International Research Journal of Multidisciplinary Scope (IRJMS), 2026; 7(1): 954-971

Original Article | ISSN (O): 2582-631X DOI: 10.47857/irjms.2026.v07i01.09827

A Multidisciplinary Framework for Sustainable Landfill Leachate Management: Integrating Phytoremediation Performance, Human Health Risk Assessment, and Community Perception

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Abstract

Landfill leachate poses significant environmental and public health challenges, particularly for communities residing near disposal sites. This study aimed to evaluate the effectiveness of a phytoremediation-based treatment system combining horsetail (Equisetum hyemale), water hyacinth (Eichhornia crassipes), and zeolite (K-BAEGZ) in reducing heavy metal contamination and microplastic abundance in leachate from the Cilowong Landfill, as well as to assess associated health risks and community expectations regarding leachate pond management. A mixed-methods approach was employed, integrating laboratory analysis of leachate quality, health risk assessment using statistical association measures, and a community survey to capture socio-environmental perceptions. The results indicate that the K-BAEGZ system demonstrates superior performance in mitigating heavy metal concentrations and suppressing microplastic abundance compared to alternative treatments, highlighting the role of porous adsorbents in enhancing phytoremediation efficiency. Health risk analysis suggests that leachate contaminants are associated with various adverse health outcomes, with heavy metals emerging as the dominant contributors, while microplastics present additional long-term risks. Furthermore, community responses emphasize strong expectations for environmentally friendly leachate management, transparent government oversight, and inclusive participation in environmental monitoring. Overall, the findings underscore that sustainable leachate management requires an integrated approach that combines effective treatment technologies with public health considerations and community engagement to ensure long-term environmental protection and social acceptance around landfill areas.

Keywords: Health, Leachate, Metals, Microplastics, Phytoremediation.

Introduction

Leachate management at landfill sites, as widely reported in recent environmental studies (1, 2) remains a persistent challenge in many developing countries, including Indonesia. Inadequate treatment systems often allow leachate to infiltrate surrounding soil, groundwater, and surface water, thereby facilitating the transport of hazardous contaminants and posing serious risks to ecosystems and human health, particularly in densely populated areas (3, 4). Driven by rapid urbanization and population growth, increasing municipal solid waste generation has further intensified these challenges, especially in urban landfill settings where infrastructure development has not kept pace with waste production (5). Ineffective leachate management has consequently been recognized as a critical environmental issue requiring urgent, sustainable, and context-appropriate solutions, as highlighted in recent landfill management assessments (6, 7). Landfill leachate typically contains elevated concentrations of hazardous heavy metals such as iron (Fe), manganese (Mn), cadmium (Cd), and mercury (Hg). Several studies have documented the widespread occurrence of these metals in landfill leachate, underscoring their significance as key contaminants (8, 9). Due to their environmental persistence, bioaccumulation potential and long-term toxicity, these metals are regarded as critical contaminants of concern in landfill leachate

(Received 24th November 2025; Accepted 16th January 2026; Published 27th January 2026)

management (10, 11). Chronic exposure to these contaminants poses significant risks to both environmental compartments and human health, as they can disrupt ecological functions and induce adverse health outcomes, including neurological disorders, renal impairment, and increased carcinogenic risk (12, 13). In recent years, microplastics have also emerged as contaminants of increasing concern in landfill leachate, primarily originating from the fragmentation of plastic waste toxicity (14). These particles exhibit high resistance to degradation and can persist in aquatic environments over extended periods, while their ability to act as carriers for heavy metals and other toxic substances further enhances contaminant mobility and bioavailability (15, 16). The coexistence of heavy metals and microplastics has been identified as creating a compounded contamination scenario that amplifies ecological and public health risks (17).

From a theoretical perspective, landfill leachate represents a complex mixture of interacting contaminants governed by principles of mass conservation, transport processes, and chemical–biological interactions. Recent studies emphasize that conventional leachate treatment frameworks, which primarily focus on individual contaminants, are insufficient for addressing such complex mixtures, particularly when emerging pollutants such as microplastics are involved (16, 17). Theoretical models increasingly recognize the need to integrate contaminant interaction mechanisms, including adsorption, phytouptake, and particle-associated transport, to better understands leachate behavior and treatment performance.

Conventional leachate treatment technologies, such as physicochemical processes, membrane filtration, and advanced oxidation methods, have demonstrated effectiveness in reducing contaminant concentrations. However, these approaches are often associated with high capital and operational costs, energy-intensive processes, and technical complexity, limiting their applicability in developing countries (7)

In response, phytoremediation has gained increasing attention as a low-cost and environmentally friendly alternative. Numerous studies have demonstrated the ability of aquatic and semi-aquatic plants to uptake, immobilize, or stabilize heavy metals through biological processes such as rhizofiltration and phytoaccumulation (10, 18, 19). Nevertheless, phytoremediation efficiency is often constrained by limited adsorption capacity, plant stress under high contaminant loads, and reduced effectiveness against non-biodegradable pollutants such as microplastics.

Recent advances in zeolite-assisted remediation theory (6) indicate that the integration of natural adsorbents with biological treatment systems can significantly enhance contaminant removal efficiency in complex wastewater matrices. Natural zeolites have been reported to exhibit strong ion-exchange properties that regulate the adsorption and desorption behavior of heavy metals, particularly in the presence of competing ions such as ammonium, which commonly occurs in landfill leachate (19, 20). This ion competition mechanism has been identified as playing a critical role in determining metal mobility and long-term retention within zeolite matrices (19).

Building upon these mechanisms, recent review studies emphasize that zeolite nanomaterials provide enhanced surface reactivity and adsorption capacity, making them effective low-cost amendments for environmental remediation applications involving multicomponent and emerging pollutants (21, 22). In addition, modified zeolites have demonstrated improved selectivity and stability in removing emerging bio-resistive pollutants and metal-associated contaminants from water resources, particularly under fluctuating environmental conditions (23). Beyond modern engineered systems, field-based and historical evidence, including the study of zeolite-based water purification infrastructure at the ancient Maya city of Tikal, provides long-term validation of zeolite effectiveness for water treatment purposes (20). Collectively, these theoretical, experimental, and historical insights support the incorporation of natural and modified zeolites into integrated remediation frameworks, particularly when combined with phytoremediation strategies, to address the complex mixture of heavy metals and emerging pollutants present in landfill leachate (6, 23). However, the application of integrated plant and adsorbent systems remains underexplored in real landfill leachate environments, particularly in terms of their effectiveness in addressing combined heavy metal and microplastic contamination. In Indonesia, these challenges have been exemplified by the Cilowong Landfill in Serang City, which operates as a semi-engineered landfill and has exceeded its design capacity (6). Uncontrolled leachate migration from this site threatens surrounding soil and groundwater resources used by nearby communities, particularly in Panggungjati Village in Figure 1, thereby increasing long-term environmental and public health risks (24). The persistence of contaminants within environmental compartments, as emphasized in recent environmental systems analyses, underscores the urgent need for leachate management strategies that are not only technically effective but also socially acceptable and aligned with local conditions (18). Despite the increasing interest in sustainable leachate treatment technologies, a significant research gap remains (18). Most previous studies have examined heavy metals or microplastics independently, focused primarily on technical performance indicators, or neglected the integration of public health risk assessment and community perspectives, particularly in developing-country contexts (24). Consequently, existing frameworks provide fragmented insights that may not adequately support practical landfill management decisions.

Therefore, building on integrated remediation frameworks, this study aims to evaluate the effectiveness of phytoremediation using *Equisetum hyemale* and *Eichhornia crassipes*, applied individually and in combination with natural zeolite, in reducing heavy metal concentrations and microplastic abundance in landfill leachate at the Cilowong Landfill (6). The specific objectives are to (i) assess the removal efficiency of heavy metals and microplastics under different treatment configurations, (ii) evaluate potential public health risks associated with leachate exposure, and (iii) examine community perceptions and expectations regarding leachate pond management. The novelty of this study, as positioned within recent sustainability-oriented leachate management discourse, lies in its integrated theoretical and methodological framework that combines phytoremediation performance, amendment-assisted treatment mechanisms, health risk assessment, and community perception analysis within a single landfill leachate management context (18). By addressing both technical and social dimensions, this study contributes to the development of sustainable, low-cost, and socially responsive leachate management strategies for rapidly urbanizing regions in developing countries.

Figure 1: Leachate Discharge from a Landfill Leachate Pond into Adjacent Rice Fields near the Cilowong Landfill, Serang City, Indonesia

Methodology

Study Location and Period

This study was conducted at the Cilowong Landfill (Tempat Pembuangan Akhir/TPA Cilowong), Serang City, Banten Province, Indonesia, from February to May 2024 during the rainy season. The leachate sampling site is geographically located at 6°07′24″ S and 106°06′54″ E (WGS 84), as illustrated in Figure 2. The site was selected due to persistent leachate management problems, limited treatment infrastructure, and its proximity to residential and agricultural areas, particularly Panggungjati Village, Taktakan Subdistrict. Uncontrolled leachate migration from the landfill poses potential risks to surrounding soil and groundwater systems that are utilized by local communities.

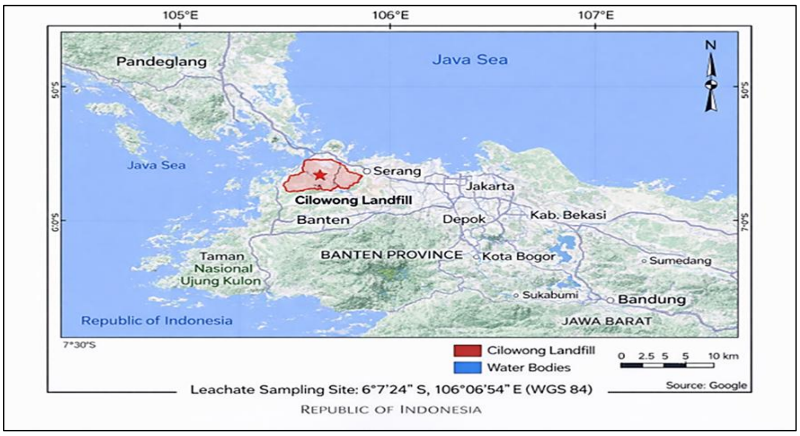

Figure 2: Map showing the Study Area at the Cilowong Landfill, Serang City, Indonesia

Study Design and Conceptual Framework

This study adopted a semi-controlled experimental and observational research design integrating environmental technology assessment, human health risk evaluation, and community perception analysis. The semi-controlled approach was selected to balance experimental control with realistic landfill leachate characteristics, acknowledging the inherent variability of leachate composition while maintaining controlled treatment conditions.

The conceptual framework in Figure 3 positions landfill leachate as the primary contamination source and links three interconnected components: (i) phytoremediation performance in constructed wetland (CW) systems, (ii) potential human health risks arising from environmental exposure pathways, and (iii) community perceptions and responses to leachate pollution. This integrated framework guided the sampling strategy, experimental treatments, risk assessment, and social data collection, ensuring methodological coherence across biophysical and socio-environmental dimensions.

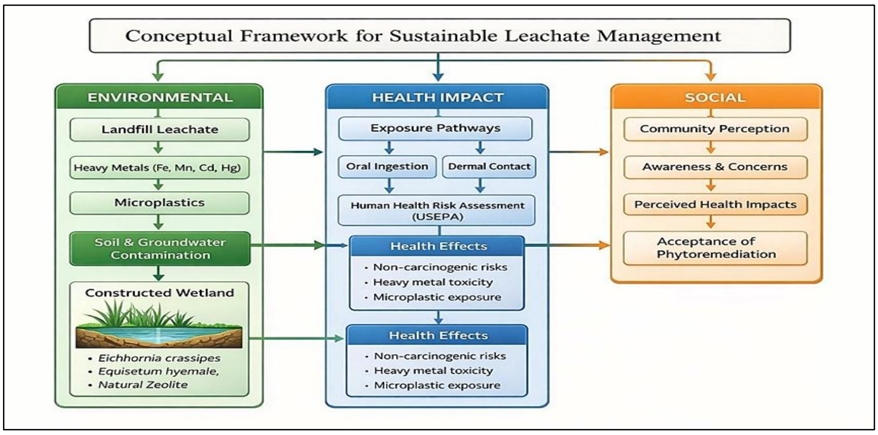

Figure 3: Conceptual Framework of the Study

Leachate Sampling and Experimental Setup

Leachate samples were collected using purposive sampling from the main leachate pond at TPA Cilowong, Serang City, Banten Province, Indonesia. This site was selected due to its persistent leachate management challenges and proximity to residential and agricultural areas, making it representative of landfill-related environmental risks.

To ensure sample representativeness, composite leachate samples were obtained using a duplo technique from multiple points within the leachate pond. Sampling was conducted on Day 1, Day 4, and Day 7 to capture short-term temporal variations in leachate characteristics.

Approximately 2,000 L of raw leachate were collected during a single bulk sampling event and subsequently distributed into four constructed wetland (CW) treatment units. Each unit consisted of a 150 L tank (65 cm × 45 cm × 27.5 cm) equipped with an electric circulation pump and aerators to maintain dissolved oxygen levels. While the leachate source reflected real landfill conditions, the treatment units were operated under controlled hydraulic retention time, tank volume, aeration, and plant density, thereby constituting a semi-controlled experimental system. All treatments were conducted in triplicate to enhance data reliability.

Phytoremediation Treatments

Four constructed wetland (CW) phytoremediation treatments were applied to evaluate contaminant removal efficiency under different plant configurations as presented in Table 1. The treatments included single-species systems, mixed-plant systems, and a combined plant–adsorbent system to assess potential synergistic effects. All treatments were conducted in three repetitions.

Table 1: Experimental Design

Treatment Code	CW Unit	Plant Composition	Repetitions
BA	CW-1	Horsetail (*Equisetum hyemale*)	3
EG	CW-2	Water hyacinth (*Eichhornia crassipes*)	3
K-BAEG	CW-3	Combination of horsetail and water hyacinth	3
K-BAEGZ	CW-4	Combination of horsetail, water hyacinth, and natural zeolite	3

Two phytoremediation plant species were employed: Eichhornia crassipes (water hyacinth) and Equisetum hyemale (horsetail), as shown in Figure 4. These species were selected based on documented hyper accumulative capacity, tolerance to contaminated aquatic environments, and relevance to nature-based leachate treatment systems.

Eichhornia crassipes is characterized by rapid growth, an extensive fibrous root system, and high uptake potential for heavy metals, with reported removal efficiencies of 80–90% for Fe, Mn, Cd, and Hg. *Equisetum hyemale* was selected for its high tolerance to metal toxicity and rigid, complex root architecture, which supports both metal absorption and the physical entrapment of microplastics. Each species was cultivated in separate CW tanks and continuously exposed to landfill leachate under standardized operational conditions. Treatment performance was evaluated across three observation periods (Day 1, Day 4, and Day 7) based on changes in pollutant concentrations.

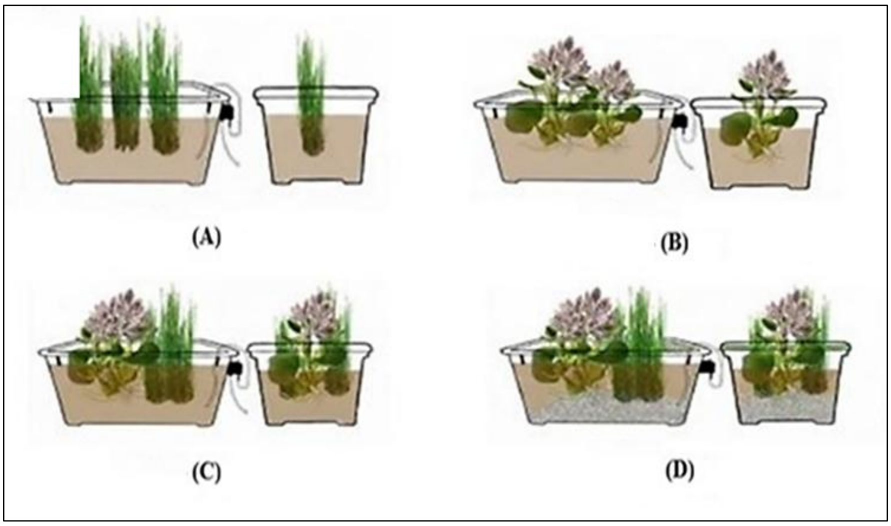

Figure 4: Experimental phytoremediation systems applied in this study: (A) *Equisetum hyemale* (BA); (B) *Eichhornia crassipes* (EG); (C) combined system of *Equisetum hyemale* and *Eichhornia crassipes* (K-BAEG); and (D) combined system of *Equisetum hyemale*, *Eichhornia crassipes*, and natural zeolite (K-BAEGZ)

Heavy Metal and Microplastic Analysis

Leachate samples from each CW unit were analyzed for iron (Fe), manganese (Mn), cadmium (Cd), and mercury (Hg) using Atomic Absorption Spectrophotometry (AAS) in accordance with Indonesian National Standard SNI 6989.8:2009. Removal efficiency was calculated as Equation [1]:

$$Removal\ Efficiency\ (\%) = \left(\frac{Co-Ct}{Co}\right) x100 \quad [1]$$

where C_0 represents the initial concentration (mg/L) and C_t denotes the post-treatment concentration at time *t* (mg/L).

Microplastic analysis was conducted through filtration, followed by polymer identification using Fourier Transform Infrared Spectroscopy with Attenuated Total Reflectance (FTIR-ATR). Micro-plastic abundance was determined by manual counting under a stereomicroscope and subsequently classified based on shape, size, and color according to established visual identification protocols.

Human Health Risk Analysis

A qualitative human health risk assessment was conducted to identify potential non-carcinogenic health risks for communities residing near the landfill. Exposure pathways through water, soil, and surrounding environmental media were evaluated. Primary data were collected through household health surveys, direct environmental observations, and in-depth interviews. The analysis focused on potential impacts of heavy metal and microplastic exposure on respiratory, digestive, and renal systems.

Community Perception Analysis

Community knowledge, awareness, and perceptions related to leachate pollution and its environmental and health implications were assessed using structured questionnaires. Variables included awareness of leachate contamination, understanding of waste management practices, familiarity with phytoremediation technologies, and perceived impacts on agriculture and food safety. Data were analyzed using descriptive statistics, including means and percentages, to characterize prevailing community perceptions.

Results

Heavy Metal Removal Using Phytoremediation Plants

Figure 5 illustrates the temporal variation of heavy metal concentrations in landfill leachate treated with *Equisetum hyemale* over a 7-day observation period. Figure 5A shows that dissolved iron (Fe) concentrations slightly increased from day 1 to day 4 and then decreased by day 7; however, Fe remained at relatively high levels, indicating limited removal. Figure 5B presents dissolved manganese (Mn) concentrations, which exhibited minimal fluctuation throughout the observation period and showed no clear decreasing trend. Figure 5C shows total cadmium (Cd) concentrations gradually increased over time, indicating ineffective removal during the treatment period. Figure 5D indicates that total mercury (Hg) concentrations increased markedly by day 7, approaching the permissible limit. Overall, the results demonstrate that *E. hyemale* as a single-species phytoremediation system showed limited effectiveness for removing heavy metals from landfill leachate.

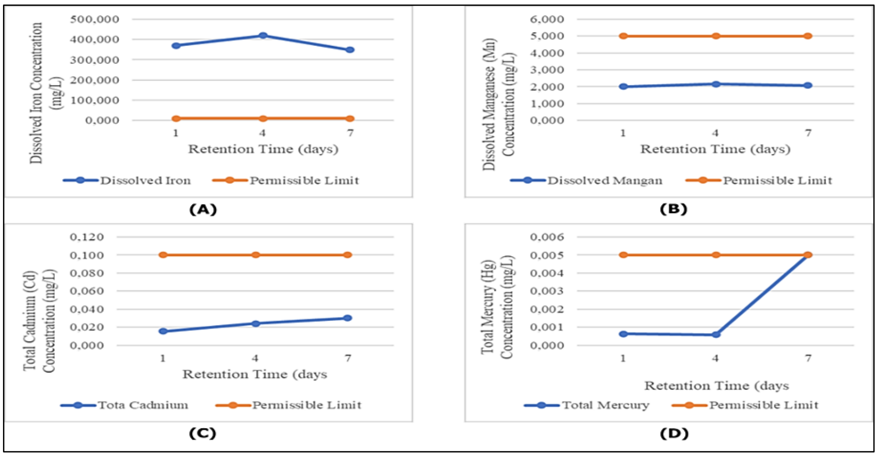

Figure 5: Heavy metal concentration dynamics in landfill leachate treated using *Equisetum hyemale* (horsetail) phytoremediation (HG): (A) dissolved iron (Fe); (B) dissolved manganese (Mn); (C) total cadmium (Cd); and (D) total mercury (Hg)

Figure 6 illustrates the changes in heavy metal concentrations in landfill leachate treated with *Eichhornia crassipes* (water hyacinth) over a 7-day observation period.

As shown in Figure 6A, dissolved iron (Fe) concentrations slightly increased from day 1 to day 4 and then decreased by day 7; however, Fe levels remained above the permissible limit throughout the observation period, indicating limited removal efficiency. In Figure 6B, dissolved manganese (Mn) exhibited a clearer decreasing trend over time and remained below the permissible limit, suggesting that water hyacinth was effective in reducing Mn concentrations. The trend of total cadmium (Cd) shown in Figure 6C indicates relatively stable concentrations during the treatment period, with minimal variation and consistent compliance with the permissible limit, reflecting limited Cd uptake by the plant.

Meanwhile, Figure 6D shows that total mercury (Hg) concentrations fluctuated during the observation period, with a noticeable decrease by day 7. Although Hg levels remained below the permissible limit, the variability indicates moderate and inconsistent removal performance. Overall, Figure 6 demonstrates metal-specific removal behavior by water hyacinth, with effective reduction of Mn, moderate improvement for Fe and Hg, and minimal change in Cd concentrations.

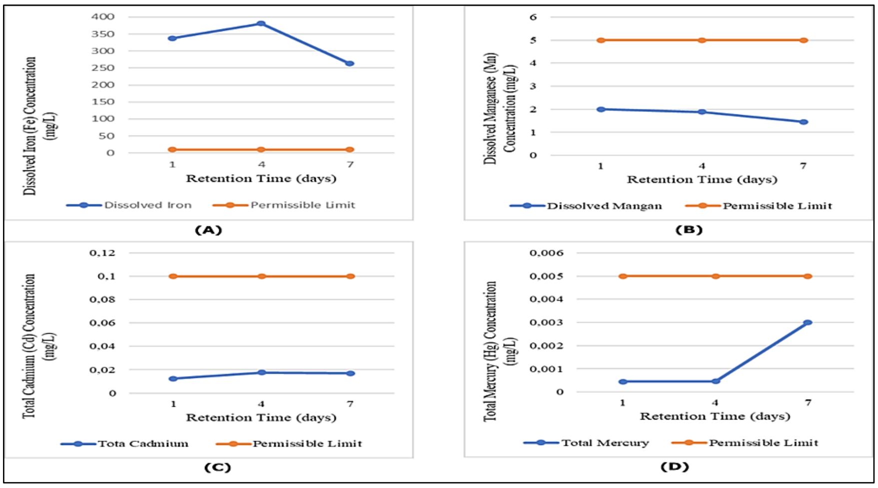

Figure 6: Heavy metal concentration dynamics in landfill leachate treated using *Eichhornia crassipes* phytoremediation (EG): (A) dissolved iron (Fe); (B) dissolved manganese (Mn); (C) total cadmium (Cd); and (D) total mercury (Hg)

Figure 7 illustrates the performance of the combined phytoremediation system using *Equisetum hyemale* and *Eichhornia crassipes* (K-BAEG) in treating landfill leachate over a 7-day observation period. As shown in Figure 7A, dissolved iron (Fe) concentrations increased slightly from day 1 to day 4 and then decreased markedly by day 7, indicating improved Fe removal compared to single-species systems, although concentrations remained above the permissible limit. Figure 7B shows that dissolved manganese (Mn) concentrations exhibited a clear decreasing trend over time and remained below the permissible limit, reflecting a synergistic removal effect of the combined plants. In Figure 7C, total cadmium (Cd) concentrations remained low and relatively stable throughout the observation period, consistently complying with the permissible limit. Meanwhile, Figure 7D shows that total mercury (Hg) concentrations increased slightly toward the end of the observation period, although values remained below the permissible limit. Overall, Figure 7 demonstrates that the K-BAEG system enhanced the removal of Fe and Mn while maintaining stable Cd levels, with Hg showing less consistent removal behavior.

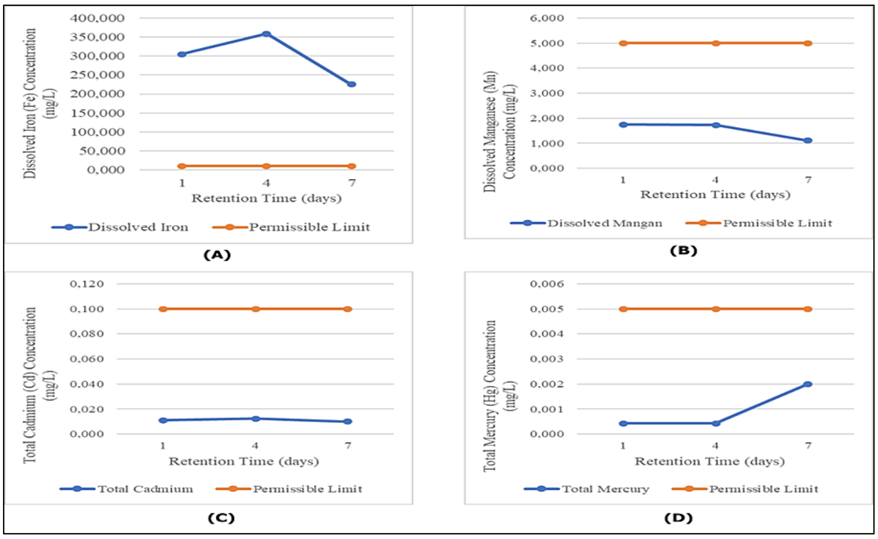

Figure 7: Heavy metal concentration dynamics in landfill leachate treated using the combined phytoremediation system consisting of *Equisetum hyemale* and *Eichhornia crassipes* (K-BAEG): (A) dissolved iron (Fe); (B) dissolved manganese (Mn); (C) total cadmium (Cd); and (D) total mercury (Hg)

The addition of natural zeolite to the combined phytoremediation system (K-BAEGZ) is illustrated in Figure 8, which shows the temporal variation of heavy metal concentrations in landfill leachate relative to their permissible limits.

As presented in Figure 8A, dissolved iron (Fe) concentrations remained relatively high throughout the observation period, although a slight decrease was observed at the final sampling point. Despite this reduction, Fe levels consistently exceeded the permissible limit, indicating limited removal efficiency for iron.

In contrast, Figure 8B shows a gradual and consistent decrease in dissolved manganese (Mn) concentrations over time, with values remaining below the permissible limit. This indicates effective Mn removal by the combined phytoremediation–zeolite system.

The trend of total cadmium (Cd) in Figure 8C reveals low and stable concentrations throughout the observation period, consistently complying with the permissible limit. This suggests that the K-BAEGZ system effectively maintained Cd at safe levels. Meanwhile, Figure 8D shows that total mercury (Hg) concentrations exhibited slight fluctuations and a minor increase toward the end of the observation period. Although Hg levels remained below the permissible limit, the inconsistent trend indicates variable removal performance. Overall, Figure 7 highlights metal-specific responses to the K-BAEGZ system, with effective control of Mn and Cd, while Fe and Hg showed less consistent removal behavior.

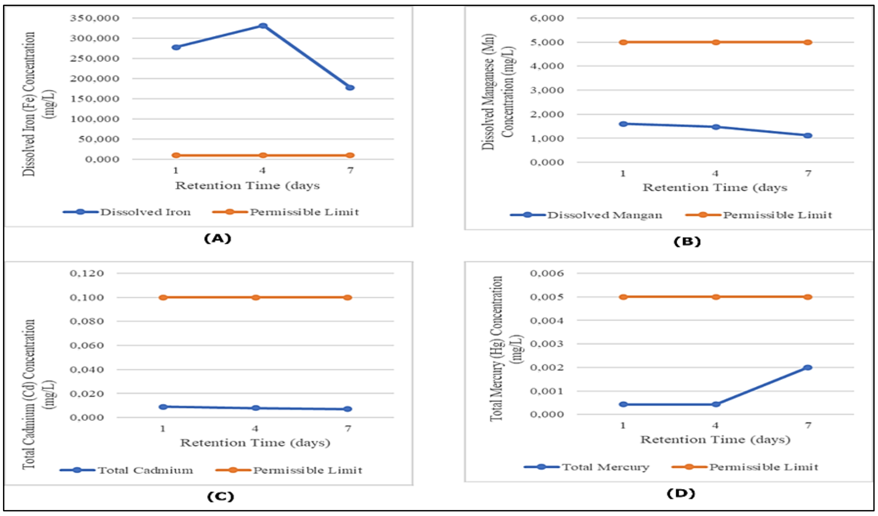

Figure 8: Heavy metal concentration dynamics in landfill leachate treated using the combined phytoremediation system consisting of *Equisetum hyemale*, *Eichhornia crassipes*, and natural zeolite (K-BAEGZ): (A) dissolved iron (Fe); (B) dissolved manganese (Mn); (C) total cadmium (Cd); and (D) total mercury (Hg)

Microplastic Abundance under Phytoremediation Treatments

Changes in microplastic abundance in landfill leachate treated with different phytoremediation systems during the observation period are summarized in Tables 2–4. Microplastics were detected at all sampling times and across all treatment variations, indicating their persistent presence in landfill leachate. Microplastic abundance generally decreased during the intermediate observation (day 4) and increased again by the final observation (day 7).

On the first day of observation, microplastics were detected across all phytoremediation treatments, indicating their immediate and persistent presence in landfill leachate. The abundance of microplastics varied depending on the type of treatment. Single-plant treatments, such as water hyacinth (EG) and horsetail (BA), exhibited intermediate microplastic concentrations, while the combined plant treatment without mineral adsorbent (K-BAEG) showed the highest concentration. Interestingly, the combined treatment including natural zeolite (K-BAEGZ) recorded a lower average concentration, suggesting that the inclusion of a mineral adsorbent may enhance the initial retention of microplastics, as shown in Table 2.

Table 2: Abundance of Microplastic Using Phytoremediation Plants on Day 1

Variation of Plants	1st Obse rvation (1)	2nd Observation (2)	3rd Observation (3)	Amount of Microplastics (particles) (4)	Average per slide (particles) (5)	Average (particles/L) (6)
BA	38	18	53	109	36.33	103.8
EG	22	67	7	96	32.00	91.42
K-BAEG	16	137	20	173	57.66	164.74
K-BAEGZ	0	83	52	135	45.00	128.57

By the fourth day of observation, a general reduction in microplastic abundance was observed in all treatments, reflecting partial removal or sedimentation over time. The combined plant treatment with natural zeolite (K-BAEGZ) achieved the lowest average concentration, indicating enhanced microplastic retention during the mid-observation period. In contrast, the combined plant system without zeolite (K-BAEG) maintained relatively higher concentrations, suggesting that the absence of a mineral adsorbent limited its removal efficiency. Single-plant treatments (BA and EG) showed intermediate reductions in microplastic levels, as summarized in Table 3.

Table 3: Abundance of Microplastic Using Phytoremediation Plants on Day 4

Variation of Plants	1st Observation (1)	2nd Observation (2)	3rd Observation (3)	Amount of Microplastics (particles) (4)	Average per Slide (Particles) (5)	Average (particles/L) (6)
BA	33	28	53	114	38.00	108.57
EG	20	24	62	106	35.00	100.00
K-BAEG	19	40	61	120	40.00	114.28
K-BAEGZ	34	36	17	87	29.00	82.86

On the seventh day, microplastic abundance increased again in all treatments compared to day four, indicating possible suspension or accumulation in the leachate. Despite this increase, the combined system with natural zeolite (K-BAEGZ) consistently exhibited lower average concentrations than the plant-only combined treatment (K-BAEG), suggesting the persistent effectiveness of the mineral adsorbent in retaining microplastics. Single-plant treatments (BA and EG) showed slightly lower or comparable values, but did not achieve the same retention efficiency as the K-BAEGZ system, as presented in Table 4.

Table 4: Abundance of Microplastic Using Phytoremediation Plants on Day 7

Variation of Plants	1st Observation (1)	2nd Observation (2)	3rd Observation (3)	Amount of Microplastics (particles) (4)	Average per slide (particles) (5)	Average (particles/L) (6)
BA	56	38	63	157	52.33	149.51
EG	50	47	62	159	53.00	151.42
K-BAEG	45	66	66	177	59.00	168.57
K-BAEGZ	49	42	63	154	51.33	146.65

Hypothetical Human Health Risk Associated with Leachate Contamination

The odds ratio analysis indicates that exposure to landfill leachate contaminants is associated with adverse health outcomes among communities residing near the Cilowong Landfill. Heavy metals present in the leachate showed statistically significant associations with multiple chronic health conditions, demonstrating a strong relationship between environmental exposure and community health status.

Microplastic exposure also exhibited statistically significant associations with several health variables; however, both the number and strength of these associations were lower compared to those observed for heavy metals. This suggests that, within the assessed exposure scenario, heavy metals pose a more substantial health risk than microplastics.

Taken together, the results indicate that heavy metals represent the dominant contributors to potential public health risks associated with landfill leachate contamination, while microplastics play a secondary but still relevant role in influencing community health outcomes.

Community Perception of Leachate Management

Community perceptions regarding the presence of leachate ponds are presented in Figure 9. The results indicate that residents primarily associate leachate ponds with environmental risks and expect environmentally sound management practices. There is also a strong expectation for greater governmental responsibility and transparency in landfill operations. In contrast, relatively limited attention is given to the potential economic benefits of treated leachate, while public health education emerges as an important community demand. These findings reflect increasing public awareness of environmental and health risks related to landfill leachate.

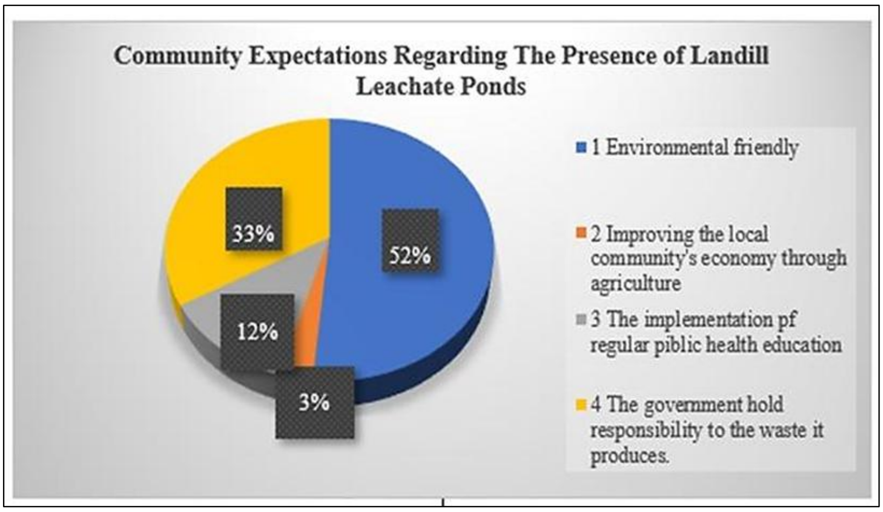

Figure 9: Community Expectations Regarding the Presence of Landfill Leachate Ponds

Discussion

Heavy Metal Removal Using Phytoremediation Plants

The environmental context of this study is illustrated in Figure 1, which shows the direct discharge of landfill leachate from the Cilowong Landfill leachate pond into adjacent rice fields in Serang City, Indonesia. This condition highlights the urgency of implementing effective leachate treatment strategies, particularly given the potential for contaminant migration into agricultural soils and surrounding water bodies. The overall research approach and variable interactions investigated in this study are summarized in the conceptual framework presented in Figure 3, which integrates phytoremediation performance, environmental risk, and community perception.

The phytoremediation plants employed in this study, namely *Equisetum hyemale* (horsetail) and *Eichhornia crassipes* (water hyacinth), are shown in Figure 4, while the distribution and behavior of heavy metals across different phytoremediation treatments are summarized in Figure 5. Based on these results, phytoremediation using horsetail alone (*E. hyemale*) was found to be ineffective in significantly reducing heavy metal concentrations in landfill leachate, particularly iron (Fe) and manganese (Mn). As shown in Figure 5, Fe and Mn concentrations exhibited substantial fluctuations throughout the observation period, with no consistent decreasing trend.

Several factors may explain this limited performance, including the relatively low metal uptake capacity of horsetail and the influence of environmental parameters such as pH, redox potential, and the presence of competing ions, which strongly affect metal bioavailability and absorption efficiency. In addition, the increase in dissolved Fe observed in the horsetail-based system suggests that phytoremediation may have promoted metal release from sediments rather than immobilization. This phenomenon is commonly associated with redox changes in anaerobic zones, where Fe(III) oxides bound to sediments are reduced to more soluble Fe(II), thereby increasing Fe concentrations in the leachate. Redox changes in anaerobic zones can promote metal mobilization, where Fe(III) oxides bound to sediments are reduced to more soluble Fe(II), thereby increasing Fe concentrations in leachate. This phenomenon was also observed in the present study, as the horsetail-based system exhibited an increase in dissolved Fe in Figure 5, consistent with previous studies reporting similar redox-driven Fe mobilization in anaerobic sediments (25, 26). Previous studies have also reported that manganese (Mn) exhibits low bioavailability under anaerobic and slightly alkaline conditions and are poorly accumulated by certain aquatic or semi-aquatic plants (25). Consistent with these reports, horsetail phytoremediation in this study failed to achieve meaningful Mn removal, as indicated by the relatively stable Mn concentrations in Figure 5.

Overall, phytoremediation using horsetail alone was insufficient to reduce Fe, Mn, Cd, and Hg concentrations under the experimental conditions applied in this study (27, 28).

In contrast, the phytoremediation results obtained using *Eichhornia crassipes* (EG) demonstrated metal-specific responses, as illustrated in Figure 6. Iron (Fe) concentrations showed limited and inconsistent reductions over time, which may be attributed to root saturation and potential re-release of accumulated Fe into the water column. Previous studies have shown that Fe uptake by aquatic macrophytes is highly dependent on pH, exposure duration, and metal bioavailability, with removal efficiency often declining over time (25). These mechanisms likely contributed to the modest Fe reduction observed in the EG system.

Conversely, *Eichhornia crassipes* exhibited a more consistent and effective capacity for manganese (Mn) uptake. As shown in Figure 6, Mn concentrations decreased continuously throughout the observation period and remained below the applicable quality standards. The effectiveness of Mn removal can be attributed to active ion transport mechanisms in plant roots and interactions with root-associated microbial communities. This finding is supported by previous studies reporting that *Eichhornia crassipes* can significantly reduce Mn concentrations in contaminated water systems, although removal efficiency is strongly influenced by pH and contact duration (29). In the present study, *E. crassipes* exhibited a more consistent and effective capacity for manganese (Mn) uptake.

For cadmium (Cd), concentrations remained relatively stable with only minor fluctuations and no clear decreasing trend in the EG system as illustrated in Figure 6, although values consistently remained below regulatory limits. This suggests that *E. crassipes* may function primarily as a buffering or stabilizing system for Cd rather than as an active phytoextractor. Similar observations have been reported in wastewater treatment studies, indicating that Cd uptake by *E. crassipes* is generally lower compared to other metals and is governed by detoxification mechanisms that favor tolerance over accumulation (29).

A notable increase in total mercury (Hg) concentration was observed during the later stages of the EG experiment in Figure 6, despite concentrations remaining below the quality threshold. This increase may be associated with mercury release from decaying plant biomass or changes in environmental parameters such as pH, temperature, and microbial activity. Previous studies emphasize that *E. crassipes* shows limited effectiveness in immobilizing mercury under fluctuating environmental conditions and that Hg remediation often requires complementary approaches, such as mineral adsorbents, to enhance stabilization duration (29).

The combined phytoremediation system using *Equisetum hyemale* and *Eichhornia crassipes* (K-BAEG) demonstrated improved performance compared to single-plant systems. As shown in Figure 6, this combined system resulted in greater reductions of Mn and Cd concentrations, indicating a synergistic effect between the two plant species. However, Fe concentrations remained largely unmitigated, while Hg removal was unstable over time, suggesting that plant interactions alone were insufficient to control redox-sensitive metals.

Further enhancement was observed with the incorporation of zeolite into the combined phytoremediation system (K-BAEGZ). As illustrated in Figure 7, the K-BAEGZ system exhibited the most consistent stabilization of Mn and Cd among all treatments. This finding supports previous evidence that synergistic phytoremediation–adsorption systems enhance remediation efficiency through the combined mechanisms of phytoextraction and surface adsorption (30, 31). Nevertheless, Fe concentrations remained relatively high and Hg removal remained inconsistent, underscoring the need for supplementary or post-treatment processes when managing redox-sensitive and highly mobile metals (25).

Beyond the technical performance of phytoremediation systems, community perception plays an important role in landfill leachate management. Community expectations regarding the presence of landfill leachate ponds are presented in Figure 8, which indicates public concern related to environmental quality, health risks, and agricultural sustainability. These perceptions reinforce the need for effective, visible, and socially acceptable leachate treatment strategies that combine technical effectiveness with community engagement.

Overall, while the phytoremediation models applied in this study demonstrate promising performance particularly for Mn and Cd, their effectiveness is not universal across all heavy metals. The integration of plant-based systems with engineered media such as zeolite significantly improves treatment outcomes, as demonstrated in Figure 7; however, further optimization is required to achieve consistent compliance with stringent environmental standards, especially for persistent contaminants such as Fe and Hg (29).

Hypothetical Human Health Risk Associated with Leachate Contamination

Beyond heavy metal removal, the incorporation of zeolite into the phytoremediation system played an important role in enhancing microplastic removal efficiency. As shown in Tables 2–4, the combined phytoremediation and adsorption system (K-BAEGZ) exhibited a clearer and more stable reduction in microplastic abundance compared to plant-only systems. The superior performance of this configuration highlights the contribution of zeolite as an effective supplementary medium in integrated leachate treatment.

Zeolite is a naturally occurring aluminosilicate mineral characterized by high surface area, porosity, and ion-exchange capacity, which enable efficient interaction with a wide range of micropollutants. The observed decline in microplastic abundance in the K-BAEGZ system in Tables 2–4 is likely attributable to the physical entrapment of microplastic particles within the porous zeolite matrix, combined with surface interaction mechanisms such as electrostatic attraction and particle adhesion. Similar mechanisms have been reported in previous studies demonstrating the effectiveness of zeolite-based materials in stabilizing microplastics within wastewater and leachate treatment systems (31).

Beyond treatment performance, the results of the health risk analysis indicate a strong association between landfill leachate contamination and adverse health outcomes among communities residing near the Cilowong Landfill. Exposure to heavy metals in leachate was associated with a broader range of health conditions compared to microplastic exposure. This pattern suggests that heavy metals represent a dominant environmental health stressor in the study area, consistent with existing epidemiological evidence linking metal exposure to systemic toxicity and chronic disease development (32).

Microplastic exposure was also associated with several adverse health outcomes although the number of affected health indicators was more limited. These findings align with emerging evidence that microplastics act as chronic stressors capable of inducing inflammatory responses, immune dysregulation, and endocrine interference. Such mechanisms may increase susceptibility to non-communicable diseases, particularly under conditions of prolonged environmental exposure (32).

The co-occurrence of heavy metals and microplastics in landfill leachate further amplifies potential health risks through combined or synergistic exposure pathways. As illustrated in Figure 9, both contaminant groups can enter human systems through shared environmental routes, increasing the likelihood of cumulative toxicological effects. Recent studies have demonstrated that both metals and microplastics are capable of crossing biological barriers, accumulating in human tissues, and disrupting physiological processes critical for long-term health (33).

Notably, the association between leachate contamination and congenital health outcomes observed in this study than can be seen in Figure 5 is supported by growing evidence that environmental pollutants can interfere with fetal development. Both heavy metals and microplastics have been shown to cross the placental barrier and influence developmental processes, potentially leading to adverse birth outcomes (33). These findings emphasize the vulnerability of sensitive populations and the importance of preventive environmental management.

Overall, the distribution of health symptoms associated with landfill leachate exposure reflects a decline in community health status in the surrounding area. While both heavy metals and microplastics contribute to environmental risk, heavy metals appear to exert a more pronounced impact on human health, as indicated by the broader range of associated health outcomes. Nevertheless, the documented associations between microplastic exposure and multiple health conditions underscore the growing concern surrounding microplastic pollution in landfill-impacted environments.

Collectively, these findings highlight the necessity of integrated landfill leachate management strategies that address both physicochemical contamination and public health protection. The improved performance of the combined phytoremediation–zeolite system in reducing microplastic abundance in Tables 2–4 demonstrates the potential of hybrid nature-based solutions. However, given the observed health associations, further optimization, long-term monitoring, and complementary treatment approaches are required to ensure sustainable risk mitigation for communities residing near landfill sites.

Community Perception of Leachate Management

Community expectations regarding the presence of leachate ponds at landfill sites reflect an increasing level of environmental awareness and concern over potential health impacts among nearby residents. In the context of the Cilowong Landfill, local communities expect leachate ponds to be effectively managed to prevent the migration of contaminants into groundwater and surrounding ecosystems. These concerns are particularly relevant given the complex composition of landfill leachate, which commonly contains hazardous substances such as heavy metals and microplastics that pose substantial environmental and ecological risks. Previous studies have demonstrated the co-occurrence of microplastic particles and heavy metals in landfill leachate and their potential for co-transport into adjacent environmental compartments when treatment systems are inadequate, reinforcing community demands for improved leachate management strategies (34).

These expectations are further shaped by growing public awareness of the pathways through which leachate contaminants can affect human health. Several studies have reported that key water quality parameters, including chemical oxygen demand and heavy metal concentrations, frequently exceed permissible limits in groundwater wells located near landfill sites, raising concerns about domestic water safety and long-term exposure risks (6, 35, 36). In parallel, research on microplastic contamination in landfill leachate and receiving surface waters has identified substantial microplastic loads that are often inadequately removed by conventional leachate treatment systems. This limitation underscores the need for more advanced or alternative treatment approaches, including nature-based solutions.

Beyond environmental contamination, community perceptions are strongly influenced by trust in landfill management practices. Previous studies have emphasized that transparency, consistent environmental performance, and the availability of accessible monitoring information are critical determinants of public acceptance and the social license to operate landfill facilities. In the absence of these elements, perceived risks related to odour, vectors, and health symptoms attributed to leachate exposure tend to persist and intensify, contributing to public dissatisfaction and opposition. Furthermore, the documented presence of contaminants such as microplastics and associated toxicants in landfill environments has been linked to broader ecosystem impacts and potential human health effects, further elevating community expectations for safer and more sustainable waste management practices.

The implementation of phytoremediation technologies, including integrated systems combining aquatic plants and adsorption media such as zeolite, represents an effort to respond to community expectations for environmentally friendly and low-impact leachate treatment. Phytoremediation has been widely investigated as a viable approach for reducing contaminant loads in landfill leachate, with various aquatic plant species demonstrating the capacity to absorb heavy metals and attenuate pollutant concentrations, albeit with effectiveness that varies according to species, environmental conditions, and system design (37, 38). While such approaches align with public preferences for natural treatment systems, communities continue to emphasize the importance of inclusive participation in environmental monitoring and decision-making processes, particularly in contexts where evidence of health risks is emerging.

Overall, the findings of this study indicate that leachate management at the Cilowong Landfill constitutes not only a technical challenge but also a complex socio-environmental issue closely linked to community expectations and public health considerations. Leachate ponds represent a critical control point in preventing the migration of contaminants, including heavy metals and microplastics, into groundwater and surrounding ecosystems. The application of the K-BAEGZ phytoremediation system demonstrates potential as a nature-based and environmentally compatible treatment approach that is broadly consistent with community demands for safer and more sustainable waste management practices. However, the persistence of environmental risks and public concern suggests that technological interventions alone are insufficient. Effective leachate management requires the integration of reliable treatment systems with transparent environmental monitoring, clear risk communication, and active community engagement. Addressing both the technical performance of leachate treatment and the social dimensions of trust, awareness, and inclusivity is therefore essential to achieving long-term environmental protection, public health safeguarding, and environmental justice in landfill-adjacent communities.

Limitations of the Study

Several limitations should be acknowledged in interpreting the results of this study. First, the experiments were conducted under semi-controlled conditions with a relatively short observation period, which may not fully capture the long-term performance, stability, and resilience of phytoremediation systems under variable field conditions. Seasonal variations, climatic influences, and long-term plant adaptation were not assessed.

Second, the human health risk assessment applied in this study was hypothetical and based on assumed exposure scenarios, rather than direct measurements of exposure pathways or bio monitoring data. As a result, the estimated risks should be interpreted as indicative rather than definitive.

Third, this study did not fully address contaminant speciation, transformation processes, or the long-term fate of accumulated heavy metals and microplastics within plant tissues and substrate media. Potential ecological impacts, including metal remobilization, trophic transfer, and plant disposal risks, were also beyond the scope of this research.

Recommendations

Future research should prioritize long-term and field-scale evaluations of combined phytoremediation systems to better assess their effectiveness, stability, and applicability under real landfill conditions. Extended monitoring periods are necessary to evaluate seasonal dynamics, plant life-cycle effects, and long-term contaminant accumulation or release.

Further investigation into the interactions between heavy metals and microplastics within phytoremediation systems is recommended, particularly regarding adsorption, co-transport, and bioavailability mechanisms. Detailed analyses of contaminant speciation and transformation processes would provide deeper insight into removal efficiency and environmental safety.

In addition, integrating phytoremediation with other engineered treatment technologies such as constructed wetlands, adsorption columns, or advanced oxidation processes, should be explored to develop more robust and sustainable landfill leachate management strategies. Finally, future studies should incorporate comprehensive human health risk assessments based on site-specific exposure data to strengthen the relevance of phytoremediation outcomes for environmental management and public health protection.

Conclusion

This study evaluated the performance of single and combined phytoremediation systems, with and without natural zeolite, for treating landfill leachate containing heavy metals and microplastics, as well as their potential implications for environmental quality and human health. The results demonstrate that phytoremediation effectiveness is strongly influenced by plant species selection, system configuration, and contaminant-specific behavior.

Single-plant systems exhibited limited and metal-specific removal capacities. *Equisetum hyemale* showed low effectiveness in reducing Fe, Cd, and Hg concentrations, whereas *Eichhornia crassipes* demonstrated more selective uptake, with consistent reductions in Mn and stabilization of Cd levels. In contrast, the combined phytoremediation system integrating aquatic plants with natural zeolite (K-BAEGZ) achieved superior treatment performance, particularly in reducing Mn concentrations and microplastic abundance. This highlights the synergistic benefits of combining biological uptake mechanisms with mineral adsorption processes.

From an applied perspective, the findings underscore the importance of hybrid treatment strategies in landfill leachate management. The capacity of the combined system to reduce both dissolved heavy metals and microplastics indicates its potential to enhance leachate treatment efficiency and mitigate environmental and public health risks associated with contaminant release. Nevertheless, the persistence and temporal fluctuations observed for Fe, Hg, and microplastics suggest that phytoremediation alone is insufficient for comprehensive leachate remediation. Therefore, phytoremediation should be considered a complementary treatment rather than a stand-alone solution within integrated leachate management systems.

Abbreviations

None.

Acknowledgement

The authors gratefully acknowledge the support provided by local authorities and community members in the vicinity of the Cilowong Landfill, Serang City, for facilitating field observations and sample collection. Appreciation is also extended to laboratory staff and colleagues who assisted with analytical procedures and data processing.

Author Contributions

Fitri Dwirani: conceptualization, conducted the fieldwork, data analysis, and writing of the original draft, Suyud Warno Utomo: critically revised the manuscript for intellectual content, Tri Edhi Budhi Soesilo and Haryoto Koesnoputranto: critically revised the manuscript for intellectual content. All authors have read and approved the final version of the manuscript.

Conflict of Interest

The authors declare no conflict of interest.

Declaration of Artificial Intelligence (AI) Assistance

The authors declare that artificial intelligence (AI) tools were used solely for language editing and clarity improvement during manuscript preparation. All scientific content, data interpretation, and conclusions were generated and validated by the authors.

Ethics Approval

This study did not involve human participants or animal subjects. All data were obtained from environmental sampling and secondary sources; therefore, ethical approval and informed consent were not required.

Funding

No funding was received.

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How to Cite: Dwirani F, Utomo SW, Soesilo TEB, Koesnoputranto H. A Multidisciplinary Framework for Sustainable Landfill Leachate Management: Integrating Phytoremediation Performance, Human Health Risk Assessment, and Community Perception. Int Res J Multidiscip Scope. 2026; 7(1): 954-971.
DOI: 10.47857/irjms.2026.v07i01.09827