Data collection and selection criteria

This review adopts a comprehensive approach to compile data on leachate, ozone technology, and its application in leachate treatment. The data were gathered from internationally esteemed scientific journals, covering research published between 2014 and 2025. Information retrieval was conducted using platforms such as Google Scholar, Scopus, and Web of Science, employing search terms like “ozone leachate treatment,” “advanced oxidation processes,” and “leachate treatment in Vietnam.” The inclusion criteria for selected studies are as follows: Pertinence to ozone-based leachate treatment; Scientific rigor, with preference given to journals with high impact factors and credible conference proceedings; Incorporation of experimental outcomes offering quantitative insights; Exclusion of non-peer-reviewed works, opinion-based articles, or studies lacking empirical evidence.

2.2. Comparative and statistical analysis methods

The investigation employs a comparative framework to assess ozone technology relative to alternative leachate treatment methods, emphasizing:

- Efficacy metrics: Efficiency of chemical oxygen demand (COD) removal.
- By-product generation.
- Economic viability: Accounting for energy usage and operational costs.
- Technical complexity.

Statistical techniques: Encompassing trend analysis and meta-analysis to integrate quantitative results from existing studies.

Potential methodological constraints:

Linguistic challenges: The majority of references are in English, a non-native language for the research team, necessitating additional time for comprehension. To address this, the authors utilized Google Translate and the Oxford Dictionary to ensure terminological precision.

Resource constraints: Limited funding precluded access to subscription-based databases. This was mitigated by leveraging freely available, reputable sources, particularly peer-reviewed scientific articles.

3. Results and Discussion

3.1. Characteristics and challenges of leachate treatment

3.1.1. Sources of leachate

Leachate refers to fluid that picks up soluble materials from waste as it percolates through a landfill. It primarily consists of organic contaminants, inorganic salts, ammonia nitrogen, and heavy metals. This liquid stands out due to its elevated pollutant levels, complex makeup, and notable variations in both quality and quantity [1].

Landfill leachate emerges as an intricate blend formed by rainwater seeping through waste, moisture generated during waste decomposition, and the natural water content of the waste itself [9]. It harbors high levels of dissolved organic matter (DOM), salts, heavy metal ions, and various organic substances, including chlorinated aliphatic and pesticides [10]. This leachate is widely noted for its hazardous nature, presenting considerable risks to nearby ecosystems and the environment [11]. The presence of DOM in leachate can affect microbial processes, contribute to membrane clogging, impair the effectiveness of coagulation effluent, interact with organic pollutants, and modify the behavior of heavy metals by influencing their mobility, stability, and availability in the environment [12].

The study [13] identified a notable correlation between the concentration of pollutants in groundwater, affected by seepage through the impermeable layer, and the age and scale of the landfill relative to leachate. The contamination potential of different pollutants varies depending on the environmental conditions. Total dissolved solids and NH_4^+-N in leachate demonstrate a high pollution risk, whereas metallic elements (Mn, Al, Ba and Fe) in the adjacent groundwater present significant environmental challenges.

The study [14] isolated 15 organisms from the air environment of a waste dumpsite, indicating a potential health risk to people living or working nearby. Residents, waste workers, and scavengers at the dumpsite are frequently exposed to various contaminants. Prolonged inhalation of these contaminants can cause anosmia, a condition where individuals lose their sense of smell due to constant exposure to offensive odors from compounds such as sulfuric acid and hydrogen sulfide.

3.1.2. Chemical and physical properties of leachate

Multiple investigations suggest that leachate exhibits an elevated pH level and a substantial concentration of suspended particulates. Landfill leachate is dark-colored and malodorous, as it contains a variety of organic pollutants, inorganic salts, toxic heavy metals, pathogens, and emerging contaminants (ECs) [10].

Leachate, originating from the percolation of water through waste material, contains high concentrations of offensive constituents. These include soluble organic matter, inorganic salts, heavy metal ions, and xenobiotic organic compounds, which result from the decomposition of organic waste. The most hazardous components of leachate are found in high concentrations during the initial acid phase due to intense decomposition processes. During the methanogenic phase, leachate stabilizes with lower concentrations of pollutants, a reduced BOD/COD ratio, and diminished heavy metal content. However, ammonia levels remain persistently high, presenting a long-term pollution concern within landfill leachate. These chemical constituents pose significant environmental pollution risks [10]. Specifically, the pollution of groundwater and potable water by emerging contaminants (ECs), including pharmaceuticals and personal care products (PPCPs) and surfactants, is documented to present a significant health threat to both humans and wildlife [15].

A range of values indicating organic pollution in leachate has been reported. Leachate typically has COD concentrations ranging from 10 to 500 mg/l, 50 to 1000 mg/l, 150 to 3000 mg/l [13]. The reduction in alkalinity varies between 10% and 22%, contingent upon the specific catalysts employed in the treatment process. With BOD_5/COD ratios of 0.691, 0.688, and 0.711 in treated wastewater compared to 0.398 in untreated wastewater, the treated effluent demonstrates a markedly higher BOD_5/COD ratio than its untreated counterpart [16].

Appropriate handling of leachate is essential for mitigating water contamination. For the effective processing of this wastewater, its specific attributes need to be evaluated, and tailored treatment strategies should be applied to meet regional discharge criteria and legal requirements. Broadly speaking, the responsible stewardship of water resources is an essential factor in wastewater management.

3.2. Comparison of ozone-based treatment with other technologies

Numerous investigations have assessed the efficacy of traditional leachate treatment techniques, revealing substantial disparities in their capacity to eliminate pollutants. The study [3] scrutinized these established methods and noted pronounced variations in their performance. The study [4] substantiated that chemical, electrochemical, and physical treatment approaches generally surpass biological methods in leachate purification, albeit at the expense of increased operational expenditures. A detailed evaluation [5] explored an array of treatment strategies, including recycling, biological processes, chemical oxidation, chemical precipitation, coagulation, and membrane technology. Their results suggested that isolated biological treatment or recycling often proves inadequate, especially for leachate enriched with heavy metals. In contrast, a synergistic biological-physical-chemical methodology markedly elevates treatment efficacy.

When juxtaposing ozonation, biological treatment, membrane filtration, and chemical precipitation across critical performance parameters:

Treatment Efficacy: Ozonation proficiently breaks down recalcitrant organic compounds and enhances leachate biodegradability, frequently achieving COD removal rates exceeding 80% when paired with biological treatment. Standalone biological treatment typically demonstrates reduced efficiency (30-60%), hindered by the presence of non-biodegradable substances. Membrane filtration yields exceptional pollutant elimination (up to 95%), though primarily via physical separation rather than degradation. Chemical precipitation excels at removing heavy metals (> 90%) but exhibits limited effectiveness against organic pollutants.

By-product generation: Ozonation can generate intermediate oxidation byproducts, some of which demand additional processing to avert secondary contamination. Biological treatment produces surplus sludge, necessitating further handling. Membrane filtration yields concentrated brine or reject streams requiring subsequent management. Chemical precipitation generates substantial quantities of metal hydroxide sludge, which must be appropriately managed to prevent environmental harm.

Operational Costs: Ozonation entails considerable expenses due to the energy-intensive nature of ozone production and equipment upkeep.

Operational Complexity: Ozonation systems demand meticulous regulation of ozone dosage, pH, and reaction parameters. Biological treatment, though less intricate, requires vigilant oversight of microbial dynamics and nutrient levels. Membrane filtration necessitates regular maintenance and cleaning to mitigate fouling. Chemical precipitation, while relatively uncomplicated, requires precise optimization of chemical inputs to reduce reagent consumption and sludge output.

Overall, although ozonation significantly improves the degradation of persistent organic pollutants and bolsters the efficacy of biological treatment, its substantial energy requirements result in heightened operational costs.

3.3. Ozone technology for treating leachate

Ozone (O_3) technology offers several benefits compared to conventional disinfection techniques like chlorine, such as accelerated disinfection rates, the lack of harmful residuals, and the capacity to tackle a diverse array of contaminants. As a result, it has emerged as a vital element in the treatment of water and air. This technology finds application across multiple industries for managing odors, sterilizing environments, and purifying substances. Nonetheless, to mitigate potential health risks, its safe and proper use is imperative. As a powerful oxidant, ozone has been harnessed in food processing since the early 20th century for its antimicrobial effects. The study [17] suggest that additional studies are necessary to thoroughly understand its strengths and constraints.

Ozone technology entails the application of electrical energy to transform oxygen into ozone molecules [12]. This method is broadly utilized across various industries for controlling odors, purifying substances, and disinfecting environments [18]. Owing to its potent oxidative capabilities, ozone technology has garnered considerable interest as an efficient approach to wastewater treatment [19]. The high reactivity of ozone allows it to break down a wide range of organic contaminants, including pesticides, petroleum-derived substances, and persistent organic compounds [20]. Furthermore, it excels at eliminating color, odors, and other impurities from wastewater. Evidence from research [21] also demonstrates its ability to remove heavy metals, nitrogen-containing pollutants, and other toxic substances from wastewater. Significantly, ozone technology serves as a highly effective disinfectant, capable of neutralizing bacteria and viruses in wastewater. Its cost-efficiency renders it an appealing solution for industrial and commercial entities. Additionally, it minimizes sludge generation during wastewater treatment, thereby reducing the expenses tied to waste disposal. The wide-ranging uses of ozone technology in wastewater management have made it a favored option across numerous sectors. Ozone is widely acknowledged as a robust disinfectant, proficient in eradicating bacteria and other microorganisms. Moreover, it demonstrates exceptional efficacy in extracting metal ions, organic pollutants, and compounds that contribute to water discoloration from the environment [22]. Many studies have been conducted on the use of ozone technology for waste treatment. The results demonstrate that ozone can be used to treat high concentrations of organic pollutants in leachate [23].

The study [1] designed a biofilm column packed with expanded clay aggregate (EBC) to investigate the potential of integrating biodegradation and ozonation processes (CBAO) for the concurrent elimination of nitrogen and persistent micropollutants from leachate. Following a 48-hour biodegradation phase, 51% of the nitrogen was eliminated, whereas the removal efficiency for the micropollutant carbamazepine (CBZ) was limited to 30%. To improve the removal performance, ozone was introduced and circulated through the EBC for a duration of 30 min. At an ozone concentration of 0.4 $gO_3/gCOD$, complete removal of CBZ was achieved. Additionally, the average nitrogen removal efficiency rose by 34%, reaching 85%, attributed to the increased activity of nitrifying and denitrifying bacteria within the EBC.

The researchers found that the application of catalytic ozonation enhances the biodegradability of wastewater. Additionally, this process significantly reduces the concentrations of total organic carbon (TOC), chemical oxygen demand (COD), and total nitrogen (TN) in the treated water [24].

The results indicated that approximately 90% reduction in chemical oxygen demand (COD) could be attained by optimizing key operational parameters, including pH, ozone generation rate, and temperature. The study revealed that this innovative approach offers a cost-effective on-site alternative, eliminating the necessity for a conventional end-of-pipe wastewater treatment system [10, 25, 26].

Table 1. Catalytic ozonation processes condition for leachate.

Catalyst material for ozonation processes	Optimum conditions	Efficiency (% COD removal)	References
Clay aggregates packed biofilm column (EBC) + Ozone	Ozone flow rate = 0.4 L/min, Reaction time = 30 min, Concentrations of NH_4^+-N, NO_2^--N, NO_3^--N = 100–250 mg/L O_3/COD ratio = 0.4 g pH = 9	COD (63%) NH_4^+-N, NO_2^--N, NO_3^--N (85%)	[27]
O_3/H_2O_2	Ozone flow rate = 0.4 L/min, Reaction times = 30 min, Concentrations of H_2O_2 = 4 g/L pH= 9	COD (43 - 45%) Color (89%) BOD_5/COD ratio up to 0.22 - 0.33	[28]
$S_2O_8^{2-}/Zn^{2+}$ + Ozone	Oxygen flow rate = 1.5 L/min, $S_2O_8^{2-}/Zn^{2+}$ dosage = 2 g/12 g, pH = 11	COD (88%) Color (98%) NH_3-N (60% - 180 mins) BOD_5/COD ratio up to 0.07 - 0.19	[29]
$O_3/VUV/Na_2S_2O_8$	Oxygen flow rate = 1.5 L/min Reaction time = 12 hours	COD (72,4%) UV254 (94,6%) Color (87,5%) NH_3-N (60% - 180 mins) BOD_5/COD ratio up to 0.07 - 0.19	[26]
MBR/Mn[sbnd]Ni + Ozone	Optimum O_3 flow rate = 4 g/h, Reaction time = 13 days, pH = 9	COD (99,8%) Color (87,5%) NH4+-N (91,14%) Axit humic (85,5%)	[23]

As illustrated in Table 1, various catalytic materials have been utilized for leachate treatment through ozonation. Specific operational conditions were optimized for each catalyst to achieve the desired level of COD removal efficiency. The optimal pH range was determined to be 9-11, while the ozone generation rate varied depending on the catalyst system, ranging from 0.4 L/min to 1.5 L/min, all experiments were conducted at room temperature, approximately 20°C.

The effectiveness of ozone as a disinfectant in wastewater treatment can be compromised by the presence of organic matter and other contaminants, thereby impacting the overall performance of ozone technology [32]. A study noted [33], organic substances in water can consume ozone, reducing its capacity to degrade pollutants. This occurs because organic matter reacts with ozone through a chain reaction, during which hydroxyl radicals compete with ozone for reactive sites. Consequently, the efficiency of ozone technology is reduced, leading to inadequate pollutant removal. The extent of this reduction, however, varies depending on the nature and concentration of organic compounds present in the water. The study [33] observed that humic acid, a prevalent organic component in wastewater, could reduce the efficacy of ozone technology by as much as 40%. This underscores the importance of understanding the impact of organic matter on ozone-based systems and developing strategies to mitigate its influence.

The effectiveness of ozone-based leachate treatment varies across different catalytic systems, as demonstrated by key performance indicators, including COD removal efficiency, NH_4^+-N reduction, and color removal:

+ Expanded clay biofilm column (EBC): As a catalyst material, EBC exhibited a COD removal efficiency of 63% at pH 9, with an ozone flow rate of 0.4 L/min, a reaction time of 30 minutes, and an O_3/COD ratio of 0.4 g. Additionally, the removal efficiency for NH_4^+-N, NO_2^--N, and NO_3^--N reached 85%.

+ O_3/H_2O_2 system: The application of ozone with hydrogen peroxide achieved a COD removal efficiency of 43-45% under similar conditions (pH 9, ozone flow rate of 0.4 L/min, reaction time of 30 minutes, and H_2O_2 concentration of 4 g/L). This system demonstrated a color removal efficiency of 89%, with a BOD_5/COD ratio ranging from 0.22 to 0.33.

+ $S_2O_8^{2-}/Zn^{2+}$ system: The use of peroxydisulfate and zinc ions as catalysts resulted in a COD removal efficiency of 88% at pH 11, with an oxygen flow rate of 1.5 L/min, a catalyst dosage of 2 g/12 g, and a reaction time of 180 minutes. The removal efficiency for color was 98%, while NH_3-N removal reached 60%, with a BOD_5/COD ratio of 0.07-0.19.

+ O_3/VUV/$Na_2S_2O_8$ system: The integration of ozone with vacuum ultraviolet (VUV) and sodium persulfate achieved a COD removal efficiency of 72.4% at pH 7.1, with an oxygen flow rate of 1.5 L/min and a reaction time of 12 hours. This system effectively removed 94.6% of UV_{254}-absorbing compounds, 87.5% of color, and 60% of NH_3-N, with a BOD_5/COD ratio of 0.07-0.19.

+ MBR/Mn-Ni with ozone: The membrane bioreactor (MBR) system incorporating Mn-Ni catalysts and ozone demonstrated the highest COD removal efficiency of 99.8% at pH 9, with an optimal ozone flow rate of 4 g/h and a prolonged reaction time of 13 days. This system also achieved 87.5% color removal, 91.14% NH_4^+-N reduction, and 85.5% humic acid removal.

These investigations highlight the promising capability of diverse catalytic materials in efficiently treating leachate via ozonation when optimized conditions are applied. Additional research is essential to assess the practicality and scalability of these approaches for broader industrial implementation.

3.4. Discussion on challenges and limitations in applying ozone-based technology for leachate treatment

A significant drawback of ozone technology lies in its substantial expense. A study emphasized [15], the high costs are primarily attributed to the energy-demanding process involved in ozone generation. Furthermore, maintenance expenses are considerable due to the regular replacement of components and consumables. These costs are exacerbated by the requirement for trained operators to manage the system and the strict safety protocols needed to safeguard both workers and the environment. These economic barriers have limited the widespread implementation of ozone technology across various sectors, driving the exploration of more economical alternatives. However, the advantages of ozone technology remain noteworthy, particularly in light of the rising demand for cleaner air and water and the increasing recognition of the adverse impacts of pollution on human health and ecosystems. To address these challenges, emphasis should be placed on lowering costs through technological advancements and improving operational and maintenance efficiencies.

Ozone technology has the potential to generate hazardous byproducts, including bromate and aldehydes, which present significant health risks, especially for individuals suffering from respiratory ailments such as asthma and chronic bronchitis. Inhalation of ozone can aggravate pulmonary conditions, elevate the frequency of asthma episodes, and impair respiratory functionality. Due to its unstable and highly reactive nature, ozone can adversely affect human health. Consequently, it is imperative to implement stringent safety measures and comply with established guidelines and regulations to mitigate the risks associated with its use [30, 31].

Some researchers suggest strategies to mitigate the high costs of ozone technology. These include using compressed or oxygen-enriched air to reduce ozone production expenses and improve efficiency, alternative reactor designs to enhance ozone mass transfer and decrease energy consumption, and implementing hybrid systems (e.g., ozone-biofiltration or ozone-UV) to improve treatment performance and reduce overall costs. Further research and development are necessary to maximize the effectiveness and efficiency of these methods in practical applications.

3.5. Potential for the treatment of leachate in Vietnam using ozone technology

In recent years, the application of ozone technology in leachate treatment in Vietnam has garnered attention. A study explored the use of AOPs to treat wastewater containing recalcitrant organic compounds under the Environmental Industry Development Program of the Ministry of Industry and Trade of Vietnam to 2015, with a vision to 2025. In 2014, a pilot-scale experiment employed the Ozone/UV process combined with biologically activated carbon (BAC) filtration to treat organic substances in domestic water supply. The results demonstrated that the Ozone/UV-BAC combination effectively removed TOC and DOC, achieving removal rates of 19.1% and 17.6%, respectively [34].

The first study applied ozonation to leachate after sedimentation, with experiments conducted at pH ranges of 5 to 10, reaction times of 20 to 120 minutes, and ozone dosages of 0.5 to 2.5 mg/L [35]. The results indicated the effectiveness of this process in removing pollutants from leachate. The second study utilized a combination of polyaluminium chloride (PAC) and the UV/O_3 process to treat leachate from a landfill in Vietnam [35]. The findings suggested that this method was effective in treating landfill leachate, emphasizing the interaction between ozone and hydrogen peroxide on treatment efficiency.

Additionally, a team of researchers in Vietnam[36] used waste iron slag as a catalyst in wet catalytic reactions to enhance the treatment of paper mill wastewater. The study [37] reported using nano Co_3O_4-SiO_2 as a heterogeneous catalyst for the ozonation of nonionic surfactant NPE (nonyl phenol ethoxylate) in water, achieving a 99% efficiency. The experiment was conducted at 30°C, with a reaction time of 10 minutes, a catalyst dosage of approximately 0.1 g/L, a solution pH of 11, an ozone input flow rate of 3 L/min, and an initial NPE concentration of 20 mg/L.

The study [37] utilized nano-Fe_2O_3-Co_3O_4 modified dolomite as a catalyst for ozonation to degrade ammonia in wastewater. The study results indicated that the catalytic ozonation process with this material achieved 96% ammonia degradation under pH 9 conditions. The ozonation reaction decomposed ammonia existing in the form of NH_3 at pH 9 due to the enhanced formation of radicals.

The findings reveal that catalytic ozonation serves as a highly efficient approach for leachate treatment in Vietnam, owing to its ability to remove pollutants and enhance biodegradability. Nonetheless, the studies underscore the necessity for additional investigation, emphasizing that the efficiency of the catalytic ozonation process under Vietnamese conditions is considerably influenced by the specific type of dye and the pH level of the wastewater.

Vietnam has implemented various policies and regulations related to leachate treatment to safeguard the environment and public health. However, there are currently no specific regulations governing the use of ozone technology in leachate treatment. The adoption of this technology should be evaluated based on its practical effectiveness and compliance with general environmental protection regulations. Furthermore, thorough research and assessment are required to ensure its safety and efficacy before large-scale implementation.

4. Conclusion

Leachate plays a substantial role in water contamination and environmental degradation, presenting significant risks to both human health and ecosystems. Ozone technology emerges as a promising solution for leachate treatment, leveraging its capabilities in disinfection, purification, and odor management. This review highlights the effectiveness of ozone technology in leachate treatment, demonstrating its high removal efficiencies for COD (up to 99.8%), NH_4^+-N (91.14%), and color. Compared to biological treatment, membrane filtration, and chemical precipitation, ozonation enhances pollutant degradation and improves leachate biodegradability. However, challenges such as high energy consumption, by-product formation (e.g., bromates, aldehydes), and operational complexity limit its large-scale application.

Key research gaps include the need for long-term performance evaluations, by-product control strategies, and cost-effective hybrid treatment approaches. Additionally, the regulatory framework for ozone-based leachate treatment remains underdeveloped, particularly in Vietnam.

Future research should focus on energy-efficient ozonation strategies, integrated treatment systems (e.g., ozone-biological, ozone-membrane hybrid processes), and pilot-scale validation under real-world conditions. Addressing these aspects will enhance the feasibility of ozone technology, supporting its broader adoption in sustainable leachate management.

Author contributions: Conceptualization and development of the research idea and framework: H.T.V., V.H.H.; Data and material collection and analysis and synthesis: T.C.L., H.T.V.; Drafting of the manuscript: T.C.L.; Editing and proofreading of the manuscript: T.C.L., H.T.V.

Acknowledgement: This research is funded by Ministry of Education and Training (MOET) under grant number B2024-TNA-06.

Conflict of interest: The authors declare that this article is their own work, has not been published elsewhere, is not copied from previous research; there is no conflict of interest among the authors.

References

1. Li, S.; Yang, Y.; Zheng, H.; Zheng, Y.; Jing, T.; Ma, J.; Nan, J.; Leong, Y.K.; Chang, J.S. Advanced oxidation process based on hydroxyl and sulfate radicals to degrade refractory organic pollutants in landfill leachate. *Chemosphere* **2022**, *297*, 134214. doi: 10.1016/j.chemosphere.2022.134214.
2. Ahmed, S.F.; M. Mofijur, M.; Samiha Nuzhat, S.; Chowdhury, A.T.; Rafa, N.; Uddin, M.A.; Abrar Inayat, A.; Mahlia, T.M.I.; Hwai Chyuan Ong, H.C.; Chia, W.Y.; Show, P.L. Recent developments in physical, biological, chemical, and hybrid treatment techniques for removing emerging contaminants from wastewater. *J. Hazard. Mater.* **2021**, *416*, 125912. doi: 10.1016/J.JHAZMAT.2021.125912.
3. Lebron, Y.A.R.; Moreira, V.R.; Brasil, Y.L.; Silva, A.F.R.; de Souza Santos, L.V.; Lange, L.C.; Amaral, M.C.S. A survey on experiences in leachate treatment: Common practices, differences worldwide and future perspectives. *J. Environ. Manage.* **2021**, 288, 112475. doi: 10.1016/j.jenvman.2021.112475.
4. Iskander, S.M.; Zhao, R.; Pathak, A.; Gupta, A.; Pruden, A.S.; Novak, J.T.; He, Z. A review of landfill leachate induced ultraviolet quenching substances: Sources,

characteristics, and treatment. *Water Res.* **2018**, *145*, 297–311. doi: 10.1016/j.watres.2018.08.035.

5. Abdel-Shafy, H.I.; Ibrahim, A.M.; Al-Sulaiman, A.M.; Okasha, R.A. Landfill leachate: Sources, nature, organic composition, and treatment: An environmental overview. *Ain Shams Eng. J.* **2024**, *15(1)*, 102293. doi: 10.1016/J.ASEJ.2023.102293.
6. Ministry of Natural Resources and Environment of Vietnam. No. 10822/BTNMT-KSONMT, Reporting on the results of implementing domestic solid waste management nationwide. 2023.
7. Lovato, M.; Buffelli, J.R.; Abrile, M.; Martín, C.; Kinetics and efficiency of ozone for treatment of landfill leachate including the effect of previous microbiological treatment. *Environ. Sci. Pollut. Res.* **2018**, *26*, 4474–4487.
8. Maroneze, M.M.; Zepka, L.Q.; Vieira, J.G.; Queiroz, M.I.; Jacob-Lopes, E. A tecnologia de remoção de fósforo: Gerenciamento do elemento em resíduos industriais. *Rev. Ambient. Agua*. **2014**, *9(3)*, 445–458. doi: 10.4136/1980-993X.
9. Moody, C.M.; Townsend, T.G. A comparison of landfill leachates based on waste composition. *Waste Manag.* 2017, 63, 267–274. doi: 10.1016/j.wasman.2016.09.020.
10. Abdel-Shafy, H.I.; Ibrahim, A.M.; Al-Sulaiman, A.M.; Okasha, R.A. Landfill leachate: Sources, nature, organic composition, and treatment: An environmental overview. *Ain Shams Eng. J.* **2024**, *15(1)*, 102293. doi: 10.1016/J.ASEJ.2023.102293.
11. Vaccari, M.; Tudor, T.; Vinti, G. Characteristics of leachate from landfills and dumpsites in Asia, Africa and Latin America: an overview. *Waste Manag.* **2019**, *95*, 416–431. doi: 10.1016/J.WASMAN.2019.06.032.
12. Boner, M.; Lau, P.J. Wastewater technology fact sheet ozone disinfection. United States Environ. Prot. Agnecy, 2019, pp. 1–7. Online Available: https://www3.epa.gov/npdes/pubs/ozon.pdf.
13. Huang, Z.; Liu, G.; Zhang, Y.; Yuan, Y.; Xi, B.; Tan, W. Assessing the impacts and contamination potentials of landfill leachate on adjacent groundwater systems. *Sci. Total Environ.* **2024**, *930*, 172664. doi: 10.1016/j.scitotenv.2024.172664.
14. Daniel, A.N.; Ekeleme, I.K.; Onuigbo, C.M.; Ikpeazu, V.O.; Obiekezie, S.O. Review on effect of dumpsite leachate to the environmental and public health implication. *GSC Adv. Res. Rev.* **2021**, *7(2)*, 51–60. doi: 10.30574/gscarr.2021.7.2.0097.
15. van Vuuren, D.P.; Stehfest, E.; Elzen, M.D.; Kram, T.; van Vliet, J.; Deetman, S.; Isaac, M.; Goldewijk, K.; Hof, A.; Beltran, A.; Oostenrijk, R. RCP2.6: exploring the possibility to keep global mean temperature increase below 2°C. *Clim. Change* **2018**, *109*, 95. doi: 10.1007/s10584-011-0152-3.
16. Khan, S.; Naushad, M.; Govarthanan, M.; Iqbal, J.; Alfadul, S.M. Emerging contaminants of high concern for the environment: Current trends and future research. *Environ. Res.* **2022**, *207*, 112609. doi: 10.1016/J.ENVRES.2021.112609.
17. Brodowska, A.J.; Nowak, A.; Śmigielski, K. Affiliations expand ozone in the food industry: Principles of ozone treatment, mechanisms of action, and applications: An overview. *Crit. Rev. Food Sci. Nutr.* **2018**, *58(13)*, 2176–2201. doi: 10.1080/10408398.2017.1308313.
18. Wang, M.X.B.; Shi, W.; Zhang, H.; Ren, H. Promoting the ozone-liquid mass transfer through external physical fields and their applications in wastewater treatment: A review. *J. Environ. Chem. Eng.* **2021**, *9*, 106115. doi: 10.1016/j.jece.2021.106115.

19. Bai, Z.W.S.; Du, S.; Liu, H.; Lin, S.; Zhao, X.; Wang, Z. The causal and independent effect of ozone exposure during pregnancy on the risk of preterm birth: Evidence from northern China. *Environ. Res*. **2022**, *214*, 113879. doi: 10.1016/j.envres.2022.113879.
20. Shi, X.S.W.; Sun, Q.; Du, P.; Tang, S.; Chen, C.; Sun, Z.; Wang, J.; Li, T. Modification Effects of Temperature on the Ozone–Mortality Relationship: A Nationwide Multicounty Study in China. *Environ. Sci. Technol.* **2020**, *54*, 2859–2868. doi: 10.1021/acs.est.9b05978.
21. Zhang, R.W.G.; Hu, Q.; Cao, R.; Fu, R.; Risalat, H.; Pan, X.; Hu, Y.; Shang, B. Yield loss in rice by acute ozone pollution could be recovered. *Agric. Environ. Lett.* **2022**, *7*, 1–5. doi: 10.1002/ael2.20093.
22. Ahmed, S.F.; Mofijur, M.; Rafa, N.; Chowdhury, A.T.; Chowdhury, S.; Nahrin, M.; Islam, A.B.M.S.; Ong, H.C. Green approaches in synthesising nanomaterials for environmental nanobioremediation: Technological advancements, applications, benefits and challenges. *Environ. Res.* **2022**, *204*, 111967. doi: 10.1016/j.envres.2021.111967.
23. Duan, Y.; Gao, B.; Liu, J.; Wang, X.; Sillanpää, M. Treatment of landfill leachate in the MBR and catalytic ozonation coupled system based on MnNi catalyst: Efficiency and bio/chemical mechanism. *J. Water Process Eng.* 2024, 66, 106033. doi: 10.1016/J.JWPE.2024.106033.
24. Song, Q.; Kong, F.; Liu, B.F.; Song, X.; Ren, N.Q.; Ren, H.Y. Ozone oxidation of actual waste leachate coupled with culture of microalgae for efficient lipid production under different temperatures. *Water Res.* **2025**, *277*, 123305. doi: 10.1016/J.WATRES.2025.123305.
25. Zhe, J.; He, H.; Yi, Z.; Guo, Z.; Xu, H.; Huang, B.; Pan, X. Mechanism and molecular level insight of refractory dissolved organic matter in landfill leachate treated by electroflocculation coupled with ozone. *Sep. Purif. Technol.* **2025**, *356*, 129812. doi: 10.1016/j.seppur.2024.129812.
26. Shi, Y.; Sun, A.; Zhang, G.; Zhang, G. Combined coagulation-adsorption-VUV (persulfate)-electrochemical oxidation processes for efficient treatment of aged landfill leachate. *J. Water Process Eng.* **2025**, *71*, 107281. doi: 10.1016/j.jwpe.2025.107281.
27. Yang, X.; Liu, Z.; Chen, C.; Zhang, T.; Wang, Q.; Zhang, R.; Duan, F.; Tian, X.; Yao, M.; Demeestere, K.; Van Hulle, S.W.H. Hybrid packed bed bioreactor using combined biodegradation and ozonation to enhance nitrogen and micropollutants removal from landfill leachate. *Bioresour. Technol.* **2024**, *412*, 131413. doi: 10.1016/j.biortech.2024.131413.
28. Amaral-Silva, N.; Martins, R.C.; Castro-Silva, S.; Quinta-Ferreira, R.M. Ozonation and perozonation on the biodegradability improvement of a landfill leachate. *J. Environ. Chem. Eng.* **2016**, *4(1)*, 527–533. doi: 10.1016/J.JECE.2015.12.002.
29. Abu Amr, S.S.; Alazaiza, M.Y.D.; Bashir, M.J.; Alkarkhi, A.F.M.; Aziz, S.Q. The performance of $S_2O_8^{2-}$/ Zn_2^+ oxidation system in landfill leachate treatment. *Phys. Chem. Earth Parts A/B/C* **2020**, *120*, 102944. doi: 10.1016/J.PCE.2020.102944.
30. Health and Safety Executive. Ozone : Health hazards and control measures. Guid. Note EH38, 2014, pp. 1–10.
31. Shah, A. Some Wastewater Reuse Processes Can Lead to Undesired Byproducts. USC Viterbi Sch. Eng. Environ. Sci. Technol., 2020. Online Available: https://viterbischool.usc.edu/news/2020/02/some-wastewater-reuse-processes-can-lead-to-undesired-byproducts/.
32. Rougé, V.; von Gunten, U.; de Sentenac, M.L.; Massi, M.; Wright, P.J.; Crouéae, J.P.; Allard, S. Comparison of the impact of ozone, chlorine dioxide, ferrate and

permanganate pre-oxidation on organic disinfection byproduct formation during post-chlorination. *Environ. Sci. Water Res. Technol.* **2020**, *6(9)*, 2382–2395. doi: 10.1039/d0ew00411a.

33. Wang, R.J.X.; Wang, X.; Mi, J.; Du, Q.; Wang, Y.; Chen, W.; Sun, D.; Song, W.; Shao, M. UV/H_2O_2/O_3 removal efficiency and characterization of algae-derived organic matter and odorous substances. *J. Environ. Chem. Eng.* **2022**, *11*, 109128. doi: 10.1016/j.jece.2022.109128.
34. Lan, N.N. Research on the application of advanced oxidation method (AOP) in wastewater treatment containing organic compounds that are difficult to biodegrade. Institute of Environmental Science and Technology, 2014, pp. 140.
35. Tap, V.H.; Van, T.T. Reatment of organic compounds of landfill leachate in Vietnam by combining coagulation and ozonation process Am. *J. Environ. Sci*. **2013**, *9*, 518–528.
36. Van, H.T.; Nguyen, L.H.; Hoang, T.K.; Tran, T.P.; Vo, A.T.; Pham, T.T.; Nguyen, X.C. Using FeO-constituted iron slag wastes as heterogeneous catalyst for Fenton and ozonation processes to degrade Reactive Red 24 from aqueous solution. *Sep. Purif. Technol.* **2019**, *224*, 431–442.
37. Nguyen, M.B.; Le, G.H.; Pham, T.T.T.; Pham, G.T.T.; Quan, T.T.T.; Nguyen, T.D.; Vu, T.A. Novel nano-Fe_2O_3-Co_3O_4 modified dolomite and its use as highly efficient catalyst in the ozonation of ammonium solution. *J. Nanomater.* **2020**, *2020*, 1–11.