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Exploring the efficacy of nanoclay additives in mitigating leachate migration through the liner layers of Tabriz landfill

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Abstract. Landfills and the associated leachate present significant threats to both biological ecosystems and environmental resources, with uncontrolled leachate pollution posing the potential for severe environmental and human disasters. To address this concern, the use of liners has emerged as a crucial strategy for managing landfill leachate. This study focuses on assessing the effectiveness of integrating nanoclay additives, specifically Montmorillonite, in reducing the permeability of landfill liner layers. A comprehensive set of geotechnical tests, including sieve analysis, hydrometry, Atterberg limits, permeability, and chemical assessments (BOD and COD), was conducted on samples extracted from the core of the Tabriz landfill liner. The samples underwent testing within control groups and varying percentages of additives (3%, 6%, and 9%) over processing durations of 1, 7, and 14 days. A comparative analysis of the results was then performed. The findings indicate that increasing nanoclay percentages led to significant improvements in Atterberg limits (LL, PL, and PI), showing increments of 48%, 33%, and 45%, respectively. Furthermore, the permeability coefficient in the control sample exhibited a substantial decrease of 98% compared to the sample enhanced with 9% nanoclay. Additionally, the addition of nanoclay facilitated the absorption of Pb and As while reducing Bod and Cod in the soil.Collectively, these results underscore the effective role of nanoclay, particularly Montmorillonite, in enhancing the landfill liner system's ability to manage leachate. The implications of this study highlight the considerable potential of nanoclay additives as instrumental agents in addressing leachate-related concerns in landfill environments.

Keywords: geotechnics landfill; leachate; nanotechnology; soil permeability

1. Introduction

Waste and excess materials can be identified as the most significant detrimental outcome of human activities in urban areas, transforming into a global concern within the environmental domain (Alavi and Babaei 2017). These wastes contribute to the proliferation of water and soil

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pollution, and the leachate from them can lead to extensive contamination of water resources and agricultural lands (Pichtel 2014). Generally, various methods exist for the disposal of waste materials, including recycling, reuse, transformation, incineration, and landfilling. Landfilling is the most common approach employed for waste disposal, claiming the highest implementation percentage (Pazoki and Ghasemzadeh 2020). Landfilling is essentially the final step, involving solid waste that lacks recyclability or reusability, and is often conducted in a conventional or unhygienic manner. Sanitary engineering landfilling involves the implementation of landfill operations along with precautions such as proper layering and waste covering to prevent pollution, particularly leachate, from penetrating into surrounding soils and waters (both surface and groundwater) due to the decomposition of materials (wastes). In a more comprehensive sense, a landfill should be equipped with various systems and measures, including preventing water entry into the landfill, collecting leachate, preventing leachate leakage, tracking potential leaks, collecting, and venting generated gases, and other necessary precautions. It is noteworthy that engineering landfills for hazardous and radioactive wastes require special precautions (King and Mureebe 1992).

When a quantity of moist waste accumulates, the biological decomposition of the waste results in the emergence of a viscous liquid called leachate, which is generally toxic and hazardous. Leachate percolates within the landfill, accumulating at the bottom among the waste layers, creating a substantial volume of this highly hazardous liquid in contact with the soil beneath the landfill liner (Alavi and Babaei 2017). The collected leachate depends on factors such as the amount of deposited waste, initial moisture content of the waste, precipitation rates, and evaporation and transpiration rates within the landfill. Collected leachate, under various mechanisms, begins to infiltrate and move among the layers of the underlying soil. In the absence of an impermeable layer, it eventually enters groundwater pathways after traversing a specific route (Pichtel 2014). The presence of leachate affects the permeability of soil layers both in the short and long term. It increases permeability and diminishes soil retention conditions due to settling, impacting soil characteristics. In the short term, the higher viscosity of leachate compared to water and the gas production during leachate infiltration can be influential. In the long term, the interaction between leachate and soil, coupled with physical and chemical changes in the soil, contributes to its impact. The concentration increase of these substances in groundwater may surpass acceptable limits and existing standards, leading to extensive contamination (Hoornweg and Bhada-Tata 2012). The movement of leachate within the main landfill body is a significant concern, requiring early control and containment to prevent widespread contamination. Failure to control leachate spread in the initial stages may result in long-term consequences, such as the leachate escaping beyond the lower layers or the landfill boundary, causing extensive contamination of soil and water and irreparable environmental damage (Azizpour *et al.* 2020). The best precautions in this regard involve effective containment of leachate on-site within the landfill. In fact, the accumulation of solid waste in landfills leads to the generation of leachate, a toxic liquid those results from the decomposition of organic matter and the percolation of rainwater through the waste layers. This leachate contains a cocktail of hazardous substances, including heavy metals, organic pollutants, and pathogens, which can contaminate soil, surface water, and groundwater. Uncontrolled leachate pollution not only poses direct risks to human health through the consumption of contaminated water and food but also disrupts delicate ecological balances, harming aquatic life and biodiversity. Furthermore, the leachate can migrate over long distances, affecting areas far beyond the immediate vicinity of the landfill site, exacerbating the scope and severity of its environmental impacts. Moreover, the management and treatment of landfill leachate present significant challenges for environmental regulators and waste management authorities. Conventional landfill liners and containment systems are often insufficient to prevent the migration of leachate into surrounding soil and water bodies, particularly in regions with high rainfall or where geological conditions facilitate the rapid movement of contaminants. The persistence of leachate pollution underscores the urgent need for innovative approaches to landfill management, including the development of advanced containment technologies, the implementation of stricter regulatory frameworks, and the promotion of sustainable waste reduction and recycling initiatives. By addressing the root causes of leachate pollution and mitigating its environmental consequences, policymakers and stakeholders can work towards creating a cleaner, healthier future for current and future generations. Over the past two decades, the conventional disposal of solid waste and the inadequacy of hydro-mechanical conditions and structures in landfill sites have led to the easy spread of leachate in the surrounding environment. This has resulted in environmental pollution, destruction of ecosystems, and the dissemination of various diseases (Pazoki and Ghasemzadeh 2020). In response, geotechnical and environmental engineers have endeavored to employ innovative engineering and management methods to enhance the existing conditions. These methods encompass appropriate site selection; based on geotechnical engineering principles, the proper implementation of liners (as a key element) to control and contain leachate spread (Pichtel 2014). The primary objective of constructing liners is to prevent contamination and the spread of pollution to water and soil resources. Therefore, these layers must prevent direct contact between waste and soil and the infiltration of leachate into the soil (Qasim 2017).

In landfill construction, the structure and number of liners can vary based on the project's significance, the scale of work, the potential for leachate production, and the volume and nature of the generated waste (Azizpour *et al.* 2020). Besides the implementation of impermeable liner layers (single or double liners), the nature of liner materials and their retention and permeability properties are crucial in effectively controlling leachate, emphasizing this aspect in the study. Liner materials must have very low permeability and high capacity to absorb pollutants, suitable flexibility against moisture changes and settlement within the landfill boundaries. Additionally, these materials must possess sufficient strength against external forces and loads. The optimal materials that meet these criteria are clayey soils. In cases where local clayey soils lack the necessary quality or transporting them is cost-prohibitive, modifying soil conditions by adding suitable additives or synthesizing existing materials proves to be cost-effective. This approach can bring about changes in some soil properties, such as reducing permeability coefficient and addressing certain soil deficiencies (Qasim 2017). In general, various approaches are employed worldwide to reduce soil permeability and enhance the properties of liner materials, with increasing attention to the use of nanomaterials in recent years. The utilization of nanomaterials has gained prominence due to notable successes, easy accessibility, environmental compatibility, geochemical interactions, and positive cation exchanges with various soils, especially fine-grained soils, making it a priority in soil improvement projects and a distinctive element in the design and implementation of landfill liners (Pichtel 2014).

The present study aims to investigate and improve the performance of landfill liners in Tabriz city, utilizing nanotechnology. It seeks to assess the capabilities of nanoclay, in combination with soil liners, for leachate control. Among the advantages of incorporating nanomaterials into soil, the enhancement of physical and chemical soil properties stands out, including increased water absorption, improved retention of soil minerals, and enhanced soil structure and strength, ultimately contributing to improved soil engineering performance. Additionally, nanoclay can serve as soil amendments to reduce toxicity resulting from heavy metals (Azizpour *et al.* 2020). This modification not only reduces soil pollution but also restricts the spread of such contaminants. Furthermore, nanomaterials can enhance the soil's ability to retain nutrients, leading to a reduction in fertilizer and chemical consumption. Beyond the advantage of increased soil fertility, this results in a decrease in the concentration of metals and chemical and biochemical pollutants in the soil, acting as a factor in preserving the original soil structure. This soil protection, in turn, prevents disturbances in soil ecosystems and active soil biomechanisms (Kananizadeh *et al.* 2011). Moreover, nanomaterials can play a significant role in water conservation in arid or prone-to-drought regions. Preventing erodibility is another advantage of nanomaterials, improving soil durability and resistance to erosion (Pazoki and Ghasemzadeh 2020). Considering these benefits and the environmental compatibility of nanomaterials, their incorporation in civil engineering projects has become a matter of great importance and a significant achievement.

This article introduces a novel approach to enhancing the performance of landfill liners in Tabriz city through the incorporation of nanomaterials, particularly nanoclay. The utilization of nanotechnology in the context of landfill engineering is relatively innovative and represents a cutting-edge solution to address issues related to soil permeability and leachate control. The study explores the unique capabilities of nanoclay, considering their successful recent applications, ease of accessibility, and favorable environmental compatibility. The emphasis on the interaction between nanoclay and different soil types, especially fine-grained soils, adds a distinctive dimension to the research, making it a pioneering endeavor in the field of geotechnical and environmental engineering. The incorporation of nanoclay into landfill liners presents several advantages. Firstly, it leads to a significant improvement in the physical and chemical properties of the soil, including enhanced water absorption, improved mineral retention, and strengthened soil structure. These enhancements contribute to the overall engineering performance of the soil, particularly in the context of landfill liners where preventing leachate spread is crucial. Additionally, the use of nanoclay as soil amendments proves advantageous in reducing the toxicity of heavy metals, thereby mitigating soil pollution. Moreover, the study explores the potential of nanoclay to enhance nutrient retention in the soil, resulting in a reduced need for fertilizers and chemical inputs, promoting sustainable environmental practices. While the incorporation of nanoclay in landfill liners presents promising advantages, certain limitations should be acknowledged. The long-term environmental impact and potential toxicity of nanomaterials need thorough investigation. Additionally, the cost-effectiveness of obtaining and implementing nanoclay on a large scale needs careful consideration. The study's findings may be influenced by variations in local soil conditions, requiring further research to ascertain the generalizability of the results. Moreover, the compatibility of nanoclay with different types of waste materials and their interactions in diverse landfill settings warrant comprehensive exploration. Overall, recognizing these limitations is crucial for ensuring the practical feasibility and sustainability of implementing nanomaterials in landfill engineering projects.

2. Nanoclay in geotechnics and leachate control

In the field of geotechnical engineering, one of the most successful materials introduced in nanotechnology is nanoclay. Nanoclays are a type of silicate nanoparticles, typically derived from montmorillonite clay and smectite group. While artificial additives in soils contribute to

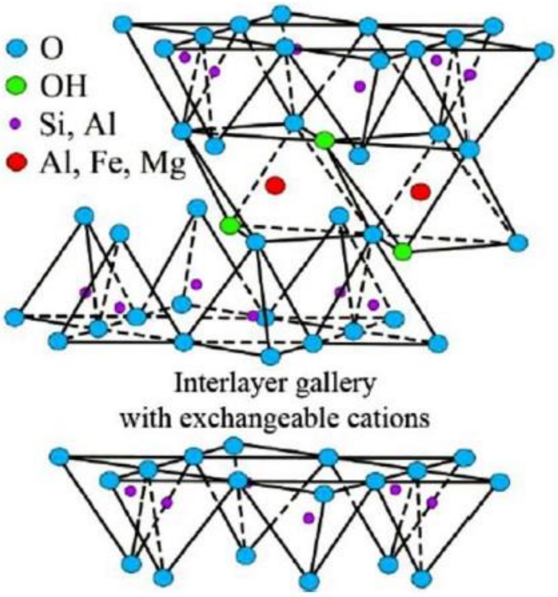

Fig. 1 The three-dimensional structure of montmorillonite (Dalmimi *et al*. 2019)

environmental pollution, nanoclayhas demonstrated favorable effects on mitigating detrimental processes in the environmental ecosystem, positioning them as environmentally compatible materials. Recognized as excellent natural pollutant adsorbing layers, nanoclay possess noteworthy specific surface area, high cation exchange capacity, and minimal permeability, particularly in the case of smectite minerals, making them extensively utilized in environmental projects (Kananizadeh *et al.* 2011). Another advantage of montmorillonite nanoclays lies in their swelling property in response to moisture, leading to self-healing of cracks in soils over time (Nikbakht *et al.* 2022). The compatibility and high performance of nanoclay materials in the construction and implementation of various infrastructure components and extensive pollution control projects, including landfills, have motivated researchers to employ these materials in diverse structures (Khodary *et al.* 2018). Recent research and various perspectives have focused on determining the extent of contamination transfer resulting from landfill waste burial in landfills and their penetration into surrounding soils, influenced by varying burial site conditions, the type of disposed waste, and different chemical reactions (Mazani and Rahimpour 2017). In general, the composition of leachate produced depends on the type and location of waste disposal, but predominantly, leachate contains decomposable and non-decomposable substances such as ammonia, chlorine, inorganic salts, and heavy metals (Pazoki and Ghasemzadeh 2020). Uncontrolled leachate infiltration into surrounding soils can lead to significant changes in the geotechnical properties of the soil, especially parameters related to shear strength. These alterations primarily contribute to the degradation of soils and underground waters, influenced by various factors such as the type of leachate derived from buried waste, the type of soil at the location, and the duration of leachate contact with the soil, as well as the interaction between leachate and soil (Mojiri *et al.* 2021). The combination of nano-resins with other nanomaterials like nanofibers not only enhances efficiency but also improves long-term resistance, strength, and stability in the layering of materials (Nikbakht *et al.* 2023).

Nano-montmorillonite can be obtained by extracting montmorillonite clays, bentonite, or other smectite groups with a purity exceeding 90%. The properties of these nanoparticles vary depending on the type of cations present between the layers in the montmorillonite structure. Montmorillonite belongs to the smectite family of minerals and is naturally found in various countries (Valenzuela *et al.* 2021). Fig. 1 illustrates the three-dimensional structure of a montmorillonite clay. Nowadays, with technological advancements, these types of clays can be synthetically produced for industrial applications. However, the primary consumption of these nanomaterials is still associated with natural clays. Currently, the industry leans towards using inorganic solids like silica or bentonite as the most effective and widely used reinforcement for polymeric structures (Dalmimi*et al*. 2019). In general, layered silicates have a sheet-like structure, comprising a two-dimensional layer that is approximately 1 nm thick and ranges in length from 300 nm to several microns (Valenzuela *et al.* 2021). This polymeric shape enhances the impermeability of molecules (Dalmimi *et al*. 2019).

Kananizadeh*et al.* (2011) investigated the performance of nanoclays in terms of swelling potential and uniaxial compressive strength (stability) of the compacted clay liner in the Kahrizak landfill in Tehran. The results of this study indicated that adding 4% nanoclays increased the soil's resistance by approximately 36.28%, significantly impacting the improvement of soil quality. The obtained results justify the construction of clay barriers with nanoclays due to the cost-effectiveness. Ahadi *et al.* (2012) conducted a study to explore the use of nanomaterials in evaluating the soil-heavy metal (e.g., lead) interaction, particularly in the context of retention and absorption capacity of nanoclays. In this regard, a three-stage soil experiment was conducted on baseline soil, soil containing nanoclays, and soil containing nanoclays-carbonate. The results indicated that nanoclay samples, due to their larger specific surface area compared to other clay samples, possess a unique capability to absorb and retain heavy metal pollutants. Li *et al*. (2013) also examined the impact of leachate pollution on the mechanical properties of compacted clay soil. For this purpose, they used soil samples from the metro construction site in Wuhan, China, with different compositions of deionized pure water and four samples of this soil with varying percentages of leachate and deionized water. Results revealed that due to chemical reactions between leachate and soil, along with the movements of suspended solids and microorganisms in the leachate that reduce effective porosity, hydraulic conductivity of compacted clay soil decreased, and compaction compressibility increased with an increase in leachate and pollution. The maximum reduction in soil porosity due to pollution was estimated to be 9.7%.

Azarafza *et al.* (2015) investigated the performance of nanomaterials in combination with fine-grained soils. The results revealed an increase in the plastic limit and liquidity index with the addition of nanoclays. Fakhri *et al.* (2015) conducted a laboratory study to examine the hydraulic properties of kaolinite clay soil in Zanjan County with the addition of nanoclays. Based on their findings, adding 8% nanoclays to kaolinite soil resulted in a maximum 2% reduction in specific weight and a 7% increase in optimum moisture density. Furthermore, adding 8% nanoclays to kaolinite soil led to a 90% corresponding increase in porosity and a 300-fold reduction in permeability coefficient, indicating a significant impact on reducing the permeability of kaolinite clay soil. Sanayei-Kermani *et al.* (2018) conducted a research study on the influence of nanobentonite particles on the engineering properties of nanobentonite-sand mixtures. They stated that this mixture could be used as consumable materials in the construction of landfills. According to the results of direct shear tests, the highest adhesion was related to the sample with 5% nanobentonite, and the highest internal friction angle was obtained for the sample with 9% nanobentonite. Permeability tests were performed on the samples with 5% and 9% nanobentonite, showing that with an increase in the percentage of nanobentonite and compaction, permeability decreased significantly, causing changes in resistance parameters. In the sample with 9% nanobentonite, permeability changes demonstrated a noticeable decrease with an increase in compaction percentage. Jafari and Abbassian (2019) conducted a study to investigate the behavior of silty soil in the Maragheh region (East Azerbaijan Province) with the addition of nanoclays (montmorillonite). Based on the obtained results, with an increase in the percentage of nanoclays from 0 to 9%, plastic limit and liquidity index of the soil increased, but the plasticity index showed a decreasing trend. Mehrabi *et al.* (2021) conducted research on the effect of adding nanoclays on the strength and permeability of concrete. In this regard, 1% to 3% nanoclays were added to the concrete, and compressive strength, void content, density, and permeability were measured. The results indicated an increase in strength and a decrease in permeability in the samples. According to this research, adding a substance like nanoclays to concrete can be a practical solution to improve its strength and permeability.

3. Materials and methods

This study was initiated in mid-Khordad (late May to early June) by initially obtaining representative samples of soil and landfill leachate from the landfill site in Tabriz, East Azerbaijan Province. These samples were then transferred to the laboratory for a series of geotechnical tests. Direct methods were employed to assess the geotechnical properties of the samples, given their ability to provide more accurate results and offer a comprehensive understanding of liner conditions at the landfill site. Sampling, sample preparation, and test execution adhered to international ASTM guidelines. The soil under investigation was collected from the municipal waste landfill in Tabriz. Geotechnically, it appears to be a typical silty-clayey soil with a high percentage of fines, where the dominance of clay is significantly higher than the silt fraction. The samples were collected based on field surveys, and then they were transported to the laboratory.

Upon initial sample preparation and thorough ultrasonic mixing, the samples were uniformly and randomly selected for further analysis. The samples were categorized into control (untreated) and modified groups for geotechnical parameter assessments. The geotechnical tests conducted in this research included particle size analysis (ASTM D422), hydrometer test (ASTM D1140), Atterberg limits ASTM D4318), and permeability (ASTM D5084). These tests aimed to identify and classify the physical and mechanical properties of the liner material. Subsequently, BOD and COD tests were conducted on the samples to assess biological and chemical contamination. For the BOD test, samples were maintained at 20 degrees Celsius for 5 days, while the COD test required only 3 hours, providing rapid results in comparison. Results of the tests are presented in graphical and tabular formats. The original samples (control group) represented the natural and existing soil conditions. In the modified group, various combinations of clay nanomaterials, specifically 3%, 6%, and 9% by weight of montmorillonite nanoclay, were considered. The geotechnical properties, including permeability, were measured, and compared with the control sample. Finally, the obtained results were classified based on the percentage of nanoclays used in the mixture, utilizing regression analysis. It is noteworthy that prepared samples were subjected to potential changes over 1, 7, and 14 days in isolated chambers, being tested at respective intervals. The use of isolated chambers aimed to maintain initial soil moisture. Additionally, considering the hazardous nature of heavy metals such as lead and arsenic, the impact of montmorillonite nanoclays on reducing these metals was evaluated and depicted in graphical representation.

Particle Size Analysis: The ASTM D422 tests, commonly known as the particle size analysis method, are utilized to determine the distribution of particle sizes within a soil sample. The resulting data allow the calculation of the distribution of soil particles across various size fractions, typically expressed as percentages of gravel, sand, silt, and clay. This information is crucial for understanding the engineering behavior of soils, particularly in assessing their permeability and suitability for various construction applications. This test helps determine the distribution of particle sizes in the soil. Understanding the particle size distribution is essential for assessing the soil's engineering properties, such as its strength, compressibility, and drainage characteristics.

Hydrometery: The ASTM D1140 test, also known as the hydrometer analysis, is employed to determine the distribution of particle sizes in fine-grained soils. This test is particularly suitable for soils with a high percentage of clay and silt. The procedure involves suspending the soil particles in water, breaking down aggregates with a dispersing agent (the soil is dispersed in a sodium hexametaphosphate solution to break down aggregates), and then using a hydrometer to measure the settling rates. The hydrometer readings enable the calculation of the particle size distribution, including the percentages of clay, silt, and sand. This information is valuable for assessing the soil's hydraulic properties, sedimentation characteristics, and overall engineering behavior. The hydrometer test is used to determine the distribution of soil particles in the fine-grained fraction. It provides information on the soil's texture, which is crucial for assessing its permeability, consolidation characteristics, and potential for erosion. This knowledge is essential for designing liners that can withstand specific environmental conditions.

Atterberg Limits: The ASTM D4318 test, commonly known as the Atterberg limits test, is crucial for evaluating the plasticity characteristics of fine-grained soils. The Atterberg limits include the liquid limit, plastic limit, and plasticity index. The liquid limit is determined by gradually adding water to a soil sample until it exhibits a specific consistency. The plastic limit is the moisture content at which the soil can be molded into a specific shape. The plasticity index is the numerical difference between the liquid and plastic limits, providing insights into the soil's plasticity and shrink-swell potential. This test aids in classifying soils and predicting their behavior under varying moisture conditions. Atterberg Limits include the liquid limit, plastic limit, and plasticity index, providing insights into the soil's consistency and behavior under different moisture conditions. These limits are essential for evaluating the suitability of the soil as liner material, understanding its shrink-swell potential, and ensuring stability over time.

Permeability: The ASTM D5084 test is employed to assess the coefficient of permeability of a soil sample. In this procedure, a constant head or falling head permeameter is used to measure the rate at which water flows through a soil specimen under controlled conditions. The test helps determine the soil's ability to transmit fluids and is crucial for understanding drainage characteristics, groundwater movement, and the effectiveness of geosynthetic barriers. The coefficient of permeability is calculated based on Darcy's Law, allowing engineers to evaluate the suitability of soils for different construction applications, such as seepage control in embankments or the design of drainage systems. Permeability testing is critical for determining the soil's ability to transmit fluids, including water and leachate. This information is crucial for assessing the effectiveness of liners in preventing the migration of contaminants into the surrounding environment. It helps design liners with appropriate permeability characteristics to control leachate flow.

In the other hand, to evaluate the chemical composition of the investigated leachate, samples were obtained from isolated compartments and then transported to a specialized laboratory. The subsequent step involved the application of various analytical techniques, including atomic absorption spectroscopy (AAS), pH measurement, and X-ray fluorescence (XRF) tests. These methods were employed to precisely identify and quantify the elements present in the leachate fluid, providing a comprehensive analysis of its chemical status.

Atomic Absorption Spectroscopy: AAS is an analytical technique used to determine the concentration of specific elements in a sample. It operates by measuring the absorption of light at characteristic wavelengths as atoms in the sample undergo electronic transitions. By analyzing the extent of absorption, the concentration of elements such as metals in the leachate can be quantified accurately. AAS is essential for quantifying the concentration of specific elements in the leachate. As leachate often contains heavy metals and other pollutants, AAS helps identify and measure these elements accurately.

pH: pH measurement is a fundamental test that determines the acidity or alkalinity of a solution, providing insights into the hydrogen ion concentration. It is a crucial parameter for evaluating the chemical characteristics of leachate. The pH scale ranges from 0 to 14, where values below 7 indicate acidity, 7 represents neutrality, and values above 7 indicate alkalinity. In the context of leachate analysis, pH measurement helps assess the potential impact on the environment and surrounding ecosystems. pH measurement is fundamental for assessing the acidity or alkalinity of the leachate. It provides insights into the leachate's corrosiveness, potential for metal mobility, and its overall chemical stability.

X-ray Fluorescence: XRF is a non-destructive analytical technique that determines the elemental composition of a material. In XRF testing, the sample is irradiated with X-rays, leading to the emission of characteristic fluorescent X-rays from the atoms within the sample. By analyzing the emitted X-rays, the elements present in the leachate can be identified and quantified. XRF is particularly useful for detecting heavy metals and other elements, providing valuable information about the leachate's chemical composition. XRF is valuable for identifying and quantifying various elements present in the leachate. It is particularly effective in detecting heavy metals, which are common contaminants in leachate.

4. Results and discussion

4.1 Chemical characteristics of leachate

To assess the chemical status of the leachate under investigation, samples were extracted from isolated compartments and transferred to a specialized laboratory. Subsequently, ASS, pH, and XRF tests were conducted to identify the elements present in the leachate fluid. Table 1displays the results of the chemical evaluation of the landfill leachate. These tests collectively provide a comprehensive analysis of the leachate's chemical composition, offering critical information for making informed decisions regarding environmental protection and management. They enable us to identify specific pollutants, evaluate their concentrations, and assess the potential risks associated with leachate discharge, ultimately contributing to the development of environmentally sustainable practices, and mitigating adverse impacts. A glance at this table reveals that the Tabriz leachate exhibits high Total Dissolved Solids (TDS) and noticeable presence of heavy metal elements. The presence of such chemical compounds in the leachate indicates its high potential for transporting salts and widespread pollution. Therefore, it can be asserted that leachate leakage from the landfill poses a serious threat to the environment, ecosystems, and human health in the region.

Table 1 Estimated values for the chemical properties of leachate obtained from Tabriz landfill

Samples	1	2	3	4	5	6	7	8	9
pH	7.22	7.13	7.20	7.22	7.17	7.22	7.13	7.13	7.13
T (^{o}C)	18.1	17.7	18.3	18.0	17.2	17.8	17.7	18.1	18.3
TDS	496.12	498.33	492.25	489.36	469.11	490.45	486.70	450.12	467.42
As	12.2	7.3	9.9	5.7	9.6	6.3	10.7	9.6	12.2
Cd	1.10	1.14	1.06	1.03	0.98	1.17	1.02	0.97	0.97
Co	47.6	45.4	47.3	45.6	47.3	45.5	47.3	47.3	45.6
Cr	63.14	71.17	75.63	79.64	63.35	71.17	66.37	65.97	71.49
Cu	96.83	96.85	97.10	96.36	97.45	96.17	96.75	97.58	96.19
Mn	91.3	102.7	95.5	97.3	95.6	91.3	91.7	95.5	97.3
Ni	87.30	87.42	85.96	87.74	87.35	86.91	87.50	87.63	87.33
Pb	192.1	189.7	196.3	190.0	196.4	196.4	182.5	194.7	190.8
Zn	234.7	248.2	239.7	237.0	237.0	235.4	239.1	231.9	238.0
Hg	7.47	6.03	7.17	7.41	7.10	6.65	6.86	7.10	6.36
Ca	65.71	67.77	65.63	97.12	65.45	67.36	65.22	67.47	65.60
Na	15.9	12.5	15.4	14.9	15.2	12.9	14.2	14.9	12.5
Mg	12.23	15.03	15.56	14.73	14.81	15.20	14.65	14.71	15.02
HCO_3^-	25.41	27.33	25.45	27.12	25.63	27.92	25.40	25.45	27.12
Cl^-	6.32	7.25	6.63	7.17	6.33	6.89	7.10	6.35	9.39
NO_3^-	17.20	16.96	17.15	17.12	16.85	17.20	16.74	15.56	17.31
SO_4^{2-}	18.85	18.63	18.74	18.52	18.25	19.12	18.78	18.45	19.02

Note: units are ppm

The chemical tests conducted on the leachate from the Tabriz landfill play a pivotal role in assessing its environmental impact. Through AAS, pH, and XRF tests, we gain valuable insights into the composition of the leachate, identifying the presence of elements and heavy metal contaminants. Elevated levels of TDS and heavy metals in the leachate, as revealed by these tests, signify a significant potential for salt transport and widespread pollution. This information is crucial for understanding the environmental hazards associated with leachate leakage from the landfill. Therefore, effective liner systems designed for the landfill must exhibit high capabilities in controlling and preventing the spread of leachate, ensuring the protection of both the environment and human health in the Tabriz region.

4.2Used nanoclay properties

Nanoclay refers to a class of nanomaterials composed of clay minerals with particle dimensions in the nanometer range. Among these, montmorillonite-type nanoclay stands out as a prominent member of the smectite mineral family, characterized by its layered structure and unique chemical composition. One of the distinctive features of nanoclays, including montmorillonite, is their exceptionally large surface area relative to their volume. This property, coupled with their nano-sized particles, contributes to their high adsorption capacity, especially for cations and heavy

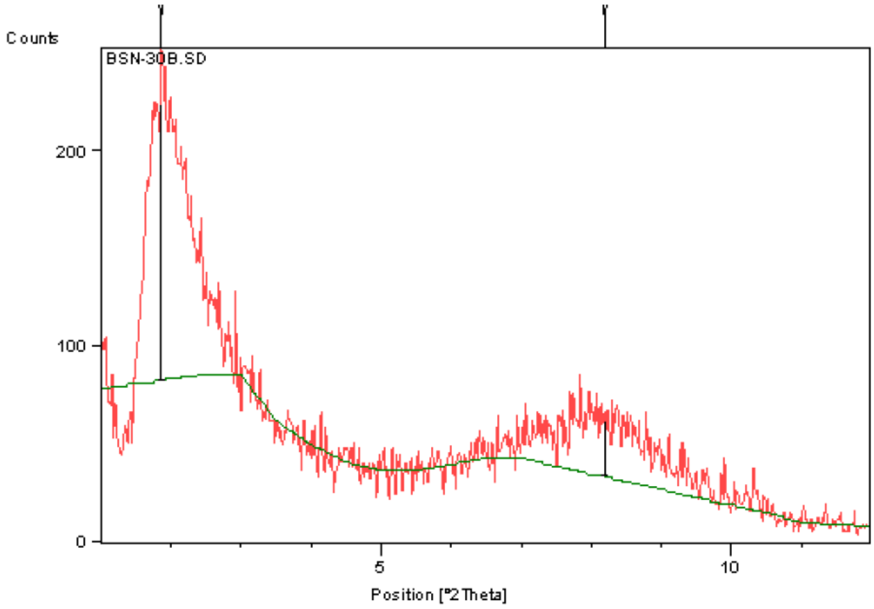

Fig. 2 AAS indicators related to nanomaterials used in this research

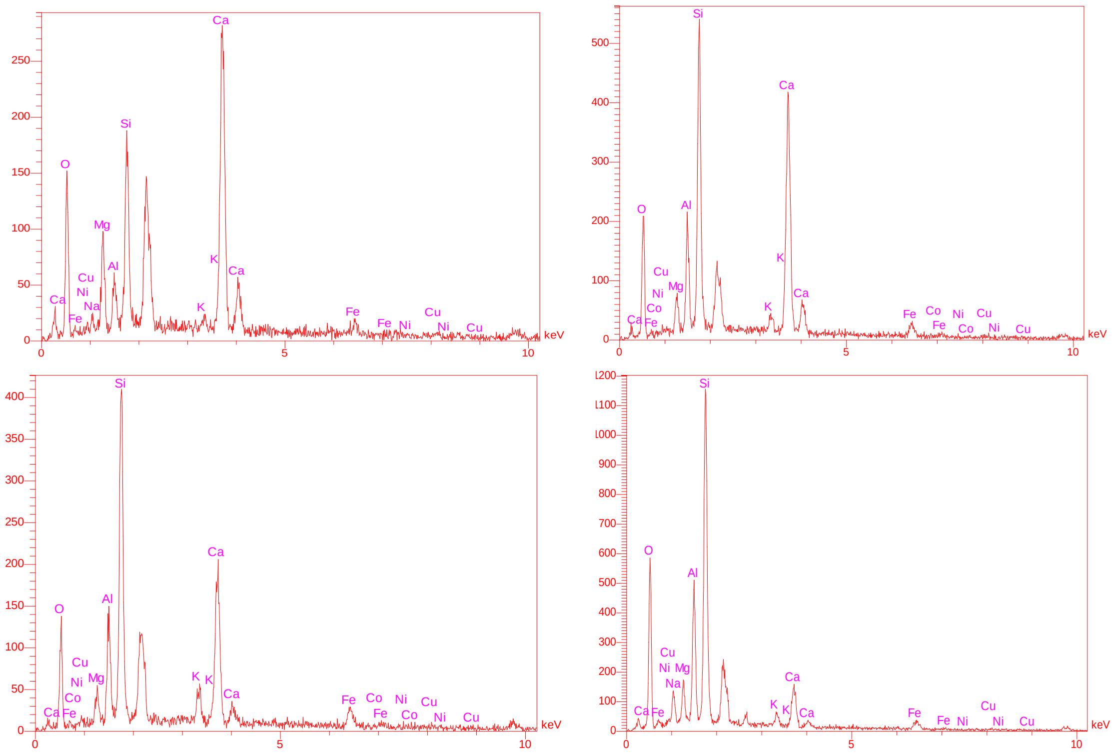

Fig. 3 Several SEM images related to nanomaterials used in this research

Table 2 Nanoclay characteristics used in this research

No.	Characteristics	Unit	Value
		Physical analysis	
1	Mineral type	-	Montmorillonite
2	Density	g/cm^2	1.1-1.35
3	Color	-	Pale cream to yellowish white
4	Particle size	nm	1-2
5	Specific surface area	m^2/g	220-270
6	Electrical conductivity	MV	25
7	Ion-exchange coefficient	Meq/100g	48
8	Particlesbetweenspace	Å	60
9	Humidity	%	1-1.5
		Chemical analysis	
1	Na_2O	%	0.99
2	MgO	%	3.20
3	Al_2O_3	%	19.10
4	SiO_2	%	50.95
5	K_2O	%	0.96
6	CaO	%	1.97
7	TiO_2	%	0.60
8	Fe_2O_3	%	5.60
9	LOI	%	15.49

metals. Nanoclay belongs to the family of smectite minerals and is an aluminosilicate. Its noteworthy and practical properties include a high percentage of cation absorption, heavy metal adsorption, adhesive characteristics, filler properties, catalytic activity, cost-effectiveness, and availability (Praveen and Sunil 2016). In this study, for soil improvement in landfill liners, varying amounts (3%, 6%, and 9%) of nano clay, specifically montmorillonite-type nanoclay, were utilized. The nanoclay, obtained in powder form with the identifier Closite 15A / mj-48 from Tamad Kala/Nanosadra Company, was pre-prepared. The soil and nanoclay were homogenized using ultrasonic mixing for 24 hours and then isolated in a dry state. The objective was to homogenize the composition of nanomaterials and treated samples. Scanning electron microscopy micrographs clearly reveal the layered structure of montmorillonite nanoclay. In clayey soils, this interlayering is crucial, and these materials, due to their nano size and significantly high surface area to volume ratio, exhibit substantial adsorption capacity, making them highly effective for adsorption purposes (Asrari *et al.*2019).

Nanoclay, specifically of the montmorillonite type, plays a pivotal role in the effective management and control of landfill leachate, offering a range of unique properties that contribute to environmental sustainability. Leachate, a byproduct of waste decomposition in landfills, contains contaminants that, if left uncontrolled, pose a threat to ecosystems and human health. Nanoclays, with their nano-sized particles and expansive surface area, exhibit a remarkable adsorption capacity. This characteristic allows them to capture and retain contaminants such as heavy metals and cations present in leachate, preventing their further dispersion into the surrounding environment. In addition to their adsorption capabilities, nanoclays contribute to the improvement of geotechnical properties in landfill liners. When incorporated into the soil, they enhance compaction, reduce permeability, and increase soil strength. This enhanced soil structure acts as a barrier, restricting the movement of leachate and controlling the spread of contaminants.

The application of nanoclays in landfill engineering thus serves as a sustainable solution to mitigate the environmental impact of waste disposal. Moreover, nanoclays play a crucial role in preventing groundwater contamination. By limiting the migration of leachate through the soil, nanoclays safeguard the groundwater, a vital natural resource. This dual action of adsorption and geotechnical enhancement positions nanoclays as valuable tools in waste containment systems, ensuring the protection of ecosystems and contributing to the overall sustainability of landfill practices.

The research findings and micrographs obtained from scanning electron microscopy (SEM) reveal that the particles of landfill leachate are predominantly characterized by fine sizes and angular shapes. Most of these particles exhibit rectangular cubic forms and polyhedral crystalline structures, displaying a broad range of particles with various sizes on their surfaces. Consequently, such angular particles may not resist flow and can easily be displaced, generating preferential flow paths. Similar results have been reported in this regard by Panchal (Panchal *et al*. 2018). Table 2 illustrates the characteristics of the nanomaterials used in this study. Fig. 2 provides an overview of the AAS curve, and Fig. 3 presents the SEM image of these nanomaterials, obtained using a BRUKER P8 ADVANCE device from Germany under conditions of 30 kilovolts voltage, 30 milliampere current, a wavelength of 15418, and a scattering angle ranging from 10 to 90 degrees.

4.3Geotechnical properties of soil

The primary aim of this research is to evaluate the performance of montmorillonite-type nanomaterials in enhancing the properties of fine-grained soils used in the landfill liners of Tabriz city. The goal is to enable resistance against the spread of leachate, a hazardous fluid to the environment, and play an effective containment role. As we know, the development and infiltration of leachate into the soil increase pollution risks and contaminant radius, potentially leading to extensive environmental disasters upon reaching groundwater. Therefore, the better the performance of liners and their resistance to leachate transfer and permeation, the higher their effectiveness in leachate containment. This study, considering this issue and utilizing nanomaterial technology, conducted a series of geotechnical experiments to enhance the engineering properties of the soil and reduce the permeability of liner materials. To achieve this, soil samples obtained from Tabriz landfill were combined with varying proportions (3%, 6%, and 9% by weight) of montmorillonite-type nanoclay. The results obtained from various geotechnical tests were analyzed and examined. To assess and compare the performance of nanomaterial additives, a control group (without nanomaterial additives) was also analyzed in parallel to measure the outcomes against the baseline conditions. Based on the test results, the obtained landfill soil underwent grain size and hydrometer tests to determine the particle size characteristics and soil classification. Fig. 4 illustrates the grain size curve from the results of this test, indicating that the investigated soil sample falls into the category of fine-grained soils. According to the results of grain size and hydrometer tests and utilizing the Unified Soil Classification System (USCS), it was determined that the characterized soil belongs to the category of low plasticity clay (CL). It should be noted that the examined sample also contains some silty materials with low plasticity (ML); however, the predominant soil material is clayey.

The USCS is a widely used method for classifying soils based on their physical and mechanical

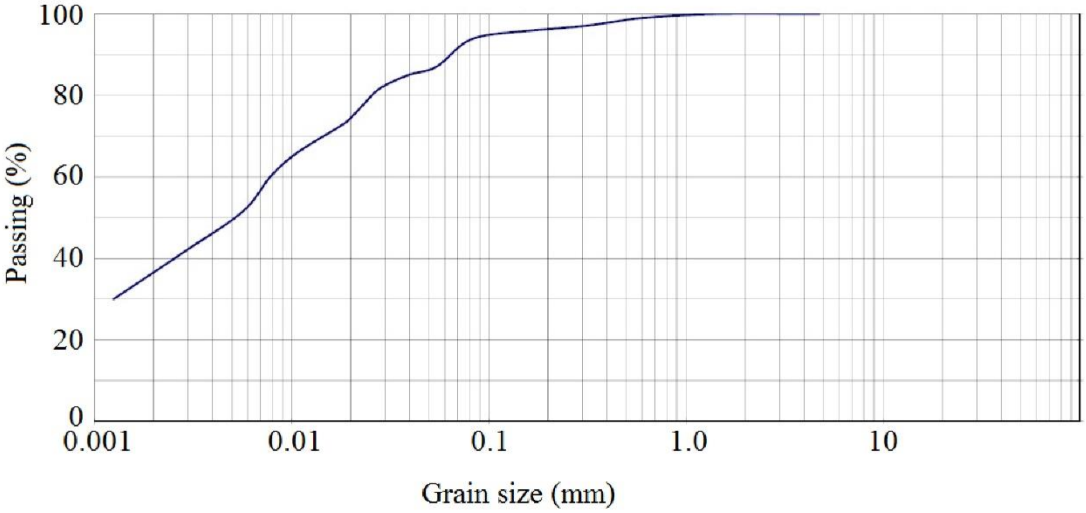

Fig. 4 Particle size distribution curve for studied soil

properties. Developed by the United States Army Corps of Engineers and the Bureau of Reclamation, the USCS provides a systematic way to categorize soils for engineering and construction purposes. It classifies soils into three primary groups: coarse-grained soils (gravels and sands), fine-grained soils (silts and clays), and highly organic soils. Each group is further subdivided based on specific criteria, such as particle size, plasticity, and soil behavior (Ghazifard *et al.* 2016, Nwachukwu and Nwachukwu 2020, Hussain *et al.* 2021). In the context of the USCS, "low plasticity clay" (CL) refers to a specific subgroup within the fine-grained soils category. This classification is based on the plasticity index (PI) of the clayey soil. Plasticity index is a measure of the plasticity or deformability of a soil, which is determined by the difference between the liquid limit (LL) and plastic limit (PL). Soils classified as CL have a plasticity index that falls within a certain range, indicating moderate plasticity. Low plasticity clays exhibit cohesive properties and may undergo minimal volume change when subjected to changes in moisture content. Understanding the soil classification, such as CL, is crucial in geotechnical engineering, as it provides insights into the engineering behavior and potential challenges associated with construction and foundation design in such soils (Wuana *et al.* 2016, Tameh *et al.* 2017).

The ML is a classification within the USCS used to categorize soils based on their physical and mechanical properties. In this context, "silty" refers to the composition of the soil, indicating that it contains a significant proportion of fine particles, such as silts, with relatively small particle sizes.

The designation "low plasticity" in ML is determined by the PI of the soil. PI is a measure of a soil's plasticity or deformability and is calculated as the difference between the LL and PL. Soils classified as ML have a moderate plasticity index, indicating that they exhibit some plastic behavior, but the plasticity is not high. The ML often have characteristics that fall between those of high-plasticity clays and non-plastic or low-plasticity soils. These soils are typically cohesive due to the presence of fine particles, but their plasticity is not as pronounced as in high-plasticity clayey soils. Silty soils are commonly found in various geological settings, and understanding their classification helps in assessing their engineering properties and behavior. In geotechnical engineering, knowledge of the soil's classification, such as ML, is essential for making informed

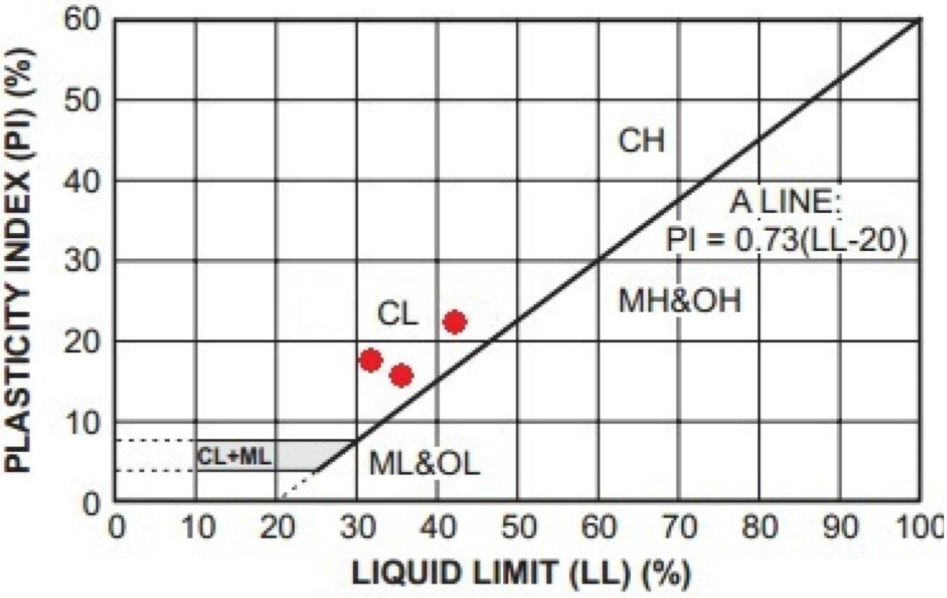

Fig. 5 Plasticity chart of the studied soil

decisions related to construction, foundations, and slope stability. Engineers consider these properties when designing structures to ensure stability and durability in specific soil conditions.

ML and CL play crucial roles in controlling leachate in landfills, offering distinct advantages in waste containment systems. ML, with its unique nanoscale structure, provides an expansive surface area for cation exchange, enhancing its adsorption capacity for cations, heavy metals, and other contaminants present in leachate. This characteristic makes ML effective in mitigating the spread of leachate and preventing its environmental hazards. On the other hand, CL, known for its low plasticity, contributes to the impermeability of landfill liners. The low plasticity of CL indicates that it exhibits minimal volume change with changes in water content, leading to greater stability. When incorporated into landfill liner materials, CL helps create a barrier that restricts the movement of leachate through the liner, minimizing the risk of groundwater contamination and environmental damage. Together, the combined use of ML and CL in landfill liner materials serves as a multifaceted approach to control leachate. ML's adsorption capabilities address the chemical aspects of leachate, while CL's low plasticity enhances the physical integrity of the liner, collectively providing an effective solution for waste containment and environmental protection in landfill systems.

The Atterberg limits tests were conducted on two groups of soil, the control group, and the treated group, to assess the changes in the plasticity characteristics of the soil by adding the investigated nanoclay. The results of the changes in Atterberg limits for different samples are depicted in Fig. 5. The analysis of the obtained results indicates that with an increase in the percentage of nanoclay, the plasticity characteristics of the soil enhance. This impact is more pronounced on the LL compared to other indicators. In general, it can be stated that the plasticity characteristics of the soil, with the addition of nanoclay from 0% to 9%, and considering the sample ages (one, seven, and fourteen days), result in a 48% increase in LL, 33% in PL, and 45% in PI. Based on the achieved outcomes, it can be inferred that the use of nanoclays can lead to

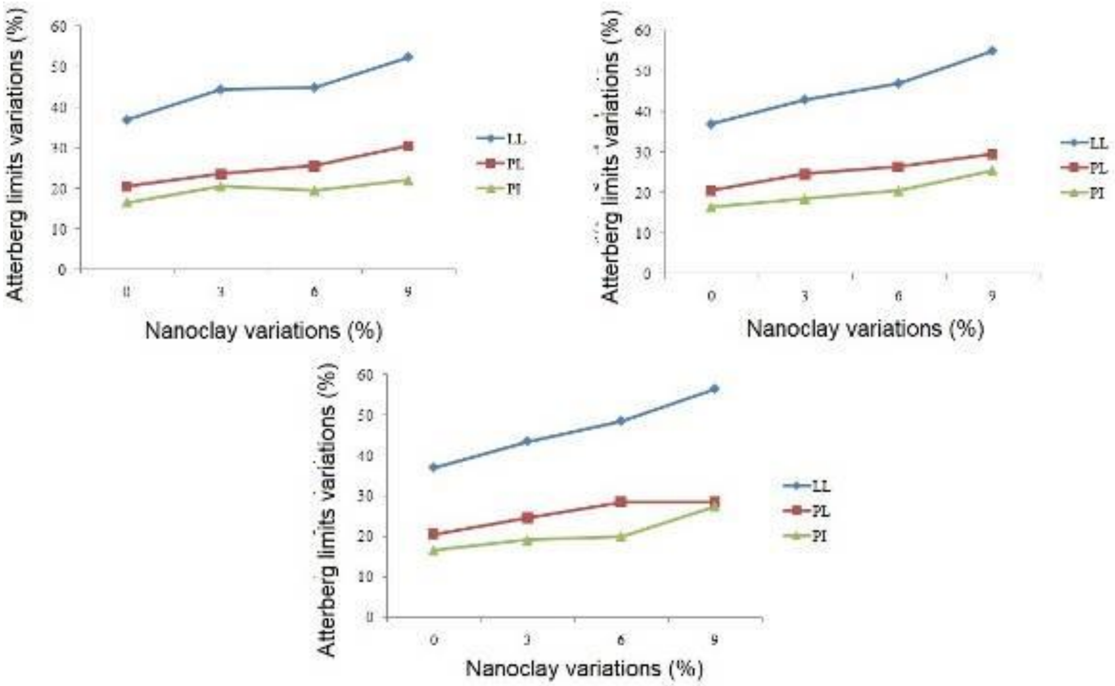

Fig. 6 Atterberg limits variations for studied soil with variety of nanoclay

changes in the surface and chemical properties of the soil. Nanoclays, due to their extremely small size, possess a significantly high surface area. The addition of these nanomaterials to the soil composition increases the cation exchange capacity and specific surface area, consequently enhancing water absorption and the plasticity characteristics of the soil. The soil sample transitions from the medium plasticity category to the high plasticity category. As a result, the soil's tolerance and resistance to deformation caused by various factors, including changes in moisture levels during different seasons, increase, and consequently, the risk of soil cracking decreases.

4.4 Permeability of materials

The permeability test serves as the core focus in this research, aiming to assess the performance of nanomaterials and nanoclay additives in enhancing the optimal functionality of landfill liners to prevent leachate migration. The test employs a falling head permeability approach, specifically utilizing leachate as the substitute fluid for water due to the fine-grained nature of the soil samples. Through this test, the permeability, and the ability to control leachate passage through the soil specimen are evaluated. The testing protocol aligns with the ASTM D5084 standard for falling head permeability. The experiments are conducted on both control and modified samples, and the changes in permeability are individually calculated for each group. Fig. 7 illustrates the variations in permeability for the samples with different percentages of nanoclay, considering the age of the samples ranging from 1 to 14 days. As observed in the figure, the addition of nanoclay leads to a reduction in the permeability of fine-grained soils used in clay liners. By determining the permeability coefficients, it is evident that incorporating nanoclay additives from 0% to 9% over

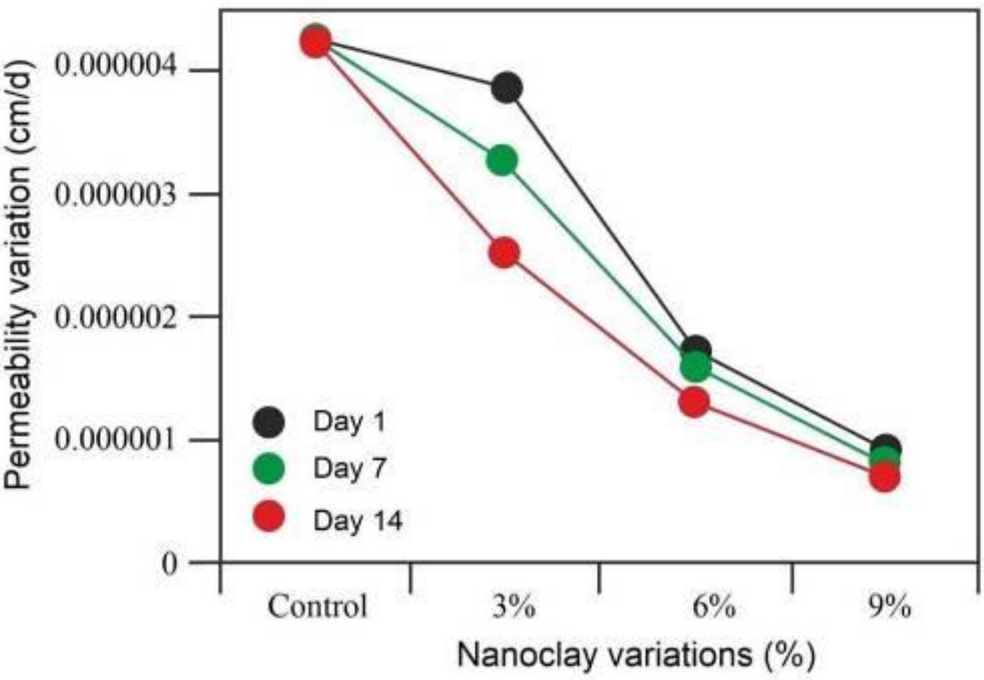

Fig. 7 Permeability variation calculated for the samples with the variety of nanoclay

14 days results in a decrease from 4.25 × 10^{-4} cm/day to 5.6 × 10^{-6} cm/day, representing a 98% reduction and falling within the acceptable permeability range for liners. This highlights the success of employing nanoclay in reducing the permeability of the clay soil used in Tabriz landfill liners. Therefore, the enhancement of liner materials with nanoclay can significantly improve their performance, endowing the modified liners with effective containment and prevention capabilities against leachate migration.

The presence of heavy metal substances in leachate (Table 1) leads to the contamination of the surrounding soil compost. Lead, arsenic, and zinc are among the most hazardous heavy metals. Consequently, the interaction of leachate with the soil results in the contamination of adjacent soils with these metals. Without proper containment, these contaminants may infiltrate surface and groundwater, leading to pollution of water and surrounding soils. Due to the toxic and carcinogenic nature of these metals, their penetration into groundwater poses a severe threat to human health (Panchal *et al*. 2018). Lead induces various harmful biological effects, impacting fetuses and infants more than adults, causing kidney problems and harm to joints and the nervous system. Fig. 8 examines the adsorption and containment effects of montmorillonite nanoclay additive in leachate-containing soil concerning lead levels. The results indicate approximately 72% lead absorption with a 9% nanoclay additive.According to medical research, arsenic can cause gastrointestinal discomfort and increase the risk of skin, lung, and bladder cancer. Fig. 9 illustrates the arsenic levels in the soil before and after the addition of montmorillonite nanoclay. As per the obtained results, the addition of 9% nanoclay leads to the absorption of 53% of the arsenic present in the leachate. This highlights the potential of nanoclay additives in mitigating the harmful effects of heavy metals, emphasizing their role in adsorption, and reducing the environmental impact of

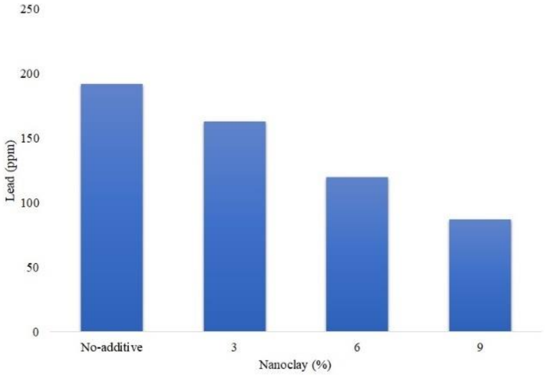

Fig. 8 Leachate lead changes in different nanoclay treatments

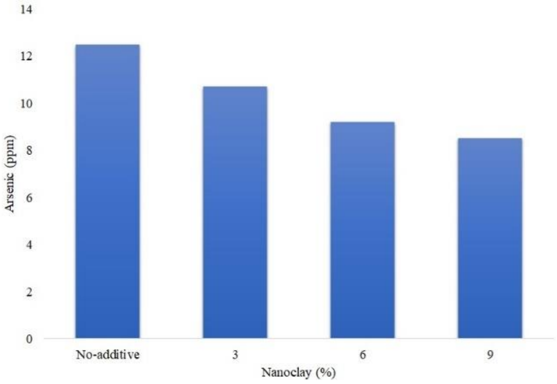

Fig. 9 Leachate arsenic changes in different nanoclay treatments

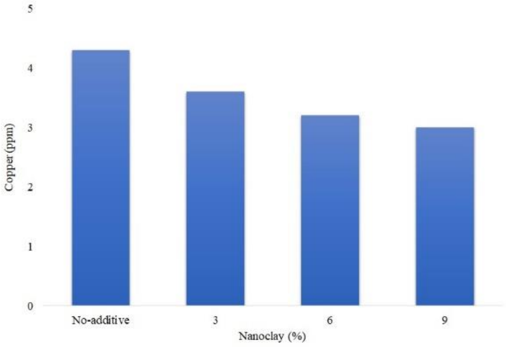

Fig. 10 Leachate copperchanges in different nanoclay treatments

leachate-contaminated soils. Other materials variations provided in Figs. 10 to 17 which considered the impact of nanoclay additive to mitigate the heavy metal distribution in studied samples.

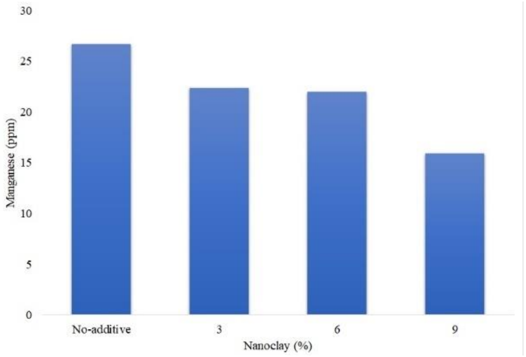

Fig. 11 Leachate manganese changes in different nanoclay treatments

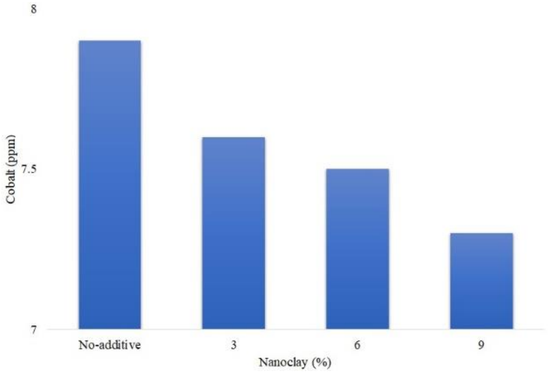

Fig. 12 Leachate cobaltchanges in different nanoclay treatments

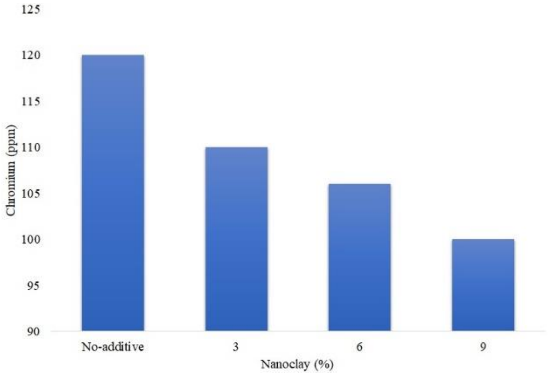

Fig. 13 Leachate chromiumchanges in different nanoclay treatments

4.5 Leachate properties

Table 3 displays some additional characteristics of the leachate examined in this study. This table provides an overview of the specific qualities of the Tabriz landfill leachate, presenting key

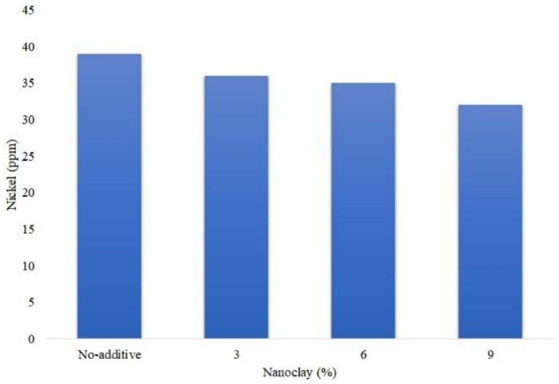

Fig. 14 Leachate nickelchanges in different nanoclay treatments

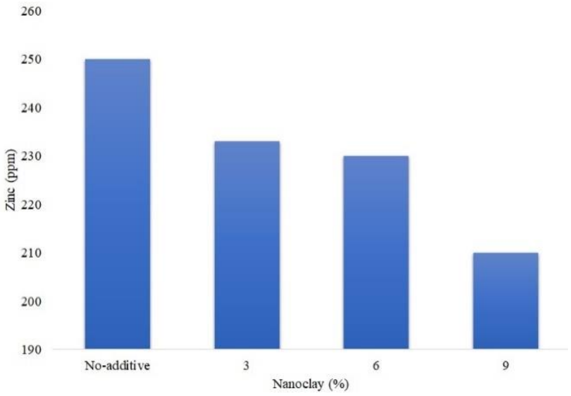

Fig. 15 Leachate zinc changes in different nanoclay treatments

parameters determining leachate quality such as pH, total suspended solids (TSS), biochemical oxygen demand (BOD), and chemical oxygen demand (COD). TSS, BOD, and COD are important parameters used to assess the quality and potential environmental impact of leachate from landfills. TSS refers to the total amount of solid particles suspended in the leachate, including both organic and inorganic matter. High TSS levels in leachate can indicate the presence of colloidal particles, silt, and other materials that may adversely affect water quality. Excessive TSS can lead to sedimentation, reduced light penetration, and increased turbidity in receiving waters, impacting aquatic ecosystems. BOD is a measure of the amount of oxygen required by microorganisms to decompose organic matter present in the leachate. High BOD levels indicate a higher concentration of biodegradable organic substances. As microorganisms break down these organics, they consume oxygen, potentially leading to oxygen depletion in water bodies. Low oxygen levels can harm aquatic life and disrupt the balance of ecosystems, causing issues like fish kills and the release of unpleasant odors. COD measures the amount of oxygen required to chemically oxidize both biodegradable and non-biodegradable organic compounds in the leachate. It provides a broader assessment of organic pollutant levels than BOD. High COD levels suggest a greater concentration of complex organic compounds that may not be easily biodegradable. Elevated COD can contribute to oxygen demand, impacting water quality similarly to BOD. In the context of

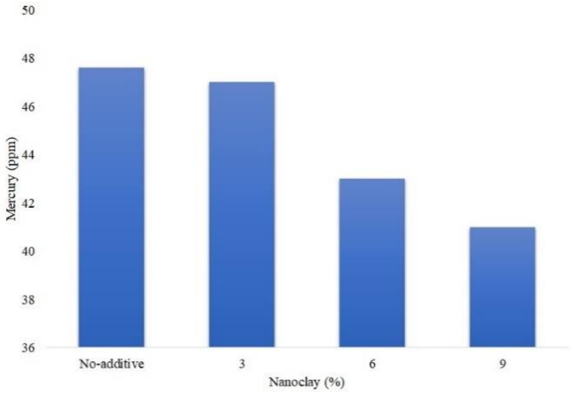

Fig. 16 Leachate mercury changes in different nanoclay treatments

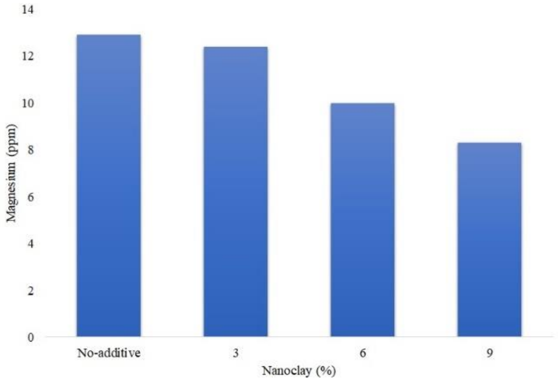

Fig. 17 Leachate magnesium changes in different nanoclay treatments

landfills, monitoring TSS, BOD, and COD in leachate is crucial for assessing the potential environmental risks associated with the discharge of contaminated water. Effective management of leachate is essential to prevent the pollution of surrounding soil, groundwater, and surface water bodies, safeguarding ecosystems, and public health. Regular monitoring of these parameters helps authorities implement appropriate treatment measures and ensure compliance with environmental regulations.

To evaluate the capability of nano-clay particles in treating leachate and determine their impact on altering leachate components in different nano-clay treatments, analysis of variance (ANOVA) has been employed. In Fig. 18, the effects of various percentages of nano-clay additive montmorillonite in the soil matrix are examined concerning the adsorption of COD in the leachate.

The results in Table 4 regarding CODindicate a statistically significant difference in the calculated F-value with degrees of freedom 4 and 10 being less than 0.05 ($P > 0.05$, $F = 247.68$), providing 95% confidence that the changes in COD among different treatments are significant. BOD is a crucial indicator for assessing biodegradable organic matter, commonly used in wastewater analysis. This method allows the calculation of oxygen required for the oxidation of organic substances by bacteria. Measurement of the available oxygen also enables the determination of the concentration of biodegradable organic matter in wastewater. The BOD value

Table 3 Potential environmental impact quality elements of Tabriz waste leachate

Leachate sample	pH	TSS (mg/l)	DO (mg/l)	COD (mg/l)	BOD (mg/l)
LS1	7.22	60	3.25	17125	8060
LS2	7.13	75	3.28	17659	8049
LS3	7.20	73	3.33	17030	8023
LS4	7.22	60	3.25	17125	8020
LS5	7.17	63	3.30	17200	8060
LS6	7.22	75	3.28	17659	8049
LS7	7.13	73	3.33	17030	8023
LS8	7.13	73	3.33	17030	8023
LS9	7.13	73	3.33	17030	8023

Table 4 Results of leachate COD and BOD variance analysis

Variations	Sum of squares	Freedom degree	Mean square	F factor	Meaningfulness
			COD		
Different treatments	455621.00	4	11395.12	247.68	0.001
Replicates	45988.33	10	4598.33	-	-
Total	501609.33	14	15993.45	247.68	0.001
			BOD		
Different treatments	11296.44	4	28241.17	278.66	0.001
Replicates	59000.30	10	5900	-	-
Total	70296.74	14	34141.17	278.66	0.001

represents the oxygen consumption during the five-day oxidation of wastewater at a temperature of 20 degrees Celsius. As shown in Figure 19, the examination of changes in BOD in leachate passing through various nano-clay treatments indicates a reduction in this parameter for all treatments. Also, the results in Table 4 regarding BOD also indicate a statistically significant level, with the calculated F-value and degrees of freedom being less than 0.05 ($P > 0.05$, $F = 478.66$). With 95% confidence, it can be stated that the variations in BOD among different treatments are significant.

Liners play a crucial role in landfill management by acting as barriers that prevent leachate from infiltrating surrounding soil and groundwater. Effective liners help contain the harmful substances within the landfill, reducing the risk of contamination to nearby ecosystems and water resources. By creating a barrier between the waste and the environment, liners mitigate the potential for leachate to spread and cause widespread pollution, thereby safeguarding public health and environmental quality. Moreover, liners contribute to the long-term stability and integrity of landfill structures, helping to minimize the risk of structural failure and environmental disasters. By preventing leachate from seeping into the underlying soil layers, liners help maintain the structural integrity of the landfill, reducing the likelihood of slope instability, erosion, and subsidence.

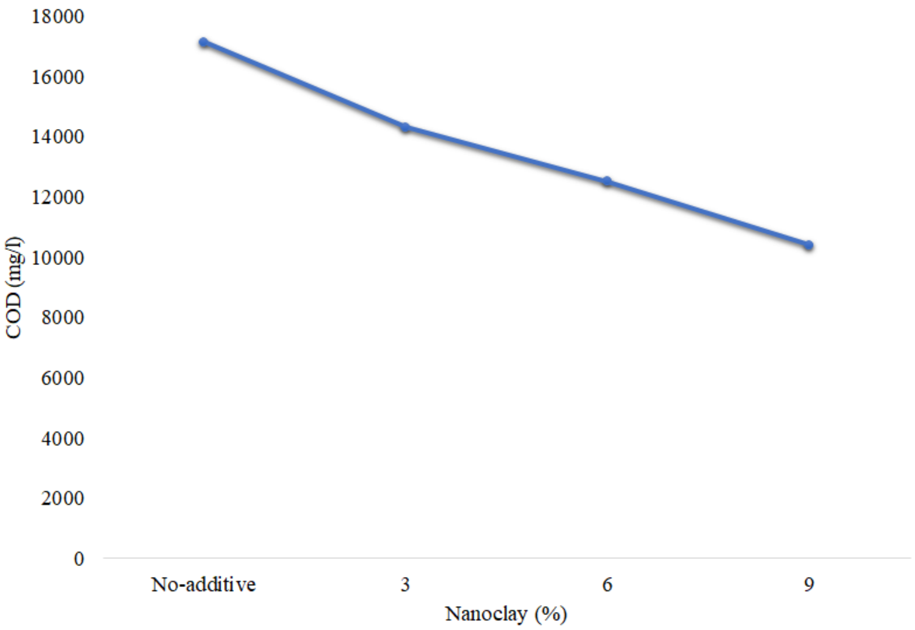

Fig. 18 COD variations of leachate in different nanoclay treatments

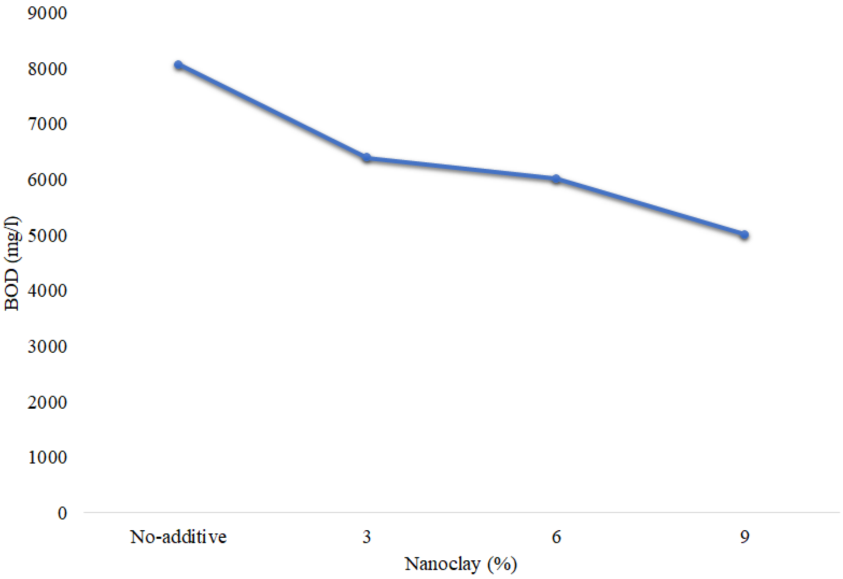

Fig. 19 BOD variations of leachate in different nanoclay treatments

This ensures the safe containment of waste materials over time, minimizing the risk of catastrophic events such as landslides or the release of hazardous contaminants into the surrounding environment. Furthermore, the implementation of liners facilitates more efficient and effective leachate management practices, enhancing overall operational efficiency and regulatory compliance. By reducing the volume and mobility of leachate within the landfill, liners streamline leachate collection and treatment processes, making it easier to monitor and mitigate potential environmental impacts. This not only helps landfill operators meet regulatory requirements but also contributes to sustainable waste management practices by minimizing the environmental footprint of landfill operations and reducing the potential for adverse impacts on surrounding communities and ecosystems.

5. Conclusions

Landfills serve as the ultimate destination for waste disposal, including human, industrial, and various production waste. Over time, municipal solid wastes, typically disposed of conventionally through burial, generate a viscous liquid known as leachate due to the decomposition and breakdown of waste materials. Depending on the nature of the waste, leachate has a high potential for environmental pollution, posing threats through infiltration and contamination of soil and water resources, leading to significant ecological and human disasters. The primary solution to address this issue lies in the design and implementation of engineered landfills to prevent the proliferation of waste and leachate in the environment. The crucial responsibility for controlling and mitigating leachate expansion lies with landfill liners, and their optimal performance directly correlates with increased leachate control and reduced environmental pollution.

This study endeavors to introduce an innovative approach based on nanomaterial technology, specifically clay nanoparticles, to enhance the performance of landfill liners. A series of geotechnical experiments, including grain size analysis, hydrometer analysis, Atterberg limits, and permeability tests, were conducted on soil samples collected from the Tabriz landfill site. The samples, prepared in two groups as control and treated with Montmorillonite nanomaterial at weight percentages of 3%, 6%, and 9%, underwent testing with curing periods of 1, 7, and 14 days. Based on the evaluation results, the addition of nanomaterials to the soil matrix at 9% with a 14-day curing period increased the Atterberg limits, including LL, PL, and PI, by approximately 48%, 33%, and 45%, respectively. The permeability coefficient of the control soil sample decreased by 98% compared to the sample treated with 9% nanomaterial. Considering that the voids between soil layers provide pathways for moisture or leachate infiltration, the addition of nanomaterials, particularly those with silicate layers, facilitates the purification of leachate passing through these pathways, effectively adsorbing heavy metals from industrial leachates. Consequently, the concentration of the hazardous element lead in leachate reduced by 72%, reaching less than 60 ppm, while arsenic decreased by 53%, dropping below 5.5 ppm in various nanomaterial treatments. Moreover, COD and BOD, crucial parameters for wastewater assessment, showed a remarkable reduction to 5000 mg/lit and 10391 mg/lit, respectively, in nanomaterial-treated samples, indicating significant decreases in pollution levels. Future research in the realm of landfill leachate control could explore various avenues to enhance the effectiveness and sustainability of nanoclay additives. Firstly, investigating different types of nanoclay additives beyond Montmorillonite could offer insights into alternative materials that may exhibit superior properties for landfill liner applications. Exploring the performance of nanoclay additives with different chemical compositions and structures could lead to the development of optimized formulations tailored to specific landfill environments and waste compositions. Additionally, assessing the long-term effects of nanoclay additives on landfill liner performance is crucial for understanding their durability and stability over extended periods. Long-term studies could evaluate the mechanical, hydraulic, and chemical properties of nanoclay-enhanced liners under realistic landfill conditions, providing valuable data on their resilience to aging, degradation, and environmental exposure. Understanding how nanoclay additives perform over time is essential for ensuring the longevity and reliability of landfill liner systems in effectively controlling leachate migration.

Acknowledgments

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