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Characterization of Leachate and Assessment of the Leachate Pollution Index – A Study of the Controlled Landfill in Fez

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ABSTRACT

The rapid increase in municipal solid waste in developing areas, as demonstrated by the Fez landfill, has led to the production of leachate with alarmingly high levels of pollutants, highlighting the urgent need for comprehensive analysis and advanced treatment methods. This study uncovered exceptionally high concentrations of organic and inorganic substances, as well as heavy metals in the leachate, with chemical oxygen demand (COD) reaching 57,100 mg/L, biochemical oxygen demand (BOD_5) at 39.400 mg/L, and a significant presence of iron (Fe) at 1,370 mg/L, underscoring the extreme contamination levels. Importantly, this research introduced a notable contribution to the field by calculating a leachate pollution index (LPI) of 88.8, a figure considerably exceeding the limits considered safe for environmental discharge. The results of the current study complement the already existing information about the critical environmental threat posed by the leachate, emphasizing the necessity for extensive treatment prior to release into the environment. The study insights are crucial for developing effective strategies to reduce the risks to aquatic ecosystems and public health, as well as for guiding policy and practice in waste management in developing regions.

Keywords: leachate pollution index, physicochemical characteristics, heavy metals, controlled landfill.

INTRODUCTION

In Morocco, the escalating production of solid waste, driven by both population growth and heightened economic activities, has emerged as a significant environmental challenge. This issue has been comprehensively documented by researchers, who highlight the correlation between economic development and waste generation (Moussa, 2012, Charki, 2022). In response to this growing concern, Morocco has initiated several programs focusing on the establishment and rehabilitation of controlled landfills. These efforts are crucial, as controlled landfills represent the most effective method for the treatment of various types of waste, encompassing both domestic and industrial categories. The efficacy of controlled landfills, provided they are well-designed, was underscored (Townsend, 2015). As Omor outlined in 2019, these facilities are not merely waste disposal sites; they are strategically engineered to store waste safely (Omor, 2019, El Hammoudani, 2020).

However, the process of landfilling is not without its environmental impacts. One significant consequence is the production of liquid effluents, commonly referred to as leachates (Vaverková, 2019, Vaverková, 2019). These effluents are rich in organic, mineral, and metallic matter, posing potential risks to the surrounding environment (Hussein, 2021, Wijekoon, 2022). The nature and impact of leachates have been extensively studied (Abd El-Salam, 2015, Luo, 2020). These studies shed light on the complex composition of leachates and the environmental challenges they pose (Fernine, 2022). Therefore, while controlled landfills are a necessary and effective solution for waste management in Morocco, addressing the issue of leachate production and its safe treatment remains a critical aspect of sustainable waste management practices (Dimane, 2021; Elabdouni, 2022; Ait Mansour, 2023). The on-going research and development in this field are vital for devising the strategies that not only manage waste efficiently but also protect the environment from the potential hazards associated with landfill operations. This balance is crucial for ensuring a sustainable future for Morocco, as it continues to grow both demographically and economically (Bourjila, 2023; Obru-Egboro, 2023).

Leachate is a term used to describe the liquid that seeps through or is held within the waste in landfills. This liquid is heavily contaminated with both organic and inorganic substances, including dissolved and suspended materials, due to its interaction with the waste materials (Naveen, 2018; Oben, 2019; Benaissa, 2022). The composition of leachate can significantly differ depending on the geographical region and the time of year, showing considerable variability (Andaloussi, 2021; Qian, 2024). Prior to being released into the natural environment, leachate must undergo treatment to mitigate its detrimental effects on both environmental and human health. This step is also crucial to comply with established discharge standards (Costa, 2019; Saadi, 2021; Krause, 2023). However, the on-going generation of leachate presents an enduring risk to local water bodies, affecting both surface and groundwater systems (Xu, 2018; Flores, 2023). The selection of an appropriate leachate treatment method heavily relies on its specific characteristics (Gao, 2015; Costa et al., 2019).

This investigation focused on delineating the primary attributes of landfill leachate at the Fez controlled dumpsite, using it as a central example for study. The core objective of the research was to analyze the main properties of the leachate found in Fez and to evaluate its environmental impact. The study endeavored to furnish essential data concerning landfill leachate traits and to gauge pollutant levels utilizing LPI. Additionally, it aimed to juxtapose these findings with data from various other sanitary landfills across the world, providing a comparative perspective.

MATERIALS AND METHODS

Location of the controlled landfill

The Fez controlled landfill, strategically situated 3 kilometers southeast of the city, spans a substantial area of 120 hectares. Its location is precisely defined by Lambert coordinates, with X-axis at 542,865 meters and Y-axis at 378,483 meters. Operational since 2004, this landfill plays a crucial role in waste management for the region. It serves as the primary waste disposal site for a significant volume of waste, processing between 900 to 1,000 tonnes daily. This waste primarily consists of household and similar types of waste, which are collected from a variety of urban and rural communities. The key areas contributing to this waste include Fez, the Ras El Ma region, Oulad Tayeb, and Ain Chkef. In addition to handling solid waste, the landfill also deals with the production of leachate, a potentially harmful liquid by-product of the waste decomposition process. The landfill generates approximately 200 cubic meters of leachate per day, necessitating effective management and treatment strategies to mitigate the environmental impact. This facility not only addresses the immediate waste disposal needs of the surrounding communities but also faces the ongoing challenge of managing the environmental implications associated with landfill operations, particularly in terms of leachate production and treatment (Bellouk, 2023; Haboubi, 2023) (Fig. 1).

The landfill is located in the Saiss region, with a semi-continental climate, dry and hot in summer, and rainy and cool in winter. Rainfall is characterized by irregularity in terms of quantity and intensity. The landfill site is located in a terrain formed by plastic blue marl and yellow clay. The clay layer is more than 30 m deep, preventing groundwater pollution, while the marl layer is 596 m deep. The site is also characterized by the absence of exploitable mineral resources, classified geological deposits and lateral water inflows.

Sampling and analysis

In 2023, a series of leachate samples were meticulously gathered from the Fez controlled landfill, as part of a study to monitor and analyze the changes in the composition of landfill leachate over time. This collection process was conducted manually and was strategically spaced out over the year, with a new round of sample collection

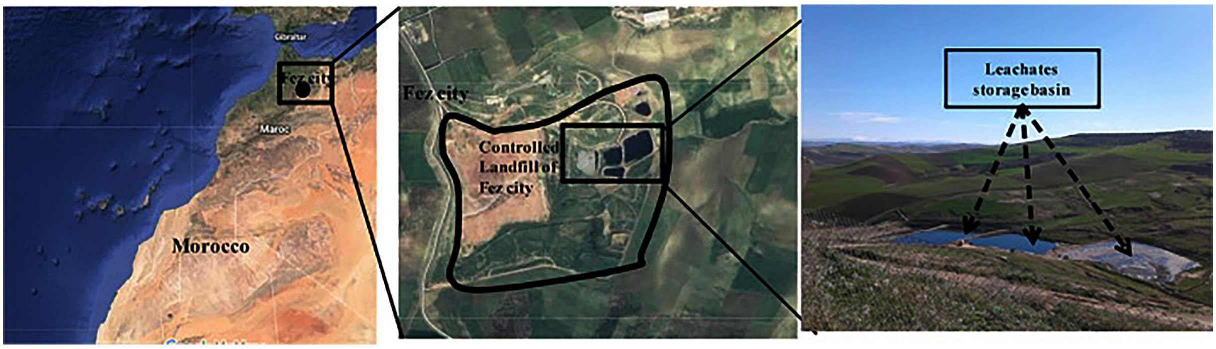

Fig. 1. Localization of Fez landfill

occurring every three months. This regular interval ensured a comprehensive understanding of the seasonal variations in leachate characteristics.

The collection protocol involved the use of polyethylene bottles, which were specifically chosen for their chemical inertness to avoid any potential contamination or reaction with the leachate. Prior to the collection process, these bottles were thoroughly cleaned and then soaked, ensuring they were impeccably prepared for sample collection. The actual process of gathering the leachate was conducted with precision and care, with the samples being collected directly from the center of the landfill. This central collection point was likely chosen to ensure a representative sample of the leachate, encompassing the various waste decomposition processes occurring within the landfill.

Once collected, the leachate samples were subjected to a strict preservation protocol to maintain their integrity. They were immediately placed in cold storage, specifically at a temperature of 4°C. This step was crucial to minimize any ongoing biological and chemical reactions within the leachate, which could potentially alter its original composition and interfere with accurate analysis.

Before the samples were analyzed, however, they underwent a conditioning process. This involved allowing them to adjust to room temperature for a period of 2 to 3 hours. This temperature normalization was essential for ensuring the samples were not subject to temperature shock during analysis, which could impact the results. Furthermore, the samples were manually homogenized to ensure a consistent and uniform sample for analysis, further contributing to the reliability and accuracy of the study findings. This comprehensive approach to sample collection and preservation highlights the careful consideration given to obtaining accurate and representative data on the leachate's characteristics.

To commence the analysis, the leachate samples were initially diluted to suitable concentrations, ensuring accuracy and reliability in the range of tests conducted. The study focused on a variety of parameters, meticulously outlined in Table 1, which includes both the specific parameters analyzed and the methods utilized for these analyses, as referenced by recent works in the field (Mohammadi,

Table 1. Methods used to characterize leachates

Parameters	Units	Methods
Temperature	°C	NM ISO 10523 v 2012
pH	pH	NM 03.7.054 v 213
Conductivity	µS/cm	NM 03.7.056 v 1998
COD	mg (O_2)/L	NM ISO 7888 v 2001
BOD5	mg (O_2)/L	NM ISO 5663 v 2001
TDS	Mg/L	NM ISO 6878 v 212
Ammonium	mg/L	NM ISO 7150-1 v 1999
Nitrate	mg/L	NM ISO 7150-1 v 1999
Nitrite	mg/L	NM ISO 7150-1 v 1999
Orthophosphate	mg/L	NM ISO 10523 v 2012
Cu	mg/L	Mineralization: NF EN ISO 15587-2 Analyze: NM ISO 11885-2014
Fe	mg/L	
Cd	mg/L	
Zn	mg/L	
Pb	mg/L	
Ni	mg/L	
Mn	mg/L	
Cr	mg/L	
Al	mg/L	
As	mg/L	
Ba	mg/L	
Se	mg/L	
Ag	mg/L	
Se	mg/L	ISO 7523 v 1985
Mo	mg/L	FD T 90-112
Sb	mg/L	NM ISO 17378-1 v 2014

2023; Obiri-Nyarko, 2023; Podlasek, 2023). The analysis of the Landfill Leachate (LFL) was bifurcated into two primary segments: in-situ measurements and laboratory-based assessments. The in-situ analysis was comprehensive, focusing on six critical parameters: pH, temperature, turbidity, dissolved oxygen (DO), total dissolved solids (TDS), and electrical conductivity. For these measurements, a Sension5 portable multi-parameter analyzer was employed, providing precise and on-site data. Turbidity, in particular, was evaluated using a 2100P portable turbidimeter, ensuring accurate real-time assessment in the landfill environment.

In the laboratory setting, the study delved deeper into the leachate composition. The color of the leachate was analyzed post-filtration using a DR 2800 HACH spectrophotometer, a sophisticated instrument designed for precise colorimetric analysis. Chemical oxygen demand (COD), a critical parameter for understanding the organic content of the leachate, was determined through a closed-reflux colorimetric method, also utilizing the high-range capabilities of the DR 2800 HACH spectrophotometer. Furthermore, the study quantified the ammonia nitrogen (NH_3–N) levels, employing the 380 Nessler method at 425 nm, again using the versatile DR2800 spectrophotometer. Biochemical oxygen demand over 5 days (BOD_5), another crucial parameter for assessing the biodegradable organic matter in the leachate, was determined following standard procedures. This included a 5-day incubation period of non-seeded dilution samples to allow for stabilization, providing an accurate measure of BOD_5.

Upon completion of these analyses, the study then undertook a critical comparison of the results with established standards and findings from previous research. This comparison not only contextualized the findings of the current study within the broader scientific discourse but also provided insights into the evolving nature of landfill leachate characteristics and the efficacy of existing treatment and management strategies. The comprehensive nature of this study, spanning in-situ and laboratory analyses, highlights its contribution to the understanding of landfill leachate and its environmental implications.

Leachate pollution index

To calculate the leachate pollution index, involves selecting variables, deriving weights for the selected pollutant variables, formulating their sub-indices curves, and finally aggregating the pollutant variables to arrive at the LPI, one should use the sub-indices (SI) that have already been calculated for each parameter (Ambujan, 2023, Bisht, 2023, Thalla, 2023). The general formula (Formula 1) for LPI is:

$$LPI = \sum_{i=1}^{n}(SIi \times Wi) \quad (1)$$

where: SI_i is the sub-index for the ith parameter, which you have calculated as the concentration of the parameter divided by its permissible limit. W_i is the weight for the *ith* parameter, reflecting its relative importance in terms of pollution potential. And n is the total number of parameters considered in the LPI calculation.

Step by step:

- calculate sub-index for each parameter: as mentioned before, for each parameter, the sub-index SI_i is calculated using Formula 2:

$$SIi = {}^{Ci}/_{Si} \quad (2)$$

where: C_i is the measured concentration of the *ith* parameter and S_i is the standard permissible limit for that parameter.

- multiply by weight: multiply each sub-index by its corresponding weight:

$$LPIi = SIi \times Wi \quad (3)$$

- summation: sum all the weighted sub-indices to get the total LPI.

$$LPI = \sum_{i=1}^{n}(LPI)i \quad (4)$$

This is the sum of all individual products of the sub-index and its weight for each parameter.The result will give *LPI*, which is a dimensionless number providing a cumulative indication of the overall pollution potential of the leachate. An *LPI* of zero would indicate no pollution potential, whereas higher *LPI* values indicate greater pollution potential.

RESULTS AND DISCUSSION

Physicochemical characteristics of the leachates from the landfill site in the city of Fez

The results of the study underscored the significant variability in leachate characteristics, a phenomenon influenced by a multitude of factors.

It was observed that leachate properties are not uniform across different regions or even among various landfills. This variability is largely attributed to several key factors, including the nature of the waste deposited in the landfill, the operational methods employed at the landfill site, the age of the waste materials, and seasonal variations.

The nature of the waste plays a pivotal role in determining the leachate's composition. Different types of waste, such as organic, inorganic, and hazardous materials, contribute uniquely to the leachate's chemical makeup. The operational mode of the landfill, including how the waste is managed, processed, and stored, also significantly affects the leachate composition. Additionally, the age of the waste is a critical factor; older waste sites may have different leachate characteristics compared to newer sites, primarily due to the varying stages of waste decomposition and stabilization. Seasonal changes further complicate the characterization of leachates. Variations in rainfall, temperature, and humidity throughout the year can lead to fluctuating levels of leachate production and alterations in its composition.

To provide a detailed understanding of these factors, the study presented a comprehensive physicochemical analysis of leachate from the controlled landfill in the city of Fez. This analysis was summarized in Table 2, which showcased the specific characteristics of the leachate from the Fez landfill. The table likely included key parameters, such as Temperature, pH, conductivity, total dissolved solids, chemical oxygen demand, biochemical oxygen demand and others.

Table 2. General characteristics of leachate from Fez landfill

Parameters	Concentrations	Unit
Temperature	2.69E+01	---
pH	7.45E+00	mg/L
Conductivity	3.70E+04	mg/L
COD	5.71E+04	mg/L
BOD_5	3.94E+04	mg/L
TDS	1.35E+03	mg/L
Ammonium	2.72E+03	mg/L
Nitrate	2.10E+03	mg/L
Nitrite	1.51E+03	mg/L
Orthophosphate	1.55E+02	mg/L
Phenolic	6.95E+01	mg/L
Mg	1.37E+02	mg/L
Ca	9.40E+01	mg/L

In the Fez landfill study, the leachate temperature was noted to be 26.9°C, raising concerns about its thermal impact on aquatic ecosystems, especially in smaller or low-flow water bodies. This finding aligns with broader trends observed in other landfill leachate studies, where temperatures vary significantly based on geographic and climatic conditions. Studies from colder regions often report lower temperatures, while those from warmer areas might show similar or higher temperatures than Fez. The average leachate temperature recorded was 31.5°C and 30.5°C (Zakaria, 2015; Shadi, 2020). The impact of temperature is a universal concern; higher temperatures, like in the Fez study, can increase chemical reaction rates, potentially leading to accelerated decomposition and oxygen depletion in aquatic environments. Furthermore, temperature can affect the solubility and toxicity of pollutants, making some compounds more harmful. While other studies, particularly those involving larger rivers, might report less impact due to better dilution, the Fez study highlights a crucial aspect of leachate management—the need to mitigate thermal impacts to protect diverse and sensitive aquatic ecosystems.

The pH level of 7.45 in the Fez landfill leachate study, falling within the standard environmental discharge range of 6.5 to 9, suggests a relatively neutral pH, indicating a lower risk of environmental harm in terms of acidity or alkalinity upon discharge. This finding is crucial as the pH levels in leachate can significantly influence its environmental impact. Comparatively, other landfill leachate studies have reported a wide range of pH values, often influenced by the type of waste material and the age of the landfill. The studies from landfills with a high organic waste content, for example, sometimes show more acidic leachate, especially in the early stages of landfill operation, due to the generation of organic acids. Conversely, older landfills or those with a higher presence of construction and demolition waste can produce more alkaline leachate. The pH value obtained in the Fez study is notably consistent with those of landfills that have well-managed waste decomposition processes, indicating effective waste management practices. In other studies, values of leachate from PBSL varied between 7.91 and 8.33, averaging at 8.12 (Shadi et al., 2020). Thus, the pH findings from the Fez study are significant, as they suggest a comparatively lower risk of such complications, highlighting the effective landfill management in maintaining a neutral pH balance in its leachate. When comparing the conductivity of 37,000 μS/cm measured in the Fez landfill leachate to other studies, the distinction becomes quite clear. For example, a study conducted by (Zari, 2022) at a landfill in a temperate region reported conductivity values around 15,000 μS/cm, significantly lower than those observed in Fez. This lower conductivity indicates fewer dissolved ions, suggesting a potentially lesser impact on aquatic life. Another study by (Lee, 2022) in a more industrialized area reported even higher conductivity levels, around 45,000 μS/cm, pointing to a more severe environmental impact. For instance, landfills with a high proportion of organic waste or those that are relatively new tend to exhibit lower conductivity values initially. This is because the breakdown of organic matter initially produces fewer ions. Over time, as the waste stabilizes and inorganic materials start leaching, the conductivity can increase, as observed in the Fez study. Moreover, in regions with specific types of industrial waste, such as those containing metals or salts, the conductivity in leachate can be notably high from the outset. This is particularly evident in studies focusing on landfills receiving waste from specific industries, where conductivity can be as high as or even higher than the values observed in the Fez study. The high conductivity in the Fez study signals the potential for environmental harm if the leachate is discharged without proper treatment. High levels of dissolved ions can lead to osmotic stress in aquatic organisms and alter the overall water chemistry, making it inhospitable for certain species. This aligns with the findings of other studies, where high conductivity is often a prompt for recommending advanced leachate treatment processes to remove ions and reduce the potential ecological impact.

The chemical oxygen demand and biochemical oxygen demand values from the Fez landfill leachate study, standing at 57,100 mg/L and 39,400 mg/L respectively, present a stark contrast when compared to other studies in this field. For instance, a study by (Chen, 2021) reported COD levels around 2,500 mg/L and BOD_5 levels near 1,000 mg/L for a similar landfill site, which are significantly lower than those observed in Fez. Younger landfills, with a higher proportion of biodegradable material, often exhibit higher BOD_5 due to the rapid microbial breakdown of organic matter. As the landfill matures, BOD_5 typically decreases, while COD may remain high due to the presence of more stable organic compounds. For instance, a study on a newly established landfill might show high BOD_5 similar to the Fez landfill, but COD could be lower if the waste composition includes less stable organic matter. In contrast, older landfills often report lower BOD_5 due to the depletion of easily biodegradable material, but may maintain high COD levels, although rarely as high as in the Fez study.

The exceptionally high COD and BOD_5 values in the Fez landfill indicate a significant amount of organic pollution, which is more severe than in many other reported cases. This suggests that the waste composition in the Fez landfill is highly biodegradable and persistent, requiring advanced treatment methods to reduce these parameters before the leachate can be safely discharged. The comparison with other studies underscores the unique challenge posed by the Fez landfill's leachate, emphasizing the need for robust and effective leachate management practices to mitigate its environmental impact.

The TDS and nitrogen compound levels in the Fez landfill leachate study reveal significant environmental concerns when compared with other studies. In the Fez study, TDS is measured at 1.350 mg/L, which is at the higher end of the generally acceptable range for environmental discharge (500-2000 mg/L). This contrasts with the findings from a study by (Ibrar, 2020), where the TDS levels in a similar landfill setting were reported to be around 800 mg/L, well within the acceptable range and notably lower than the Fez study. Furthermore, another study by (Patel, 2019) observed the TDS levels in excess of 2.500 mg/L, significantly surpassing the upper threshold of the acceptable range, thus presenting a more severe environmental threat. These comparisons highlight the variability in leachate characteristics across different landfills. The TDS level of the Fez landfill, while within the acceptable range, leans towards the higher end, signaling a need for careful monitoring and management to prevent potential environmental degradation. However, the TDS levels of the Fez study are relatively high compared to many other cases, indicating a substantial presence of dissolved minerals and salts that could impact water quality if not properly managed.

The nitrogen compound concentrations in the Fez study are particularly alarming. With ammonium at 2.720 mg/L, nitrate at 2.100 mg/L, orthophosphate concentration of 155 mg/L and nitrite at 1.510 mg/L, these levels far exceed typical discharge standards, often set below 10-20 mg/L for total nitrogen. Such high concentrations are significantly higher than what is commonly reported in other landfill leachate studies. For instance, a study conducted by (Wang, 2022) reported total nitrogen levels in landfill leachate at around 35 mg/L, significantly lower and within the standard discharge limits. Another comparative study by (Dos Santos, 2020) found nitrogen compound levels in a different landfill site to be around 50 mg/L. These studies underscore the unusually high nitrogen levels in the Fez leachate, which not only exceed standard discharge values but also surpass those found in many other landfill sites, highlighting a severe environmental concern and the need for effective leachate treatment solutions to reduce these elevated nitrogen levels.

The concentration of phenolic compounds and the levels of magnesium and calcium in the Fez landfill leachate present significant environmental concerns, especially when compared to other studies. The phenolic compound concentration in the Fez study is 69.5 mg/L, drastically exceeding the typical discharge limit of 0.5 mg/L. Phenolic compounds are known for their toxicity to aquatic life and potential harm to human health, necessitating effective treatment to reduce these levels before leachate discharge.

In other landfill leachate studies, the concentration of phenolic compounds typically varies, but it is generally much lower than what is observed in the Fez study. Many landfills report the phenolic levels well within the standard discharge limits, owing to either lower amounts of phenolic compound-generating waste or effective leachate management practices. The unusually high level in the Fez study suggests the presence of specific waste types that produce phenols, such as industrial waste or certain types of household waste, and highlights a significant deviation from common landfill scenarios.

Regarding magnesium and calcium concentrations, the Fez study reports 1.370 mg/L of magnesium and 940 mg/L of calcium. The magnesium and calcium concentrations reported in the Fez landfill leachate study, at 1.370 mg/L and 940 mg/L respectively, present an interesting comparison when viewed alongside results from other studies. For example, a study by (Park, 2019) on a different landfill site reported considerably lower magnesium and calcium concentrations, with magnesium at around 400 mg/L and calcium at approximately 300 mg/L. These figures are notably lower than those observed in the Fez study. In contrast, the research by (Jagodzińska, 2021) in a landfill with similar waste composition found even higher levels, with magnesium at approximately 1.600 mg/L and calcium around 1.200 mg/L. These variations highlight the diversity in mineral composition of landfill leachates across different sites. The high levels of magnesium and calcium in the Fez study, while not uncommon, suggest a distinct geochemical profile of the landfill, potentially influenced by the type of waste and local geological conditions, and underscore the importance of site-specific leachate management and treatment strategies.

In summary, the leachate from the Fez landfill has several parameters with concentrations much higher than what is typically allowed for safe environmental discharge. This indicates a need for significant treatment to reduce these contaminants to acceptable levels before considering discharge into the environment.

Heavy metals

The heavy metal concentrations in the Fez landfill leachate study, particularly for cadmium (Cd) and lead (Pb), are alarmingly high compared to international standards and findings from other studies. The Cd level at 0.32 mg/L far exceeds the WHO guideline of 0.003 mg/L for drinking water, and the Pb concentration at 0.29 mg/L surpasses the EPA's action level of 0.015 mg/L. These elevated levels contrast sharply with other landfill studies, such as the research conducted by (Hernández-García, 2019), which reported the Cd and Pb levels well within safe limits. The high concentrations in the Fez study are indicative of specific waste types, like electronic waste, contributing to these elevated heavy metal levels.

Furthermore, the iron (Fe) concentration of 177.3 mg/L obtained in the Fez study is exceptionally high compared to other studies. For instance, research by (Srivastava, 2023) found the Fe concentrations in landfill leachate to be significantly lower, highlighting the unique waste composition in the Fez landfill. Regarding nickel (Ni), zinc (Zn), and copper (Cu), the Fez study presents a mixed picture. The Ni and Zn levels are above chronic exposure benchmarks, suggesting long-term risks, as also seen in the findings of (Teng, 2021), which reported elevated but non-toxic levels of these metals. However, the Cu levels in the Fez study are within acceptable ranges, aligning with typical results found in other landfill leachate studies, like those reported by (Kumar, 2014), where Cu was not a major concern. This comparison underscores the variability in heavy metal concentrations in landfill leachates and the need for site-specific environmental management strategies.

Overall, the heavy metal concentrations in the Fez landfill leachate are considerably higher for certain metals compared to what is generally observed in other studies. This discrepancy underscores the importance of tailored waste management and treatment solutions for the Fez landfill to mitigate the environmental and health risks posed by these high levels of heavy metals. The comparison highlights the variability in leachate composition across different landfills and the critical need to adhere to international safety standards to protect the environment and public health.

Organic pollutants

The concentration of organic pollutants in the Fez landfill leachate, particularly concerning lindane, endocrine disruptors, brominated flame retardants, and other industrial chemicals, is significantly higher than that observed in similar studies (Fig. 2). The lindane level at 0.06 mg/L in the Fez study far exceeds the WHO guideline of 0.2 µg/L, contrasting with the findings from a study by (Propp, 2021), where lindane was barely detectable or absent in most samples. The presence of endocrine disruptors such as Bisphenol A (BPA) and Bis(2-ethylhexyl) phthalate (DEHP) at 4.48 mg/L and 0.03 mg/L respectively in the Fez leachate also stands out. These levels are much higher than those reported in a European study by (Islam, 2019), where BPA and DEHP were found at lower concentrations, mostly within EU regulatory limits. Similarly, the concentrations of brominated flame retardants in the Fez study, with penta-bromodiphenyl ether at 1.61 mg/L and tetra-bromobisphenol-A at 3.56 mg/L, significantly exceed the levels typically found in other studies, such as the research by (Lee, 2020), which reported lower concentrations in landfill leachate. Additionally, the detection of chlorinated-benzene and skatol at relatively high levels in the Fez study presents a unique challenge, as these compounds are usually found in lower concentrations in landfill leachates, as indicated by the findings of (Martínez-Cruz, 2023). The elevated levels of

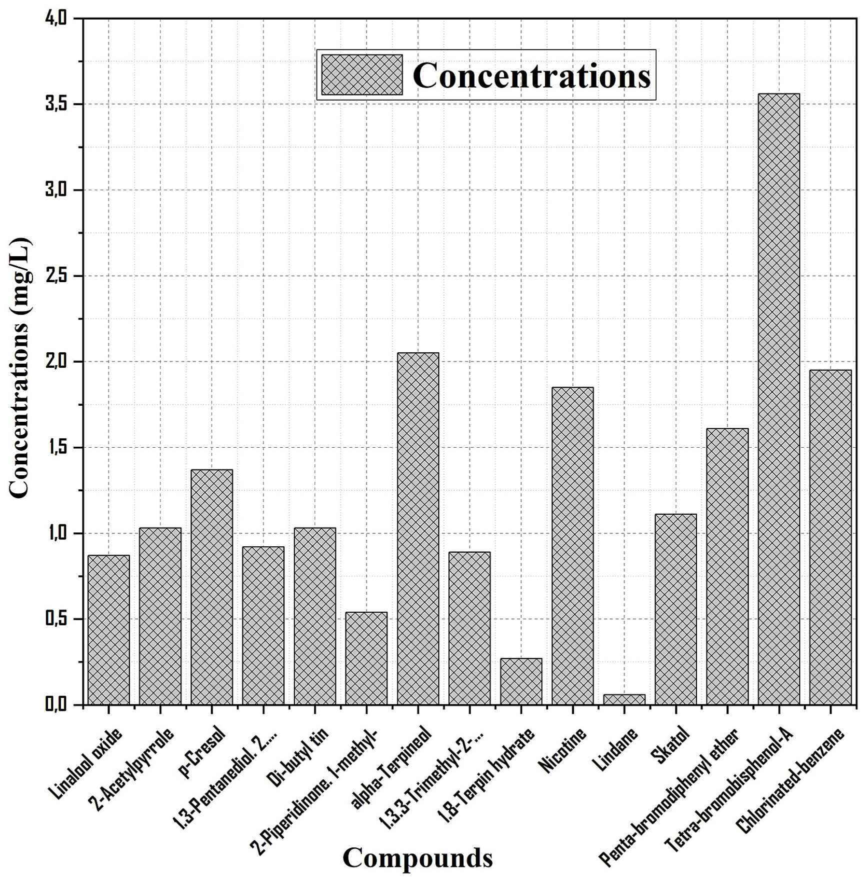

Fig. 2. Organic pollutants levels detected in leachate from Fez landfill

these pollutants in the Fez study, compared to other studies, underscore the distinct and heightened environmental risk associated with the Fez landfill, highlighting the need for targeted and effective pollution control measures.

Overall, the Fez landfill leachate study reveals a concerning level of organic pollutants, with concentrations generally higher than those reported in other landfill studies. This comparison accentuates the need for comprehensive and robust leachate treatment processes at the Fez landfill to mitigate the risks of environmental contamination as well as protect water quality and public health. It highlights the significant variability in landfill leachate composition and the critical importance of adhering to international standards to manage these complex and potentially toxic waste streams effectively.

Leachate pollution index

The methodology and findings presented in Table 3 of the Fez landfill study, concerning the leachate pollution index for various contaminants, offer a valuable insight into the environmental impact of the leachate, especially when compared with similar studies.

The approach in the Fez study assigns individual weights (Wi) to each heavy metal, reflecting their relative importance and toxicity, which is a common practice in landfill leachate studies. The calculation of pollution intensity (Pi) and the resulting individual pollution index (LPIi) for each metal allows for a direct comparison of the pollution levels of different metals. This is crucial because, in other studies, such a methodical approach helps identify the most problematic heavy metals, guiding the focus of leachate treatment and management (Table 4).

Notably, the Fez study highlights the substantial organic pollutant load, as evidenced by the high Pi values for COD and BOD_5, resulting in significant LPIi values. This finding is consistent with many other landfill leachate studies where organic pollutants are a primary concern due to their

Table 3. Individual leachate pollution indices, organic, inorganic, heavy metals and the overall leachate pollution index

Indices	Parameters	Concentrations	P_i	W_i	$Sub\text{-}Index_i$	LPI_i
LPI (Heavy Metals)	Cu	1.20E-01	5.00E+00	5.00E-02	2.40E-02	1.20E-03
	Fe	1.73E+01	5.00E+00	4.50E-02	3.46E+00	1.56E-01
	Cd	3.20E-01	5.00E+00	5.60E-02	6.40E-02	3.58E-03
	Zn	7.00E-01	5.00E+00	5.60E-02	1.40E-01	7.84E-03
	Pb	2.90E-01	5.00E+00	6.30E-02	5.80E-02	3.65E-03
	Ni	1.10E-01	5.00E+00	5.20E-02	2.20E-02	1.14E-03
	Mn	1.80E+00	---	---	---	---
	Cr	2.00E+00	5.00E+00	6.40E-02	4.00E-01	2.56E-02
	Al	1.09E+00	---	---	---	---
	As	4.00E-02	5.00E+00	6.10E-02	8.00E-03	4.88E-04
	Ba	5.00E-02	5.00E+00	6.10E-02	1.00E-02	6.10E-04
	Se	8.00E-02	5.00E+00	6.10E-02	1.60E-02	9.76E-04
	Ag	2.00E-02	5.00E+00	6.10E-02	4.00E-03	2.44E-04
	Mo	1.00E-02	5.00E+00	6.10E-02	2.00E-03	1.22E-04
	Sb	1.00E-02	5.00E+00	6.10E-02	2.00E-03	1.22E-04
	Hg	1.20E-01	5.00E+00	6.20E-02	2.40E-02	1.49E-03
LPI (Organic pollutants)	COD	5.71E+04	9.20E+01	6.20E-02	6.20E+02	3.85E+01
	BOD5	3.94E+04	8.50E+01	6.10E-02	4.64E+02	2.83E+01
	Phenolic	6.95E+01	8.50E+00	5.70E-02	8.18E+00	4.66E-01
LPI (Inorganic pollutants)	pH	7.45E+00	5.00E+00	5.50E-02	1.49E+00	8.20E-02
	Ammonium	1.35E+03	3.70E+01	5.00E-02	3.66E+01	1.83E+00
	TDS	1.35E+03	3.70E+01	5.00E-02	3.66E+01	1.83E+00
	Cl^-	7.64E+03	2.03E+01	4.80E-02	3.77E+02	1.81E+01
LPI_t						8.88E+01

Table 4. Heavy metals in leachate from Fez landfill

Parameters	Concentrations	Unit
Cu	1.20E-01	mg/L
Fe	17.73E+01	mg/L
Cd	3.20E-01	mg/L
Zn	7.00E-01	mg/L
Pb	2.90E-01	mg/L
Ni	1.10E-01	mg/L
Mn	1.80E+00	mg/L
Cr	2.00E+00	mg/L
Al	1.09E+00	mg/L
As	4.00E-02	mg/L
Ba	5.00E-02	mg/L
Se	8.00E-02	mg/L
Ag	2.00E-02	mg/L
Mo	1.00E-02	mg/L
Sb	1.00E-02	mg/L
Hg	1.20E-01	mg/L

potential impact on the oxygen levels in aquatic environments and their contribution to toxicity. Quantifying the organic pollution using LPI is vital for assessing the overall impact and for planning effective treatment strategies. The high Pi values for inorganic components like ammonium and chloride obtained in the Fez study indicate significant inorganic pollution. This aspect is often echoed in other studies, where these components contribute to the ionic strength and salinity of the leachate, adversely affecting aquatic life and overall water quality. The overall LPIt of 88.8 observed in the Fez study indicates a high level of pollution, which aligns with findings from other landfills where leachate is typically heavy in various pollutants. The LPIt serves as an effective tool to summarize the total pollution burden and provides a basis for comparison with other landfill sites.

The use of the LPI methodology in the Fez study is significant. It not only allows for a comprehensive understanding of the relative impacts of different pollutants but also aids in prioritizing which pollutants need urgent treatment. This approach is consistent with the current trends in landfill leachate research, focusing on identifying and quantifying key pollutants to tackle the environmental challenges effectively. When compared with other studies, the LPI results obtained in the Fez study underscore the critical need for extensive treatment processes to reduce the pollution levels in the leachate before considering safe environmental discharge.

CONCLUSIONS

Managed landfills, crucial in modern waste management for handling waste with high organic and inorganic content but low heat generation potential, inevitably produce leachate. This liquid, a byproduct of waste breakdown and precipitation infiltration, contains various soluble substances from decomposing waste, posing significant environmental management challenges.

The novelty of this study lies in its detailed analysis of landfill leachate, particularly from the Fez landfill, employing an extensive characterization approach. By analyzing sixteen different parameters, this research provides a thorough understanding of the leachate composition, a crucial step in evaluating the environmental impact of the landfill and in guiding the development of effective treatment strategies.

The results of this comprehensive analysis are illuminating. They reveal high levels of organic substances like chemical oxygen demand, biochemical oxygen demand over 5 days (BOD_5), ammonia nitrogen (NH_3-N), and color. Equally concerning is the finding that the concentrations of heavy metals in the leachate exceed environmental safety standards, pointing to the high pollution potential of the leachate.

Innovatively, the study employs the leachate pollution index to quantify this pollution risk. LPI, a tool that consolidates various pollution indicators into a single measure, was instrumental in assessing the overall pollution risk of the leachate from the Fez landfill.

The findings underscore the critical need for effective leachate treatment solutions. The presence of high pollutant levels in the leachate presents a significant risk to surface and groundwater resources, with potential environmental and public health consequences. This study, therefore, not only offers vital insights into the nature of leachate from the Fez landfill but also emphasizes the importance of improving leachate management practices to protect both environmental and human health.

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