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RESEARCH ARTICLE

Water Hyacinth Phytoremediation for Reducing COD, BOD, and Pb in Leachate: An Environmental Geoscience Perspective

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Abstract

Leachate generated from landfill disposal sites poses a serious environmental threat due to its high content of organic pollutants and heavy metals. Elevated levels of chemical oxygen demand (COD), biochemical oxygen demand (BOD), and lead (Pb) may contaminate soil and surrounding water bodies if the leachate is not properly treated. Phytoremediation using water hyacinth offers an eco-friendly and low-cost alternative for leachate treatment. This study was conducted to evaluate the effectiveness of water hyacinth in reducing COD and BOD concentrations and removing Pb from leachate. An experimental method with a batch reactor system was applied, using 30 clumps of water hyacinth in each tank and contact time variations of 7, 14, and 21 days. COD, BOD, and Pb concentrations were measured before and after treatment using standard water quality analysis methods. The results showed that the 21-day contact time produced the highest removal efficiency. COD decreased from 1551.21 mg/L to 520.32 mg/L, representing a 66.44% reduction, while BOD decreased from 576.34 mg/L to 150.62 mg/L, equivalent to a 73.88% reduction. Pb concentration also decreased from 0.92 mg/L to 0.18 mg/L, with a removal efficiency of 80.43%. These reductions are attributed not only to the physiological activity of water hyacinth but also to the interactions among hydrological conditions, root zone architecture, and rhizosphere-mediated microbial communities, which collectively facilitate biodegradation, assimilation, and bioaccumulation of pollutants. Overall, the study highlights the critical role of integrating environmental geoscience principles with phytoremediation to optimize leachate treatment. Understanding the geochemical characteristics of leachate, subsurface hydrodynamics, and plant-microbe interactions provides a scientific basis for designing sustainable, low-cost, and efficient treatment systems. The findings indicate that water hyacinth can serve as a practical and geoscience-informed solution for mitigating organic and heavy metal pollution from landfill leachate, with 21 days identified as the optimum contact time.

Keywords: Leachate, Phytoremediation, Water Hyacinth

1. Introduction

1.1 Sub Introduction

Urban solid waste management constitutes a significant challenge to sustainable development, particularly in developing countries characterized by rapid population growth and accelerated urbanization (Puspitaningsari et al., 2024). As the final stage in waste management systems, landfills play a critical role and may exert substantial environmental pressure if not properly managed (Ekha et al., 2021). Leachate represents one of the most critical environmental issues associated with municipal solid waste disposal; it is a complex liquid generated through rainwater percolation, biological decomposition of organic matter, and chemical dissolution processes within the landfill mass (Rezagama et al., 2017). Leachate is typically characterized by high concentrations of organic matter, nutrients, and heavy metals, which can lead to soil and water contamination, posing long-term environmental risks and adverse impacts on human health (Apriyani & Lesmana, 2020).

The physicochemical composition of leachate is strongly influenced by landfill age, waste characteristics, hydrogeological conditions, and local climatic factors (Priscillia et al., 2019). Common pollution indicators, such as chemical oxygen demand (COD) and biochemical oxygen demand (BOD), are widely used to assess the level of organic contamination in leachate, as they directly reflect the organic load requiring oxygen for oxidation processes (Syahdo et al., 2025). Elevated COD and BOD levels in wastewater can significantly deplete dissolved oxygen in receiving water bodies, ultimately leading to water quality degradation and detrimental effects on aquatic ecosystems (Ihtiar et al., 2024). Furthermore, the presence of heavy metals such as lead (Pb) in leachate is of particular concern due to their toxicity, persistence, and potential for bioaccumulation and trophic transfer within the food chain (Sudheer Kumar et al., 2018).

From an environmental geoscience perspective, leachate and associated contaminants are not merely considered waste-related issues but are understood as products of complex interactions among geomorphological, hydrological, biogeochemical, and anthropogenic factors (Elvania et al., 2025). The migration of leachate into soil and groundwater systems is strongly governed by geological conditions, soil permeability characteristics, and subsurface flow dynamics, which may facilitate the spread of contamination in areas surrounding landfill sites (Elvania, 2022). Therefore, sustainable leachate management requires consideration not only of the physical environment but also of natural processes that can be effectively harnessed to reduce pollutant loads (Elvania, 2025).

Various leachate treatment methods have been developed, including complex biological, physical, and chemical processes, as well as COD removal techniques (Adi et al., 2020). However, the widespread application of conventional technologies remains limited due to high operational costs, significant energy consumption, and the generation of secondary residues requiring further treatment (Miguel & Guerrero, 2026). These limitations highlight the need for more cost-effective and environmentally friendly alternatives, such as phytoremediation (Aoust et al., 2026). As a biologically based approach to addressing environmental problems, phytoremediation is considered a sustainable and eco-friendly solution that utilizes plants to absorb, accumulate, stabilize, or degrade contaminants from water and soil media (Yin et al., 2025).

Water hyacinth (*Eichhornia crassipes*) has been widely recognized for its phytoremediation potential due to its rapid growth rate, high biomass production, and extensive root system, which enhances microbial activity and pollutant uptake (Tshikovhi et al., 2025). Its biomass has been shown to reduce heavy metal concentrations through bioaccumulation and biosorption processes, as well as to decrease organic pollutant levels, as indicated by reductions in COD and BOD values (Auchterlonie et al., 2021). Numerous studies have demonstrated that the effectiveness of water hyacinth depends on wastewater characteristics, environmental conditions, and contact time.

The Banjarsari Landfill has the potential to generate leachate containing high concentrations of organic pollutants and hazardous heavy metals, which may adversely affect the surrounding environment (Elvania, 2025). To date, studies integrating environmental geoscience approaches with the application of water hyacinth-based phytoremediation for leachate treatment at this site remain limited (Elvania, 2022). Such research is essential to evaluate the effectiveness of water hyacinth in leachate treatment, particularly in reducing COD and BOD levels, as well as in the adsorption and attenuation of Pb (Elvania et al., 2025).

The integration of environmental geoscience with phytoremediation provides a comprehensive framework for understanding and optimizing leachate treatment processes within landfill environments. From this perspective, phytoremediation using water hyacinth (*Eichhornia crassipes*) is not solely viewed as a biological treatment method but as a process inherently influenced by subsurface geological conditions, hydrological flow regimes, and biogeochemical interactions. The efficiency of contaminant removal, including COD, BOD, and Pb, is closely linked to factors such as soil permeability, groundwater flow patterns, and redox conditions, which control contaminant mobility, availability, and plant uptake mechanisms. Consequently, integrating geoscientific parameters into phytoremediation design enables a more site-specific and process-based approach to leachate management.

Furthermore, this interdisciplinary approach allows for a better evaluation of natural attenuation processes occurring alongside phytoremediation. Interactions between plant roots, microbial communities, and geochemical conditions can enhance contaminant immobilization, transformation, and degradation within the leachate–soil–water system. By incorporating environmental geoscience insights, this study not only assesses the removal efficiency of water hyacinth but also elucidates the underlying mechanisms governing pollutant behavior and transport. Such an approach strengthens the scientific basis for developing adaptive, sustainable, and locally appropriate leachate treatment strategies that align with the geological and hydrological characteristics of landfill sites.

Overall, this study aims to assess the effectiveness of water hyacinth in reducing COD and BOD concentrations and to analyze its capacity to adsorb and reduce Pb levels in leachate. The findings are expected to contribute to the development of sustainable leachate treatment methods and to provide a scientific basis for decision-making in environmentally sound landfill management, adapted to local geological and hydrological conditions.

2. Materials and Methods

2.1 Research Design and Methodological Approach

This study employs a quantitative experimental design grounded in an environmental geoscience perspective to investigate the potential of phytoremediation using water hyacinth (*Eichhornia crassipes*) for reducing COD, BOD, and Pb concentrations in leachate. This perspective is applied to elucidate the interrelationships among leachate chemical characteristics, hydrological processes, and plant biological activity in response to organic and inorganic contaminants.

The experiment was conducted using controlled laboratory-scale reactor systems with uniform plant conditions, applying contact time intervals of 7, 14, and 21 days. The effectiveness of water hyacinth in the phytoremediation process, from an environmental geoscience standpoint, was evaluated by analyzing COD, BOD, and Pb concentrations before and after treatment.

2.2 Population, Sample, and Sampling Method

Leachate generated from waste disposal activities at the Banjarsari Landfill served as the study population (Elvania et al., 2025). This leachate exhibits variable physicochemical characteristics and represents a suitable medium for geoscience-based environmental assessment, particularly with respect to COD, BOD, and Pb parameters.

Fig 1. Leachate Sampling Pond

The research samples consisted of leachate collected from the leachate holding ponds at the Banjarsari Landfill and subsequently utilized as the phytoremediation medium within reactor systems. Water hyacinth specimens with relatively uniform physical characteristics were selected, with 30 clumps introduced into each reactor tank. Treatments were differentiated based on contact duration—7, 14, and 21 days—to evaluate pollutant reduction efficiency over time.

Leachate sampling was conducted using a purposive sampling approach, targeting locations that represent active leachate characteristics within the landfill site (Elvania, 2025). This approach ensures that the collected samples are representative and contain significant pollutant concentrations relevant to the study area (Amira et al., 2022). Water quality parameters were analyzed both prior to and following treatment to quantitatively determine changes in COD, BOD, and Pb concentrations (Purwaningrum et al., 2023).

2.3 Data Types and Collection Methodology

The study utilizes both primary and secondary data (Wijaya et al., 2022). Primary data were obtained through direct measurements of leachate quality parameters, including COD, BOD, and Pb, before and after phytoremediation treatment using water hyacinth (Siswoyo, 2023). Secondary data include background information on the Banjarsari Landfill, leachate characteristics, and applicable water quality standards, derived from governmental reports and published literature.

Leachate samples were directly collected from the landfill site and analyzed in the laboratory throughout the study period. Measurements of COD, BOD, and Pb were conducted in accordance with relevant standard analytical procedures. Data collection was performed at baseline (pre-treatment) and subsequently on days 7, 14, and 21 of phytoremediation to quantitatively assess pollutant reduction efficiency.

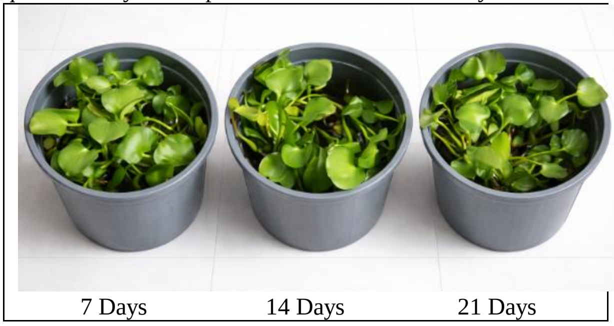

Fig 2. Phytoremediation with Water Hyacinth

2.4 Data Analysis

A quantitative descriptive analysis approach was employed to evaluate the effectiveness of water hyacinth in reducing COD, BOD, and Pb concentrations. Laboratory measurements were analyzed by comparing water quality parameter values before and after treatment across each contact time interval.

Phytoremediation effectiveness was determined based on the percentage reduction of each pollutant parameter, calculated by comparing initial and final concentrations following treatment (Oktavia, 2020). This approach enables the identification of trends in COD, BOD, and Pb reduction as a function of increasing contact time, as well as the determination of optimal contact duration for pollutant removal.

The analytical results were subsequently interpreted within an environmental geoscience framework, considering natural processes influencing phytoremediation, including organic matter degradation, heavy metal bioaccumulation by plants, and plant–microorganism interactions. This study is designed to provide a holistic evaluation of pollutant reduction mechanisms and their implications for sustainable leachate management.

3. Results and Discussion

3.1 Leachate Quality Test Results

The results of COD, BOD, and Pb analyses in leachate indicate that contact durations of 7, 14, and 21 days, with 30 clumps of water hyacinth (*Eichhornia crassipes*) in each reactor tank, exert a significant influence on the reduction of pollutant concentrations, as shown in the graph below :

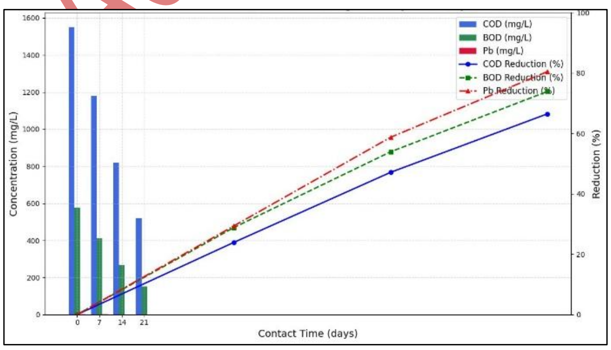

Fig 3. COD, BOD, and Pb Concentration and Reduction Using Water Hyacinth Phytoremediation

The initial COD concentration in the leachate was recorded at 1551.21 mg/L, indicating a high organic load and substantial levels of dissolved organic matter prior to treatment. Such elevated COD values reflect a significant potential for environmental contamination if the leachate is not properly managed. Following phytoremediation using water hyacinth (*Eichhornia crassipes*), a consistent decline in COD concentrations was observed with increasing contact time (Megagupita et al., 2024). After 7 days of treatment, COD decreased to 1180.45 mg/L, suggesting the initiation of organic matter uptake and degradation processes by the plant system.

A more pronounced reduction was observed after 14 days, with COD decreasing to 820.67 mg/L, indicating enhanced efficiency of organic matter removal through synergistic interactions between plant roots and associated microbial communities in the rhizosphere (Fery et al., 2020). The most substantial reduction occurred at 21 days, where COD reached 520.32 mg/L. Overall, COD removal amounted to 1030.89 mg/L, corresponding to a reduction efficiency of 66.44%. This significant decrease demonstrates the high effectiveness of water hyacinth in reducing organic pollutant loads in leachate. The results further indicate that extended contact time enhances phytoremediation performance, as both the plant and its symbiotic microorganisms become more effective in degrading and assimilating organic compounds (Ihtiar et al., 2024). Thus, contact time is identified as a critical parameter, with 21 days representing the optimal duration for COD reduction in this study.

Similarly, the initial BOD concentration in the leachate was measured at 576.34 mg/L, indicating a high content of biodegradable organic matter that can substantially deplete dissolved oxygen during decomposition processes (Syahdo et al., 2025). Following phytoremediation treatment, BOD levels exhibited a gradual decline with increasing contact time. After 7 days, BOD decreased to 410.28 mg/L, reflecting the onset of biodegradation facilitated by microorganisms associated with plant roots.

At 14 days, a more substantial reduction was observed, with BOD decreasing to 265.74 mg/L, suggesting improved plant growth and enhanced microbial activity contributing to more effective organic matter degradation (Vidiyanti et al., 2025). The greatest reduction was recorded at 21 days, where BOD reached 150.62 mg/L. The total reduction in BOD was 425.72 mg/L, corresponding to a removal efficiency of 73.88%. This high percentage reduction indicates that water hyacinth is highly effective in removing biodegradable organic pollutants from leachate (Syahdo et al., 2025).

The observed trend also highlights the role of contact time in enhancing biodegradability, likely due to increased microbial population density and activity within the rhizosphere (Adi et al., 2020). Overall, the findings confirm that a 21-day contact period represents the optimal condition for BOD reduction, further supporting the effectiveness of water hyacinth-based phytoremediation in treating leachate.

The initial Pb concentration in the leachate was measured at 0.92 mg/L, indicating the presence of potentially toxic heavy metal contamination with implications for environmental and human health. Following phytoremediation using water hyacinth, Pb concentrations decreased progressively with increasing contact time (Rahmi & Sajidah, 2017). After 7 days, Pb levels declined to 0.65 mg/L, suggesting the initial uptake of heavy metals through the plant's submerged root system.

A more substantial reduction was observed at 14 days, with Pb concentrations decreasing to 0.38 mg/L. This decline may be attributed to the capacity of water hyacinth as a heavy metal accumulator, which becomes more effective as the plant adapts to the leachate medium (Rahayu et al., 2023). The lowest Pb concentration was recorded at 21 days, reaching 0.18 mg/L.

Overall, the total reduction in Pb concentration from initial to final conditions was 0.74 mg/L, corresponding to a removal efficiency of 80.43%.

This percentage reduction is higher than those observed for COD and BOD, indicating that water hyacinth is particularly effective in the removal of heavy metals such as Pb. The results suggest that longer contact durations enhance the binding and accumulation of heavy metals within plant tissues, especially in the root zone. Therefore, a contact time of 21 days can be considered the optimal condition for Pb removal in leachate through water hyacinth-based phytoremediation.

3.2 Effectiveness of Water Hyacinth in Reducing COD and BOD

Water hyacinth (*Eichhornia crassipes*) demonstrated considerable potential for the removal of organic pollutants from leachate. Based on experimental observations at contact times of 7, 14, and 21 days, the plant exhibited promising capability in reducing both COD and BOD concentrations.

The initial COD and BOD values, recorded at 1551.21 mg/L and 576.34 mg/L, respectively, indicate that the leachate was heavily contaminated with organic matter prior to treatment. Following phytoremediation, both parameters decreased progressively with increasing contact time, suggesting that water hyacinth is capable of adapting to leachate conditions and contributing to the reduction of organic pollutant loads (Eden et al., 2024). The gradual decline observed from day 7 onward indicates that phytoremediation processes were actively occurring, although not yet at maximum efficiency. These findings highlight the plant's strong initial potential for organic pollutant removal.

Table 1. Leachate Quality Test Results

Parameter	Before (Mg/L)	After			Decrease (Mg/L)	Percentage (%)
		7 Days (Mg/L)	14 Days (Mg/L)	21 Days (Mg/L)		
COD	1551,21	1180,45	820,67	520,32	1030,89	66,44
BOD	576,34	410,28	265,74	150,62	425,72	73,88
Pb	0,92	0,65	0,38	0,18	0,74	80,43

After 7 days of exposure, COD and BOD values decreased to 1180.45 mg/L and 410.28 mg/L, respectively. This reduction indicates the onset of organic matter uptake and enhanced microbial activity in the rhizosphere. Water hyacinth possesses a dense root system that provides a favorable substrate for microbial colonization, facilitating the establishment of biofilms that contribute to the biodegradation process (Claquin et al., 2025). However, at this early stage, the reduction remains relatively limited due to the adaptation and growth phase of the plant (Skrubbeltrang et al., 2024). Nevertheless, these results confirm that water hyacinth can exert a positive effect even during the initial phase of treatment (Auchterlonie et al., 2021), including reducing both chemical and biological oxygen demand in leachate.

At 14 days of contact, the removal efficiency of COD and BOD increased significantly, with concentrations decreasing to 820.67 mg/L and 265.74 mg/L, respectively. This substantial decline indicates that the plant had effectively acclimatized to the leachate environment and that phytoremediation processes were operating more optimally. Enhanced microbial activity within the root zone likely contributed to increased biodegradation of organic matter (Sangkham et al., 2025). In addition, the reduction in COD and BOD can be attributed to the direct uptake and assimilation of organic compounds by plant tissues (Aoust et al., 2026). These findings suggest that longer contact durations facilitate synergistic interactions among plants, microorganisms, and environmental conditions, thereby improving treatment performance.

The highest removal efficiency was achieved at 21 days of contact, where COD and BOD concentrations decreased to 520.32 mg/L and 150.62 mg/L, respectively. Overall, COD and BOD reductions reached 66.44% and 73.88%, respectively, demonstrating the effectiveness of water hyacinth in reducing organic pollutant loads in leachate. The higher reduction percentage observed for BOD compared to COD indicates that water hyacinth is particularly effective in facilitating the biodegradation of readily degradable organic matter. The influence of contact time on phytoremediation performance is evident, as extended exposure enhances the plant's capacity to adsorb, assimilate, and degrade organic pollutants (Yang et al., 2025). These results confirm that water hyacinth can be effectively applied as a phytoremediation agent for the reduction of COD and BOD in leachate, with a 21-day contact period identified as the optimal condition in this study.

3.3 Phytoremediation Potential of Water Hyacinth for Lead (Pb) Removal

Experimental results indicate that water hyacinth (*Eichhornia crassipes*) exhibits a high efficiency in the removal of lead (Pb) from leachate across contact durations of 7, 14, and 21 days. The initial Pb concentration in the untreated leachate was 0.92 mg/L, reflecting a significant risk of heavy metal contamination. Following phytoremediation, Pb concentrations decreased progressively with increasing contact time. After 7 days, the Pb concentration declined to 0.65 mg/L, providing evidence that the plant's root system had initiated the uptake of dissolved heavy metals. This reduction suggests that metal binding and absorption processes were actively occurring.

At 14 days of contact, Pb concentrations decreased more substantially to 0.38 mg/L. This finding indicates that water hyacinth is well adapted to the leachate environment and maintains its capacity for heavy metal uptake over time. The plant's dense and well-developed root system provides a large surface area, which plays a critical role in the adsorption and accumulation of heavy metals (Yin et al., 2025). In addition, microbial activity within the rhizosphere contributes to Pb immobilization and reduction in aqueous concentrations (Wdowczyk & Szyma, 2024). These results further demonstrate that contact time is a key factor influencing the efficiency of heavy metal removal (Auchterlonie et al., 2021).

The highest Pb removal efficiency was observed at 21 days of contact, with concentrations decreasing to 0.18 mg/L. Overall, the reduction in Pb concentration from initial to final conditions was 0.74 mg/L, corresponding to a removal efficiency of 80.43%. This reduction is notably higher than those observed for COD and BOD, indicating that water hyacinth is particularly effective in removing Pb among the studied pollutants. Longer contact durations enhance the accumulation of heavy metals within plant tissues, especially in the root system, where adsorption and sequestration processes are most active. These findings confirm that water hyacinth has strong potential for Pb phytoremediation in leachate systems, with a 21-day contact period identified as the optimal condition in this study.

3.4 Implications of Research Results

The findings of this study demonstrate that water hyacinth (*Eichhornia crassipes*) can be effectively applied for the removal of COD, BOD, and Pb from leachate. The significant decreasing trends observed in COD and BOD concentrations indicate that the water hyacinth-based phytoremediation system is capable of continuously reducing organic pollutant loads with increasing contact time. Consequently, water hyacinth represents a simple, cost-effective, and environmentally friendly alternative for leachate treatment, particularly in landfill sites with limited technological options and financial resources. This study therefore contributes to ongoing efforts to mitigate environmental pollution in areas surrounding landfill sites.

The markedly higher removal efficiency of Pb further highlights the strong potential of water hyacinth as a heavy metal adsorbent. These results suggest that the plant is highly suitable for treating leachate containing toxic heavy metals, thereby reducing the risk of soil and water contamination in landfill environments. The maximum Pb removal observed at 21 days of contact also emphasizes the importance of retention time as a critical parameter in achieving optimal phytoremediation performance. Accordingly, sufficient hydraulic retention time is essential when applying water hyacinth systems to ensure maximum heavy metal uptake. These findings also open opportunities for the application of water hyacinth in the treatment of other types of wastewater contaminated with heavy metals.

From a practical perspective, this study has important implications for landfill management, particularly in leachate treatment operations. The use of water hyacinth can be implemented as a preliminary treatment stage prior to further processing or discharge into aquatic systems. Early reduction of COD, BOD, and Pb concentrations can significantly decrease the treatment load on subsequent units, thereby improving the overall efficiency of the leachate management system. In addition, the rapid growth and widespread availability of water hyacinth make this approach highly sustainable and adaptable. However, despite its high treatment efficiency, proper management of the resulting plant biomass remains a critical consideration.

Plant biomass that accumulates organic pollutants and heavy metals may become a secondary source of contamination if not properly handled. Therefore, appropriate post-treatment strategies—such as regular harvesting and environmentally sound disposal or processing of contaminated biomass—are essential in accordance with applicable environmental regulations. Furthermore, the present findings provide a foundation for future research aimed at optimizing key parameters, including plant density, contact time, and integration with complementary treatment technologies. Overall, this study underscores the importance of developing efficient, low-cost, and environmentally sustainable approaches for leachate treatment.

3.5 Environmental Geoscience Perspective in Leachate Phytoremediation

The environmental geoscience approach provides a comprehensive conceptual framework for understanding the interactions among physical, chemical, and biological factors in leachate management systems. In the context of phytoremediation using water hyacinth (*Eichhornia crassipes*), this perspective allows a holistic analysis of how leachate characteristics, hydrological dynamics, and plant-microbe interactions contribute to pollutant reduction. According to the study data, the initial concentrations of COD, BOD, and Pb in the leachate were 1551.21 mg/L, 576.34 mg/L, and 0.92 mg/L, respectively, indicating a substantial pollutant load. Environmental geoscience provides insights into how the variability in leachate chemical composition is influenced by local hydrological processes, soil permeability, and rhizosphere-microbial interactions, all of which directly affect the water hyacinth's capacity for pollutant uptake and degradation.

From this perspective, contact time emerges as a critical parameter that can be explained through geoscience mechanisms. The study data show that COD and BOD decreased progressively over 7, 14, and 21 days of contact, reaching 520.32 mg/L and 150.62 mg/L at the end of the experiment. These reductions reflect the activity of microorganisms associated with the water hyacinth root system and direct absorption by plant tissues. Environmental geoscience emphasizes that the dense and extensive root zone provides an optimal substrate for microbial colonization, thereby enhancing the efficiency of organic matter degradation. This phenomenon demonstrates how geoscience principles, including dissolved oxygen distribution and pollutant mass transport within the aqueous medium, interact with biological phytoremediation mechanisms to achieve significant pollutant reductions.

The effectiveness of heavy metal Pb removal can also be interpreted through an environmental geoscience perspective. Pb concentrations decreased from 0.92 mg/L to 0.18 mg/L after 21 days of contact, highlighting the water hyacinth's capacity for bioaccumulation and biosorption of heavy metals. Microbial activity in the rhizosphere further facilitates the mobilization and reduction of Pb in the aqueous phase. The geoscience perspective helps explain the distribution of metals within the leachate system, how hydrological interactions and chemical characteristics influence metal bioavailability, and how root-microbe mechanisms mediate adsorption and accumulation processes. Therefore, integrating geoscience knowledge and phytoremediation enables a more accurate assessment of leachate treatment efficiency at both laboratory and field scales.

Furthermore, the environmental geoscience perspective provides a basis for developing sustainable leachate management strategies. The study data indicate that the optimal contact time of 21 days achieved the highest reductions in COD, BOD, and Pb, demonstrating that leachate management depends not only on plant presence but also on surrounding physical and chemical conditions. This approach supports the design of phytoremediation systems that optimize retention time, plant density, and environmental conditions to maximize organic degradation and heavy metal adsorption. Consequently, the integration of environmental geoscience and phytoremediation offers opportunities for more efficient, cost-effective, and environmentally sustainable leachate treatment while providing a scientific foundation for decision-making in landfill management.

4. Conclusions

From the experimental results, it is evident that water hyacinth (*Eichhornia crassipes*) is highly efficient in reducing COD and BOD levels in leachate. The initial COD value of 1551.21 mg/L decreased to 520.32 mg/L after 21 days of contact time, corresponding to a reduction of 66.44%. Similarly, the initial BOD value of 576.34 mg/L was reduced to 150.62 mg/L, achieving a reduction of 73.88%. These results indicate that both contact time and the physiological activity of water hyacinth significantly enhance the attenuation of organic pollutant loads in leachate. From an environmental geoscience perspective, these reductions can be attributed to the interactions among hydrological conditions, root zone architecture, and microbial communities, which collectively facilitate biodegradation and assimilation of organic matter. Consequently, the first objective of this study—to assess the suitability of water hyacinth for reducing COD and BOD in leachate—was successfully achieved.

In addition, water hyacinth demonstrated a high capacity for adsorbing Pb from leachate. After 21 days of contact, the initial Pb concentration of 0.92 mg/L decreased to 0.18 mg/L, corresponding to a reduction of 80.43%. These findings confirm that water hyacinth can effectively accumulate Pb heavy metals through its root system. From a geoscience perspective, the efficiency of Pb removal is influenced by the physicochemical characteristics of leachate, hydrodynamic transport, and rhizosphere-mediated bioavailability, which collectively optimize metal uptake and sequestration. This outcome aligns with the second objective of the study, which aimed to investigate the capacity of water hyacinth to reduce Pb concentrations in leachate.

Overall, the integration of environmental geoscience with phytoremediation in this study highlights the critical importance of understanding leachate chemistry, hydrological processes, and plant-microbe interactions to optimize treatment performance. The root-mediated processes and associated microbial activity were identified as the primary mechanisms through which water hyacinth reduces both organic and inorganic pollutants. Furthermore, this approach provides a scientific foundation for designing sustainable, low-cost, and environmentally friendly leachate treatment systems at landfill final treatment facilities. The potential of water hyacinth can be further leveraged for large-scale, efficient, and geoscience-informed phytoremediation of leachate.

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