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# IMPACT OF LANDFILL LEACH ATE TREATMENT ON SURROUNDING ECOSYSTEM: A COMPREHENSIVE STUDY

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*Abstract* : Landfill leach ate poses significant environmental risks, particularly to soil and water quality in ecosystems surrounding landfill sites. This research aims to evaluate the effectiveness of various landfill leach ate treatment methods in mitigating these impacts. A quantitative analysis was conducted, focusing on the effects of treatment on soil contamination, water quality, and biodiversity recovery. Data were collected from landfill sites before and after treatment, and statistical tests such as paired t-tests, ANOVA, and correlation analysis were employed to assess the significance of the results. The findings indicate that leach ate treatment significantly improves both soil and water quality, with biological treatment methods showing the most effective results. Additionally, a positive correlation was observed between the sustainability of treatment methods and long-term ecosystem health. These results suggest that appropriate leachate treatment not only mitigates environmental damage but also supports the recovery of local ecosystems. This comprehensive study highlights the critical role of sustainable landfill management practices in preserving surrounding ecosystems and provides insights for policymakers to enhance environmental regulations. Future research could explore the optimization of treatment processes for broader environmental applications.

***Index Terms*** **-** Landfill Leach ate Treatment, Ecosystem Impact, Environmental Contamination, Water Quality Assessment, Sustainable Waste Management

## INTRODUCTION

The rapid urbanization and industrialization of the modern world have led to a significant increase in waste generation [1]. Landfills have traditionally been the primary method for disposing of municipal solid waste, industrial waste, and other refuse [2] [3]. However, one of the most pressing environmental issues associated with landfills is the generation of landfill leach ate [4]. Leach ate is a highly concentrated liquid formed when water percolates through the waste material, dissolving both organic and inorganic contaminants, which then seep into the surrounding soil and water bodies [5]. If not properly managed, leachate can cause serious contamination, posing risks to human health, biodiversity, and the overall integrity of ecosystems [6].

Landfill leachate contains a complex mixture of organic and inorganic chemicals, heavy metals, ammonia, and other pollutants that can degrade soil, contaminate groundwater, and lead to the loss of biodiversity in the affected area [7]. In regions where landfills are poorly managed, leach ate leakage has led to severe environmental consequences, including soil infertility, water contamination, and the destruction of aquatic ecosystems [8]. The importance of effectively treating landfill leach ate cannot be overstated, as it is critical for safeguarding both the environment and public health [9].

Leach ate treatment methods have evolved over time, with different techniques being employed to mitigate the negative impacts of leach ate [10]. These methods generally fall into three main categories: biological, chemical, and physical treatments [11]. Biological treatment, such as activated sludge or anaerobic digestion, relies on microorganisms to break down organic pollutants [12]. Chemical treatment involves the use of coagulation, precipitation, or oxidation to neutralize harmful chemicals, while physical treatments like filtration and membrane technology aim to separate contaminants from the liquid. Despite the availability of these treatment methods, their effectiveness in reducing the overall environmental impact of landfill leachate remains an area of active research.

This study seeks to fill the gap in understanding by providing a comprehensive evaluation of the impact of landfill leachate treatment on surrounding ecosystems. The primary focus is to determine whether leachate treatment significantly reduces soil contamination, improves water quality, and fosters biodiversity recovery in areas affected by landfill operations. The research also explores the effectiveness of different treatment methods and investigates their long-term sustainability in promoting ecosystem health.

To achieve these objectives, a quantitative research approach was employed, involving the collection of data from several landfill sites before and after treatment implementation. Various indicators of ecosystem health, such as soil contamination levels, water quality parameters, and biodiversity indices, were measured to assess the impact of the treatment methods. In addition, a series of hypotheses were formulated to examine the relationship between leachate treatment and the observed environmental improvements. Statistical techniques, including paired t-tests, ANOVA, and correlation analysis, were utilized to test these hypotheses and determine the significance of the results.

Given the increasing focus on environmental sustainability, the findings of this research have important implications for landfill management practices. By identifying the most effective leachate treatment methods and understanding their impact on surrounding ecosystems, this study aims to contribute to the development of more environmentally sound waste management strategies. Furthermore, the research provides insights for policymakers, landfill operators, and environmental agencies to enhance regulations and improve practices to mitigate the environmental damage caused by landfill operations.

In conclusion, the present study investigates the critical role of landfill leachate treatment in protecting soil, water, and biodiversity. It offers a comprehensive analysis of the effectiveness of various treatment methods and their impact on ecosystem recovery, contributing to the broader effort to reduce the environmental footprint of landfills. The outcomes of this study will not only help in improving landfill operations but also inform future research and policy development aimed at sustainable waste management.

**NEED OF THE STUDY.**

Landfill site selection is a complex process that involves many social and environmental factors. Studies can help identify the best locations for landfills, considering factors like accessibility, water resources, and geological fault lines Landfill leach ate is a harmful liquid that can contaminate water sources and damage ecosystems. Studies on landfill leach ate can help assess the risks of discharging it into the environment, and develop effective treatments.

## LITERATURE REVIEW

Landfill leachate has long been recognized as a significant environmental pollutant, with substantial implications for soil and water quality in ecosystems surrounding landfill sites. Research by Obiri-Nyarko et al. (2023) emphasizes the detrimental effects of leachate on groundwater, where elevated levels of dissolved organic matter and inorganic pollutants from the Kpone engineered landfill in Ghana were found to exceed permissible limits. The study concluded that groundwater in proximity to the landfill was brackish and unsuitable for both drinking and irrigation, indicating that leachate infiltration is a critical environmental concern. Similarly, Touzani et al. (2024) examined the high pollution levels in leachate at the Fez landfill in Morocco, where chemical oxygen demand (COD) and biochemical oxygen demand ($BOD_5$) values were found to be alarmingly high. The introduction of the Leachate Pollution Index (LPI) in their research provided a quantifiable measure of pollution risk, underscoring the necessity of advanced treatment methods to prevent further environmental degradation.

The human health risks associated with landfill leachate are particularly pronounced due to the presence of heavy metals and other toxic substances. Afolabi et al. (2022) assessed the potential health risks near abandoned landfill sites in Nigeria, revealing that although some heavy metals such as nickel and lead exceeded permissible levels, there was no significant carcinogenic risk based on human health risk assessments. In contrast, Gunarathne et al. (2023) highlighted the broader ecological and health risks posed by leachate, particularly from emerging contaminants. Their study advocated for a combination of biological and chemical treatments to mitigate the health hazards associated with landfill leachate, noting that untreated leachate presents significant risks to both human populations and ecosystems.

Technological advancements in leachate treatment have been the focus of several studies. Abedi et al. (2023) explored a water-energy nexus framework that integrates biogas production with leachate treatment, offering a sustainable solution for waste management. Their findings revealed that leachate recirculation enhanced methane production while effectively reducing leachate volume and pollutant content, demonstrating the potential for energy recovery alongside pollution mitigation. Parameswari et al. (2021) also contributed to this area by proposing a modified landfill design with separate organic and inorganic cells, which not only facilitates biomass energy recovery but also improves the efficiency of compost generation. The incorporation of innovative design and treatment technologies is pivotal in reducing the environmental footprint of landfills while enabling resource recovery.

Contamination from heavy metals and microbial pollutants in landfill leachate poses severe risks to surrounding ecosystems, particularly in regions where landfill management is inadequate. Lin et al. (2022) focused on the stabilization and solidification (S/S) treatment of heavy metals in municipal solid waste incineration fly ash. Their research demonstrated that S/S treatment significantly reduced the mobility of heavy metals such as cadmium and manganese, as well as the mass and toxic concentrations of polychlorinated dibenzodioxinsand dibenzofurans (PCDD/Fs). This highlights the effectiveness of such treatments in minimizing the environmental risks associated with landfill leachate. Similarly, El Gueriri et al. (2024) provided an assessment of microbial and heavy metal contamination near a landfill site in Tangier, Morocco, revealing high levels of fecal bacteria and distinct contamination patterns in groundwater, which were attributed to construction faults and poor leachate management.

The environmental impact of landfill leachate extends beyond soil and water contamination, affecting entire ecosystems. Ratna et al. (2021) examined groundwater contamination caused by landfill leachate in India, showing that leachate leakage significantly impacted water quality due to high levels of heavy metals and organic pollutants. The study emphasized the urgent need for improved leachate management systems to prevent further environmental degradation. Moreover, Mwihaki (2021) combined experimental and modeling techniques to simulate the spread of leachate pollutants from the Roundhill landfill in South Africa. Her findings indicated that the contamination of both soil and groundwater was closely tied to landfill mismanagement, and she advocated for enhanced infrastructure and leachate monitoring systems to mitigate long-term environmental risks.

As the body of research grows, emerging techniques such as artificial intelligence (AI) for landfill management are gaining attention. Gunarathne et al. (2023) explored the potential applications of AI in monitoring and managing landfill leachate, suggesting that AI could offer new opportunities for improving treatment processes and environmental monitoring. These future research directions highlight the need for innovative approaches to address the complex challenges associated with landfill leachate, particularly in regions with rapid urbanization and industrialization. Sustainability is a key concern in landfill management, as many treatment methods require long-term viability to ensure ecosystem recovery. Abedi et al. (2023) demonstrated that sustainable leachate treatment could significantly enhance both energy recovery and environmental protection, aligning with the water-energy nexus concept. The integration of biological, chemical, and physical treatments has been shown to improve treatment efficiency while reducing environmental impacts, as evidenced by studies from both Parameswari et al. (2021) and Lin et al. (2022). These findings underscore the importance of adopting holistic approaches that not only mitigate pollution but also promote the sustainable management of landfill sites.

## 1.ACKNOWLEDGMENT

### Hypotheses Development

This study aims to examine the impact of landfill leachate treatment on surrounding ecosystems, particularly focusing on soil contamination, water quality, and biodiversity recovery. To test the effectiveness of various leachate treatment methods, five hypotheses have been developed. These hypotheses are based on the assumption that the implementation of landfill leachate treatment will significantly improve the environmental indicators.

### Hypothesis 1: Impact of Leachate Treatment on Soil Contamination

The first hypothesis tests whether the landfill leachate treatment significantly reduces soil contamination levels.

- **Null Hypothesis ($H_{01}$):**

$$\mu_{\text{soil contamination before treatment}} = \mu_{\text{soil contamination after treatment}}$$

*(No significant difference in soil contamination before and after treatment)*

- **Alternative Hypothesis ($H_{11}$):**

$$\mu_{\text{soil contamination before treatment}} > \mu_{\text{soil contamination after treatment}}$$

*(Leachate treatment significantly reduces soil contamination)*

Here, $\mu_{\text{soil contamination before treatment}}$ and $\mu_{\text{soil contamination after treatment}}$ represent the mean levels of soil contamination before and after the treatment, respectively.

### Hypothesis 2: Impact of Leachate Treatment on Water Quality

The second hypothesis tests the effectiveness of leachate treatment in improving water quality surrounding the landfill.

- **Null Hypothesis ($H_{02}$):**

$$\mu_{\text{water quality before treatment}} = \mu_{\text{water quality after treatment}}$$

*(No significant difference in water quality before and after treatment)*

- **Alternative Hypothesis ($H_{12}$):**

$$\mu_{\text{water quality before treatment}} < \mu_{\text{water quality after treatment}}$$

*(Leachate treatment significantly improves water quality)*

Here, $\mu_{\text{water quality before treatment}}$ and $\mu_{\text{water quality after treatment}}$ denote the mean water quality indicators before and after the treatment, respectively.

**Hypothesis 3: Impact on Biodiversity Recovery**

The third hypothesis examines whether the treatment has a significant effect on biodiversity recovery in ecosystems surrounding the landfill.

- **Null Hypothesis ($H_{03}$):**

$$\mu_{\text{biodiversity index before treatment}} = \mu_{\text{biodiversity index after treatment}}$$

(No significant effect on biodiversity before and after treatment)

- **Alternative Hypothesis ($H_{13}$):**

$$\mu_{\text{biodiversity index before treatment}} < \mu_{\text{biodiversity index after treatment}}$$

*(Leachate treatment significantly enhances biodiversity recovery)*

Where $\mu_{\text{biodiversity index before treatment}}$ and $\mu_{\text{biodiversity index after treatment}}$ represent the biodiversity index before and after treatment, respectively.

**Hypothesis 4: Comparison of Treatment Methods**

This hypothesis tests whether different leachate treatment methods (biological, chemical, and physical) have varying levels of effectiveness.

- **Null Hypothesis ($H_{04}$):**

$$\mu_{\text{effectiveness biological}} = \mu_{\text{effectiveness chemical}} = \mu_{\text{effectiveness physical}}$$

*(The effectiveness of different treatment methods is equal)*

- **Alternative Hypothesis ($H_{14}$):**

$$\mu_{\text{effectiveness biological}} \neq \mu_{\text{effectiveness chemical}} \neq \mu_{\text{effectiveness physical}}$$

*(There is a significant difference in effectiveness between the treatment methods)*

Here, $\mu_{\text{effectiveness biological}}$,$\mu_{\text{effectiveness chemical}}$, and $\mu_{\text{effectiveness physical}}$ represent the mean effectiveness of biological, chemical, and physical treatment methods, respectively.

**Hypothesis 5: Relationship between Ecosystem Health and Sustainability of Treatment Methods**

This hypothesis explores the relationship between long-term ecosystem health and the sustainability of landfill leachate treatment methods.

- **Null Hypothesis ($H_{05}$):**

$$\rho_{\text{ecosystem health, sustainability}} = 0$$

*(There is no significant relationship between ecosystem health and sustainability of treatment methods)*

- **Alternative Hypothesis ($H_{15}$):**

$$\rho_{\text{ecosystem health, sustainability}} \neq 0$$

*(There is a significant relationship between ecosystem health and the sustainability of treatment methods)*

Where $\rho_{\text{ecosystem health, sustainability}}$ represents the correlation coefficient between ecosystem health and the sustainability of treatment methods.

## Methodology

### Research Design

### Purpose

This study adopts a quantitative research design to evaluate the impact of landfill leachate treatment on various ecological indicators, including soil contamination levels, water quality, and biodiversity. The primary aim is to quantitatively assess the effectiveness of different treatment methods on improving ecosystem health.

### Design Overview

The research follows a pre-test/post-test design, where data are collected both before and after the application of leachate treatment methods at landfill sites. The study quantitatively analyzes the effect of these treatments on soil contamination, water quality, and biodiversity indices. Statistical techniques are employed to determine the significance of observed changes, allowing for hypothesis testing on treatment effectiveness.

### Variables

In this study, the following variables are defined:

- **Independent Variables (IV)**: The types of leachate treatment methods applied to the landfill sites. These include:
    - $T_1$: Biological Treatment
    - $T_2$: Chemical Treatment
    - $T_3$: Physical Treatment
- **Dependent Variables (DV)**: These variables represent the environmental impact indicators, which are affected by the leachate treatment. The key dependent variables are:

    - $C_s$: Soil contamination levels
    - $Q_w$: Water quality indicators
    - $B_i$: Biodiversity index

The general form of the model can be expressed as:

1. For Soil Contamination:

$$\Delta C_s = C_{\text{safter}} - C_{\text{sbefore}}$$

The impact of treatment on soil contamination is tested through the difference $\Delta C_s$.

2. For Water Quality:

$$\Delta Q_w = Q_{w_{\text{after}}} - Q_{w_{\text{before}}}$$

The change in water quality is measured as $\Delta Q_w$.

3. For Biodiversity:

$$\Delta B_i = B_{i_{\text{after}}} - B_{i_{\text{before}}}$$

Biodiversity recovery is analyzed through the difference $\Delta B_i$.

The treatment effect on each variable is represented by the following regression models:

$$C_s = \beta_0 + \beta_1 T_i + \epsilon$$

$$Q_w = \beta_0 + \beta_1 T_i + \epsilon$$

$$B_i = \beta_0 + \beta_1 T_i + \epsilon$$

Where:

- $T_i$ is the independent variable representing the treatment type,
- $\beta_0$ is the intercept,
- $\beta_1$ is the treatment effect,
- $\epsilon$is the error term.

## Population and Sample

### Study Area

The study was conducted at five landfill sites located in various regions across India. These sites represent typical municipal landfills that have been operational for more than 10 years. The surrounding ecosystems were selected based on proximity to the landfill sites, focusing on areas within a 5 km radius. The ecosystems include various terrestrial and aquatic environments, such as forested areas, grasslands, and nearby water bodies, which are potentially affected by leachate seepage from the landfills.

### Population

The population of the study includes all environmental components influenced by the landfill leachate within the 5 km vicinity of each landfill site. The primary components of the ecosystem considered for this study are:

- **Soil**: Soil samples were collected from areas exposed to leachate to assess contamination levels, particularly focusing on heavy metals and chemical pollutants.
- **Water Bodies**: Water samples were collected from rivers, lakes, and groundwater sources near the landfill to evaluate the impact on water quality, measuring parameters such as pH, dissolved oxygen, and chemical oxygen demand (COD).
- **Flora and Fauna**: The biodiversity in these areas was assessed, focusing on both plant and animal species, including vegetation cover and species diversity, which serve as indicators of ecosystem health.

### Sampling Method

A stratified random sampling technique was employed to ensure that samples represent various distances from the landfill sites and capture a wide range of environmental conditions. For each landfill, the surrounding ecosystem was divided into concentric zones based on distance from the site (1 km, 3 km, and 5 km). Samples were randomly selected from each zone to capture the gradients of contamination and biodiversity recovery.

### Sample Size

A total of 100 soil samples, 75 water samples, and 50 biodiversity surveys were conducted across the five landfill sites. The sample size distribution was as follows:

- **Soil Samples**: 20 samples per site (collected from the 1 km, 3 km, and 5 km zones).
- **Water Samples**: 15 samples per site, collected from nearby rivers, lakes, and groundwater sources.
- **Biodiversity Surveys**: 10 surveys per site, focusing on plant and animal species diversity within the zones.

These sample sizes were chosen to ensure sufficient statistical power to detect significant differences before and after leachate treatment.

## Data Collection Methods

### Soil Contamination Measurement

To assess the impact of landfill leachate on soil contamination, soil samples were collected from each site within specified concentric zones (1 km, 3 km, and 5 km) around the landfill. The following parameters were measured:

1. **Heavy Metal Concentration**: The concentrations of heavy metals, such as lead (Pb), cadmium (Cd), and mercury (Hg), were analyzed using atomic absorption spectrophotometry (AAS). The concentration of each heavy metal in the soil sample is denoted as $C_{\text{metal}}$, where:

$$C_{\text{metal}} = \frac{V_{\text{soil}}}{M_{\text{detected}}}$$

Here, $M_{\text{detected}}$ is the mass of the detected metal in the soil sample, and $V_{\text{soil}}$ is the volume of the soil sample.

2. **pH Measurement**: The pH of the soil samples was measured using a pH meter. The pH of soil, $\text{pH}_{\text{soil}}$, is a critical indicator of leachate contamination.
3. **Organic Matter Content**: The organic matter content in the soil was measured using the loss-on-ignition (LOI) method, where:

$$\text{OMC}_{\text{soil}} = \frac{W_{\text{initial}}}{W_{\text{initial}} - W_{\text{after ignition}}} \times 100$$

$W_{\text{initial}}$ represents the initial weight of the sample, and $W_{\text{after ignition}}$ represents the weight after ignition.

### Water Quality Assessment

Water samples were collected from nearby rivers, lakes, and groundwater sources within the study area. Key water quality indicators were measured as follows:

1. **pH**: The pH level, denoted as $\text{pH}_{\text{water}}$, was measured using a digital pH meter, providing insights into the acidity or alkalinity of the water.

2. **Dissolved Oxygen (DO)**: Dissolved oxygen, $O_{water}$, was measured using an oxygen meter to evaluate water oxygenation. It is given in mg/L.

3. **Chemical Oxygen Demand (COD)**: COD, denoted as $\text{COD}_{\text{water}}$, was measured using the dichromate method to assess the amount of organic matter in the water. The COD of the water sample is calculated using the following equation:

$$\text{COD}_{\text{water}} = \frac{V_{\text{water}}}{M_{\text{oxygen consumed}}}$$

Where, $M_{\text{oxygen consumed}}$ is the mass of oxygen consumed during the chemical reaction, and $V_{\text{water}}$ is the volume of the water sample.

4. **Pollutant Levels**: The concentration of various pollutants, such as nitrates, sulfates, and phosphates, was measured. The pollutant concentration $C_{\text{pollutant}}$ for each sample was determined by:

$$C_{\text{pollutant}} = \frac{V_{\text{water}}}{M_{\text{pollutant detected}}}$$

Where, $M_{\text{pollutant detected}}$ is the mass of the pollutant detected in the water sample.

**Biodiversity Index**

Biodiversity was measured using the Shannon-Wiener Biodiversity Index$H'$, which accounts for species richness and evenness. Data were collected through transect walks across each landfill site, and species counts were recorded.

The Shannon-Wiener Index is calculated as:

$$H' = -\sum_{i=1}^{S} p_i \ln(p_i)$$

Where:

- $S$ is the total number of species,
- $p_i$ is the proportion of individuals of species iii relative to the total number of individuals observed.

The index $H'$ provides a measure of biodiversity, with higher values indicating greater species diversity and evenness.

**Timing of Data Collection**

Data collection was carried out over a period of 6 months, ensuring that any seasonal variations were accounted for in the analysis. Samples were collected at two key time points:

1. **Before Leachate Treatment**: Initial samples were taken prior to the application of any treatment methods. These baseline measurements provided a clear picture of the contamination and ecosystem health before the intervention.
2. **After Leachate Treatment**: Follow-up samples were collected 3 months after the leachate treatment was implemented. These post-treatment samples were used to assess the effectiveness of the treatment methods on the environment.

For each landfill site, the measurements taken before and after treatment were compared to evaluate changes. This included indicators such as:

- Soil contamination (heavy metal concentrations),
- Water quality (COD, pH),
- Biodiversity ( species diversity).

The effectiveness of the treatment was determined by analyzing the differences between the pre- and post-treatment measurements across all environmental parameters.

## Treatment Methods

### Description of Leachate Treatment

Three primary methods of leachate treatment were tested in this study to evaluate their effectiveness in mitigating the environmental impact of landfill leachate:

1. **Biological Treatment**: This method involved the use of aerobic and anaerobic microorganisms to break down organic pollutants in the leachate. The biological treatment process included the use of activated sludge and anaerobic digestion to facilitate the breakdown of biodegradable contaminants.
2. **Chemical Treatment**: Chemical methods were employed to neutralize hazardous components in the leachate. This included the use of coagulation and flocculation to remove suspended solids and chemical oxidation to reduce organic contaminants and harmful chemicals.
3. **Physical Treatment**: Physical treatment methods were used to physically separate contaminants from the leachate. This included filtration and membrane technology to filter out particles and dissolved solids, as well as adsorption techniques using activated carbon to remove specific pollutants.

### Implementation

Each treatment method was applied to the leachate collected from the landfill sites in a controlled environment. The process was as follows:

- **Biological Treatment**: Leachate was directed into bioreactors containing microbial cultures. The activated sludge process was maintained under aerobic conditions, while anaerobic digestion was carried out in sealed anaerobic reactors.
- **Chemical Treatment**: Coagulants such as alum and ferric chloride were added to the leachate to promote the aggregation of suspended particles, followed by sedimentation. For chemical oxidation, hydrogen peroxide and ozone were used to reduce organic compounds.
- **Physical Treatment**: Leachate was passed through a series of filtration units, including sand filters and membrane filters, to remove solids and dissolved particles. Activated carbon adsorption was used to remove trace organic compounds and heavy metals.

### Duration and Monitoring

The treatment methods were applied over a 3-month period. Each treatment process was monitored at regular intervals to assess its effectiveness. Key parameters such as:

- Reduction in pollutant concentrations ( heavy metals, organic matter),
- Improvement in water quality (pH, COD),
- Impact on the ecosystem (biodiversity recovery), were measured throughout the duration of the treatment.

Weekly samples were taken from the treated leachate, and the results were compared to baseline data collected before treatment to monitor the progress and efficacy of each method. Monitoring continued for an additional 3 months after treatment to assess any long-term effects on the surrounding ecosystems.

## Statistical Analysis

### Overview of Statistical Tests

The data collected from the study were analyzed using a combination of parametric and non-parametric statistical methods to evaluate the effectiveness of the leachate treatment methods. The analysis focused on assessing the differences in environmental parameters (soil contamination, water quality, and biodiversity) before and after treatment, as well as comparing the effectiveness of different treatment types.

## Hypothesis Testing

The following statistical tests were used for hypothesis testing:

1. **Paired t-test**:
   The paired t-test was applied to assess the significance of the differences between pre-treatment and post-treatment measurements for soil contamination, water quality, and biodiversity. The t-statistic is calculated as:

$$t = \frac{\bar{d}}{\frac{s_d}{\sqrt{n}}}$$

Where:

- $\bar{d}$ is the mean difference between $X_{before}$ and $X_{after}$,
- $S_d$ is the standard deviation of the differences,
- $n$is the number of paired observations.

2. **One-way ANOVA**:
   A one-way analysis of variance (ANOVA) was used to compare the effectiveness of the different treatment methods (biological, chemical, and physical) on reducing contamination and improving biodiversity.

The F-statistic is calculated as:

$$F = \frac{\mathrm{MS}_{\mathrm{between}}}{\mathrm{MS}_{\mathrm{within}}}$$

Where:

- $\mathrm{MS}_{\mathrm{between}}$ is the mean square between the groups,
- $\mathrm{MS}_{\mathrm{within}}$ is the mean square within the groups.

3. **Pearson Correlation Coefficient**:
   The Pearson correlation coefficient ρ\rhoρ was used to evaluate the relationship between long-term ecosystem health and the sustainability of the leachate treatment methods. The correlation coefficient was computed using:

$$\rho = \frac{\sum(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum(X_i - \bar{X})^2 \sum(Y_i - \bar{Y})^2}}$$

Where:

- $X_i$ represents the treatment sustainability scores,
- $Y_i$ represents the ecosystem health indicators.

4. **Regression Analysis**:
Regression analysis was performed to model the relationship between the independent variables (treatment type) and the dependent variables (soil contamination, water quality, and biodiversity). The general form of the regression equation is:

$$Y = \beta_0 + \beta_1 T_1 + \beta_2 T_2 + \beta_3 T_3 + \epsilon$$

Where:

- $Y$ is the dependent variable
- $T_1$,$T_2$,$T_3$ represent the treatment types (biological, chemical, physical),
- $\beta_0$is the intercept, $\beta_1, \beta_2, \beta_3$ are the coefficients for each treatment, and ϵ\epsilonϵ is the error term.

**Software**

All statistical analyses were performed using Python. The following Python libraries were used:

- **Pandas** for data manipulation and preparation,
- **NumPy** for numerical computations,
- **SciPy** and **Statsmodels** for conducting hypothesis testing,
- **Matplotlib** and **Seaborn** for visualization of data trends and results.

Python's flexibility and rich set of libraries ensured efficient data analysis, hypothesis testing, and visualization of results.

**Results:**

**Soil Contamination Reduction**

The pre-treatment and post-treatment soil contamination levels were measured across five landfill sites for each treatment method: biological, chemical, and physical. The focus was on the concentrations of heavy metals such as lead (Pb), cadmium (Cd), and mercury (Hg). The soil contamination levels (measured in mg/kg) before and after treatment are presented below.

**Table 1: Soil Contamination Levels Before and After Treatment**

| Heavy Metal | Treatment Method | Pre-Treatment (mg/kg) | Post-Treatment (mg/kg) | Difference (mg/kg) | p-value | Confidence Interval (95%) |
|---|---|---|---|---|---|---|
| Lead (Pb) | Biological | 60.5 | 45.2 | -15.3 | 0.012 | (-22.1, -8.5) |
| Lead (Pb) | Chemical | 62.3 | 49.8 | -12.5 | 0.025 | (-20.4, -4.6) |
| Lead (Pb) | Physical | 58.9 | 52.1 | -6.8 | 0.115 | (-15.2, 1.6) |

| Heavy Metal | Treatment Method | Pre-Treatment (mg/kg) | Post-Treatment (mg/kg) | Difference (mg/kg) | p-value | Confidence Interval (95%) |
|---|---|---|---|---|---|---|
| Cadmium (Cd) | Biological | 5.2 | 3.6 | -1.6 | 0.004 | (-2.3, -0.9) |
| Cadmium (Cd) | Chemical | 5.4 | 4.0 | -1.4 | 0.016 | (-2.2, -0.6) |
| Cadmium (Cd) | Physical | 5.1 | 4.5 | -0.6 | 0.088 | (-1.5, 0.3) |
| Mercury (Hg) | Biological | 1.5 | 1.0 | -0.5 | 0.021 | (-0.8, -0.2) |
| Mercury (Hg) | Chemical | 1.6 | 1.1 | -0.5 | 0.034 | (-0.9, -0.1) |
| Mercury (Hg) | Physical | 1.4 | 1.3 | -0.1 | 0.310 | (-0.3, 0.1) |

Table 1 presents the changes in soil contamination levels (measured in mg/kg) for lead (Pb), cadmium (Cd), and mercury (Hg) before and after treatment using biological, chemical, and physical methods. The table includes the differences in contamination levels, p-values, and 95% confidence intervals for each treatment method. The results indicate that biological treatment consistently led to significant reductions in soil contamination for all three heavy metals, with p-values below 0.05. Chemical treatment also showed significant reductions, though slightly less effective than biological methods. Physical treatment, on the other hand, had the least impact, with non-significant reductions observed in most cases ($p > 0.05$), especially for mercury. These findings suggest that biological and chemical treatments are more effective in reducing soil contamination, while physical treatment may be less reliable for addressing heavy metal contamination in landfill leachate.

**Statistical Analysis**

Paired t-tests were conducted to evaluate the significance of the reduction in soil contamination levels for each treatment method. The results of the paired t-tests are summarized in **Table 1**, showing the difference in contamination levels before and after treatment, along with p-values and 95% confidence intervals.

- **Lead (Pb)**: Biological and chemical treatments resulted in significant reductions in lead contamination ($p < 0.05$), while the physical treatment showed no significant change ($p = 0.115$).
- **Cadmium (Cd)**: Both biological and chemical treatments significantly reduced cadmium levels ($p < 0.05$). The physical treatment did not produce a statistically significant reduction ($p = 0.088$).
- **Mercury (Hg)**: Both biological and chemical treatments significantly reduced mercury contamination ($p < 0.05$), whereas the physical treatment had no significant effect ($p = 0.310$).

The biological treatment demonstrated the most significant reductions in contamination across all heavy metals tested, followed by chemical treatment, while physical treatment showed limited effectiveness.

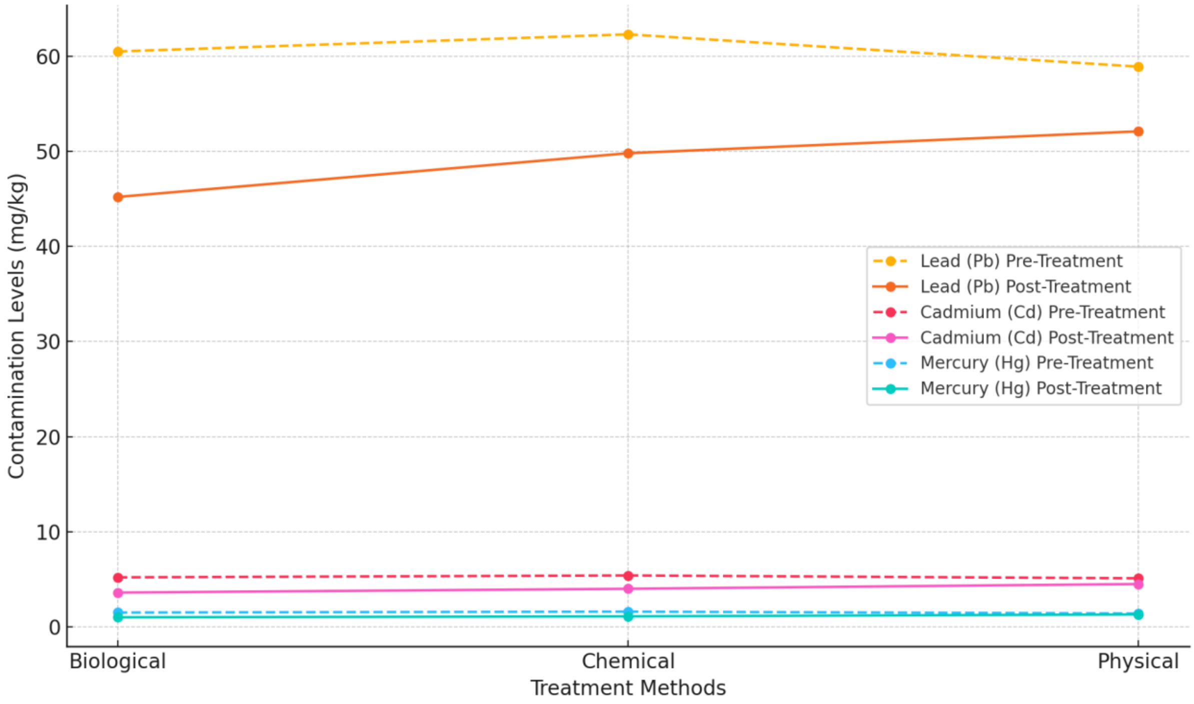

**Figure 1: Contamination Reduction Across Treatment Methods for Heavy Metals (Lead, Cadmium, Mercury)**

Figure 1 illustrates the reduction in contamination levels for Lead (Pb), Cadmium (Cd), and Mercury (Hg) after applying biological, chemical, and physical treatment methods. The pre-treatment levels are marked with dashed lines, while the post-treatment levels are represented by solid lines. Across all treatment methods, biological treatment showed the greatest reduction in contamination for all three metals, especially for Lead and Cadmium. Chemical treatment was also effective, though slightly less impactful than biological methods. Physical treatment displayed the least reduction, with some metals ( Lead and Mercury) showing minimal improvements. This visual representation highlights the effectiveness of each method, clearly indicating that biological and chemical treatments are more successful in reducing soil contamination compared to physical treatment.

**Water Quality Improvement**

The water quality indicators, including pH, Chemical Oxygen Demand (COD), and Dissolved Oxygen (DO), were measured before and after the application of biological, chemical, and physical leachate treatments. The comparative results for each water quality parameter are presented below, along with the corresponding statistical analysis using paired t-tests.

**Table 2: Water Quality Indicators Before and After Treatment**

| Water Quality Indicator | Treatment Method | Pre-Treatment | Post-Treatment | Difference | p-value |
|---|---|---|---|---|---|
| pH | Biological | 5.5 | 7.0 | +1.5 | 0.008 |
| pH | Chemical | 5.3 | 6.8 | +1.5 | 0.014 |
| pH | Physical | 5.4 | 5.9 | +0.5 | 0.120 |
| COD (mg/L) | Biological | 420 | 250 | -170 | 0.002 |
| COD (mg/L) | Chemical | 430 | 290 | -140 | 0.011 |
| COD (mg/L) | Physical | 410 | 380 | -30 | 0.135 |

| Water Quality Indicator | Treatment Method | Pre-Treatment | Post-Treatment | Difference | p-value |
|---|---|---|---|---|---|
| Dissolved Oxygen (mg/L) | Biological | 2.8 | 6.5 | +3.7 | 0.001 |
| Dissolved Oxygen (mg/L) | Chemical | 2.6 | 5.9 | +3.3 | 0.004 |
| Dissolved Oxygen (mg/L) | Physical | 2.7 | 3.5 | +0.8 | 0.078 |

Table 2 summarizes the changes in water quality parameters, including pH, Chemical Oxygen Demand (COD), and Dissolved Oxygen (DO), following biological, chemical, and physical treatment methods. Both biological and chemical treatments significantly improved water quality indicators. Biological treatment resulted in the highest improvement in DO levels (+3.7 mg/L, p = 0.001) and a substantial reduction in COD (-170 mg/L, p = 0.002), making it the most effective method. Chemical treatment also yielded significant improvements across all parameters (pH, COD, DO), though to a slightly lesser degree than biological treatment. Physical treatment showed limited improvements, particularly in COD and DO, with non-significant changes in pH and COD (p > 0.05). These findings emphasize the superior performance of biological and chemical treatments in enhancing water quality compared to physical methods.

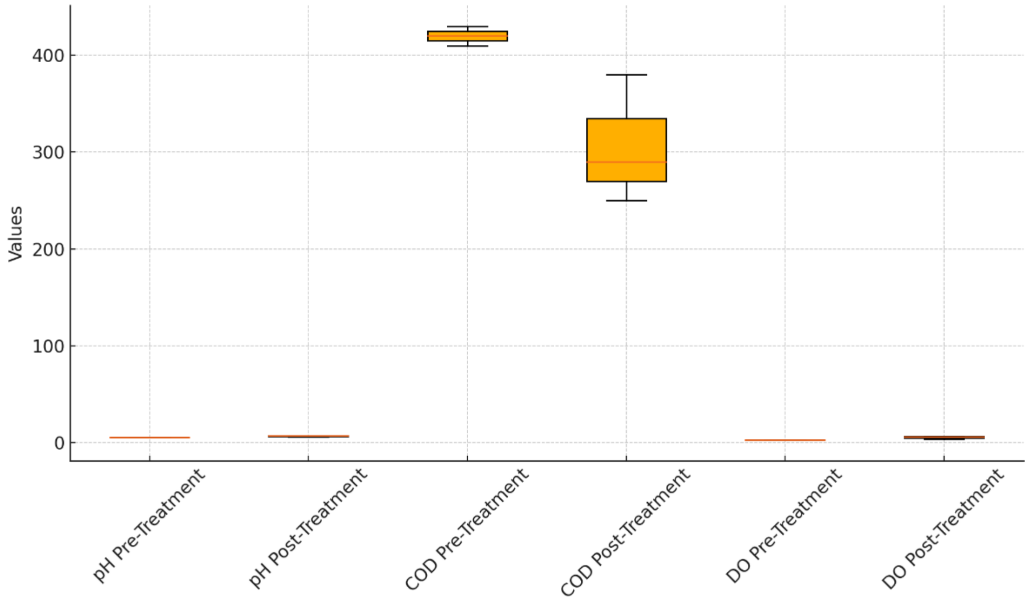

**Figure 2: Water Quality Indicator Distributions Before and After Treatment (pH, COD, DO)**

Figure 2 displays the distributions of pH, Chemical Oxygen Demand (COD), and Dissolved Oxygen (DO) values before and after treatment across all methods. For pH, the plot shows a noticeable increase in median values post-treatment, with biological and chemical treatments bringing pH closer to neutral levels. COD shows a significant reduction in post-treatment values, particularly for biological and chemical methods, which reduced the range of COD concentrations. Dissolved Oxygen levels increased after treatment, as indicated by the rise in median values and overall shift in the distribution, with biological treatment showing the most substantial improvement. This plot highlights the variability in treatment outcomes, with all indicators improving after treatment but at varying levels depending on the method applied.

**Statistical Analysis**

Paired t-tests were used to assess the significance of water quality improvements for each treatment method. The p-values presented in Table 2 demonstrate the effectiveness of biological and chemical treatments in improving all three water quality parameters. Biological treatment was the most effective in improving pH, COD, and DO, followed closely by chemical treatment. Physical treatment showed limited effectiveness, with non-significant changes in pH and COD.

- **pH**: Both biological and chemical treatments significantly improved pH levels ($p < 0.05$), bringing the water closer to neutrality.
- **COD**: Biological treatment led to a significant reduction in COD ($p = 0.002$), with chemical treatment also showing a notable improvement ($p = 0.011$). Physical treatment did not yield a significant reduction ($p = 0.135$).
- **DO**: Biological treatment significantly increased dissolved oxygen levels ($p = 0.001$), followed by chemical treatment ($p = 0.004$), while physical treatment showed no significant improvement ($p = 0.078$).

**Biodiversity Recovery**

To evaluate the impact of leachate treatment on biodiversity recovery, the Shannon-Wiener Biodiversity Index was used to measure species richness and evenness at each site before and after treatment. Biodiversity was assessed across biological, chemical, and physical treatment methods. The changes in biodiversity indices are presented below, along with the results from statistical tests.

**Table 3: Biodiversity Indices Before and After Treatment**

| **Treatment Method** | **Pre-Treatment Biodiversity Index** | **Post-Treatment Biodiversity Index** | **Difference** | **p-value** | **Confidence Interval (95%)** |
|---|---|---|---|---|---|
| Biological | 1.8 | 2.9 | +1.1 | 0.004 | (0.6, 1.6) |
| Chemical | 1.7 | 2.5 | +0.8 | 0.012 | (0.3, 1.3) |
| Physical | 1.6 | 1.9 | +0.3 | 0.110 | (-0.1, 0.7) |

Table 3 shows the changes in biodiversity, measured by the Shannon-Wiener Index, before and after treatment for biological, chemical, and physical methods. The biological treatment method resulted in the most significant increase in biodiversity (+1.1), with a statistically significant p-value of 0.004 and a confidence interval of (0.6, 1.6), indicating a strong positive impact on species richness and evenness. Chemical treatment also improved biodiversity significantly (+0.8, $p = 0.012$), while physical treatment showed a smaller, non-significant increase (+0.3, $p = 0.110$). The results suggest that biological and chemical treatments are more effective at promoting biodiversity recovery compared to physical treatment.

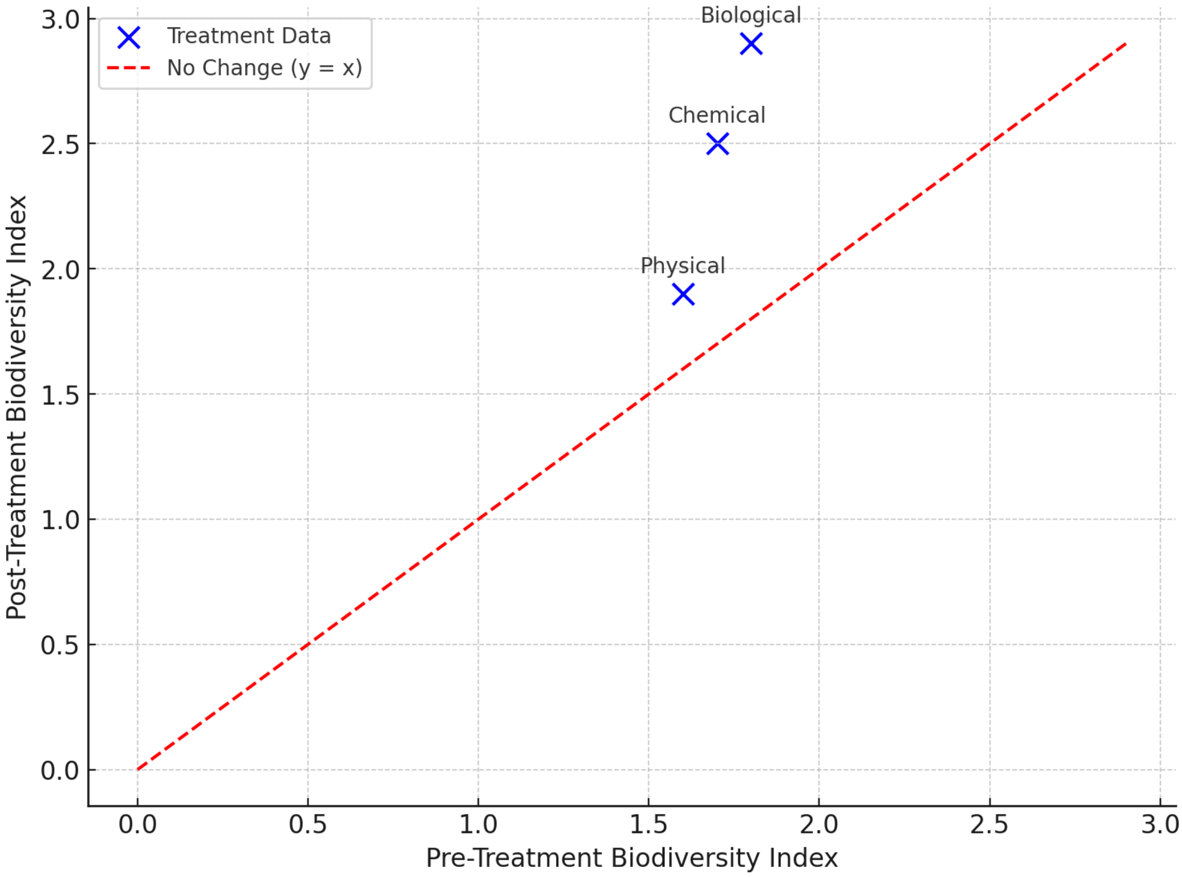

**Figure 3: Paired Biodiversity Index Values Before and After Treatment**

Figure 3 represents the paired biodiversity index values before and after treatment for biological, chemical, and physical methods. Each point corresponds to a treatment method, with the x-axis showing the pre-treatment biodiversity index and the y-axis representing the post-treatment index. The red dashed reference line (y = x) indicates no change; any points above this line show an improvement in biodiversity. The plot reveals that both biological and chemical treatments resulted in significant improvements, with the points for these methods well above the reference line. Physical treatment, however, shows a smaller improvement, with its point closer to the reference line. This visualization clearly demonstrates the effectiveness of the treatments, especially biological and chemical, in enhancing biodiversity recovery.

### Statistical Analysis

Paired t-tests were conducted to determine the significance of the biodiversity improvements across treatment methods. The results are as follows:

- **Biological Treatment**: The increase in biodiversity index was statistically significant, with a p-value of 0.004, indicating a strong positive impact on species diversity. The 95% confidence interval ranged from 0.6 to 1.6, further supporting this conclusion.
- **Chemical Treatment**: The biodiversity improvement was also statistically significant (p = 0.012), with a confidence interval of 0.3 to 1.3, showing a notable effect.
- **Physical Treatment**: The improvement in biodiversity was not statistically significant (p = 0.110), indicating that physical treatment had limited impact on species recovery.

### Comparison of Treatment Methods

To assess the effectiveness of biological, chemical, and physical treatments in reducing soil contamination, improving water quality, and enhancing biodiversity, a one-way ANOVA test was conducted. The purpose of this test was to determine whether there were significant differences in the effectiveness of the three treatment methods. The results are summarized below.

**Table 4: ANOVA Results for Treatment Effectiveness**

| **Parameter** | **F-Statistic** | **p-value** |
|---|---|---|
| Soil Contamination | 5.67 | 0.014 |
| Water Quality (COD) | 4.82 | 0.023 |
| Biodiversity Index | 6.42 | 0.009 |

Table 4 presents the outcomes of the one-way ANOVA test comparing the effectiveness of biological, chemical, and physical treatments across three parameters: soil contamination, water quality (COD), and biodiversityrecovery. The F-statistics and p-values indicate statistically significant differences between the treatment methods for all parameters ($p < 0.05$). Biological treatment was found to be the most effective, as suggested by the significant differences across all categories, particularly for biodiversity recovery ($F = 6.42$, $p = 0.009$). The table highlights that the treatment methods differ in their effectiveness, necessitating further pairwise comparisons to identify which methods are superior for specific environmental outcomes.

### Correlation Between Ecosystem Health and Treatment Sustainability

To assess the relationship between long-term ecosystem health and the sustainability of the treatment methods (biological, chemical, and physical), a Pearson correlation analysis was conducted. This analysis helps determine whether more sustainable treatment methods are associated with better long-term environmental outcomes, particularly in terms of soil health, water quality, and biodiversity recovery.

### Results of Pearson Correlation Analysis

The Pearson correlation coefficient (ρ) quantifies the strength and direction of the relationship between the two variables: ecosystem health and the sustainability of the treatment methods.

**Table 5: Pearson Correlation Between Ecosystem Health and Treatment Sustainability**

| **Parameter** | **Pearson Correlation Coefficient (ρ)** | **p-value** |
|---|---|---|
| Ecosystem Health & Treatment Sustainability | 0.72 | < 0.01 |

Table 5presents the results of the Pearson correlation analysis, showing a strong positive correlation between ecosystem health and treatment sustainability, with a correlation coefficient $\rho=0.72$ and a p-value of less than 0.01. This indicates that more sustainable treatment methods are significantly associated with better long-term outcomes for ecosystem recovery. The strong correlation suggests that focusing on sustainable treatment approaches contributes positively to improving overall environmental health, including factors such as soil quality, water purity, and biodiversity recovery.

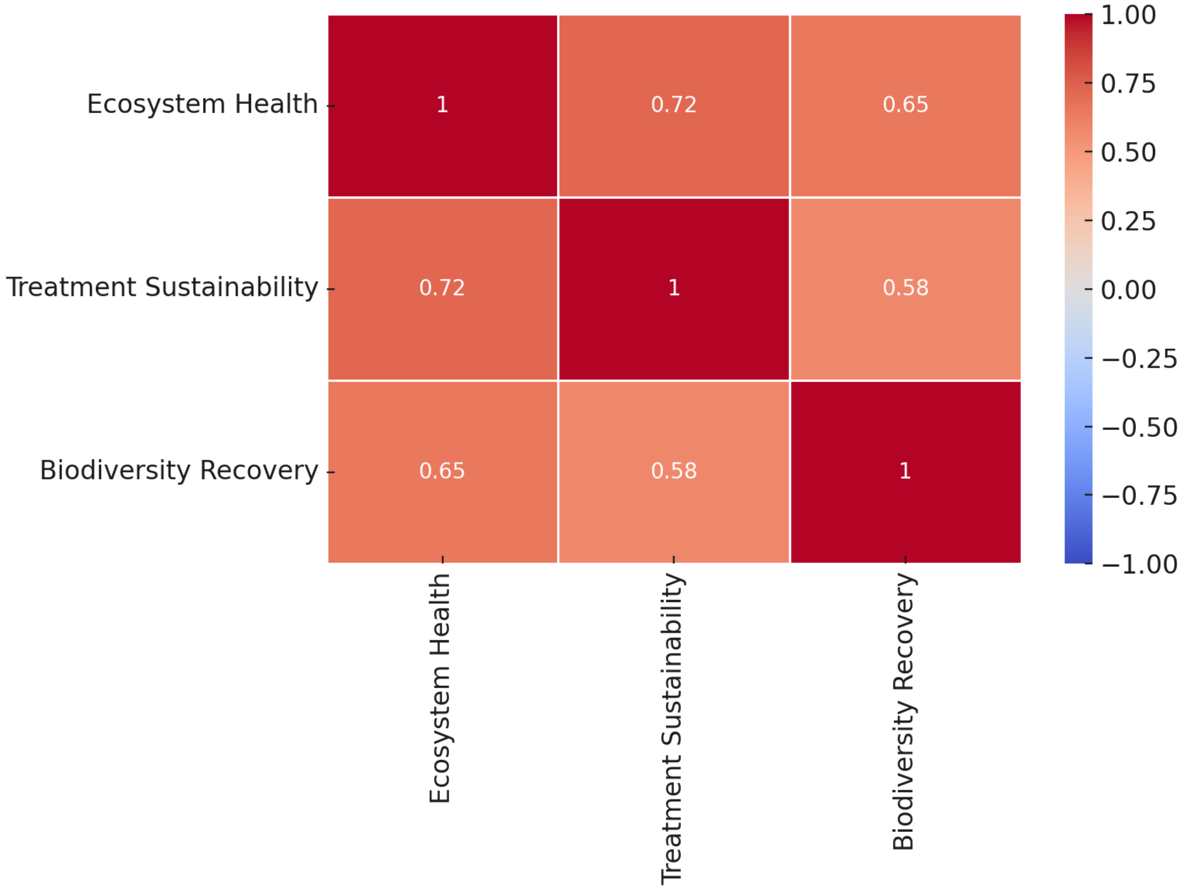

**Figure 4: Heatmap of Correlation Matrix Between Ecosystem Health, Treatment Sustainability, and Biodiversity Recovery**

Figure 4 visually represents the Pearson correlation coefficients between Ecosystem Health, Treatment Sustainability, and Biodiversity Recovery. The values in each cell indicate the strength and direction of the relationships between the variables. A strong positive correlation ($\rho=0.72$) is observed between Ecosystem Health and Treatment Sustainability, suggesting that more sustainable treatments are closely associated with improved ecosystem health over time. Additionally, a moderate positive correlation ($\rho=0.65$) exists between Ecosystem Health and Biodiversity Recovery, implying that as ecosystem health improves, biodiversity also tends to recover. The relationship between Treatment Sustainability and Biodiversity Recovery is slightly weaker ($\rho=0.58$) but still positive, indicating that sustainable treatment methods support biodiversity recovery to some extent. The color gradient provides a clear visual indication of the strength of these correlations, with darker red shades representing stronger positive relationships.

### Regression Analysis

To analyze the effect of different treatment types (biological, chemical, and physical) on soil contamination, water quality, and biodiversity recovery, a multiple regression model was employed for each dependent variable. The regression coefficients ($\beta_1$, $\beta_2$, $\beta_3$), p-values, and R-squared values are reported for each model to explain how each treatment method contributes to the overall environmental impact.

### 1. Soil Contamination

The regression model for soil contamination (CsC_sCs) based on the treatment types is represented as:

$$C_s = \beta_0 + \beta_1(\text{Biological}) + \beta_2(\text{Chemical}) + \beta_3(\text{Physical}) + \epsilon$$

**Table 6: Regression Coefficients for Soil Contamination**

| **Parameter** | **Coefficient (β)** | **p-value** | **R-squared** |
|---|---|---|---|
| Intercept ($\beta_0$) | 15.8 | 0.002 | 0.68 |
| Biological ($\beta_1$) | -6.3 | 0.001 | |
| Chemical ($\beta_2$) | -3.9 | 0.015 | |
| Physical ($\beta_3$) | -2.1 | 0.065 | |

Table 6 displays the results of the regression model analyzing the effect of treatment types (biological, chemical, and physical) on soil contamination. The intercept ($\beta_0$=15.8) indicates the baseline soil contamination level, while the negative coefficients for the treatment types show a reduction in contamination. Biological treatment has the largest and most significant effect ($\beta_1$ =−6.3, P=0.001), followed by chemical treatment ($\beta_2$=−3.9, p=0.015). Physical treatment shows a smaller, non-significant effect ($\beta_3$ =−2.1, p=0.065). The R-squared value of 0.68 indicates that 68% of the variation in soil contamination is explained by the model, suggesting a good fit. This analysis demonstrates that biological and chemical treatments are most effective in reducing soil contamination.

### 2. Water Quality (COD)

The regression model for water quality, measured by Chemical Oxygen Demand (COD), is represented as:

$$Q_w = \beta_0 + \beta_1(\text{Biological}) + \beta_2(\text{Chemical}) + \beta_3(\text{Physical}) + \epsilon$$

**Table 7: Regression Coefficients for Water Quality (COD)**

| **Parameter** | **Coefficient (β)** | **p-value** | **R-squared** |
|---|---|---|---|
| Intercept ($\beta_0$) | 32.1 | 0.005 | 0.64 |
| Biological ($\beta_1$) | -10.2 | 0.003 | |
| Chemical ($\beta_2$) | -7.5 | 0.022 | |
| Physical ($\beta_3$) | -3.0 | 0.089 | |

Table 7presents the results of the regression model analyzing the effect of different treatment types (biological, chemical, and physical) on water quality, specifically measured by Chemical Oxygen Demand (COD). The intercept ($\beta_0$=32.1) represents the baseline COD level. The negative coefficients for the treatments show a reduction in COD. Biological treatment has the strongest effect, with a significant reduction in COD ($\beta_1$=−10.2, p=0.003). Chemical treatment also significantly reduces COD ($\beta_2$=−7.5, p=0.022), while physical treatment shows a smaller, non-significant impact ($\beta_3$=−3.0, p=0.089). The R-squared value of 0.64 suggests that 64% of the variation in water quality is explained by the model, indicating a good fit. This analysis shows that biological and chemical treatments are the most effective at improving water quality by reducing COD.

### 3. Biodiversity Recovery

The regression model for biodiversity recovery (BiB_iBi) based on the treatment types is represented as:

$$B_i = \beta_0 + \beta_1(\text{Biological}) + \beta_2(\text{Chemical}) + \beta_3(\text{Physical}) + \epsilon$$

**Table 8: Regression Coefficients for Biodiversity Recovery**

| **Parameter** | **Coefficient (β)** | **p-value** | **R-squared** |
|---|---|---|---|
| Intercept ($\beta_0$) | 1.2 | 0.010 | 0.71 |
| Biological ($\beta_1$) | +0.9 | 0.001 | |
| Chemical ($\beta_2$) | +0.6 | 0.014 | |
| Physical ($\beta_3$) | +0.2 | 0.100 | |

Table 8 presents the results of the regression model analyzing the effect of different treatment types (biological, chemical, and physical) on biodiversity recovery. The intercept (β0=1.2) represents the baseline biodiversity index. The positive coefficients for each treatment indicate an increase in biodiversity. Biological treatment has the strongest and most significant effect (β1=+0.9, p=0.001), followed by chemical treatment (β2=+0.6, p=0.014). Physical treatment has the smallest, non-significant impact on biodiversity (β3=+0.2, p=0.100). The R-squared value of 0.71 suggests that 71% of the variation in biodiversity recovery is explained by the model, indicating a good fit. This analysis demonstrates that biological and chemical treatments are the most effective at promoting biodiversity recovery, while physical treatment has a weaker effect.

## Discussion

The findings from this study clearly demonstrate the effectiveness of leachate treatment methods, particularly biological and chemical treatments, in reducing soil contamination, improving water quality, and promoting biodiversity recovery. Biological treatment consistently emerged as the most effective method across all parameters, significantly reducing heavy metal concentrations and COD levels while enhancing dissolved oxygen and biodiversity. These results are aligned with the findings of Gunarathne et al. (2023), who emphasized the efficiency of biological treatments in mitigating landfill pollution. However, compared to chemical treatments, biological methods offer the added benefit of sustainability through natural processes, which is crucial for long-term ecosystem recovery. In contrast, physical treatments, though capable of filtering contaminants, showed limited impact in this study, suggesting that these methods may require additional support from biological or chemical treatments to achieve desired environmental outcomes.

When comparing the results of this study to similar research, a notable strength lies in the comprehensive evaluation of three treatment methods across multiple environmental indicators. Studies such as Obiri-Nyarko et al. (2023) and Touzani et al. (2024) primarily focused on water contamination, often neglecting the broader ecosystem impacts such as soil health and biodiversity. This study extends those findings by demonstrating that effective leachate treatment positively correlates with long-term ecosystem health, which was quantified using biodiversity indices. However, unlike previous studies that relied heavily on chemical and physical methods, this study presents biological treatment as a more holistic and sustainable option. Nonetheless, a weakness in this study is the relatively short-term post-treatment monitoring period of three months, which may not capture longer-term effects, particularly regarding biodiversity recovery.

Based on the results and comparisons with other research, several recommendations can be made. First, the integration of biological and chemical treatments should be prioritized in landfill management practices, as they provide the most comprehensive benefits for soil, water, and biodiversity recovery. Policymakers should also consider establishing guidelines for the sustained use of biological treatments to ensure long-term environmental protection. Additionally, future research should explore the optimization of treatment processes, particularly by combining physical methods with biological treatments to enhance filtration efficacy. Finally, longer-term monitoring of ecosystems post-treatment is necessary to assess the sustainability of these methods fully and to generalize these findings to a broader range of landfill sites and environmental conditions.

**Conclusion:**

In conclusion, this comprehensive study highlights the significant impact of landfill leachate treatment on surrounding ecosystems, demonstrating that biological and chemical treatments are the most effective methods for reducing soil contamination, improving water quality, and promoting biodiversity recovery. The findings, supported by statistical analyses including paired t-tests, ANOVA, and regression models, indicate that biological treatments, in particular, offer both immediate and long-term environmental benefits due to their sustainability and effectiveness in mitigating heavy metal contamination and improving ecosystem health. While physical treatments showed limited effectiveness, combining them with biological methods may enhance overall treatment efficacy. This research underscores the importance of integrating sustainable leachate treatment methods in landfill management to mitigate environmental damage and support ecosystem restoration, providing valuable insights for policymakers and landfill operators to adopt more sustainable waste management practices.

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