E3S Web of Conferences **678**, 02001 (2025) https://doi.org/10.1051/e3sconf/202567802001
IES 2025

Environmental Pollution Analysis and Bioremediation Strategies at Landfills in Pekanbaru City

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Abstract. Pekanbaru City in Riau Province is experiencing rapid urban growth, accompanied by a significant rise in solid waste, especially household waste. This increase contributes to soil pollution at the Final Disposal Site (TPA), primarily from organic waste such as food scraps, which dominate household waste composition. These materials decompose easily and generate leachate that contaminates soil and groundwater, as well as methane gas (CH_4) that threatens atmospheric quality. This study analyzes the types and levels of soil pollution caused by organic waste at Pekanbaru's landfills and evaluates the potential of bioremediation strategies. Using a qualitative approach through field observations, interviews with landfill managers and environmental agencies, and secondary data analysis, the study finds that pollution comes mainly from organic leachate containing nitrogen compounds, phosphates, and pathogenic microorganisms. Bioremediation using local soil microorganisms, such as decomposer bacteria (e.g., Pseudomonas aeruginosa and Bacillus subtilis), shows promise in accelerating organic degradation, reducing soil toxicity, and improving soil structure. However, challenges include the absence of proper leachate treatment, limited bioremediation technology, and low public awareness of waste segregation. The study recommends collaborative efforts among government, landfill operators, academia, and communities to implement sustainable bioremediation for reducing soil pollution in Pekanbaru City.

1 Introduction

Pekanbaru City, the capital of Riau Province, has undergone rapid growth over the past two decades in terms of population, urbanization, and economic activity. While this development brings positive impacts such as improved infrastructure and public welfare, the dynamics of urbanization also lead to increasingly complex environmental challenges, especially in solid waste management. The growing volume of waste, unmatched by management system capacity, has become a critical issue requiring serious attention from various stakeholders, including the government, academia, industry players, and the general public.

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According to data from the Pekanbaru City Environmental and Sanitation Agency, household waste production exceeds 600 tons per day and is projected to continue rising with population growth and the consumer-oriented lifestyles of urban residents [1]. The main composition of household waste is organic, such as food scraps, kitchen waste, and leaves, accounting for around 60–70% of the total waste volume. Although biodegradable, this organic waste is a major contributor to environmental pollution in landfills, particularly through leachate and greenhouse gases such as methane (CH_4) [2].

Leachate formed from the decomposition of organic waste is a thick liquid containing various harmful substances, including nitrogen compounds (ammonia, nitrite, nitrate), phosphates, heavy metals, and pathogenic microorganisms [3]. If not properly managed, leachate can seep into the soil and contaminate groundwater and nearby surface water bodies. Additionally, the decomposition of organic waste produces methane gas, which contributes to global warming and increases the risk of explosions and fires in landfills lacking adequate safety standards [4].

Muara Fajar II Landfill, located in Rumbai District, Pekanbaru City, is a clear example of waste management issues that still face many limitations. The landfill continues to apply an open dumping system, where waste is heaped without sorting or pre-treatment. As a result, large volumes of organic waste accumulate, accelerating leachate formation and the buildup of pollutants in the soil. This condition is exacerbated by the lack of leachate treatment facilities, suboptimal landfill sanitation infrastructure, and the limited use of environmentally friendly and sustainable waste-processing technologies.

Soil pollution around landfills is a major concern due to its risks to environmental quality and public health. Previous studies have shown that soil near landfills contains heavy metals and nitrogen levels that exceed environmental quality thresholds, and also harbors pathogenic microorganisms hazardous to human health [5]. This indicates that current waste management systems are ineffective in mitigating pollution risks and require the adoption of applicable and efficient environmental science and technology solutions [6].

One approach increasingly being developed to address soil contamination from organic waste is bioremediation. Bioremediation is a process of cleaning or restoring polluted environments by using microorganisms, such as bacteria, fungi, and other microbes, that degrade harmful compounds into non-toxic forms [7]. This strategy is considered more environmentally friendly, economical, and sustainable than physical or chemical remediation methods, which are often costly and may have negative effects on ecosystems [8].

Several studies have demonstrated the effectiveness of bioremediation in reducing pollutant levels in soils contaminated by leachate, especially when using local microorganisms that have adapted to site-specific environmental conditions. Bacteria such as *Pseudomonas aeruginosa.*, *Bacillus subtilis.*, and *Actinomycetes* are known for their ability to decompose complex organic compounds and improve soil structure and fertility [9]. The application of bioaugmentation (the addition of specific microbial strains) and biostimulation (the enhancement of natural microbial activity through nutrient supplementation) has been identified as a viable strategy to increase the effectiveness of soil remediation around landfills [10, 11].

However, the implementation of bioremediation strategies in Pekanbaru City still faces several structural and technical barriers. These include the lack of support facilities, such as environmental microbiology laboratories; limited human resources with expertise in bioremediation techniques; and a lack of policy and budgetary support from local governments. Moreover, low public awareness of source-separated waste continues to result in high volumes of organic waste entering landfills, hindering bioremediation due to contamination by non-organic and hazardous materials.

These issues call for an integrated approach combining technological innovation, policy reform, and community participation to realize an effective waste management system. A collaborative approach involving government authorities, landfill operators, academic institutions, and the public is key to encouraging the broad adoption of bioremediation strategies. Environmental education, technical training for waste management personnel, and incentives for local technology innovation are strategic steps needed to ensure the sustainability of soil remediation efforts.

This study aims to comprehensively analyze the forms of soil pollution at landfills in Pekanbaru City resulting from organic waste accumulation and to evaluate the potential of bioremediation as an effective biological solution. A qualitative approach was employed, with data collection methods including field observation, in-depth interviews with landfill managers and relevant agencies, and literature review of pertinent studies. The findings of this research are expected to contribute to urban pollution control efforts, particularly in the context of ecologically based and appropriate technology for waste management.

Furthermore, the results of this study are expected to serve as a foundation for the formulation of more adaptive and contextually relevant urban waste management policies, strengthen soil quality monitoring systems around landfills, and open opportunities for cross-sector collaboration in developing local solutions based on endemic microbial potential. Through this approach, Pekanbaru City may serve as a model for other cities in implementing waste management strategies oriented toward environmental sustainability and public health.

2 Methods

This study employs a descriptive qualitative approach to gain an in-depth understanding of the types and levels of environmental pollution at the Final Disposal Site (TPA) in Pekanbaru City, as well as to evaluate the potential of bioremediation strategies. This approach was selected because it enables a comprehensive depiction of actual conditions based on empirical data from multiple sources. Data quality is assured through QA/QC with the accuracy of secondary data and interview responses validated through government sources and expert review.

2.1 Research Location and Period

The Study was conducted at Muara Fajar II Landfill, Pekanbaru, as it is the main final disposal site for municipal waste and has a significant environmental impact. The study was carried out from February to May 2025.

2.2 Data types and sources

The data consisted of both primary and secondary sources. Primary data were collected through field observations and interviews with landfill managers, officers from the Pekanbaru City Environmental and Sanitation Agency (DLHK), and surrounding residents. Secondary data were sourced from DLHK's annual reports, scientific literature, and other relevant documents.

2.3 Data collection technique

Data collection in this study was carried out through three complementary approaches. Field observations were conducted directly at the landfill site to examine indicators of soil contamination, patterns of leachate flow, and the operational conditions of the waste management system. These observations were systematically documented using structured observation sheets as well as photographic evidence. To deepen the understanding of institutional practices and community experiences, in-depth interviews were held with landfill managers, officials from the Department of Environment and Hygiene (DLHK), and local residents. These interviews were semi-structured, allowing respondents to elaborate on issues such as environmental impacts, management challenges, and community perceptions. All interview responses were transcribed for analysis. In addition, a document review and literature study were conducted by examining DLHK reports, relevant academic studies, and soil and water quality standards issued by the Ministry of Environment and Forestry (KLHK). This triangulation of methods ensured the reliability and comprehensiveness of the data obtained.

2.4 Data Analysis Techniques

Data analysis in this study was carried out through several systematic stages. First, data reduction was performed to filter, categorize, and simplify the information obtained from observations, interviews, and document reviews, ensuring that only relevant data were retained for further interpretation. Second, the refined data were organized and presented in the form of descriptive narratives, tables, and visual figures to facilitate clearer understanding of key patterns and relationships. Finally, conclusions were drawn by synthesizing the analytical findings to formulate the main results of the study. To strengthen the analysis's validity, source triangulation was used by comparing information across respondents and supporting documents, enabling cross-verification and reducing potential bias.

2.5 Criteria and Indicators for Analysis

Soil pollution criteria were based on nitrogen and phosphate content, the presence of pathogenic microorganisms, and physical soil characteristics. The success of bioremediation was measured by reduced toxicity, improved soil quality, and increased microbial activity—particularly from organisms such as Pseudomonas aeruginosa and *Bacillus subtilis.*

3 Results and Discussion

3.1 General Conditions of Muara Fajar II Landfill

The Muara Fajar II Final Disposal Site (TPA) is the main location for domestic waste disposal in Pekanbaru City. This site replaced the previous landfill (Muara Fajar I) due to land capacity limitations. Based on field observations and secondary data from the Pekanbaru Environmental and Sanitation Agency (DLHK), this landfill operates using an open dumping system, where waste is disposed of openly without adequate further processing. The data were cross-checked and verified as part of the triangulation process.

The waste dumped at the site is a mixture of household waste, market refuse, plastic waste, and organic leftovers, without prior sorting. It is estimated that approximately ±750 tons of waste are disposed of at this location daily, with an annual increase of about ±10%. However, no Material Recovery Facility (MRF) is available for sorting and recycling, resulting in all waste being directly accumulated on the soil surface.

Muara Fajar II landfill is located near residential areas only ±600 meters from the nearest homes and directly borders agricultural land. This geographical condition creates a high potential for cross-media pollution of soil, water, and air, affecting the health and productivity of the surrounding community.

One resident interviewed, Mr. S (52 years old), stated: *"When the wind comes from the direction of the landfill, the smell is very pungent, sometimes* *it causes difficulty breathing. Especially during the rainy season, water from the landfill sometimes enters the rice fields and wells."*

3.2 Soil Pollution

The soil layers around the landfill have undergone significant physical changes, with the soil turning dark brown to black, sticky, and emitting a strong foul odor. These conditions indicate the accumulation of degraded organic matter under anaerobic conditions. Laboratory test results from DLHK Pekanbaru (2024) are presented in **Table 1**, which summarizes the soil pH, total nitrogen, phosphate content, and physical indicators.

Table 1. Soil Quality Parameters at Muara Fajar II Landfill

Parameter	DLHK Test Results (2024)	KLHK Soil Quality Standard	Status
Soil pH	5.2	6.0–8.5	Acidic
Total Nitrogen	280 mg/kg	≤ 75 mg/kg	Exceeds threshold
Phosphate (P_2O_5)	190 mg/kg	≤ 50 mg/kg	Exceeds threshold
Soil color/texture	Black and slimy	-	Decomposition indicator
Soil odor	Strong foul smell	-	Anaerobic decomposition

Source: Laboratory tests (DLHK Pekanbaru, 2024)

The acidic nature of the soil can inhibit the activity of natural decomposer microorganisms and promote the growth of pathogenic microbes. The accumulation of nitrogen and phosphate not only reduces soil fertility but also increases the risk of eutrophication when these nutrients are carried by rainwater into nearby water bodies.

According to Mrs. R, the landfill manager: *"We don't have equipment or budget for soil testing, so we rely only on visual observation."*

The measured soil pH of 5.2 is considered acidic and falls below the KLHK (2024) standard range of 6.0 to 8.5. Acidic soil conditions can suppress the activity of natural decomposer microorganisms, which play a vital role in the biodegradation of organic waste. A pH that is too low disrupts the balance of the soil microbial ecosystem and tends to promote the dominance of pathogenic microbes [12]. Furthermore, the total nitrogen content of 280 mg/kg and phosphate (P_2O_5) content of 190 mg/kg greatly exceed the permissible thresholds set by KLHK (75 mg/kg and 50 mg/kg, respectively). This excessive accumulation of nutrients not only disrupts the soil's chemical balance and reduces its fertility but also poses a risk of surface and groundwater contamination via leachate, potentially leading to eutrophication in nearby aquatic systems.

Visually, the soil at the landfill appears black, slimy, and emits a pungent odor. This condition is characteristic of anaerobic decomposition, in which a lack of oxygen allows anaerobic microorganisms to break down organic matter, releasing toxic gases such as ammonia and hydrogen sulfide [13]. This is reinforced by Mrs. R's statement that no laboratory tests were conducted due to limited resources and funding, so monitoring is based solely on visual assessment.

Although this study did not perform direct microbiological testing, previous research has shown the presence of pathogenic microorganisms such as *Escherichia coli*, *Clostridium spp.*, and *Salmonella spp.* in active landfill dumping zones. These microorganisms pose serious health risks, particularly if they come into direct contact with human skin or contaminate groundwater sources [14].

These findings indicate that Muara Fajar II landfill is not only a source of chemical pollution but also of microbiological contamination, both of which can jeopardize public health if not addressed holistically. Remediation strategies such as bioaugmentation or biostimulation should be considered to improve soil quality and sustainably reduce the presence of pathogenic microorganisms.

3.3 Leachate Water Pollution

Leachate is a liquid formed when rainwater percolates through waste piles. At the Muara Fajar II landfill, leachate flows freely without sedimentation ponds or a wastewater treatment plant (WWTP), and it directly enters open drainage systems used by local residents.

The leachate is highly concentrated, dark greenish-black in color, and emits a strong odor of ammonia and hydrogen sulfide. This condition worsens during the rainy season, when water volume increases, leading to leachate overflow beyond the landfill boundaries. The leachate quality parameters measured by DLHK Pekanbaru (2024) are summarized in **Table 2**, which includes BOD, COD, and physical characteristics.

Table 2. Leachate Water Quality Parameters

Parameter	DLHK Test Result (2024)	KLHK Standard (PP 22/2021)	Notes
BOD	290 mg/L	< 50 mg/L	Exceeds standard by 6×
COD	760 mg/L	< 100 mg/L	Exceeds standard by 7×
Color and Odor	Greenish-black, pungent	–	Indicates heavy organic load

Interview with Local Farmer (Mr. A): *"For the past three years I haven't used well water to irrigate my crops, fearing it's been contaminated by the landfill. The plant leaves yellow quickly, and the soil seems dead."*

Leachate is one of the most hazardous by-products of landfill activity, especially when not managed through proper treatment systems. Its composition is highly complex and typically contains large loads of both organic and inorganic pollutants, including toxic substances such as ammonia, heavy metals, and phenolic compounds [15]. The leachate quality test results from Muara Fajar II show a Biochemical Oxygen Demand (BOD) of 290 mg/L and a Chemical Oxygen Demand (COD) of 760 mg/L—each exceeding national environmental standards by six to seven times. High BOD and COD levels indicate an accumulation of organic waste, which can reduce dissolved oxygen in receiving water bodies and be fatal to aquatic life [16].

The phenomenon of leachate flowing directly into open water channels without sedimentation or treatment reflects a structurally weak waste-management system at the landfill. According to a study by Heryadi et al. [17], the absence of a leachate holding pond or wastewater treatment installation accelerates the diffusion of contaminants into surrounding environments, including residents' wells and agricultural land. The real-world impact of this is evident in complaints from local residents, such as the aforementioned farmer, who has observed crop damage and declining soil quality. These observations are consistent with findings by Dimiati and Hadi [18], who note that leachate pollution can reduce the soil's capacity to support plant growth by altering its physicochemical properties and disrupting soil microbial activity, which is essential for fertility. Similar governance-related challenges—particularly institutional inaction, inadequate infrastructure, and delayed response to community concerns—have also been documented in other urban environmental contexts in Southeast Asia, highlighting how weak institutional capacity exacerbates pollution risks and community vulnerability [19].

Given the leachate's greenish-black color and pungent odor—caused by toxic gases such as ammonia and hydrogen sulfide—it is clear that the leachate at Muara Fajar II has undergone intensive anaerobic decomposition without any follow-up purification process.

This underscores the urgent need for a leachate management system based on integrated treatment technology, such as a combination of anaerobic-aerobic ponds or biofilter reactors, to prevent further environmental degradation and safeguard public health and the sustainability of agricultural land surrounding the landfill.

3.4 Social and Health Impacts

The impact of landfill pollution on surrounding communities is clearly evident. Based on interviews with eight local residents living near the Muara Fajar II landfill, most reported experiencing various health complaints, including shortness of breath, skin rashes or irritation, eye discomfort, and, in some cases, nausea and loss of appetite. These health problems are observed to worsen during the rainy season or when strong winds carry foul odors from the landfill area into residential zones.

Health workers from the local public health center (Puskesmas) also confirmed an increase in cases of skin diseases and Acute Respiratory Infections (ARI) within a one-kilometer radius of the landfill. The data recorded by health staff indicated that five residents frequently suffered from shortness of breath, six experienced skin irritation, four complained of eye stinging and redness, and three reported nausea and reduced appetite. Such recurring symptoms, particularly during periods of heavy rainfall, illustrate the direct link between landfill pollution and community health.

In addition to physical health impacts, residents also expressed concerns about the odor, smoke, and water contamination affecting their daily activities and agricultural productivity. Reports from the Puskesmas reinforced these findings, documenting a notable increase in cases of ARI and irritant contact dermatitis during the first quarter of 2025. Collectively, these observations underscore the urgent need for improved landfill management and pollution control measures to safeguard the health and well-being of nearby communities.

3.5 Potential of Bioremediation Strategies

Bioremediation is one of the environmental management strategies that utilizes the biological capabilities of microorganisms to degrade, neutralize, or eliminate pollutants from soil and water. In the context of pollution occurring at the Muara Fajar II landfill, this strategy offers an environmentally friendly approach, relatively low cost, and the ability to be applied locally and in stages.

Based on a literature review and analysis of field conditions, microorganisms such as *Pseudomonas aeruginosa*, *Bacillus subtilis*, *Trichoderma harzianum*, and *Aspergillus niger* have demonstrated high potential in degrading complex organic compounds, heavy metals, and nutrient pollutants such as nitrogen and phosphate. The microorganisms assessed for their suitability to the Muara Fajar II conditions are summarized in **Table 3**.

Two principal approaches to bioremediation—bioaugmentation and biostimulation—are particularly relevant to the landfill's conditions. Bioaugmentation involves the addition of specific microbial strains that have proven effective in pollutant degradation. These microorganisms are typically cultured in laboratories and subsequently introduced into contaminated soils or leachate areas. For the Muara Fajar II site, the application of *Pseudomonas aeruginosa* is considered promising for decomposing organic waste residues. In contrast, biostimulation focuses on enhancing the activity of indigenous microorganisms by supplying nutrients or organic matter that promote microbial growth. This method is relatively low-cost and well-suited to environments that still sustain viable native microbial populations.

Research by Ashkanani et al. demonstrated that a combination of bioaugmentation and biostimulation was able to reduce heavy metals such as Pb and Cd by up to 40% within 60 days [20]. This suggests that the dual strategy is not only effective but also efficient in the medium term.

An interview with Mr. D, a technical staff member of the Environmental and Sanitation Agency (DLHK) of Pekanbaru City, yielded the following response:

"We've heard of bioremediation technology before, but it has never been directly implemented here. If any university or institution could assist in a pilot trial, we would be very open to it."

This statement indicates that although there has been no direct field implementation, there is institutional willingness to collaborate in applying the technology.

Table 3. Evaluation of Microorganisms for Bioremediation Strategy at Muara Fajar II Landfill

Microorganism	Bioremediation Potential	Relevance to Muara Fajar II Landfill Conditions	Ref.
Pseudomonas aeruginosa	Degrades complex organic compounds and leachate waste	High: suitable for leachate waste	Reem et al. [21]
Bacillus subtilis	Reduces heavy metals, ammonia, and nitrogen	Medium: effective for contaminated soils	Rocco et al. [22]
Trichoderma harzianum	Neutralizes heavy metals and improves soil structure	Medium: suitable for surrounding vegetation	Fitria et al. [23]
Aspergillus niger	Biodegrades toxic compounds in moist environments	High: suitable for active leachate areas	Giri et al. [24]

3.6 Feasibility Evaluation of Bioremediation Strategy Implementation

The feasibility of implementing bioremediation at the Muara Fajar II landfill depends on several critical factors, including technical, economic, and human resource aspects. From a technical standpoint, the landfill currently lacks laboratory facilities for microbial culturing and toxicity testing, limiting the ability to monitor and optimize bioremediation processes. However, adopting a community-based approach using indigenous microbial populations through biostimulation remains technically feasible and could serve as an initial step toward larger-scale implementation.

From an economic perspective, the limited operational budget available to landfill management poses a constraint. Nonetheless, compared with conventional physical or chemical remediation methods, bioremediation is considerably more cost-effective and sustainable in the long term. In terms of human resources, the lack of technical knowledge among field personnel remains a major challenge. This gap highlights the importance of capacity building through training and technical assistance, potentially in collaboration with academic institutions such as the University of Riau or the Pekanbaru Environmental Research Center.

Considering these factors, biostimulation emerges as the most realistic strategy to be implemented in the initial phase at Muara Fajar II Landfill. This strategy does not require external inputs of new microorganisms but instead adjusts soil or leachate conditions to support the optimal growth of existing local microbes. The subsequent phase may involve limited bioaugmentation trials at active leachate hotspots.

 https://doi.org/10.1051/e3sconf/202567802001

3.7 Integration of Findings and Strategic Recommendations

Based on field observations, interviews, and secondary data analysis, it can be concluded that pollution at the Muara Fajar II landfill is chronic and widespread, particularly in soil and water, due to the accumulation of untreated solid waste and leachate.

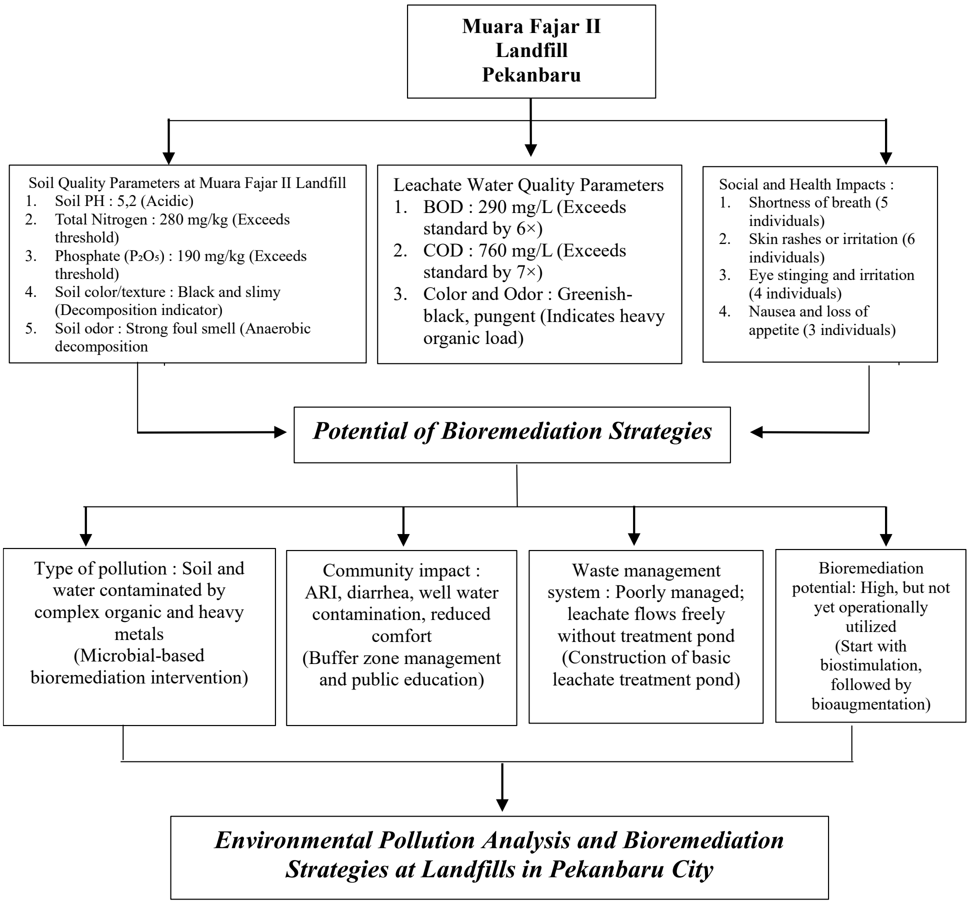

Fig 1. Flowchart Connection between parameters research

Bioremediation strategies, which have not yet been systematically implemented at the site, offer a solution that is not only cost-effective but also sustainable. Implementing local microbial biostimulation at critical contamination points is the most viable short-term step, while further research collaboration can support the gradual adoption of bioaugmentation.

In the short to medium term, several strategic actions can be implemented to improve the management of contaminated landfill areas. Priority should be given to mapping high-risk zones by using field observation data and visual documentation to identify locations with the highest pollution levels. Furthermore, biostimulation trials—such as the application of organic fertilizers and aeration—should be conducted in areas with active leachate accumulation to enhance the natural degradation of contaminants. Strengthening institutional capacity is also essential; therefore, collaborative partnerships with environmental research institutions or universities are recommended to support technical training and enable more advanced laboratory analyses.

To synthesize the multidimensional findings of this study, key pollution characteristics, community impacts, system weaknesses, and bioremediation opportunities were consolidated. **Table 4** provides a structured summary of these findings together with the recommended strategic interventions.

Table 4. Summary of Findings and Strategic Recommendations

Aspect	Key Findings	Strategic Recommendations
Type of pollution	Soil and water contaminated by complex organic and heavy metals	Microbial-based bioremediation intervention
Community impact	ARI, diarrhea, well water contamination, reduced comfort	Buffer zone management and public education
Waste management system	Poorly managed; leachate flows freely without treatment pond	Construction of basic leachate treatment pond
Bioremediation potential	High, but not yet operationally utilized	Start with biostimulation, followed by bioaugmentation

To ensure remediation efforts can be executed consistently and effectively in the field, practical bioremediation Standard Operating Procedures (SOPs) must be developed, particularly those that can be applied by landfill staff with minimal specialized training. These measures collectively form a foundational roadmap for improving environmental quality and operational management at the landfill. The connection between the parameters of environmental pollution analysis and bioremediation strategies at landfills in Pekanbaru city was displayed in a flowchart, as shown in **Fig. 1**.

4 Conclusion

The assessment of the Muara Fajar II Landfill in Pekanbaru City shows that open dumping practices have led to significant soil and water pollution, with laboratory data indicating acidic soil conditions and nitrogen–phosphate levels far exceeding national standards. Unmanaged leachate, characterized by extremely high BOD and COD values, flows directly into residential drainage systems, affecting public health, agricultural productivity, and overall community well-being. Reported impacts include respiratory problems, skin irritation, declining well water quality, and crop damage. Bioremediation presents a practical and environmentally friendly alternative for mitigating contamination at the site. Initial biostimulation of indigenous microbes, followed by targeted bioaugmentation, offers a feasible strategy for improving soil and water conditions. This study acknowledges certain limitations, including the reliance on secondary laboratory data and the absence of field-based bioremediation trials. Future research should incorporate pilot applications and longitudinal monitoring to validate and strengthen the proposed remediation framework.

Research Ethics

Research ethics were maintained by obtaining informed consent from participants, protecting respondent confidentiality, and avoiding any negative impact on the environment or participants.

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