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Solutions for landfill management with a focus on slope stability and improved management performance using Fuzzy logic-based approach

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Abstract

In recent decades, with the expansion of urbanization and increased waste production, optimal waste management and disposal have become one of the most important urban challenges. One of the biggest challenges associated with landfills is maintaining their slope stability over time. The instability of these slopes can lead to waste spillage, the release of hazardous pollutants, and increased environmental and public health threats. This study examines the problems and challenges of landfill management with a special focus on the issue of slope stability. In this regard, modern geotechnical engineering methods for strengthening slopes and preventing waste from falling are analyzed, and the environmental and social impacts of landfills are also addressed. The main objective of this research is to provide sustainable and intelligent solutions to improve the management of landfills and reduce their negative environmental and social impacts. The results of this research show that by using modern technologies in the design and maintenance of landfill slopes and using intelligent waste management systems, it is possible to improve not only the stability of slopes, but also reduce the negative environmental and health impacts on the community. These solutions are especially important in urban and densely populated areas where the volume of waste generation is high. In addition, the use of materials with better degradability and the development of more efficient waste management systems can help reduce the volume of landfill waste and improve the overall performance of landfills.

Keywords: geotechnical engineering, landfill slope stability, waste management, environmental pollution, energy recovery systems, landfill management optimization, sanitary landfill
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1 Introduction

The rapid pace of urbanization and consumption has led to a dramatic increase in municipal solid waste (MSW) generation, posing serious environmental and geotechnical challenges [2, 9]. One of the most critical concerns in modern

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landfill management is slope instability, which can result in hazardous landslides, leachate leakage, and damage to nearby infrastructure [11, 19]. The structural integrity of landfill slopes is therefore vital not only for operational safety but also for protecting surrounding ecosystems and human settlements [1].

These stability challenges are exacerbated by the heterogeneous and time-dependent nature of waste materials, as well as dynamic factors such as biological degradation, rainfall infiltration, and seismic loading [2, 15]. In response, geotechnical engineering has developed a range of innovative solutions, including mechanical-biological treatment (MBT) of waste, geosynthetic and geogrid reinforcement, enhanced drainage systems, and advanced numerical modelling tools for performance prediction [1, 12, 19].

Landfills play a critical role in modern waste management systems, providing a practical solution for the disposal of municipal solid waste (MSW). However, the increasing volume and complexity of waste, combined with environmental and safety concerns, have intensified the need for improved landfill management strategies. Among the most pressing challenges is slope stability, which directly impacts the structural integrity, operational safety, and environmental sustainability of landfills. Slope failures in landfills can lead to catastrophic consequences, including human casualties, environmental contamination, and infrastructure damage.

Furthermore, modern landfill management increasingly integrates risk-based assessment, probabilistic stability modelling, and decision-making frameworks such as life cycle assessment (LCA) to ensure long-term safety, environmental compliance, and economic feasibility [11, 18]. This paper aims to explore integrated, performance-oriented solutions that enhance both slope stability and overall landfill management practices, grounded in recent advances in geotechnical research and real-world case studies.

2 Literature review

Slope Design in Earth Structures provides a specialized and sophisticated perspective on the field of geotechnical engineering. This chapter introduces and explains the theoretical foundations that are fundamental to slope stability design. The theoretical foundations of this chapter guide this research into the depth of issues related to slope stability of earth structures and familiarize engineers with the fundamental principles and information necessary for optimal design. Slope design of earth structures requires a deep knowledge of theoretical principles and concepts. These principles, including geology, soil mechanics, soil hydrology, and geotechnical engineering principles, are of great importance in developing effective solutions for slope stability. A complete understanding of these theoretical foundations makes engineers resilient to the complex challenges when dealing with slope design in various conditions.

2.1 Definitions and terms

2.1.1 Concept of geology

Geology, as a scientific and engineering field, is an attempt to understand the history and composition of the Earth, as well as how various factors affect its structures and compositions. In addition, Geology is the study of Earth materials (soils, rocks, sediments) and processes (erosion, weathering, slope failure) critical to designing, monitoring, and rehabilitating landfill sites. It provides the scientific foundation for assessing slope stability through geotechnical analysis of shear strength, permeability, and compaction properties [13]. It studies the Earth's materials, structure, processes, and history, encompassing subdisciplines such as tectonics, sedimentology, and geomorphology. Geological mapping and subsurface investigations (e.g., borehole logging, geophysical surveys) identify weak zones prone to landslides or leachate seepage, enabling proactive mitigation [17]. Additionally, geology informs landfill management performance by evaluating site suitability, liner integrity, and long-term settlement risks [14].

2.1.2 Basic principles of geology

One of the basic principles of geology is the principle of "uniformitarianism," which provides the basis for studying Earth processes over time. In other words, this principle of uniformity means that Earth processes have continued in the same way in the past as they have in the present. Information from geology provides valuable information for researchers and engineers, from observations of past rock formations, various earth activities, and even the effects of human activities. In the context of engineering geology, information obtained from geology helps structural designers to best deal with problems and challenges related to soil and rock at the site of construction projects. Geological information is used in engineering geology, particularly in areas such as foundation, piling, and foundation design of structures. A detailed understanding of the mechanical and hydrological properties of soil and rock is the basis for principled decision-making in the design and implementation of large structural projects.

Understanding the basic principles of geology is essential for effective landfill management, particularly in ensuring slope stability and enhancing overall site performance. Geology plays a critical role in determining the suitability of a site for landfill development, influencing factors such as subsurface composition, groundwater movement, and geotechnical behavior of soils and rocks.

One of the foundational principles is the law of superposition, which states that in any undisturbed sequence of rocks, the oldest layers lie at the bottom and the youngest at the top [8]. This concept assists in understanding the stratigraphy of landfill sites, which is crucial when assessing subsurface stability and predicting material behavior under loading from waste deposits.

Another key concept is lithology, which refers to the physical characteristics of the rocks or soils present at the site, including grain size, composition, porosity, and permeability. These properties directly affect the drainage and consolidation behavior of landfill materials. For example, sites underlain by clay-rich formations may exhibit poor drainage and increased risk of slope instability due to water retention and low shear strength [5].

Structural geology, including the presence of faults, folds, and fractures, must also be considered. Discontinuities in the subsurface can act as pathways for leachate migration or zones of mechanical weakness, which can compromise landfill liner systems and affect slope integrity [7]. Moreover, the orientation of bedding planes and joint sets can influence the direction and magnitude of potential slope failures.

Hydrogeology is another critical aspect. Groundwater flow patterns and aquifer characteristics govern the movement of leachate and the potential for environmental contamination. Understanding recharge zones, hydraulic gradients, and water table fluctuations is fundamental in designing effective landfill drainage and leachate control systems [4].

In addition, engineering geology principles guide the characterization and modification of natural ground conditions to ensure safe landfill development. Techniques such as site investigation, in-situ testing, and geotechnical modeling help assess the stability of slopes and design appropriate reinforcement or drainage systems [6].

In summary, integrating geological principles into landfill management ensures the identification of risks related to slope failure, groundwater contamination, and settlement issues, thereby improving the safety, performance, and sustainability of landfill operations.

2.1.3 Slope stability

In the field of geotechnical engineering, slope stability is a critical aspect that requires a detailed understanding of the mechanical properties of soil and rock, geology, and various environmental factors. Slope stability refers to the ability of an earthen structure or trench to remain stable against external forces, including the weight of the structure itself, earth pressure, and other forces such as earthquakes and water loads. The challenges of slope stability are complicated by the presence of various variables such as soil properties, geographical conditions, and various forces. For example, soils with different characteristics such as shear strength, compressive strength, and different grain sizes have a direct impact on slope stability.

The basic principles of slope stability include force balance, the necessary balance between slope resistance and soil pressure, and avoiding water entrapment within the soil. Geotechnical engineering methods such as the use of earth walls, reinforcement with geosynthetics, and optimization of environmental conditions are used to increase slope stability. By considering these principles and applying advanced engineering techniques, construction projects can be implemented more safely and effectively and contribute to the sustainable and safe development of the living environment in metropolitan areas.

2.1.4 Soil mechanics

As a fundamental field in geotechnical engineering, soil mechanics studies the behavior and mechanical properties of soil and rock in response to various forces and pressures. This scientific field plays a fundamental role in the foundation of structures and slope stability by providing vital information in the fields of soil strength, compaction, and deformation.

In soil mechanics, topics such as determining the shear and compressive strength of soil, determining elastic and plastic properties, and analyzing changes in soil volume under loading are discussed and investigated. The information obtained from soil mechanics experiments helps engineers better understand the behavior of soil under different conditions and is used to design important structural components such as foundations, piles, and earthen walls. The importance of soil mechanics in geotechnical engineering is obvious because every structure, from the smallest bridge and building to the largest traffic points and dams, interacts with soil. Accurate and complete information about the mechanical behavior of soil allows engineers to design and implement structures that resist a variety of environmental forces and pressures with optimal, safe, and sustainable solutions.

2.1.5 Soil hydrology

Soil hydrology, as a fundamental field in geotechnical engineering, studies the flow and effects of water in and under structures and soils. Water, as a major factor in soil deformation and its mechanical behavior, plays a vital role in the stability of structures and engineering geology.

In soil hydrology, water flow within and under the soil surface, the effects of rain, snowmelt, and surface water on soils and structures are studied. Also, the way water penetrates and condenses in soils and its relationship to the hydrological properties of the soil are also important topics in this field. Information obtained from soil hydrology is used in the design of drainage systems, water resource management, and determining the effects of water on the stability of structures. An accurate concept of water flow in structures and soils allows engineers to design structures more resistant and stable against potential water-related problems, such as soil erosion and water infiltration, by performing hydrological analyses. This vital information is of particular importance in ensuring the safety and stability of structures and preventing future problems.

3 Research background

Hossain and Haque [9] conducted stability analyses of municipal solid waste (MSW) landfills with decomposition effects. They focused on the impact of waste degradation on landfill slope stability, using a numerical modeling approach. The study took into account the variation in the mechanical properties of waste as it decomposes over time, considering both the reduced shear strength and the changes in waste composition. The results showed that the decomposition process significantly influences the stability of landfill slopes, and the reduction in waste strength over time must be accounted for in stability analyses. This study emphasizes the importance of considering the time-dependent properties of MSW in the design and maintenance of landfill slopes to ensure long-term stability.

Li et al. [15] analyzed the influence of rainfall infiltration on the stability of landfill slopes through numerical modeling and hydrological simulation. Their study demonstrated that increased rainfall infiltration leads to elevated pore water pressure and reduced shear strength in the soil mass, especially under saturated conditions. As saturation progresses, the safety factor of the slope decreases significantly, increasing the risk of failure. The study emphasized the importance of incorporating effective drainage and moisture control systems in landfill design to mitigate rainfall-induced slope instability and to ensure long-term structural performance and environmental safety of waste disposal sites.

Jahanfar et al. [11] developed a probabilistic approach for modeling slope stability in municipal solid waste (MSW) landfills. In their study, they used probabilistic methods to account for the inherent uncertainties in the properties of MSW, such as shear strength and waste composition. The authors employed Monte Carlo simulations to assess the stability of landfill slopes, calculating failure probabilities under different conditions. The results revealed that probabilistic analysis is an effective tool for understanding the risks associated with landfill slope failure, providing a more robust framework for landfill design and management. This method helps in predicting the variability in the safety factor and assessing the likelihood of slope instability over time.

Babu et al. [2] investigated the shear strength characteristics of mechanically biologically treated municipal solid waste (MBT-MSW) from Bangalore, India. The study involved conducting large-scale direct shear tests on MBT waste samples to determine key geotechnical parameters such as cohesion and internal friction angle. The results indicated that MBT processing significantly alters the mechanical behavior of MSW, improving its shear strength and making it more suitable for stable landfill design. The research highlighted the importance of MBT treatment in enhancing the geotechnical performance of landfills, especially in urban contexts where slope stability is a critical concern. Their findings are crucial for informed design and management of modern sanitary landfills incorporating MBT technologies.

Jahanfar [10], in his doctoral dissertation titled ”Landfill Slope Stability Risk Assessment”, conducted a comprehensive evaluation of the risks associated with slope failure in municipal solid waste (MSW) landfills. The research focused on integrating probabilistic methods with geotechnical modeling to assess slope stability under variable waste properties and environmental conditions. Using case studies and simulation tools, Jahanfar developed a framework to calculate the probability of failure and identify critical factors influencing stability, such as shear strength parameters, leachate levels, and landfill geometry. The study emphasized the need for risk-informed design and monitoring strategies to improve landfill safety and performance over time. His approach provides a valuable methodology for practitioners aiming to manage uncertainties in landfill engineering.

Akbar et al. [1], investigated the displacement-based seismic performance of geogrid-reinforced earth-retaining walls using advanced three-dimensional finite element modeling (FEM) techniques. Their study focused on evaluating how such retaining systems behave under seismic loading conditions, particularly in terms of wall displacement, stress distribution, and failure mechanisms. The simulations considered various parameters such as wall geometry, seismic input intensity, and geogrid layout. Results demonstrated that the use of geogrid reinforcement significantly enhances seismic stability and reduces lateral displacements of retaining structures. This research contributes valuable insights into the seismic design of landfill containment systems and other infrastructure involving earth-retaining walls, offering guidance for improving slope stability in seismically active regions.

Jalali Moghadam et al. [12], conducted an experimental evaluation of mechanically stabilized earth (MSE) walls incorporating recycled crumb rubber as a reinforcing material. The study aimed to explore the feasibility of using crumb rubber in MSE systems by examining parameters such as lateral earth pressure, wall deformation, and overall stability under surcharge loads. Laboratory-scale wall models were constructed and tested under controlled conditions to simulate real-world scenarios. The results showed that the inclusion of crumb rubber reduced earth pressures, enhanced ductility, and improved the energy absorption capacity of the walls. This study highlights the potential of sustainable reinforcement strategies using recycled materials in improving the performance and environmental sustainability of landfill slopes and retaining structures.

Batali et al. [3], explored slope stability aspects of municipal solid waste (MSW) landfills by combining case studies with numerical modeling approaches. Their research focused on identifying the key factors that influence landfill slope behavior, such as waste heterogeneity, moisture variation, and mechanical properties of the deposited material. The team employed finite element modeling techniques to simulate real-world landfill conditions and to analyze potential failure mechanisms under various loading scenarios. The case studies revealed that neglecting waste decomposition and time-dependent changes in material strength could lead to underestimation of failure risk. Their findings support the importance of incorporating material variability and long-term settlement into slope stability assessments for improved landfill design and management.

Tighnavard Balasbaneh and Bin Marsono [18], applied multi-criteria decision-making (MCDM) methods to evaluate and compare various alternatives for earth-retaining walls, including those applicable in landfill slope stabilization. Their study integrated Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (S-LCA) to comprehensively assess environmental, economic, and social impacts. The analysis allowed for a holistic understanding of retaining wall alternatives, highlighting that sustainable and cost-effective solutions often require balancing performance with long-term environmental and social consequences. This approach offers valuable insights for landfill management, especially where slope stabilization measures intersect with broader sustainability goals.

Zhang et al. [19] conducted a stability analysis of landfills supported by retaining walls using the Continuous Stress Method (CSM). This method allowed for a more refined understanding of stress distribution and failure mechanisms in landfill-retaining wall systems compared to traditional limit equilibrium methods. By incorporating actual waste behavior, retaining wall interaction, and layered stress paths, the study highlighted that wall geometry, waste properties, and backfill compaction significantly influence overall slope stability. The findings contribute to optimized design strategies for reinforced landfill structures, particularly in urban or space-limited environments where retaining systems are essential.

4 Methodology

The first step of this research method is to conduct extensive field studies and collect the necessary data from the studied landfills. In this step, first, several landfills are selected as case studies. These sites should be diverse in terms of geological, climatic and operational characteristics so that the results can be generalized to different environments. Then, important geotechnical data such as soil characteristics, shear strength, internal friction angle and soil cohesion are collected through field and laboratory tests on soil samples. These data are essential for determining soil strength parameters and analyzing slope stability. In addition, the slope of the landfill slopes is measured using mapping and remote sensing methods such as LiDAR. Finally, information on soil moisture, leachate leakage and other factors affecting slope stability such as precipitation, relative humidity and wind will be collected through on-site measurement and monitoring stations. These data are essential for identifying key stability factors and entering them into the fuzzy logic system. Collecting accurate and comprehensive data at this stage will play a vital role in developing a successful fuzzy logic model.

The next step in the research methodology involves the development of a fuzzy logic-based analytical model designed to evaluate and predict landfill slope stability under varying geological and environmental conditions. This model is built upon both field data and core geotechnical equations, allowing for enhanced accuracy even in the presence of uncertainty.

At the heart of slope stability analysis lies the Factor of Safety (FoS), which is traditionally calculated using the limit equilibrium method:

$$FoS = \frac{c' \cdot L + (W \cdot \cos\alpha - u \cdot L) \cdot \tan\phi'}{W \cdot \sin\alpha} \tag{4.1}$$

where,

c': effective cohesion of the soil (kPa), ϕ': effective internal friction angle (degrees), L: length of the potential slip surface (m), W: weight of the sliding mass (kN), u: pore water pressure (kPa), and α: slope angle (degrees).

This formula is applied to different sections of the landfill slope to provide a baseline understanding of mechanical stability under current conditions.

To incorporate uncertainties in geotechnical and environmental data, a fuzzy logic model is constructed. Each input parameter is fuzzified into linguistic variables using membership functions, typically triangular or trapezoidal. For example, the membership function for cohesion ($\mu_{c'}(x)$) might look like:

$$\mu_{c'}(x) = \begin{cases} 0, & x \le a \\ \frac{x-a}{b-a}, & a < x < b \\ 1, & b \le x \le c \\ \frac{d-x}{d-c}, & c < x < d \\ 0, & x \ge d \end{cases} \tag{4.2}$$

Where a, b, c, d are parameters defining the fuzzy set boundaries (e.g., for "medium" cohesion).

The fuzzy inference system (FIS) then applies a series of IF–THEN rules, such as:

"IF cohesion is low AND slope is steep AND moisture is high, THEN stability is low."

Each rule maps input fuzzy sets to an output fuzzy set, and the degree of fulfillment for each rule is calculated using the minimum operator or product operator:

$$\mu_{rule} = \min[\mu_{c'}(x), \mu_{\alpha}(x), \mu_{\theta}(x)] \tag{4.3}$$

or,

$$\mu_{rule} = \mu_{c'}(x) \cdot \mu_{\alpha}(x) \cdot \mu_{\theta}(x) \tag{4.4}$$

The output of all rules is aggregated using the max operator and defuzzified using the centroid method:

$$\text{Output (Stability Index)} = \frac{\int x \cdot \mu_{output}(x)dx}{\int \mu_{output}(x)dx} \tag{4.5}$$

This yields a crisp value representing the landfill's stability index, which can be translated into qualitative labels (e.g., stable, critical, unstable) or numerical thresholds to guide decision-making.

This index is then classified as:

- Stable if $FoS > 1.5$
- Marginally Stable if $1.1 < FoS \le 1.5$
- Unstable if $FoS \le 1.1$

To validate the fuzzy model, the output stability index is compared with observed stability states and classical FoS results, computing correlation metrics such as:

$$R^2 = 1 - \frac{\sum(y_i - \hat{y}_i)^2}{\sum(y_i - \bar{y}_i)^2} \tag{4.6}$$

And sensitivity analysis is conducted using normalized weights:

$$S_i = \frac{\partial\, Output}{\partial x_i} \cdot \frac{x_i}{Output} \tag{4.7}$$

Where S_i reflects the relative influence of input parameter x_i on the stability output.

5 Analysis

5.1 Implementation of results

5.1.1 Identification of factors affecting the stability of a landfill slope

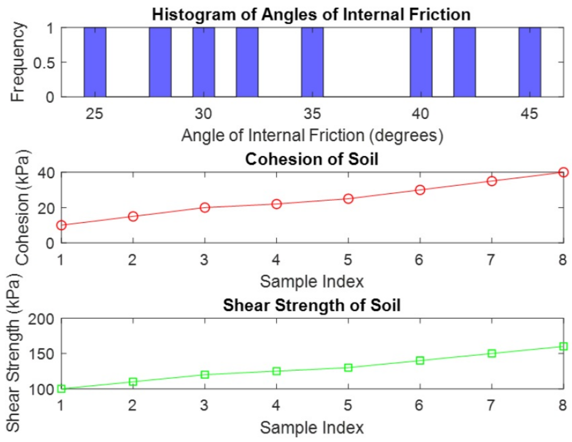

Figure 1: Histogram diagram of soil internal friction angles - soil cohesion diagram - soil shear strength diagram

5.1.2 Procedure used in calculating resistance from cohesive strength

The resistance offered by soil cohesion is a critical factor in evaluating the stability of foundations, particularly against lateral loads. This resistance is calculated in both the horizontal X and Z directions, considering contributions from both the pedestal and the footing pad. The following methodology is based on the principles outlined by V.N.S. Murthy [16].

1. Resisting Force Calculations:
   The resisting force due to cohesive strength is calculated for the horizontal directions X and Z by using the cohesive strength parameter C and the passive earth pressure coefficient K_p.

   - Resisting Force along the X-direction:

   $$R_X = 2C\sqrt{K_p} \cdot (h \cdot b + D \cdot B) \tag{5.1}$$

   where, C: Cohesion of the soil, K_p: Coefficient of passive earth pressure, h: Height of the pedestal, b: Pedestal dimension along the Z-direction, D: Thickness of the footing pad, and B: Footing dimension along the Z-direction.

   - Resisting Force along the Z-direction:

   $$R_Z = 2C\sqrt{K_p} \cdot (h \cdot l + D \cdot L) \tag{5.2}$$

   where, l: Pedestal dimension along the X-direction, and L: Footing dimension along the X-direction.

2. Resisting Moment Calculations:
   The resisting moment is calculated by considering the distribution of forces along the height of the pedestal and the footing dimensions.

- Moment about the global X-axis:

$$M_X = 2C\sqrt{K_p} \cdot [h \cdot b \cdot (0.5h + D) + D \cdot B \cdot (0.5D)]) \tag{5.3}$$

- Moment about the global Z-axis:

$$M_Z = 2C\sqrt{K_p} \cdot [h \cdot l \cdot (0.5h + D) + D \cdot L \cdot (0.5D)]) \tag{5.4}$$

where, M_X: Moment about the X-axis, M_Z: Moment about the Z-axis, L: Footing dimension along the global X-direction, B: Footing dimension along the global Z-direction, l: Pedestal dimension along the global X-direction, bPedestal dimension along the global Z-direction, D: Thickness of the footing pad, and h: Height of the pedestal.

5.2 Drainage leakage over time graph

The changes in drainage leakage over time are displayed. The horizontal axis is days and the vertical axis is the drainage leakage rate in liters per day. Displays the drainage leakage rate over a specific time period, indicating the changes and fluctuations in drainage leakage over time.

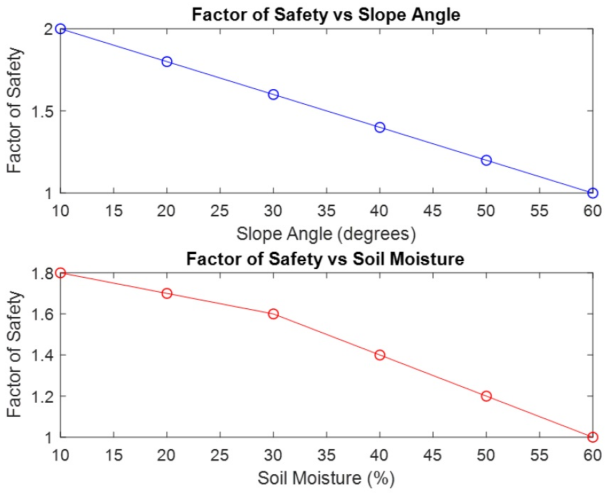

Figure 2: Safety factor versus slope angle chart

The relationship between the safety factor and the slope angle is shown. The horizontal axis is the slope angle (degrees) and the vertical axis is the safety factor. Examining the relationship between the safety factor and the slope angle shows that as the slope angle increases, the safety factor decreases. This graph shows that as the slope angle increases, the safety factor decreases. In other words, steeper slopes (with a greater angle) are less stable and more likely to slip.

6 Conclusion

Management of landfills is one of the major environmental and public health challenges that has profound impacts on the sustainability of local slopes and ecosystems. These challenges include soil subsidence and landslides, water pollution, and health problems resulting from waste decomposition. However, adopting effective solutions can help improve management performance and reduce the negative impacts of these systems.

Among the proposed solutions are the use of modern technologies in the design and management of landfills, the improvement of waste disposal methods, and comprehensive planning for monitoring and controlling environmental impacts. Also, educating the local community and increasing their awareness of waste management and its effects on the environment will play a significant role in the success of these measures.

Finally, addressing social, economic, and environmental issues in landfill management not only helps improve management performance, but also contributes to achieving sustainability and natural resource conservation goals. Therefore, it is essential to establish collaboration between government agencies, non-governmental organizations, and local communities to achieve comprehensive and effective solutions that are consistent with environmental sustainability.

6.1 Research challenges

1. Data Access: Research related to municipal waste management requires access to comprehensive and accurate data on waste, urban climate, and landfill characteristics. Obtaining and aggregating this data can be difficult.
2. Complexity of variables: Analyzing the slope stability of municipal landfills is a complex problem that considers the effects of various variables, including waste type, climate conditions, and landfill characteristics. Accurate modeling of these effects presents statistical and mathematical challenges.
3. Use of Fuzzy Logic: Using fuzzy logic for slope stability analysis requires precision and expertise in the field of fuzzy logic. Determining appropriate logic functions and selecting appropriate parameters for these functions can be a challenge.

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