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Physicochemical and microbiological characterization of leachate from the Dar El Gueddari municipal landfill Morocco

Brahim ELFAKIR[1*], Abderrahim BENZAKOUR[2], Mohammed OUHSSINE[3], Hicham LABIOUI[4]
[1,2,3,4]Laboratory of Natural Resources and Sustainable Development, Ibn Tofail University, Faculty of Sciences, BP 242, Kénitra 14000, Morocco; brahimelfakir1979@gmail.com (B.E.F.) abderrahim.benzakour@uit.ac.ma (A.B.) mohammed.ouhssine@uit.ac.ma (M.O.) labioui_h@yahoo.fr (H.L.).

Abstract: To evaluate the physicochemical and microbiological characteristics of leachate from the Dar El Gueddari public landfill and assess its environmental impact on soil, surface water and groundwater, representative samples were collected and analyzed. The leachate exhibited an alkaline pH, low dissolved oxygen concentration (1.20 mg O_2/L), high suspended solids content (790 mg/L), and high electrical conductivity (42,900 µS/cm), elevated biochemical oxygen demand (1,422 mg O_2/L) and chemical oxygen demand (4,250 mg O_2/L). High concentrations of heavy metals were detected, in particular lead (23.56 mg/L), cadmium (14.46 mg/L), arsenic (11.20 mg/L), zinc (9.80 mg/L), iron (21.68 mg/L), copper (14.74 mg/L), nickel (9.80 mg/L), and chromium (15.55 mg/L). Microbiological analyses revealed severe contamination, with total coliform counts 1.9×10^6 CFU/mL at 30°C, thermotolerant coliforms at 1.7×10^4 CFU/mL at 44°C, Clostridium perfringens at 3.3×10^6 CFU/mL at 37°C, coagulase-positive staphylococci at 5.1×10^6 CFU/100 mL, yeasts at 2.3×10^6 CFU/mL, and molds at 6.5×10^5 CFU/mL. The measured concentrations significantly exceed World Health Organization discharge standards, posing a serious threat to the environment and health in the Dar El Gueddari region. Consequently, appropriate treatment of the leachate before its discharge into the environment is essential.

Keywords: *Dar El Gueddari, Heavy metals, Landfill, Leachate, Physicochemical parameters, Pollution.*

1. Introduction

In Morocco, the production of household waste has been steadily increasing due to population growth and the intensification of economic and agricultural activities. Despite ongoing efforts to improve waste management practices, uncontrolled open dumping remains the most common disposal method, especially in developing countries [1]. This practice poses serious environmental and public health risks because of the lack of containment and treatment systems.

In response to these challenges, Morocco has implemented several programs aimed at improving solid and liquid waste management. Among these initiatives is the National Household Waste Management Program (PNDM), which promotes the establishment of controlled landfills and the rehabilitation of illegal dumpsites. The Ministry Delegate to the Minister of Energy, Mines, Water, and the Environment, in charge of the Environment, 2004. For many years, landfilling has been the primary method of waste disposal, resulting in the burial of large quantities of urban and industrial waste containing significant amounts of heavy metals. These metals are present in most waste components and represent a major source of environmental contamination [2].

Landfill leachate is the primary vector for transporting metallic and organic pollutants. It is a complex wastewater generated by rainwater percolating through waste deposits, during which physical, chemical, and biological processes occur within the landfill. Consequently, leachate typically exhibits

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* Correspondence: brahimelfakir1979@gmail.com

high electrical conductivity, elevated chemical oxygen demand (COD), biochemical oxygen demand (BOD_5), significant concentrations of anions, cations, ammonia, heavy metals, and considerable microbiological contamination. The composition of leachate varies depending on several factors, including waste composition, landfill age, and meteorological conditions [3, 4].

The formation of leachate involves not only the characteristics of the waste but also the interactions between water, soil, and waste materials. Although leachate generation and discharge are strictly controlled in modern sanitary landfills, older landfills continue to produce leachate for decades after their closure. This prolonged generation contributes to environmental pollution and increases the risk of heavy metal migration into surrounding soil and water resources.

Heavy metal concentrations in leachate are generally low during the active operational phase of landfills [5]. However, the presence of organic and mineral matter in leachate enhances metal mobility through complexation processes, increasing their potential environmental impact [6]. One of the most significant environmental consequences of landfilling is the production of leachate rich in organic, mineral, and metallic constituents. These leachates, originating from rainwater percolating through waste deposits, represent a persistent source of pollution to ecosystems and groundwater resources [7].

The primary environmental risk associated with landfill leachate production is the contamination of groundwater resources. Such contamination can affect drinking water wells, depriving local populations of a vital resource essential for human survival. In addition, the direct discharge of untreated leachate into surface water bodies significantly alters their physicochemical characteristics [8, 9]. Owing to its high organic load and the presence of toxic pollutants, leachate can exert harmful effects on aquatic and terrestrial fauna and flora.

In Morocco, several studies have highlighted the environmental risks posed by landfill leachate. Saadi et al. [1] reported high concentrations of biodegradable organic matter, heavy metals, minerals, and suspended solids in leachate from the Oujda landfill. Similarly, Mokhtaria et al. [10] demonstrated that leachate from the Tiaret landfill contained significant levels of organic and metallic contaminants, including Pb, Zn, Cd, Ni, and Cr, exceeding applicable regulatory standards. Comparable findings were also reported by Bennama et al. [11] in their study of the El Kerma landfill. Beyond Morocco, an Ivorian study employing a mathematical modeling approach assessed the temporal evolution of leachate from the Akouédo landfill and evaluated its impact on groundwater quality, while also characterizing the chemical and microbiological pollution of the surrounding environment to estimate associated health risks.

Despite these documented impacts, household waste treatment remains insufficiently developed in Morocco, with uncontrolled landfilling still representing the predominant disposal practice in many municipalities. Pollution resulting from the discharge of untreated leachate leads to substantial environmental degradation, including contamination of groundwater and surface water, soil pollution, adverse effects on human health, and the emission of greenhouse gases. In this context, the objective of the present study is to characterize the physicochemical and microbiological pollution associated with untreated landfill leachate.

2. Materials and Methods

2.1. Site Description

The town of Dar El Gueddari is located in the Rabat–Salé–Kénitra region, approximately 104 km north of Morocco's capital, Rabat. The local climate ranges from humid to semi-arid and is influenced by the Atlantic Ocean, resulting in mild winters and relatively hot summers. Average annual temperatures vary between 10°C and 40°C [12].

According to the 2004 census, Dar El Gueddari has a population of 6,011 inhabitants. The town is equipped with a wastewater treatment plant based on a natural lagoon system, consisting of two anaerobic basins followed by two facultative basins.

From a geological perspective, the Dar El Gueddari landfill is located within a sandy, clay formation. Borehole investigations have revealed a highly weathered subsurface layer dominated by clay

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fractions. Hydrogeological studies indicate that groundwater flow occurs predominantly in a northeast-southwest (NE–SW) direction. Furthermore, the piezometric level of the aquifer shows significant seasonal fluctuations, suggesting a strong dependence on surface rainfall recharge.

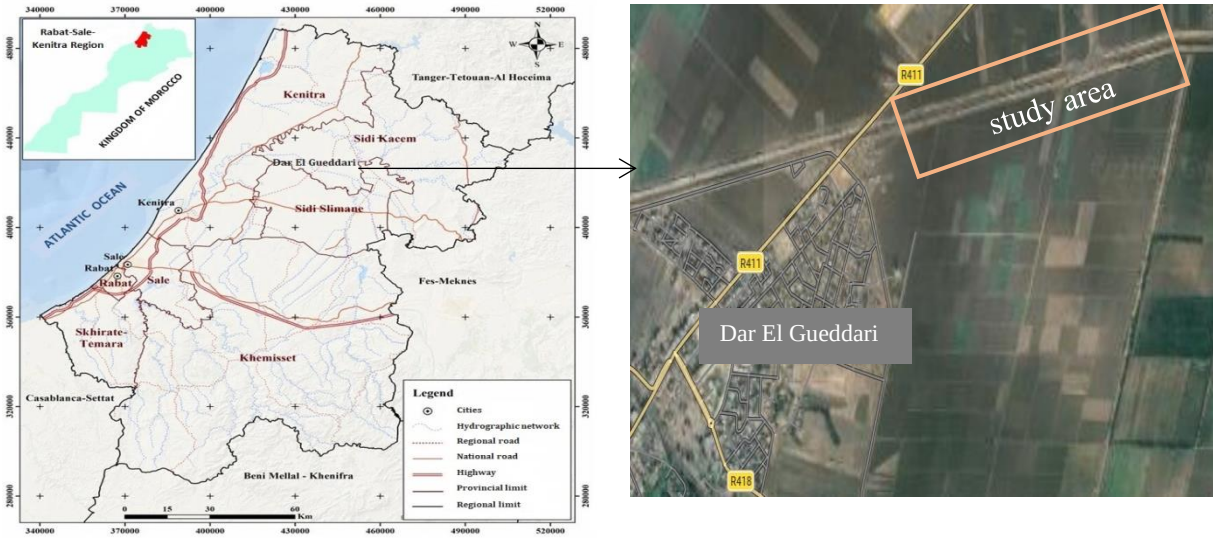


Figure 1.
Location of the study area.



Figure 2.
Photo of the Dar El Gueddari landfill.

2.2. Leachate Sampling and Analysis Methods

Physicochemical analyses were conducted on leachate samples collected from points located at the center of the landfill to ensure representative sampling of the site. The sampling locations were selected to reflect the overall characteristics of the leachate environment. All samples were preserved and handled in accordance with the general guidelines for sample preservation and handling [13] and the good laboratory practice guide of the National Office for Drinking Water [14].

In situ measurements of pH, temperature, electrical conductivity, and dissolved oxygen were performed using a Consort 835 multiparameter analyzer equipped with a temperature probe, following Moroccan Standard [15]. All laboratory analyses aimed at quantifying organic, nitrogenous, and sulfate pollutants were conducted using standardized methods.

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Nitrate and nitrite concentrations were determined by photometric analysis in accordance with DIN 1993c. Total suspended solids (TSS) were measured using the gravimetric method [16] with a Baxtrane analytical balance having a precision of 5 µg. Chemical oxygen demand (COD) was determined by oxidation of oxidizable substances in an acidic medium, using mercury sulfate as a catalyst [17]. Biochemical oxygen demand over five days (BOD_5) was measured using the respirometric method with a WTW BOD meter (model 1020T), following Deutsches Institut für Normung (DIN) [18].

Chloride concentrations were determined using pre-dosed titration tablets. Total phosphorus (TP) was quantified after mineralization in an acidic medium with sodium persulfate at 200°C for two hours, converting organic and condensed phosphorus forms into soluble orthophosphates, which were then measured according to Association Française de Normalisation (AFNOR) [19] procedures. Calcium and magnesium concentrations were analyzed by complexometric titration with ethylenediaminetetraacetic acid (EDTA). Sulfate concentrations were determined using a Perkin Elmer Lambda 20 visible spectrophotometer.

Heavy metals (Fe, Zn, Ni, and Cu) and selected major elements (Na^+) were analyzed using inductively coupled plasma atomic emission spectrometry (ICP-AES, Jobin Yvon model).

For microbiological analyses, leachate samples were collected in 225 mL glass bottles, previously sterilized by autoclaving at 120°C for one hour. The microbiological analytical methods used are summarized in Table 1.

Table 1.
Microbiological parameters.

Germs	Crop environments	incubation conditions	counted colonies	Methods	Unit
Total Coliform at 30°C	Deoxycholate Lactose Agar (DLA)	aerobic or anaerobic at 37°C for 24 hours	dark red colonies	NM ISO 4832: 2008	ufc/ml
Thermotolerant coliform at 44°C	Deoxycholate Lactose Agar (DLA)	aerobic or anaerobic, at 44°C for 24 hours	dark red colonies	NM 08.0.124: 2012	ufc/ ml
Staphylococcus with positive coagulase at 37°C	Baird Parker environment (BP)	aerobic, at 37°C for 24 to 48 hours	colonies with blackish coloration	NM ISO 6888-1: 2022	ufc/ 100ml
Clostridium perfringens at 37°C	Sulfite Polymyxin Sulfadiazine Agar (SPS)	anaerobic, at 37°C for 24 hours	black colonies measuring 1 to 2.5 mm in diameter	NM ISO 7937: 2009	ufc/ ml
Yeast at 25 °C	agar, YPG	aerobic, at 25-30°C, for 48 hours	Creamy white to yellowish colonies	NM 08.0.123 : 2006	ufc/ ml
Molds 25°C	Sabouraud Dextrose Agar (SDA)	Aerobic, Humidity (50-60%), at 20-30°C	Circular, flaky, granular or hairy spots	NM 08.0.123 : 2006	ufc/ ml

3. Results

3.1. Physico-Chemical Parameters

The physico-chemical characteristics of the leachate from the Dar El Gueddari landfill are grouped in Tables 2, 3, and 4, and Figures 3, 4, 5, 6, and 7.

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Table 2.
Major parameters of leachate from the Dar El Gueddari landfill.

Measured parameters	Results	IFC (*)-WHO criteria	Unit
PH at 25°C	8.20	6-9 (*)- 6.5 – 8.5	pH
Conductivity at 25°C	42 900	2800	µS/cm
Chlorides (Cl^-)	390.65	250(*) – 200	mg/l
Sulfates (SO_4^{2-})	1400	400(*) -250	mg/l
Magnesium (Mg^{2+})	130.55	50 (*) – 50	mg/l
Calcium (Ca^{2+})	205	100	mg/l
Sodium (Na^+)	1230.56	200	mg/l
Alkalinity (CaCO3)	3144.6	20-200	mg/l
Dissolved Oxygen (O2)	1.20	< 2-3	mg O2/L

IFC (*): International Finance Corporation

Table 3.
Overall parameters of leachate from the Dar El Gueddari landfill.

Measured parameters	Results	IFC (*)-WHO criteria	Unit
Nitrates (NO_3^-)	43.80	50 (*) -50	mg/l
Nitrites (NO_2^-)	0.98	3 (*) – 0.1	mg/l
Ammonium (NH_4^+)	0.66	1.5 (*) – 0.5	mg/l
SM	790	<35	mg/l
BOD_5	1422	30(*). <30	mg O2/L
COD	4250	125(*). <90	mg O2/L
Total organic carbon	130.0	<0.5	mg/l
Phosphorus Total P	0.09	<0.05	mg/l

Note: SM: Suspended matter, BOD5: Biochemical Oxygen Demand, and COD: Chemical Oxygen Demand., IFC (*): International Finance Corporation

Table 4.
Comparison of heavy metal concentrations in leachate from the Dar El Gueddari landfill with leachate from other landfills.

Concentration of heavy metals in leachates (mg/l)	Landfill of Dar El Gueddari (Morocco)	Landfill of El-Kerma d'Oran (Algeria) [11]	Landfill of FES (Morocco) [20]	Landfill of Jadida (Maroc) [21]	Landfill of Etueffont (France) [22]	Range of variation of a household discharge [23]	Guidelines WHO* (mg/l)
Lead (Pb)	23.56	0.13	0.18	nd	nd	0.001-50	0.01
Cadmium (Cd)	14.46	0.4	4.36	0.034	0.01	0.001-0.4	0.03
Arsenic (As)	11.20	nd	0.14	nd	nd	nd	0.01
Chromium (Cr)	15.55	0.04	2.04	0.15	0.27	0.02-150	0.05
Nickel (Ni)	8.64	1.26	3.74	0.13	0.21	0.015-130	0.07
Zinc (Zn)	9.80	0.32	4.68	0.74	0.74	0.03-104	3
Iron (Fe)	21.68	6	33.72	24	2.63	0.03-55.102	0.3
Copper (Cu)	14.74	0.58	0.4	0.15	0.27	0.005-102	2

Note: *Water consumption. nd: non detected.

Table 5.
Comparison of leachates according to the age of the waste.

Parameters	Young leachates	Intermediate leachates	Stabilized leachates
Landfill age	< 5 years	5-10 years	>10 years
pH	< 6.5	6.5-7.5	>7.5
COD (mgO2/L)	> 10,000	4,000-10,000	< 4,000
BOD_5/COD (biodegradability)	> 0.5 Good	0.1-0.5 Fairly low	< 0.1 Very low
Volatile fatty acids (% of TOC)	>70	5 à 30	< 5
TOC/COD	< 0.3	0.3-0.5	> 0.5

Source: Alvarez-Vazquez, et al. [24]; Li, et al. [25] and Renou, et al. [26].

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3.1.1. Concentration of Dissolved Ions

Figure 3 shows the concentrations of dissolved ions. The results indicate that the leachate contains higher or lower concentrations of sulfate (1400 mg/l), sodium (1230.56 mg/l), chlorides (390.65 mg/l), magnesium (130.55 mg/l), and calcium (205 mg/l).

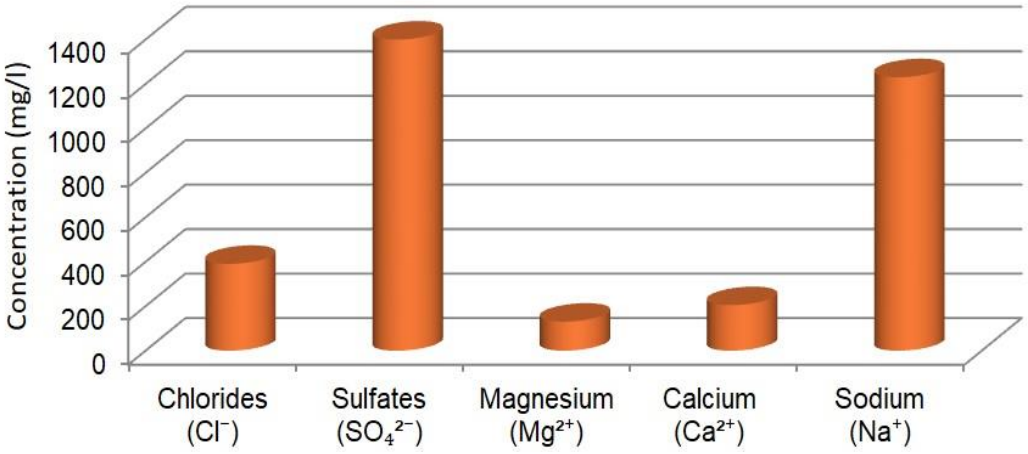


Figure 3.
Concentration of dissolved ions.

3.1.2. Organic Matter Content

Figure 4 shows high concentrations of BOD5 (1422 mg O2/L) and COD (4250 mg O2/L) in the leachate.

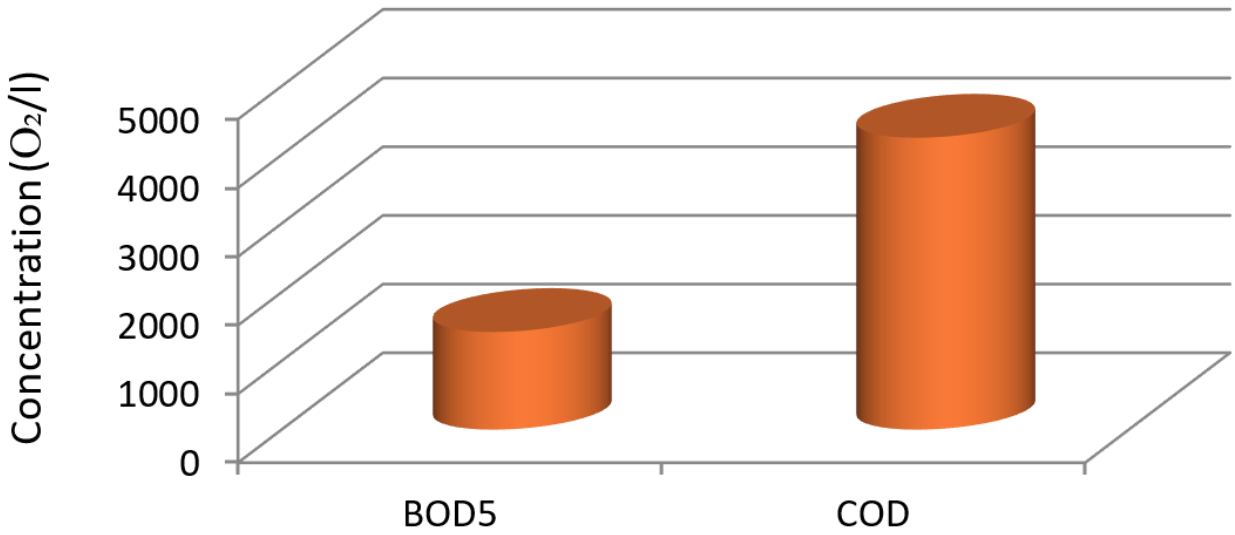


Figure 4.
BOD_5 and COD concentration.

3.1.3. Nitrogen level

Figure 5 shows the levels of nitrogen compounds, especially ammoniacal nitrogen (0.66 mg/l), nitrites (0.98 mg/l), and nitrates (43.80 mg/l).

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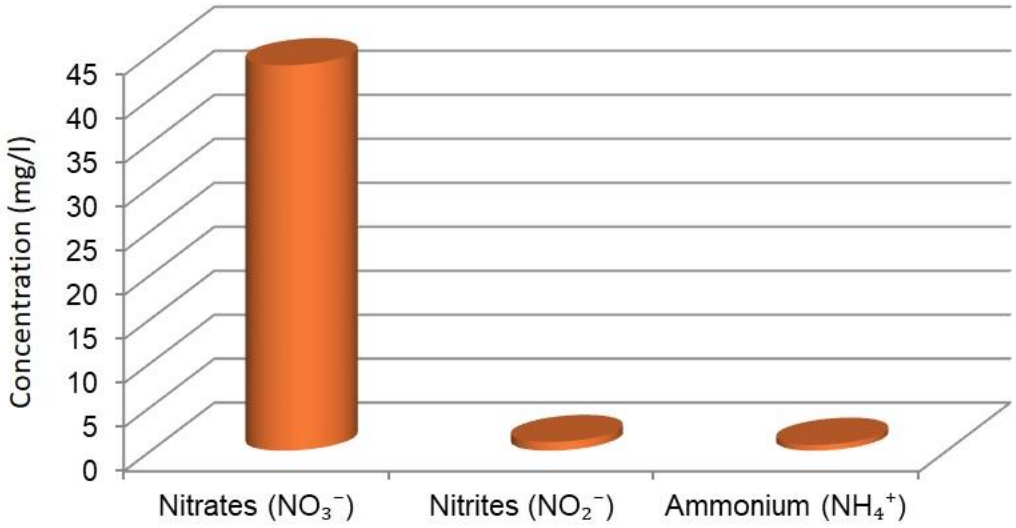


Figure 5.
Nitrogen molecules in the analyzed leachate.

3.1.4. Carbon and Phosphorus

Figure 6 shows the concentrations of carbon and total phosphorus. The results indicate that the leachate contains a concentration of 130 mg/l of carbon and 0.09 mg/l of total phosphorus.

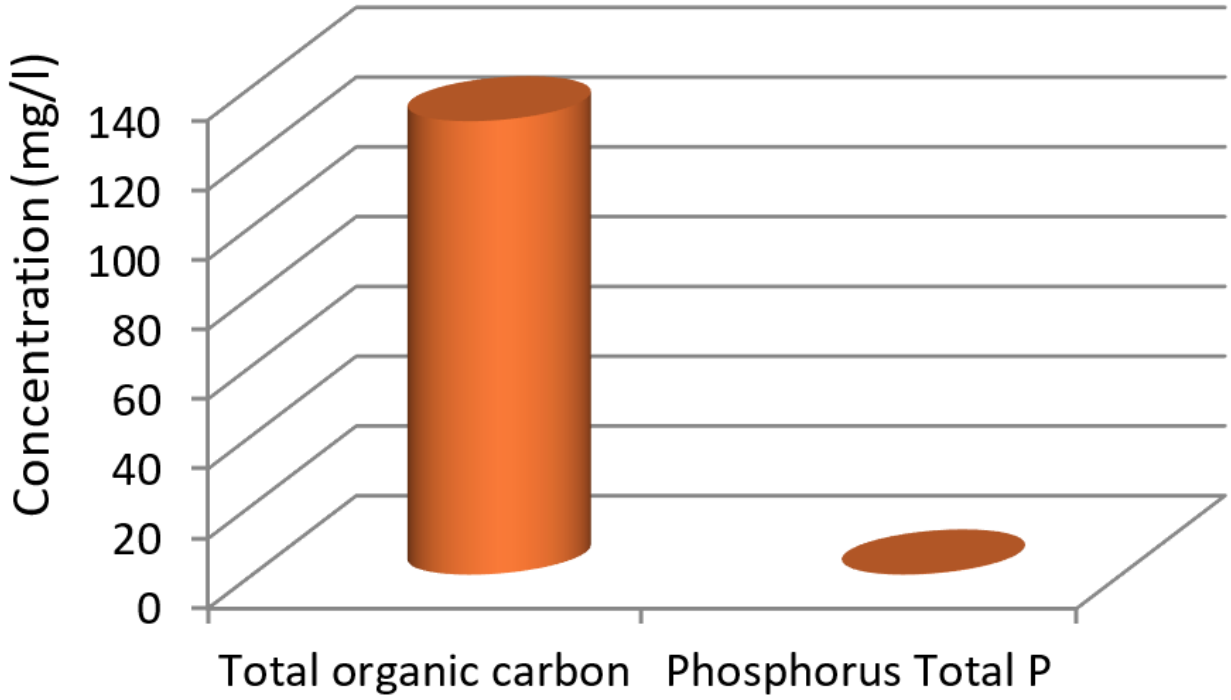


Figure 6.
Total carbon and phosphorus levels.

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3.1.5. Heavy Metal Content

Figure 7 shows the concentrations of heavy metals, measured in mg/L, in a given sample. Among these metals, lead (Pb) has the highest concentration (23.56 mg/L), followed by iron (Fe) (21.68 mg/L). Intermediate concentrations are found for copper (Cu) (14.74 mg/L), chromium (Cr) (15.55 mg/L), arsenic (As) (11.20 mg/L), and cadmium (Cd) (14.46 mg/L), while zinc (Zn) (9.8 mg/L) and nickel (Ni) (8.64 mg/L) have the lowest concentrations among the metals analyzed.

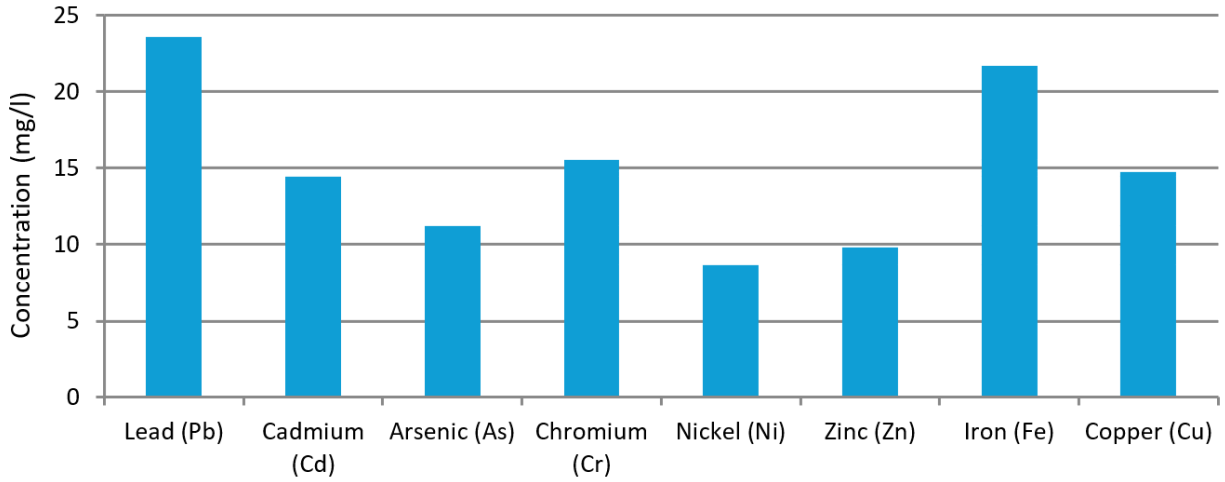


Figure 7.
Heavy metal concentration.

3.2. Microbiological Evaluation

The microbiological characteristics of leachate from the Dar El Gueddari landfill are grouped in Table 6.

Table 6.
Microbiological parameters.

Germs	Number	WHO criteria	Unit
Total Coliform at 30°C	$1.9.10^6$	0/100ml	CFU/ml
Thermotolerant coliform at 44°C	$1.7.10^4$	0/100ml	CFU/ml
Staphylococcus with positive coagulate at 36°C	$5.1.10^6$	0/100ml	CFU/100ml
Clostridium perfringens at 37°C	$3.3.10^6$	0/100ml	CFU/ml
Yeast at 25 °C	$2.3.10^6$	100 CFU /100 ml	CFU/ml
Molds at 25°C	$6.5.10^5$	100 CFU /100 ml	CFU/ml

According to Table 6 and Figure 8, the microbiological analysis indicates high levels of contamination. The total coliform count at 30°C reached 1.9 x 10^6 CFU/ml, while the thermotolerant coliform count at 44°C was 1.7 x 10^4 CFU/ml. The coagulated Staphylococcus count at 36°C was 5.1 x 10^6 CFU/100 ml. A very high level of Clostridium perfringens was also observed at 37°C (3.3 x 10^6 CFU/ml), while yeast was 2.3 x 10^6 CFU/ml and mold was 6.5 x 10^5 CFU/ml at 25°C.

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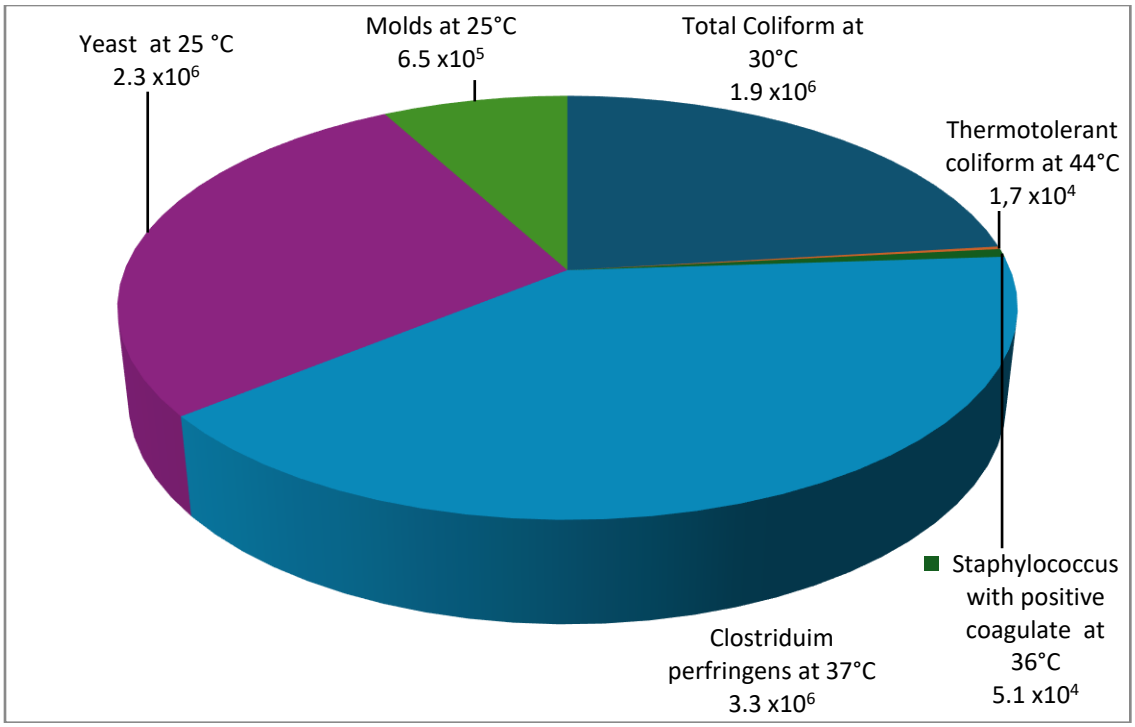


Figure 8.
Microbiological parameters in CFU/ml.

4. Discussion

4.1. Electrical Conductivity, Chlorides, and Dissolved Oxygen

Electrical conductivity (EC) is a key indicator of water mineralization and overall quality. In the present study, the maximum EC value recorded in the landfill leachate reached 42,900 µS/cm (Table 2), reflecting an extremely high level of mineralization. This value is markedly higher than those reported in several previous studies, where maximum conductivity values ranged between 6,410 µS/cm [27], 334–8,680 µS/cm [28], 310–1,470 µS/cm [29],300–1,170 µS/cm [30], and 54–1,670 µS/cm [31]. Such elevated conductivity indicates a strong accumulation of dissolved inorganic ions, characteristic of highly polluted and mature landfill leachates.

The chloride concentration measured in the leachate was 390.65 mg/L, which significantly exceeds the maximum guideline value of 200 mg/L recommended by the World Health Organization. The high chloride content is consistent with the elevated EC values observed, as chlorides contribute substantially to electrical conductivity. These ions may originate from the dissolution of waste materials within the landfill [32], as well as from agricultural inputs and irrigation runoff infiltrating the landfill area [33].

The leachate also exhibited high alkalinity, expressed as 3144.6 mg/L $CaCO_3$. This elevated alkalinity can be attributed to the oxidation and biodegradation of fermentable organic matter, processes that generate significant amounts of CO_2. The presence of CO_2 enhances the dissolution of calcium carbonate into bicarbonate ions, thereby increasing alkalinity. This value is comparable to that reported by Naji [34], indicating similar geochemical and biodegradation conditions.

Dissolved oxygen (DO) concentrations in the leachate were particularly low, with a measured value of 1.20 mg/L. This concentration is lower than that reported by Khattabi et al. [22] but remains comparable to values observed by Naji [34]. When assessed using the surface water quality classification grid [35], this DO level classifies the leachate as having poor to very poor quality. Dissolved oxygen is a critical parameter, as it directly influences aerobic biodegradation processes and

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governs the biological equilibrium of aquatic environments. Low DO levels indicate intense microbial activity and a high organic load, conditions that can severely impair receiving ecosystems if untreated leachate is discharged into natural waters.

4.2. Major Elements

The concentrations obtained in the leachate from the Dar El Gueddari landfill reached 130.55 mg/L for magnesium, 1230.56 mg/L for sodium, and 205 mg/L for calcium (Table 2). The high levels of calcium and magnesium in this leachate cause excessive hardness [36]. The concentrations of Mg^{2+}, Na^{+}, and Ca^{2+} are highly dependent on the content of dissolved organic matter and the season [23]

4.3. Suspended Matter

Suspended matter (SM) represents all mineral and organic particles contained in water. Their effects on water quality are very detrimental (altering turbidity, reducing light penetration, and therefore photosynthesis). Analysis of the results shows that the leachate from the Dar El Gueddari landfill is characterized by a fairly high average SM concentration of 790 mg/l (Table 3). These concentrations far exceed the discharge limit (50 mg/l) according to the standards of the Moroccan Committee for Standards and Norms (CNS, 1994).

4.4. Organic Matter and pH

In our case, it appears that the Dar El Gueddari landfill is an old landfill currently undergoing methanogenesis (BOD5/COD ratio of 0.33) (Table 5). The basic pH (8.2 on average) (Table 2), measured on this leachate, clearly reflects this phase of biological evolution. This revealed basic character is consistent with that obtained by Kouadio et al. [37], Kouamé [38]. These values are also of the same order of magnitude as those obtained by El Khamlichi et al. [39] at the Rabat landfill (Morocco). The pH values obtained in the leachates could be linked to the low concentration of volatile organic compounds (VOCs). Indeed, during acid fermentation, the first phase of anaerobic waste decomposition, young leachates are rich in VOCs. During this phase, the recorded pH values are generally below 4 [40]. As the landfill ages, the leachate becomes depleted of VOCs. This then leads to a rise in pH to 7 or higher [41].

COD represents the amount of oxygen consumed by chemically oxidizable matter in water. It is indicative of most organic compounds and oxidizable mineral salts [42]. The recorded concentration is 4250 mg O2/l (Table 3), which exceeds the reference value. The high COD indicates a significant organic load. The pollutant load values, expressed as COD, are comparable to those reported by Kouadio et al. [37], Kouamé [38], and Mokhtaria et al. [10] at the Tiaret landfill in Algeria, as well as those obtained by Saadi et al. [1] in Oujda, Morocco. This difference could be linked to the age, nature, and quantity of waste, along with climatic factors such as rainfall, air humidity, and temperature. According to Christensen et al. [23], these factors contribute to the variability of pollutant loads.

The concentration of oxidizable organic matter (BOD_5) imported by the landfill reached 1422 mg O_2/l (Table 3). BOD_5 is an indicator of organic water pollution, reflecting the level of biodegradability of the effluent [42]. This concentration exceeds the reference value. The organic fractions (BOD_5/COD) provide information on the biodegradability of organic molecules and the relative age of the leachates studied. The BOD_5/COD ratio is greater than 0.5 for young leachates and less than 0.1 for stabilized leachates. It ranges between 0.1 and 0.5 for intermediate leachates. The average BOD_5/COD ratio is approximately 0.33, indicating that the leachate studied is an intermediate leachate with average biodegradability. This suggests that the organic molecules in the leachate have not yet reached the final stage of degradation. At this stage, they are characterized by an unstable phase of methanogenic fermentation, promoting anaerobic conditions and maintaining the landfill in an active degradation phase [43].

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4.5. Total Organic Carbon and Total Phosphorus

The Total Organic Carbon (TOC) in this leachate, reaching a value of 130.0 mg/l (Table 3), is a key measure of pollution exceeding standards. It represents the quantity of dissolved or suspended carbon compounds resulting from the fermentation of waste in the landfill. This parameter, essential for environmental monitoring, indicates the level of organic pollution (soluble organic matter, humic acids, etc.). Its treatment is vital to comply with discharge standards and protect groundwater. Total Phosphorus (P), with a value of 0.09 mg/L (Table 3), represents the sum of all forms of phosphorus in a leachate sample, including inorganic phosphates (orthophosphates, polyphosphates) and organic phosphorus, which is essential for life but problematic in excess, causing eutrophication of waterways (algal blooms). Its measurement (often after digestion) is crucial for assessing water quality and kidney/bone health.

4.6. Nitrogen Compounds

Ammoniacal nitrogen (NH4+) is one of the components of the complex nitrogen cycle in its primary state. It is a water-soluble gas, with concentrations reaching 0.66 mg/l. This chemical element is the main reducing agent in landfill leachate and constitutes a significant long-term pollutant [23]. Nitrates (NO3--), with a recorded concentration of 43.80 mg/l (Table 3), represent the final stage of nitrogen oxidation and are the most highly oxidized form of nitrogen present in the water, resulting from agricultural runoff due to the use of chemical fertilizers [36]. A literature review on groundwater nitrate contamination supports this pollution pathway [44]. Nitrites (NO2-) originate either from the reduction of nitrates or from the incomplete oxidation of ammonium ions [45]. NO2- levels in leachates are low, reaching 0.98 mg/L. These low levels are due to the low values of dissolved oxygen and redox potential in the leachate. The comparative study of these nitrogen compounds indicates a sharp increase in their concentrations, likely due to an excessive input of nitrogen and sulfate. The sulfate concentration is quite high at 1400 mg/l. The sulfates are then reduced to sulfides (H_2S), which are among the gases responsible for the unpleasant odors emitted by the landfill [22, 46].

4.7. Heavy Metals

The most abundant metallic elements in the leachate from the Dar El Gueddari landfill are iron, copper, zinc, and nickel. The zinc concentration is 9.80 mg/L, while the copper concentration reaches 14.74 mg/L (Table 4). Nickel and iron concentrations show a similar trend to that observed for copper. The nickel and iron concentrations in the leachate reach 8.64 mg/L and 21.68 mg/L, respectively. These relatively high concentrations of metallic elements recorded in the leachate from the Dar El Gueddari public landfill originate primarily from domestic and industrial waste. The Dar El Gueddari landfill is a permeable site. In the absence of a drainage system, the generated leachate seeps into the subsoil and reaches the underlying water table, which flows at very shallow depths (10 to 20 m), with a minimum depth of 0.9 m, and is exposed at the bottom of the quarries located within the landfill. The groundwater flows from the landfill towards the ocean, causing the pollution to spread to wells located downstream. Metals, which have very low mobility, are therefore mostly trapped in landfills. Several studies show that more than 99.9% of heavy metal stocks are still trapped in the landfill after 30 years [47, 48]. The low solubility of heavy metals can be explained by the forms in which they are found in the landfill. Indeed, all studies concerning the chemical speciation of metals in old waste conclude that mobilizable metals are associated with sulfides and organic matter in landfills [49, 50]. The concentrations measured for certain metals, notably lead, copper, cadmium, and nickel, are abnormally high compared to environmental and health standards established by organizations such as the WHO or the EPA (which generally set maximum limits in µg/L, well below 1 mg/L for several of these toxic elements). These high levels, particularly for lead, cadmium, and arsenic, suggest severe contamination of the analyzed source. These metals are highly toxic and associated with various adverse effects.

Lead causes neurotoxicity and cardiovascular effects; cadmium causes nephrotoxicity and carcinogenic effects [51]. Arsenic causes systemic toxicity and is a known carcinogen; nickel and

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chromium have respiratory, allergic, and potentially carcinogenic effects. High concentrations of iron, zinc, and copper can become toxic if physiological thresholds are exceeded. For example, an overload of copper or iron can cause oxidative damage. These results suggest serious environmental pollution, potentially of industrial, mining, or urban origin. The presence of high levels of toxic metals such as lead (23.56 mg/L), cadmium (14.46 mg/L), arsenic (11.20 mg/L), and chromium (15.55 mg/L) poses a significant risk to human health, particularly in cases of chronic exposure. Even essential metals like iron, zinc, and copper, when present at such high concentrations, can become harmful by causing oxidative stress or metabolic disturbances. These data underscore the need for a thorough assessment of pollution sources and urgent interventions to limit impacts on the environment and public health. Chemical trapping creates reservoirs where heavy metals concentrate; their solubility in leachate is low [52, 53]. These metals are potentially mobilizable under changing conditions. Processes identified in the literature as likely to increase metal mobility include: a decrease in pH resulting from oxidation or external factors (acid rain, etc.); oxidation of anaerobic zones within the landfill, leading to the redissolution of trapped metals into oxidizable forms (sulfides and organic matter); and complexation of metals by organic and mineral matter present in the leachate. These various processes can be interconnected and play a significant role in metal mobility.

The physico-chemical analyses of the leachate showed that all characteristic parameters exceeded the general discharge standards. Indeed, the composition of the leachate from the Dar El Gueddari landfill is typical of a household landfill and comparable to other Moroccan landfills, namely Kasba Tadla (T=22°C, pH=4.49, Conductivity=26720 µs/cm, and COD=25700 mgO2/L) [54] and the Agadir landfill (T=20°C, pH=4.3, EC=14700 µs/cm, COD=72.00 mgO2/L, BOD5=44.000 mgO2/L, and SM=12.560 mg/L) [55], Regarding mineral and metallic pollution, a high concentration was observed, with values exceeding those found in the Fes landfill (Cd = 4.36 mg/L, As = 0.14 mg/L, Pb = 0.18 mg/L) [56], the Etueffont landfill in France (Cr = 0.27 mg/L, Ni = 0.21 mg/L, Fe = 2.63 mg/L, Cu = 0.27 mg/L, Cd = 0.01 mg/L, Zn = 0.74 mg/L), and Rabat (Cr = 0.5 mg/L, Ni = 0.1336 mg/L, Cd = 0.838 mg/L, Cu = 0.118 mg/L), but lower than those of the Oran landfill in Algeria (Ca = 5216 mg/L, Mg = 4800 mg/L) [11] and Larache (Fe = 650 mg/L) [57].

4.8. Microbiological Parameters

The microbiological analysis revealed high levels of contamination, represented by a significant number of total coliforms at 30°C reaching 1.9 x 10^6 CFU/ml, 1.7 x 10^4 CFU/ml of thermotolerant coliforms at 44°C, 5.1 x 10^6 CFU/100ml of coagulase-positive staphylococci, and 3.3 x 10^6 CFU/ml of Clostridium perfringens at 37°C (Table 6). The presence of 2.3 x 10^6 CFU/ml of yeasts and 6.5 x 10^5 CFU/ml of molds was also noted (Table 6). These results indicate that the analyzed samples did not meet hygiene standards, raising concerns about their suitability for consumption. The presence of total and thermotolerant coliforms indicates recent fecal contamination. Studies conducted in other countries have reported values remarkably similar to those in our study [58]. These bacteria generally originate from human or animal excrement, posing a significant health risk as they are often associated with pathogens capable of causing gastrointestinal illnesses [59]. The presence of coliforms reveals direct contamination by fecal matter, indicating poor sanitation or a lack of effective treatment. A similar study reported that the presence of fecal coliforms in well water could be explained by surface water infiltration [60].

Ez Zoubi et al. [61] and Abed et al. [62] confirmed the high presence of fecal coliforms in leachate at all times. This persistent presence of these bacteria in leachate means that, regardless of the time of year, if this liquid infiltrates the water table, it can constitute a source of groundwater contamination. Indeed, it has been shown that the amount of leachate increases with rainwater infiltrating waste [63]. As rainwater passes through the waste within the landfill, it becomes laden with pathogens that contaminate the groundwater [64-66]. In the leaching process, water input facilitates biochemical reactions, thus increasing the potential for strong microbial growth. The higher the water content in

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the waste, the faster the biodegradation will be [63, 67-70]. The higher the microbiological load in the leachate, the more questionable the quality of the groundwater will be in the event of infiltration. The results also reveal that an average concentration of Staphylococcus was found. According to Belle [63]; Filip et al. [71], pathogenic staphylococci cause suppurative and necrotic lesions. They can be responsible for several diseases, such as skin and mucous membrane infections [72]. Meanwhile, a study conducted in France by Delmas, et al. [73] between 1996 and 2005 revealed that Clostridium perfringens was implicated in 136 outbreaks of foodborne illness, representing 5,375 cases. The species was suspected in 383 outbreaks encompassing 8,956 cases [73, 74]. Fungi (yeasts and molds) reproduce by sexual or asexual spores. Although these spores exhibit some resistance in dry environments, it is significantly less than that of bacterial endospores [75]. They are considered the primary contaminants of garbage, among other microscopic fungi, and are frequently associated with allergic reactions. However, they rarely cause infections in humans [76]. The main route of human contamination by garbage-borne molds is through inhalation, with pulmonary involvement being the most common [77]. The results found are identical to those of other Moroccan landfills, such as the one in Kenitra, where the leachate shows a microbial load of 80.59 x 10^6 CFU/ml of total coliforms, 0.93 x 10^6 CFU/ml of fecal coliforms, 0.12 x 10^6 CFU/ml of Staphylococcus [63] and 0.9 x 10^5 CFU/ml of total coliforms and 0.7 x 10^4 CFU/ml of fecal coliforms at the same landfill [78]. Similarly, for the Fes landfill, Ez Zoubi et al. [61] showed the presence of high concentrations of total coliforms (6.28 x 10^6 CFU/ml) and fecal coliforms (1.39 x 10^5 CFU/ml). Sackey and Meizah [79] found almost identical results in the leachates from the Accra landfill (Ghana): 26.10^6 ufc/100 ml for CT; 33.10^5 ufc/100 ml for CF. Thus, for CF, this remains largely close to the values mentioned at the Larache landfill (152,000 UFC/100 ml) [57] and at the El Kerma landfill (18,000 germs/100 ml) [11]. These results are above the recommended thresholds for human consumption, indicating a high health risk and the need for urgent corrective measures, particularly in hygiene, processing, and quality control.

5. Conclusion

The results of this study clearly demonstrate the significant pollution generated by leachate from the Dar El Gueddari landfill. The organic matter content, expressed by biochemical oxygen demand (BOD_5) and chemical oxygen demand (COD), is comparable to values reported by Ehrig [80] for landfills in the methanogenic phase. These findings are also consistent with those obtained by Kato [81] and Marvalin et al. [82]. Given that the Dar El Gueddari landfill operates as an open-air site and is therefore highly sensitive to climatic variations, heterotrophic bacterial activity plays a major role in modulating the physicochemical composition of the leachate.

The concentrations of zinc measured in the leachate are comparable to those reported by Park et al. [83], whereas iron concentrations are particularly high, reaching 21.68 mg/L. According to Buffle et al. [84], such elevated iron levels are likely linked to the high organic matter content, which enhances metal solubility through complexation processes. Several measured parameters exceed discharge standards established by the World Health Organization (WHO) [36].

In parallel, the leachate exhibits pronounced mineral pollution, characterized by high concentrations of ammonium, nitrites, nitrates, sulfates, and phosphates, exceeding commonly accepted environmental quality thresholds. This chemical composition reflects the combined effects of organic matter degradation and mineral dissolution during waste decomposition. The high ionic load is further confirmed by elevated electrical conductivity values, indicating strong mineralization of the effluent.

The presence of toxic metals such as lead, cadmium, arsenic, and chromium poses a serious threat to human health, especially under conditions of chronic exposure. Additionally, although iron, zinc, and copper are essential trace elements, their elevated concentrations may still present ecological and health risks to the population of Dar El Gueddari. Therefore, treating leachate before its discharge into the environment is crucial. In the absence of a fully controlled landfill management system, implementing

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effective leachate collection and treatment facilities is vital to reduce potential impacts on soils, water resources, and surrounding ecosystems.

Furthermore, the detection of high concentrations of pathogenic microorganisms, including total coliforms, thermotolerant coliforms, *Clostridium perfringens*, coagulase-positive staphylococci, as well as yeasts and molds, indicates severe microbiological contamination. This level of contamination poses a substantial public health risk and underscores the urgent need for corrective and preventive measures.

Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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