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Environmental Impact Assessment of a Dumping Site: A Case Study of Kakia Dumping Site

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Abstract: Open dumping threatens the environment and public health by causing soil, water, and air pollution and precipitating the deterioration of the environmental balance. Therefore, sustainable waste management practices and compliance with environmental regulations are important to minimize these negative impacts. In this context, it is very important to identify the environmental damage inflicted by open dumping areas and to take measures to prevent this damage. Makkah is among the cities that still use open dumping for solid waste disposal. The rapid increase in this city's population is generating large quantities of municipal solid waste (MSW), making it difficult to manage waste economically without harming the environment or public health. During Umrah and Hajj, the rate of MSW generation increases to an even greater degree. The sustainable management of MSW in holy cities is of great importance. This study aimed to investigate the environmental impact of the Kakia Open Dumping Site in Makkah on air quality, soil, and nearby groundwater wells. It also conducted analyses of essential elements (Ca, Mg, and Na), heavy metals (Pb, Cd, and Cr), and a metalloid (As) in leachate produced at the Kakia Open Dumpsite, enabling the development of management strategies. In addition, the correlations between the essential elements, the metalloid, and the heavy metals were also analyzed. The goal is not only to mitigate the negative effects of open dumping, but also to highlight the need to adopt sustainable management strategies for MSW in religiously significant cities like Makkah.

Keywords: municipal solid waste management; Kakia Dumping Site; heavy metals; essential elements; environmental pollution

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1. Introduction

In today's world, a rapid increase in municipal and industrial waste production is occurring globally due to exponential population growth and industrial manufacturing [1–3]. Due to changes in domestic and commercial consumption patterns, the amount of solid waste (SW) increases every year globally [4]. This situation has made waste management a challenge for all countries [5,6]. The waste management process includes many steps, such as waste collection, selecting the appropriate disposal method, and recycling [7–9]. Waste management in numerous developing countries presents substantial environmental challenges because of inadequate information, limited municipal budgets, and a shortage of accessible statistical data [10].

Municipal solid waste management (MSWM) includes five main elements: reduction, recycling, recovery, reuse, and disposal [11–13]. Each step of the solid waste management chain (waste generation, waste collection, waste treatment, and disposal) should be carefully monitored to minimize negative impacts on the environment [14]. The world generates

2.01 billion tons of municipal solid waste (MSW) each year, of which at least 33% is not managed in an environmentally safe manner [15]. The global amount of waste is expected to almost double, reaching 2.2 billion tons per year, by 2025 [16]. In this situation, cities around the world are developing new strategies to meet waste reduction targets [17]. Therefore, choosing an MSW disposal method with the least-harmful impact on public and environmental health is crucial for the well-being of communities. Different methods have been proposed to manage MSW, but landfilling is at the forefront of MSWM, especially in developing countries [18].

Various methods, such as composting, incineration, sanitary landfilling (with landfill gas collection), open dumping, and recycling, are used for MSW disposal worldwide [19]. Open dumping, sanitary landfilling (with landfill gas collection), and controlled landfilling account for about 45% of these disposal methods, amounting to 33%, 7.7%, and 3.7%, respectively [15]. A landfill represents a well-designed reactor capable of accommodating solid waste (SW) that cannot be reused in any way. In such a reactor, the solid waste entering it undergoes physical, chemical, and biological changes [20]. The primary objective of controlled landfilling is to protect the environment from potential water, air, and soil pollution [21]. For this reason, leachate-and-landfill-gas (LFG)-controlled landfilling is carried out [22]. However, there is no leachate and LFG control in the open dumping method used in developing and underdeveloped countries [23].

The byproduct of open dumping, LFG, is a result of a decomposition process influenced by various factors [24]. LFG typically consists of approximately 50–55% methane (CH_4) and 45–50% carbon dioxide (CO_2) [25]. Landfill gas may also contain small quantities of ammonia, hydrogen sulfides, Volatile Organic Compounds (VOCs), and carbon monoxide [26]. Uncontrolled emissions of LFG can lead to incidents such as fires and explosions [27]. In open dumping sites, organic wastes can cause fires under high temperature conditions (i.e., during the summer season) [28]. In the winter months, however, the risk of fire generally decreases due to the more humid and cold weather conditions. Leachate, another byproduct of open dumping, poses a threat to water sources due to its complex composition and inclusion of numerous pollutants [29]. Leachate transported by precipitation causes various environmental issues, including surface water, groundwater, and soil contamination [30,31]. Leachate generation remains a major concern for agricultural land and urban life around open dumping sites, as it poses a critical hazard to air, water, and soil [32,33]. Therefore, it is crucial to identify the environmental damage caused by open dumping areas and rehabilitate these sites.

Individuals living in close proximity to these dumping sites may experience negative health effects from the indiscriminate disposal of MSW through open dumping techniques. These health hazards include conditions like gastrointestinal disorders, skin and eye irritation, fever, respiratory distress, and a host of other illnesses [34]. In addition to putting people's health at risk, open dumping can damage underground water supplies and produce gases that have the potential to cause cancer in local populations [35]. Furthermore, this kind of illicit landfill raises dangers to human health and the environment by trapping different animals and creating an environment that is conducive to the growth of pests, most notably mosquitoes [36]. Therefore, continuous monitoring of open dumping site and initiation of necessary rehabilitation efforts are important for the community and public health.

There are many studies on the public and environmental health hazards of open dumping [28,37–40]. In a study conducted in 2022, researchers highlighted the widespread environmental hazards of open dumping and landfilling in terms of MSWM, advocating for exploring sustainable alternatives like landfill mining and closed-loop systems such as enhanced landfill mining to mitigate these impacts and transition towards a circular economy for a more sustainable future [41]. A study conducted in 2022 aimed to reveal the global prevalence of landfilling, highlighting its various types and emphasizing the urgent need for advanced waste management strategies and strict regulations to mitigate the significant environmental and health risks associated with this common waste disposal method [42]. Another study, conducted in 2021, highlighted the escalating global issue of MSW generation, particularly in developing countries like India, emphasizing the pressing need to transition from unscientific open dumping to sustainable waste management systems. The authors underscore the environmental and health risks associated with open dumping and advocate for using holistic approaches and self-sustainable revenue models to address the challenges of MSW's impact on water, air, and soil [43].

In this study, we aim to investigate the environmental impact of the Kakia Open Dumping Site in Makkah on air quality, soil, and nearby groundwater wells. In addition, we provide an analysis of essential elements, a metalloid, and heavy metals in leachate produced at the Kakia Open Dumping Site, enabling the development of management strategies. The scope of this study also includes summarizing the threats posed by the Kakia Open Dumping Site and recommendations on how to mitigate these threats.

2. Materials and Methods

2.1. Site Description

Makkah is among the cities still using open dumping for MSW disposal. The rapid increase in this city's population has led to the generation of large quantities of MSW, making it difficult to manage this waste economically without harming the environment or public health. Examining the rate of MSW production in Makkah reveals that the MSW generation rate for pilgrims during the Hajj season in 1994–2006 reached 2.05 kg/pilgrim/day, whereas it reached 1.60 kg/person/day for local people [44]. A previous study reported the MSW generation rate to be 1.4 kg/person/day for the local population and 1.9 kg/pilgrim/day for pilgrims [45]. Moreover, MSW generation in 2004 was reported to reach 1.2 kg/day, which increased to 1.5 kg/day in Riyadh city and 2 kg/day during Hajj and Ramadan in Makkah City [46]. However, in 2013, the MSW generation rate for all citizens in Saudi Arabia averaged 1.3 kg/day [47]. Finally, the MSW generation rate varied, being 1.5 kg/day in major Saudi cities (Riyadh, Makkah, Medina, Jeddah, Dammam, and Al-Ahsa), 1.2 kg/day in medium-sized population cities, and 1.0 kg/day in low-population cities and villages [48]. In addition to this information, 4500 tons of MSW is produced per day during the Hajj season [18]. This MSW is mostly composed of organic materials and plastics [49,50]. Upon analyzing MSWM in Makkah, it was determined that the historical disposal process (dumping) was employed at two main sites, namely, the Muasiam Site, which closed in 2003, and the Kakia Site, which has been operational from 2003 to the present.

The Kakia Dumpsite is located in the southwest part of Makkah city, on the extension of Aranah wadi, between longitudes 39°47′60″ and 39°48′39″ E and latitudes 21°15′53″ and 21°15′29″ N (Figure 1). Makkah is located in the southern part of the Hijaz area in the western middle sector of the Arabian shield, which mainly consists of various constituents from igneous rocks, metamorphosed rock, and rocks of sedimentary origin belonging to the Precambrian and Paleozoic eras, in addition to basaltic intrusions from the Tertiary and Quaternary eras [51,52].

The Kakia Dumpsite is situated in a valley surrounded by a group of mountains [53]. The depth of subsurface sand deposits reaches approximately 12 m. The estimated area for the Kakia Dumpsite is about 452,489 m^2, while the expanded area has reached 1,077,188 m^2. Its assumed operational period is seven years. The site's maximum elevation above the ground surface is 10 m, and it lacks a liner as well as a gas and leachate collection system. On a daily basis, it receives an average of approximately 3100 tons of solid waste, with the amount of waste increasing during Hajj and the month of Ramadan.

However, the Kakia Dumping Site is surrounded by highways and residential, health, sports, industrial, and educational facilities, whose activities are concentrated in the eastern direction and around the dumping site. These facilities consist of residential areas (Waly Al-Ahd residential community), ready-mix concrete plants, hospitals, educational facilities, scrap collection sites, sports centers, vehicle maintenance shops, showroom centers, and a stadium (Figure 1). For these reasons, managing waste in a way that does not harm the environment and public health is of vital importance.

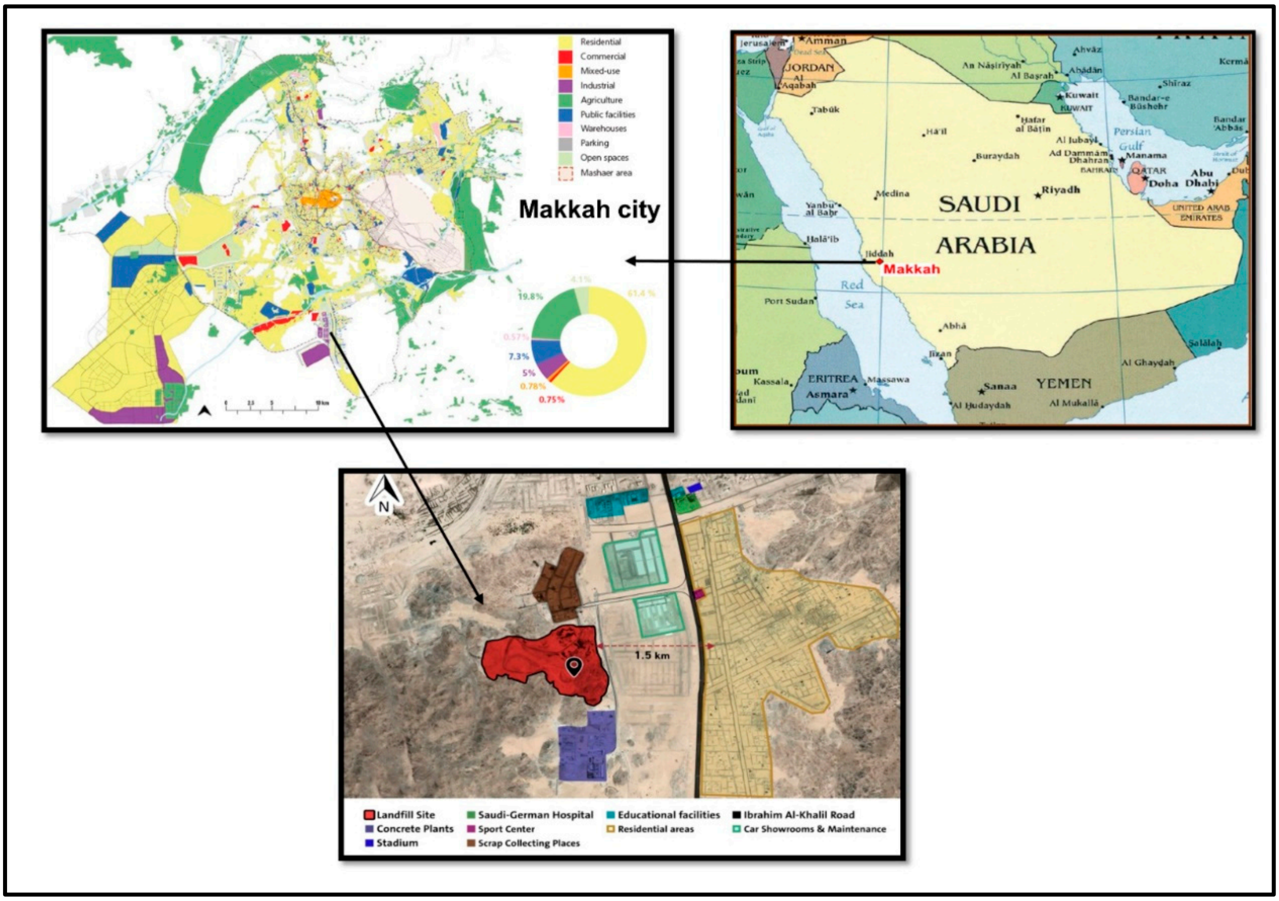

Figure 1. Study area (Kakia Dumpsite) and land-use map showing the major activities that take place around the dump.

2.1.1. SW Management and SW Quantities in Makkah

Open dumping is still practiced in MSW management in Makkah. The collected waste is initially taken to transfer stations and then transported to open dumps. However, leachate, which is not subjected to any collection and treatment system in open dumps, contaminates the soil, groundwater, and surface water resources. The current practices are environmentally unacceptable but heavily adopted due to a lack of advanced technologies and skilled professionals [54]. The compositions of MSW collected with waste bins or containers from various cities vary significantly from city to city depending on the source and community [55]. The disposal of waste without a proper landfilling system is an old practice largely followed in Saudi Arabia. Millions of Muslims from all over the world visit Makkah every year to fulfill commitments regarding Umrah and Hajj. The dramatic increase in urbanization, in addition to the local population of Makkah city and in parallel with the gradual increase in visitors, leads to extensive MSW generation every year. Nowadays, the majority of MSW is disposed of at dumping sites without obeying the traditional protection guidelines, thus posing a potential environmental and health threats (Figure 2) [56].

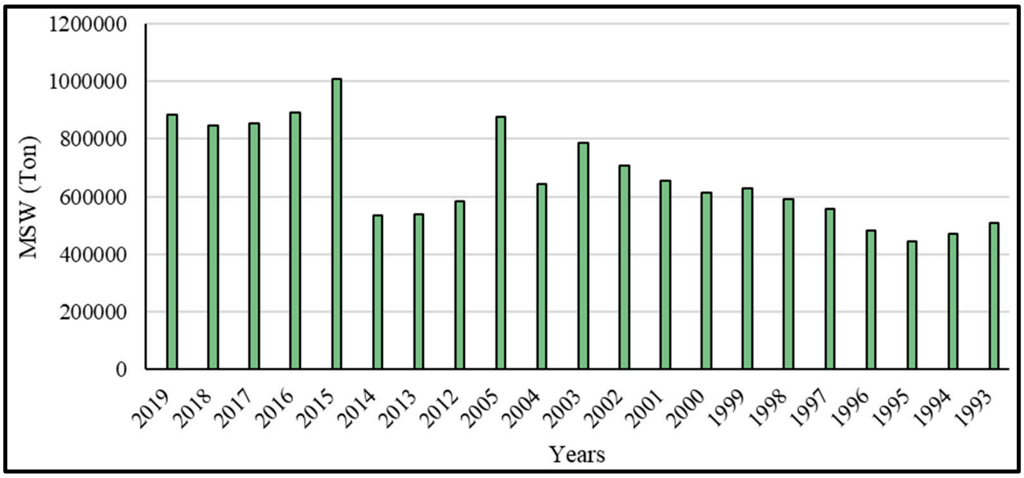

Figure 2. Generated solid waste quantities in Makkah during the 1993–2019 period [56].

2.1.2. MSW Characteristics in Makkah

MSW can be identified physically by its composition, moisture content, and density. These features directly affect its management methods, including collection, transfer, and disposal. The solid waste (SW) generated in Makkah city generally consists of food wastes, plastic, paper, and aluminum cans. However, there are great differences in the composition of the waste produced across its sources (Figure 3).

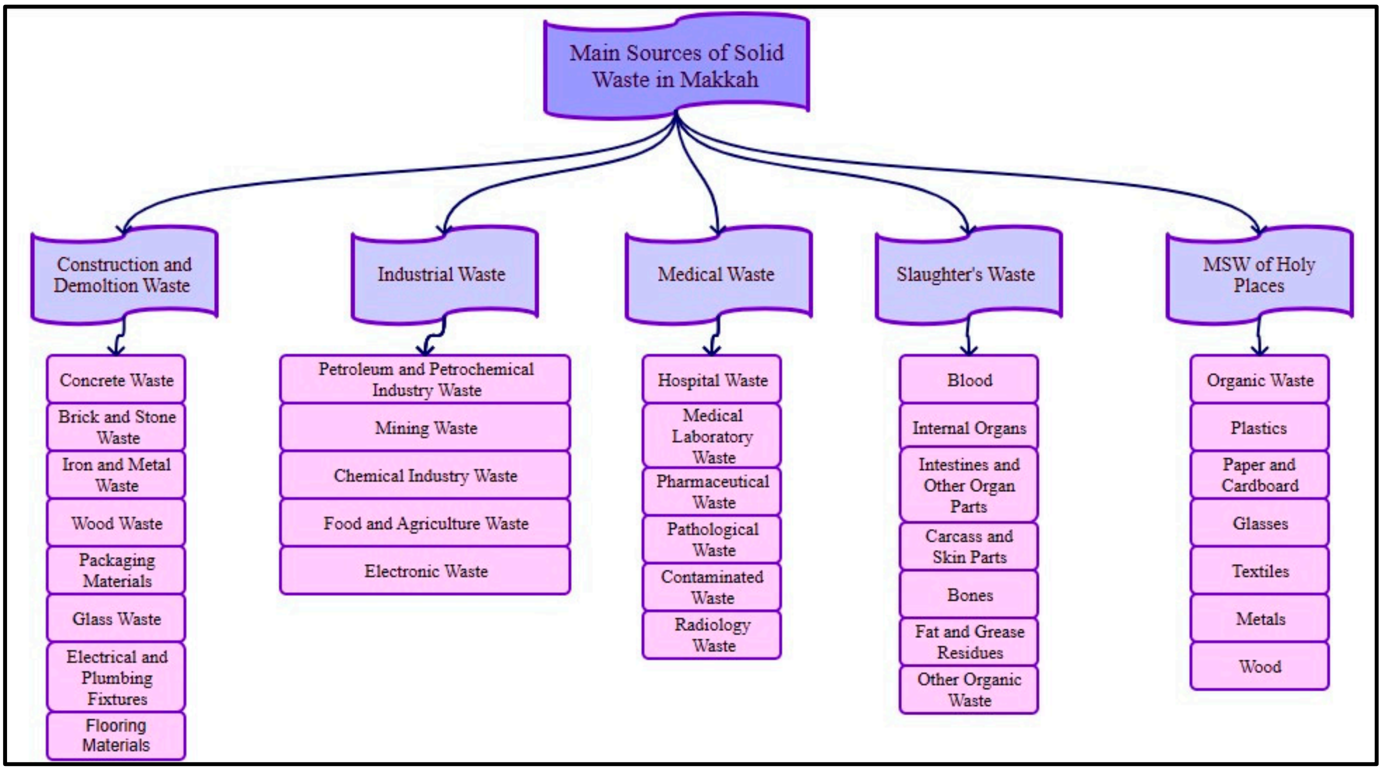

Figure 3. Waste composition of solid waste in Makkah.

Several previous studies have been conducted on the classification of MSW components (Figure 4) [50].

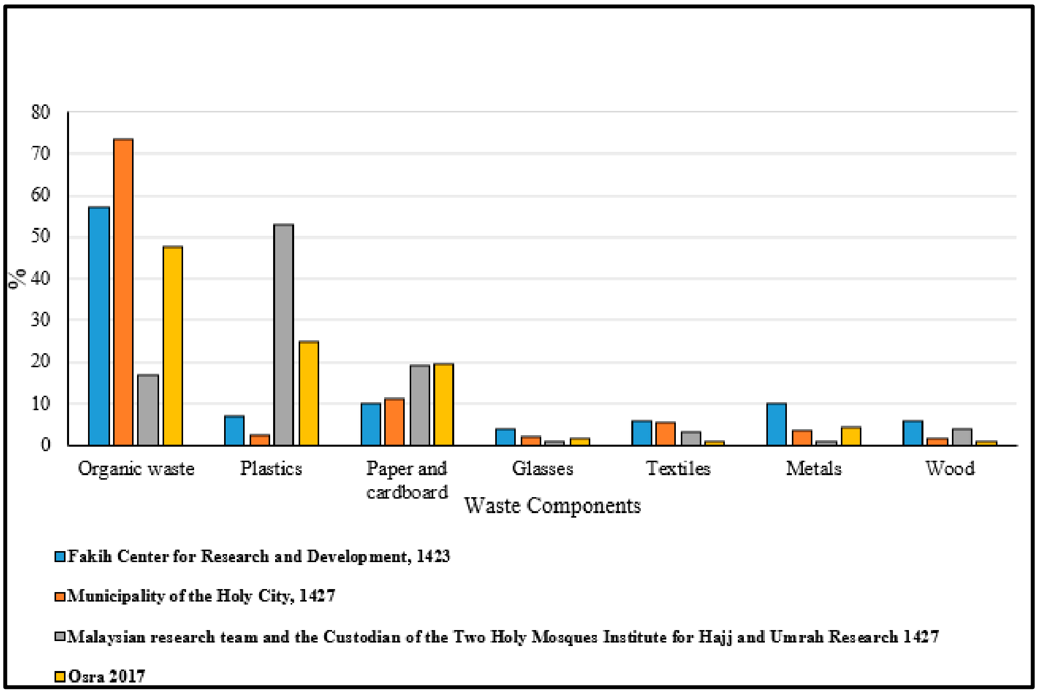

Figure 4. Composition of MSW in Makkah [50].

2.1.3. Climate and Hydrology in Makkah City

The climate of the city of Makkah can be described as arid throughout the year. Due to its complex topography, numerous researchers have studied Makkah's weather patterns and flood models. The Hajj Research Institute (HRI) meteorological monitoring network consists of eight meteorological stations distributed across Makkah (Abdaih station, Arafat station, Azzizia station, Nawaraih station, Shara'a station, Takhsosy station, Leith station, and Z_Kudy station), tracking minimum, maximum, and average temperature data [50]. Makkah is characterized by a harsh desert climate with extremely hot temperatures, particularly during the Hajj pilgrimage when heat stress levels can exceed the 'extreme danger' threshold defined by the U.S. National Weather Service. This threshold corresponds to a wet-bulb temperature of approximately 29.1 °C, which combines temperature and humidity [57]. Projections from coupled atmosphere–ocean global climate models suggest that these extreme heat conditions are expected to increase in frequency and intensity throughout the 21st century, regardless of climate mitigation efforts, necessitating aggressive adaptation measures during high-risk years.

In terms of hydrology, Makkah relies significantly on the Zamzam water well, which provides essential water resources for the city and its numerous visitors. The climatic conditions also affect water demands, which peak significantly during the Hajj season due to the influx of pilgrims and the extreme temperatures. Predictive models, such as neural networks, have been employed to forecast monthly and yearly water demand in Makkah, taking into account factors such as economic progress, climate conditions, population growth, and the expected number of visitors. These models assist in managing the substantial and variable water needs of the city, which are exacerbated by the climatic extremes typical of the region [58]. Generally, the amount of precipitation varies from 3.8 mm to 319 mm, with an average precipitation of 103 mm [50]. Due to the various geographical locations and the presence of separate mountain heads and chains, the neighborhoods of Makkah exhibit variations in precipitation patterns.

2.2. Sampling

Soil, groundwater, and leachate samples were taken to study the environmental impact of the Kakia Open Dumpsite in Makkah and investigate air quality, soil, and nearby groundwater wells. In addition, PM10 was measured at certain locations. The pollutant parameters and analysis methods for the soil samples, groundwater samples, and leachate samples are given in Table 1.

Table 1. Methods and units used in the analysis of the samples taken. a—Pollutant parameters and analysis methods for soil samples. b—Pollutant parameters and analysis methods for groundwater samples. c—Pollutant parameters and analysis methods for leachate samples.

Parameter	Pollutant Parameters and Analysis Methods for Soil Samples (a)		Pollutant Parameters and Analysis Methods for Groundwater Samples (b)		Pollutant Parameters and Analysis Methods for Leachate Samples (c)	
	Method	Unit	Method	Unit	Method	Unit
pH	APHA 9040 B	-	APHA 9040 B	-	APHA 9040 B	-
Calcium (Ca)	EPA 200.7	mg/kg	EPA 200.7	mg/L	EPA 200.7	mg/L
Magnesium (Mg)	EPA 200.7	mg/kg	EPA 200.7	mg/L	EPA 200.7	mg/L
Sodium (Na)	EPA 200.7	mg/kg	EPA 200.7	mg/L	EPA 200.7	mg/L
Lead (Pb)	EPA 200.7	mg/kg	EPA 200.7	mg/L	EPA 200.7	mg/L
Cadmium (Cd)	EPA 200.7	mg/kg	EPA 200.7	mg/L	EPA 200.7	mg/L
Arsenic (As)	EPA 200.7	mg/kg	EPA 200.7	mg/L	EPA 200.7	mg/L
Chromium (Cr)	EPA 200.7	mg/kg	EPA 200.7	mg/L	EPA 200.7	mg/L

2.2.1. Soil Sampling

Within the scope of this study, four soil samples were collected to observe the impact of the Kakia Dumping Site on the soil environment within and around its boundaries. Two of these samples (S1 and S2) were taken within the boundaries of the Kakia Dumping Site, while another two samples (S3 and S4) were taken outside the dumping site. Each sample from the different locations weighed roughly 500 g (Figure 5). The soil samples were then analyzed for pH, and the studied essential elements (Ca, Mg, and Na), metalloid (As), and heavy metals (Pb, Cd, and Cr). Sample preparation consisted of four stages. In the first stage, four soil samples were collected at a depth of approximately 10 cm. Each sample consisted of four sub-samples from within a radius of approximately 1 m from the sampling point. The soil samples were placed in plastic bags and brought to a laboratory. In the second stage, the soil samples were dried in an electric oven for 24 h. Subsequently, in the third stage, the collected soil samples were ground, homogenized, and smoothed. The fourth stage involved the chemical preparation of the samples. Half a gram of each sample was taken, and hydrofluoric acid was added to dissolve the samples and convert them into a solution. A sand heater device was used to apply heat to melt the samples. After the samples were taken out of the sand heater, the next step proceeded. An electrophoresis pH meter was utilized to determine the pH values of the samples. In the fifth stage, specific elements were measured using two distinct methods. Atomic Absorption Spectrometry (AAS) was employed to detect elements such as Na, Ca, Mg, Pb, and Cd, while Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES) was utilized for As and Cr. In this method, the sample preparation procedure differed from the previous one in the following manner: half a gram of each sample was taken, and nitric acid was added to dissolve the samples, creating a solution. A cooling and heating device was used to ensure the samples became a homogeneous solution.

2.2.2. Groundwater Sampling

Groundwater wells (W1, W2, and W3) located in the northern and northeastern parts of the Kakia Dumping Site and used for agricultural activities were sampled. These wells are located 3.1, 4.8, and 5.7 km from the Kakia Dumping Site, respectively (Figure 6). The groundwater levels of the three sampled groundwater wells (W1, W2, and W3) ranged between 13, 30, and 24 m from the ground surface, respectively. Three samples were taken from each site, and each sample consisted of four sub-samples. Subsequently, pH measurement was performed using a METTLER DL77 Titrator device. Following this, samples were prepared, and the proportions of the required elements were measured. An Inductively Coupled Plasma–Optical Emission Spectrometry (ICP-OES) device was applied to detect essential elements such as Na, Ca, and Mg. Additionally, an Inductively Coupled Plasma–Optical Mass Spectrometry (ICP-MS) device was utilized to detect heavy elements, including Pb, Cd, Cr, and As. Regarding the analysis method, ICP-OES is a technique utilized for determining the composition of elements in predominantly water-dissolved samples through the use of plasma and a spectrometer. ICP-MS is an analytical technique employed to ascertain the elemental composition of a sample. It involves the utilization of inductively coupled plasma (ICP) as the ionization source, which generates ions from the sample.

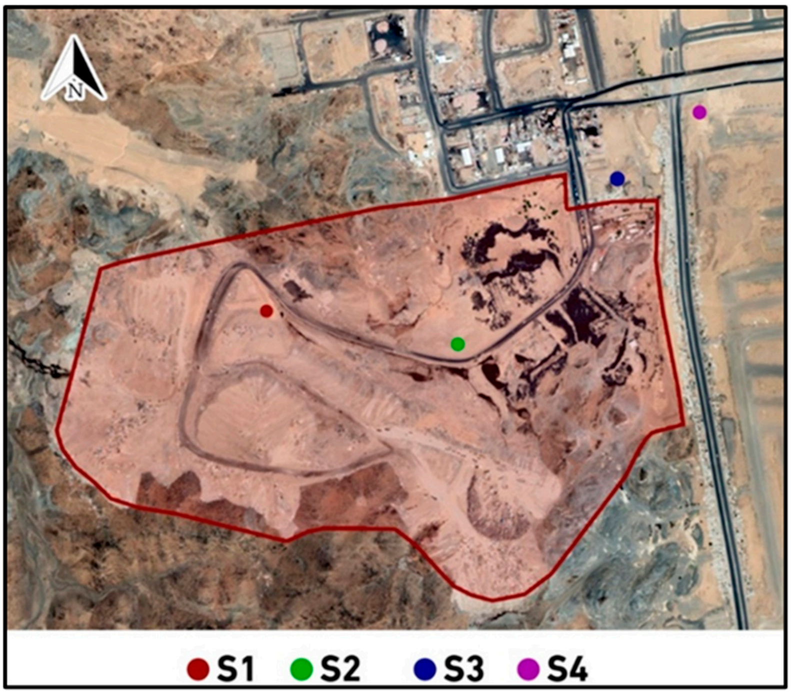

Figure 5. Location map of soil samples collected from Kakia Dumping Site and its surroundings.

2.2.3. Leachate Sampling

We implemented a sampling program to collect a total of three samples of the generated leachate from the Kakia Dumping Site (Figure 7). First, leachate samples were collected. Three samples were taken from each site, and each sample consisted of four sub-samples. Subsequently, in the preparation stage, nitric acid was added to dissolve the samples and create a solution. To ensure homogeneity, a cooling and heating device was utilized, and the sample preparation process was finalized upon the completion of the heating process. Following sample preparation, concentrations of the required elements were measured. The analysis method employed was Method 200.7 for the determination of the studied heavy metals, metalloid (As), and essential elements in leachate using an ICP-AES device. This method is widely recognized in engineering for its accuracy and reliability in determining heavy metal, metalloid, and essential element concentrations in various environmental samples, including leachate from dumping sites like Kakia. The samples were analyzed for pH, and the studied essential elements (Ca, Mg, and Na), metalloid (As), and heavy metals (Pb, Cd, and Cr) in order to reveal the current pollution load of the leachate. In the Kakia Open Dumping Site located in the city of Makkah, Saudi Arabia, there are no leachate control measures in place.

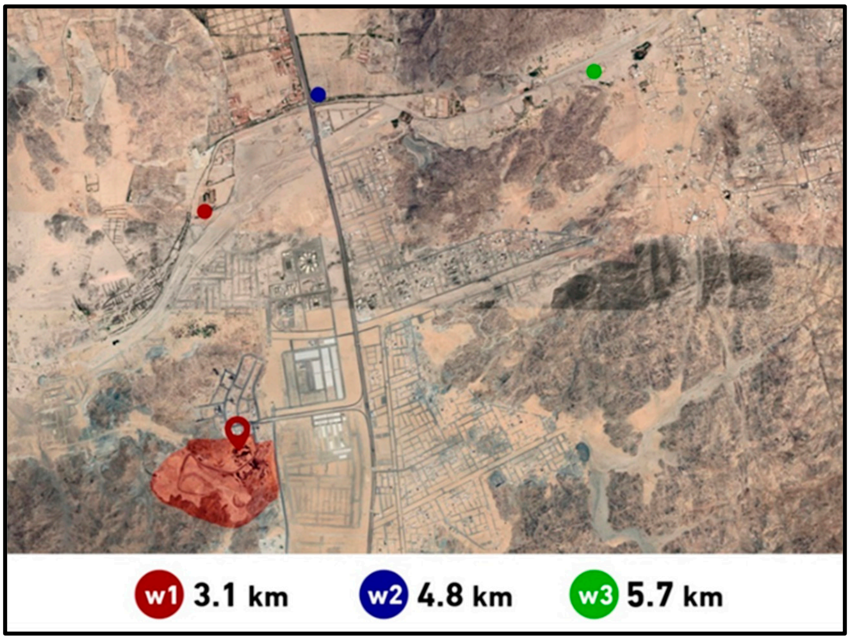

Figure 6. Location map of the sampled groundwater wells around Kakia Dumping Site.

Figure 7. Location map of the collected leachate samples of Kakia Dumping Site.

2.2.4. Air Sampling

PM10 was measured, utilizing a portable aerosol monitor (TSI Dusttrak™ model), based on measuring airborne dust levels. PM10 measurements were performed at the following locations: the main gate of the dumping site, the storage area for soil cover, and the operating cell of the dumping site.

3. Results and Discussion

3.1. Assessment of Air Quality Levels

The activities associated with dumping sites have a confirmed potential to generate suspended particulate matter due to the movement of MSW on- and off-site, the compacting and handling of MSW, compactor traffic on- and off-site, and dust from the surface of the dumping site and produced via erosion [59].

PM10 levels at the main gate of Kakia Dumping Site are given in Figure 8. They ranged between 144 and 325 µg/m^3 on a daily average basis; between 298 and 633 µg/m^3 for the area used for the storage of soil cover; and between 389 and 645 μg/m^3 for the site of the operating cell of the dumping site. According to the World Health Organization (WHO) Global Air Quality Guidelines, the Recommended Air Quality Guideline level (AQG) for PM10 pollutants should not exceed 150 μg/m^3. The PM concentrations measured at the main gate, the soil cover storage area, and the operating cells of the Kakia Open Dump significantly exceeded these values (Figure 8) [60]. By comparing the levels of PM10 at the surveyed three points of Kakia Dump, the levels observed at the operating cells and soil cover storage area are unquestionably higher than what is permitted. However, this is not the case at the main gate site, where the concentrations were mitigated by the continuous wetting of the gate area and pavement of the gate roads.

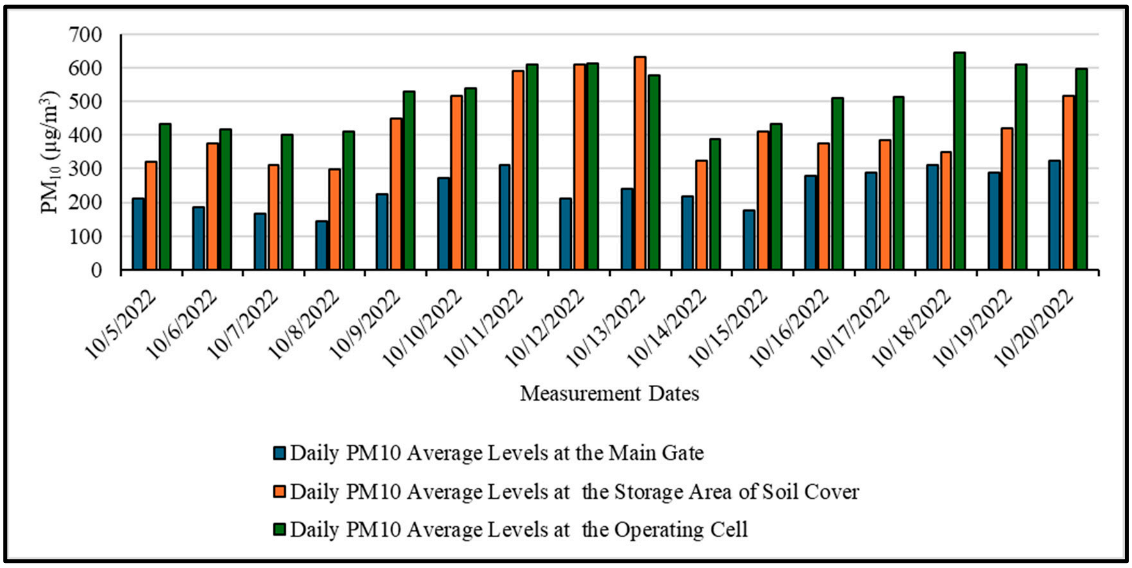

Figure 8. Daily average PM_{10} levels at the Kakia Dumping Site.

Elevated levels of PM10 concentrations of 645 μg/m^3 were detected at the operating site of the Kakia disposal site. These concentrations were produced by the increased volume of trucks and compactors, waste offloading within the operating cells, vehicle movement, and diesel truck exhaust.

3.2. Assessment of Soil Pollution

Evaluation of Analysis Results

The average pH values, ranging between 8.45 and 9.00, exhibit a noticeable decrease towards the dumping site, a phenomenon attributed to the elevated content of exchangeable bases surrounding the site. In conjunction with this, concentrations of essential elements such as calcium (Ca), observed in the collected soil samples, ranged from 29,900 to 52,400 mg/kg, while magnesium (Mg) concentrations ranged from 11,100 to 21,200 mg/kg, and sodium (Na) concentrations ranged from 17,500 to 18,700 mg/kg. Furthermore, the quantity of heavy metals, notably lead (Pb), in the soil samples collected around the Kakia Dumping Site, which ranged from 10.0 to 26.0 mg/kg, as indicated in Table 2A,B, raises concerns, especially considering the potential penetration of these contaminants into subsurface layers and their impact on the groundwater table. On the other hand, concentrations of the other studied heavy metals and metalloid, such as cadmium (Cd), arsenic (As), and chromium (Cr), were detected in the collected soil samples but at lower levels: Cd concentrations were lower than 1 mg/kg, As concentrations were lower than 0.001 mg/kg, and Cr concentrations ranged from 28.42 to 45.96 mg/kg (Table 2A,B). These studied heavy metals and metalloid, though present, pose a less immediate danger compared to lead, but their potential migration into subsurface layers is still a concern, particularly in the context of reaching the groundwater table.

Table 2. (**A**) Chemical analysis data of collected soil samples ((S1, S2), inside the dumpsite) compared to Saudi Standards for Protecting Soil from Pollution in/around Kakia Dumping Site. (**B**) Chemical analysis data of collected soil samples ((S3, S4), outside the dumpsite) compared to Saudi Standards for Protecting Soil from Pollution in/around Kakia Dumping Site.

(**A**)

Test Name	Unit	Result (S1)	Result (S2)	Saudi Standards for Protecting Soil from Pollution
pH	-	8.45	9	8.50
Calcium (Ca)	mg/kg	52,400	29,900	-
Magnesium (Mg)	mg/kg	20,600	11,100	-
Sodium (Na)	mg/kg	17,700	18,200	-
Lead (Pb)	mg/kg	10	12	600
Cadmium (Cd)	mg/kg	<1	<1	22
Arsenic (As)	mg/kg	<0.001	<0.001	26
Chromium (Cr)	mg/kg	45.96	33.86	87
SAR (Sodium Adsorption Ratio)	meq/L	16.55	22.78	<13

(**B**)

Test Name	Unit	Result (S3)	Result (S4)	Saudi Standards for Protecting Soil from Pollution
pH	-	8.67	8.94	8.50
Calcium (Ca)	mg/kg	41,100	33,700	-
Magnesium (Mg)	mg/kg	21,200	12,800	-
Sodium (Na)	mg/kg	17,500	18,700	-
Lead (Pb)	mg/kg	26	13	70
Cadmium (Cd)	mg/kg	<1	<1	1.4
Arsenic (As)	mg/kg	<0.001	<0.001	17
Chromium (Cr)	mg/kg	37.14	28.42	64
SAR (Sodium Adsorption Ratio)	meq/L	17.44	21.95	<13

Based on the values of sodium, calcium, and potassium that were obtained, we calculated the rate of sodium absorption in the soil samples to provide further evidence of the occurrence of soil pollution. The sodium adsorption ratio (SAR) is used to measure the relative concentration of sodium (Na^+) compared to calcium (Ca^{2+}) and magnesium (Mg^{2+}) in the soil solution extracted from a saturated soil paste according to the following equation [61]:

$$\mathbf{SAR} = \frac{[\mathbf{Na^+}]}{\left\{\frac{([\mathbf{Ca^{2+}}]+[\mathbf{Mg^{2+}}])}{\mathbf{2}}\right\}^{\frac{1}{2}}}$$

This ratio, expressed in milliequivalents per liter (meq/L), helps in assessing soil sodicity. The presence of excessive sodium quantities can negatively impact soil structure and plant growth [62,63]. Soils with SAR values greater than 13 are generally classified as sodic [64]. The SAR values that were calculated are shown in Table 2A,B.

Evaluation According to Environmental Standards

Based on the Saudi Standards for Protecting Soil from Pollution issued by the Ministry of the Environment, Water, and Agriculture of the Kingdom of Saudi Arabia, which classifies soil based on both particle size and land use, the samples taken from within the boundaries of the Kakia Dump (S1 and S2) were classified as soft soil samples on land with industrial use. Similarly, the samples located outside the Kakia Dump's boundaries (S3 and S4) were classified as soft soil samples on land with agricultural use.

Soil sample S2 within the dumping site and samples S3 and S4 outside of it exhibited pH values exceeding the Saudi standard of 8.5 [65]. However, within the dumping site, S1's pH does not exceed 8.5. This alkalinity can be attributed to various factors, including those listed below:

- Decomposition of organic waste—organic matter breakdown in an open dump releases alkaline compounds, contributing to a rise in pH [66,67];
- Leachate infiltration—leachate, a liquid produced by the decomposition of waste, can migrate beyond an open dump's boundaries and contaminate surrounding soils with its high pH and dissolved salts [67–69].

The SAR values for all the samples further suggest soil pollution. The SAR indicates the relative concentration of sodium compared to calcium and magnesium in a soil solution [70]. High SAR values, exceeding the recommended threshold of 13 in all samples [71], indicate the following:

- Soil sodicity—sodium ions displace calcium and magnesium from soil binding sites, leading to clay dispersion and reduced soil stability, disrupting drainage, aeration, and nutrient availability for plants [72];
- Potential impact on surrounding areas—the elevated SAR values for S3 and S4, which are outside the dumping site's boundaries, suggest that leachate or other contaminants have migrated beyond the dump, impacting surrounding soil quality.

Regarding the studied heavy metals and metalloid, while lead, cadmium, arsenic, and chromium levels were below the Saudi standards in all the samples, their presence requires continued monitoring. Heavy metals can accumulate in soils over time, posing long-term risks regarding ecosystem health and potentially entering the food chain [73–77]. Based on available data and established scientific principles, it is evident that the Kakia Dumpsite has significantly contributed to soil pollution within and beyond its boundaries. The elevated pH, sodicity, and presence of heavy metals in the soil samples highlight the pressing need for further investigation and the implementation of appropriate mitigation measures to protect soil and avert potential environmental and human health risks. All the measured heavy metal and metalloid levels remained below Saudi Arabia's environmental standards, suggesting no immediate threat. In addition, it is crucial to take proactive measures through regular monitoring efforts to safeguard both the environment and human health.

Evaluation of Correlations between the Studied Essential Elements, Heavy Metals, and Metalloid

When the correlation matrix from the soil samples is analyzed in terms of pH, and the studied heavy metals and metalloid, Cd-As and Pb-Cd have a strong positive relationship (with correlation coefficients of 0.74 and 0.68, respectively). pH and Cr have a very strong negative relationship (with a correlation coefficient of -0.9). At the same time, there is a moderate negative relationship between pH and As (with a correlation coefficient of -0.55) (Figure 9a). When the correlation matrix is analyzed in terms of pH and essential elements, there is a very strong negative relationship between pH-Ca and pH-Mg (with correlation coefficients of -0.99 and -0.92, respectively). At the same time, Mg-Na and Ca-Na have a moderate negative relationship (with correlation coefficients of -0.56 and -0.4, respectively). Additionally, a very strong positive relationship was observed for Ca-Mg, and a moderate positive relationship was observed for pH-Na (with correlation coefficients of 0.86 and 0.4, respectively) (Figure 9b).

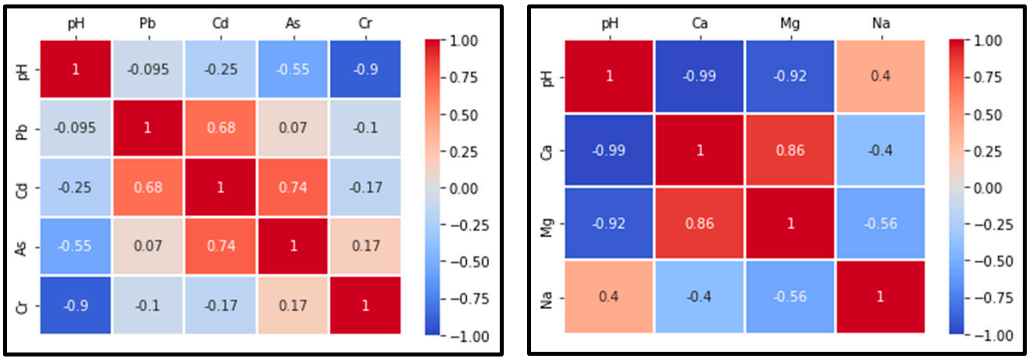

Figure 9. Correlation matrix for the parameters analyzed in the soil samples: (**a**) pH, heavy metals, and metalloid; (**b**) pH and essential elements.

3.3. Assessment of Groundwater Pollution

Evaluation of Analysis Results

There are no leachate treatment facilities at the dumping site in Makkah. Instead, the leachate at the site is exposed to the sun to reduce its volume through evaporation. Afterward, it is covered with a layer of soft clay. No surface water bodies are present around Kakia Dumping Site, Makkah City. However, due to the operational practices and the age of the dumping site, which is about twenty years, the topographic level of the dumping site was elevated compared with the surrounding environment [56]. These factors can lead to some threats to the surrounding environmental conditions, which can be brought about by the accompanying surface deposits of a dumping site during rainfall events in the surrounding environment, especially through the adjacent streams and wadis.

There is an urgent need for a comprehensive and detailed analytical study of the distribution and content of heavy metals and the physiochemical properties of groundwater samples around the solid waste dumping site in Kakia, Makkah City. This step will be the starting point for a rehabilitation program for the dumping site after the closure phase.

The collected groundwater samples, earmarked for agricultural utilization, manifest a transparent nature. Key parameters, including pH levels, and concentrations of the studied essential elements, metalloid, and heavy metals, are outlined as follows. The pH values, presented as an average with a standard range, spanned from 6.83 to 7.46. Calcium (Ca) concentrations within the groundwater samples exhibited a range of 206.45–433.42 mg/L, while magnesium (Mg) concentrations ranged from 84.14 to 173.81 mg/L. Sodium (Na) concentrations displayed variability, ranging between 329.72 and 1049.34 mg/L (Table 3). Notably, the presence of heavy metals such as lead (Pb) in the collected groundwater samples around the Kakia Dumping Site was observed, with concentrations ranging from less than 0.1 to 0.19 µg/L. Similarly, cadmium (Cd) concentrations in the same vicinity ranged from less than 0.1 to 0.19 µg/L. Chromium (Cr) and arsenic (As) were also identified, with concentrations around the Kakia Dumping Site ranging from 0.96 to 3.88 µg/L and 1.31 to 3.33 µg/L, respectively (Table 3).

Evaluation According to Environmental Standards

The nature of the collected groundwater samples seems physically clear and practically utilized for agricultural purposes. For further clarification and interpretation of the water samples, we calculated the values of the sodium absorption rate for each sample and created a table to compare the concentrations of chemical elements with the Saudi standards for potable groundwater and for irrigation water (Table 3).

In terms of sodium and SAR, notably, well W2 exhibited a significantly elevated sodium concentration (1049.34 mg/L) exceeding the Saudi standard for potable water (150 mg/L). This finding suggests a potential intrusion of landfill leachate, as sodium is a common component of leachate plumes due to its high mobility in the subsurface. Further supporting this evidence, W2 also displayed a high SAR value (14.93) exceeding the Saudi standard for irrigation water (<9). The SAR is an important parameter used to determine the suitability of groundwater for irrigation [78–80]. An elevated SAR indicates a potential risk of soil salinization and decreased agricultural suitability due to sodium's detrimental effect on soil permeability and nutrient availability [81,82].

Table 3. Results of the chemical analysis of collected groundwater samples in/around Kakia Dumping Site.

Test Name	Unit	Result (W1)	Result (W2)	Result (W3)	Saudi Standards for Irrigation Water	Saudi Standards for Potable Groundwater
pH	-	6.83	7.46	7.05	6.5–8.5	6.5–9
Calcium (Ca)	mg/L	433.42	223.92	206.45	-	10–100
Magnesium (Mg)	mg/L	173.81	90.5	84.14	-	-
Sodium (Na)	mg/L	819.56	1049.34	329.72	-	150
Lead (Pb)	mg/L	0.00019	0.00016	<0.0001	5	0.0075
Cadmium (Cd)	mg/L	0.00013	0.00019	<0.0001	0.01	0.003
Arsenic (As)	mg/L	0.00333	0.00193	0.00131	0.1	0.0075
Chromium (Cr)	mg/L	0.00096	0.00388	0.00159	0.1	0.037
SAR (Sodium Absorption Rate)	meq/L	8.39	14.93	4.88	<9	-

While wells W1 and W3 showed elevated sodium concentrations compared to the potable water standard (819.56 mg/L and 329.72 mg/L, respectively), their values were lower than those of W2, and their SAR values (8.39 and 4.88, respectively) remained within the irrigation water standard. These findings suggest a possible gradient of leachate influence, with W2 closer to the source and experiencing the most significant impact. In terms of the studied heavy metals and metalloid, no immediate concerns were revealed regarding lead, cadmium, arsenic, or chromium. All wells remained within the relevant Saudi standards for both irrigation and potable water. Analysis of groundwater from wells near the Kakia Dumping Site revealed a potential leachate impact, particularly in well W2. W1 and W2 displayed significantly high sodium values exceeding potable groundwater standards of 819.56 mg/L and 1049.34 mg/L, respectively. This suggests leachate intrusion, threatening water quality and agricultural suitability near the dumping site [83,84]. Wells W1 and W3 showed sodium elevations but ones that remained within irrigation standards, suggesting a possible leachate gradient with W2 closest to the source. Continued monitoring and improved dumping site management practices are crucial to protect water resources and mitigate future contamination risks [85].

Evaluation of Correlations between the Studied Essential Elements, Heavy Metals, and Metalloid

When the correlation matrix from the groundwater samples is analyzed in terms of pH and the studied heavy metals and metalloid, it can be seen that pH-Cr and Pb-As have a very strong positive relationship (with correlation coefficients of 0.99 and 0.86, respectively). Pb-Cd, Cd-Cr, and pH-Cd have a strong positive relationship (with correlation coefficients of 0.75, 0.75, and 0.64, respectively). There is a moderate negative relationship between pH-As and As-Cr (with correlation coefficients of −0.54 and −0.41, respectively) (Figure 10a). When the correlation matrix is analyzed in terms of pH and essential elements, it becomes evident that Ca-Mg has a very strong positive relationship (with a correlation coefficient of 0.98). pH-Mg and pH-Ca have a strong negative relationship (with correlation coefficients of −0.73 and −0.72, respectively) (Figure 10b).

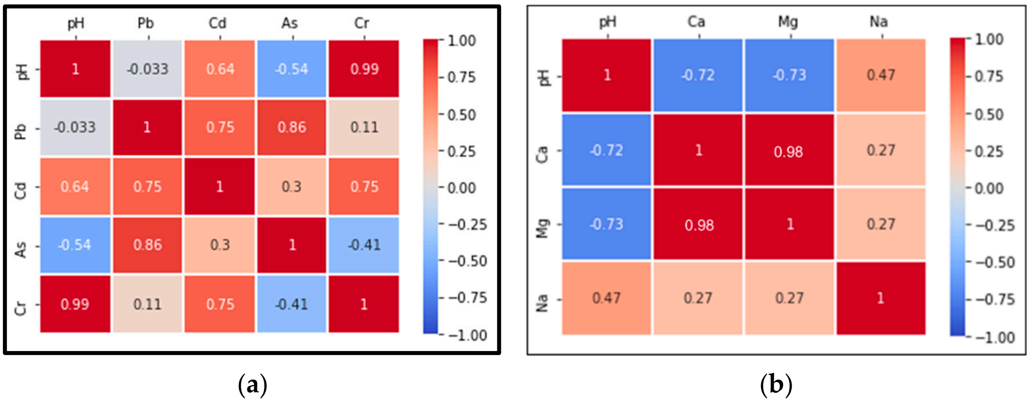

Figure 10. Correlation matrices for the parameters analyzed in groundwater samples: (**a**) pH, heavy metals, and metalloid; (**b**) pH and essential elements.

3.4. Assessment of Generated Leachate

Evaluation of Analysis Results

The generated leachates from the dumping sites constituted complicated mixtures of different substances containing dissolved organic and inorganic matter as well as hazardous substances. Many of the substances contained in the leachate of the dumping sites were toxic and greatly threaten the surrounding environment [86].

The collected leachate samples from the Kakia Dumping Site are characterized by specific attributes, encompassing pH levels, and the studied essential elements, metalloid, and heavy metals, as outlined below. The pH parameter, denoted by average values within a standard range, ranged from 7.19 to 7.23. In terms of calcium (Ca), its concentrations in the collected leachate samples exhibited a range of 1083.00–1171.00 mg/L (Table 4). Similarly, magnesium (Mg) concentrations in the leachate samples ranged from 461.00 to 481.00 mg/L. Sodium (Na) concentrations demonstrated variability, ranging between 4588.00 and 5034.00 mg/L (Table 4). The presence of heavy metals, such as lead (Pb) and cadmium (Cd), in the leachate samples from the Kakia Dumping Site was notably low, with concentrations less than 0.001 mg/L. Chromium (Cr) concentrations ranged from 0.957 to 0.989 mg/L, and arsenic (As) concentrations were less than 0.001 mg/L in the collected leachate samples (Table 4).

Table 4. Results of the chemical analysis of the collected leachate samples.

Test Name	Unit	Result (L1)	Result (L2)	Result (L3)	Saudi Standards for Potable Groundwater	Saudi Standards for Irrigation Water	Saudi Standards for Surface Water (Non-Potable)
pH	-	7.19	7.23	7.23	6.5–9	6.5–8.5	6.5–9
Calcium (Ca)	mg/L	1171	1083	1099	10–100	-	10–100
Magnesium (Mg)	mg/L	481	461	473	-	-	-
Sodium (Na)	mg/L	4588	4789	5034	150	-	150
Lead (Pb)	mg/L	<0.001	<0.001	<0.001	0.0075	5	0.01
Cadmium (Cd)	mg/L	<0.001	<0.001	<0.001	0.003	0.01	0.000025
Arsenic (As)	mg/L	<0.001	<0.001	<0.001	0.0075	0.1	0.15
Chromium (Cr)	mg/L	0.98	0.957	0.989	0.037	0.1	0.05
SAR (Sodium Absorption Rate)	meq/L	28.45	30.66	31.92	-	<9	-

Evaluation According to Environmental Standards

We compiled a table to compare the analysis results for the leachate water samples with specific environmental standards set forth by the Ministry of the Environment, Water, and Agriculture of the Kingdom of Saudi Arabia (Table 4). In terms of high sodium hazard and soil impacts, the leachate exhibited alarmingly high sodium (Na) concentrations and Sodium Absorption Ratio (SAR) values exceeded the standards for both potable and non-potable surface water. This poses a substantial threat to soil permeability and drainage in the surrounding areas, potentially hindering agricultural productivity and jeopardizing soil quality. The chromium contamination risk posed by consistently elevated chromium (Cr) levels, which exceeded all the analyzed standards, warrants serious concern. Depending on the specific chromium species (Cr^{3+} or Cr^{6+}), a high risk of contamination for groundwater, irrigation water, and surface water ecosystems exists. This could have detrimental consequences for aquatic life and potentially human health if groundwater serves as a drinking water source.

The diverse waste composition within this dumping site, including municipal solid waste, construction and demolition debris, and slaughterhouse waste, suggests the potential presence of organic pollutants, ammonia, and other heavy metals beyond those analyzed. A comprehensive analysis of these additional contaminants is crucial for a complete risk assessment and implementing effective mitigation strategies. The dumping site's proximity to groundwater (10–19 m below the surface) amplifies the risk of contaminant migration. Furthermore, the elevated topographic level relative to its surroundings and potential transport of surface deposits during rainfall events increase the vulnerability of adjacent streams and wadis. These factors necessitate robust containment measures and continuous monitoring to prevent environmental contamination. The leachate from the Kakia Dumping Site presents serious environmental risks due to high sodium, chromium, and calcium levels. Establishing effective treatment and monitoring measures is essential to protect groundwater, soil quality, and surrounding ecosystems.

Evaluation of Correlations between the Studied Essential Elements, Heavy Metals, and Metalloid

When the correlation matrix for the leachate samples is analyzed in terms of pH, and the studied metalloid and heavy metals, it is seen that Pb-Cr and Cd-As have very strong positive correlations (with correlation coefficients of 0.95 and 0.81, respectively). There is a very strong negative relationship between pH-Cd and pH-As (with correlation coefficients of −1 and −0.8, respectively). There is a strong negative relationship for Pb-As (with a correlation coefficient of −0.64) (Figure 11a). When the correlation matrix is analyzed in terms of pH and essential elements, Ca-Mg and pH-Na have very strong positive correlations (with correlation coefficients of 0.89 and 0.84, respectively). pH-Ca and pH-Mg have very strong negative correlations (with correlation coefficients of −0.99 and −0.80, respectively). There is a strong negative relationship for Ca-Na (with a correlation coefficient of −0.73) (Figure 11b).

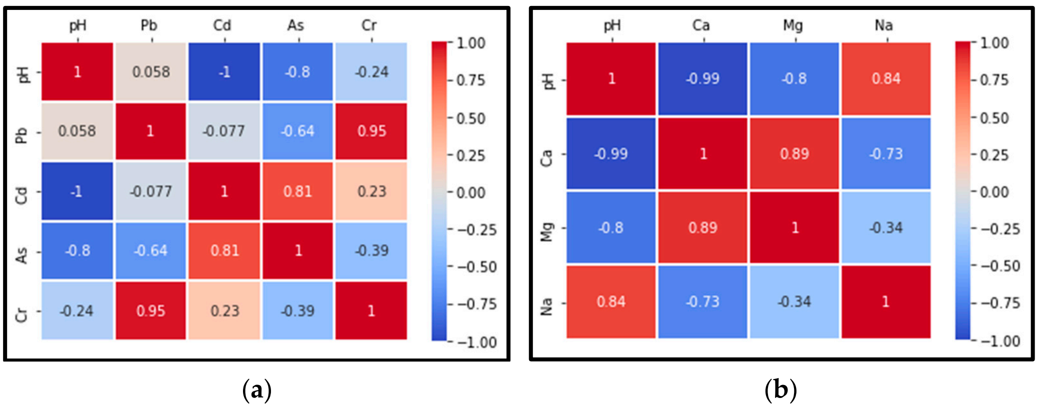

Figure 11. Correlation matrices for the parameters analyzed in the leachate samples: (**a**) pH, heavy metals, and metalloid; (**b**) pH and essential elements.

4. Conclusions and Recommendations

The impacts of the Kakia Dumping Site on the adjacent environment, particularly with respect to the surrounding soil, were evaluated. The average pH values ranged from 8.45 to 9.00, suggesting elevated exchangeable bases around the Kakia Dumping Site, exceeding local permissible limits.

A comprehensive assessment of the Kakia Dumping Site's impact on the environment, specifically on groundwater quality, is imperative. A detailed analytical study encompassing the distribution and content of heavy metals, as well as their physiochemical properties, was conducted on groundwater samples collected around the solid waste dumping site in Kakia, Makkah City. Physically clear groundwater samples suitable for agricultural purposes were observed, with pH values ranging from 6.83 to 7.46. The currently detected presence of heavy metals such as Pb, Cd, and Cr does not directly harm humans, animals, or plants. However, it is imperative that the open dumpsite be continuously monitored, and necessary rehabilitation efforts should be initiated. Otherwise, it is likely to cause adverse effects that could threaten environmental and public health.

The correlations between the studied essential elements, metalloid, and heavy metals were also analyzed in all three environments (soil, groundwater, and leachate). A very strong positive relationship between Ca and Mg appears to exist. Simultaneously, a very strong negative relationship and a strong negative relationship between Ca-pH and Mg-pH were observed in all three environments. Therefore, Pearson's correlation was recognized as a suitable method for experimentally determining a few crucial parameters to obtain a reasonably accurate indication of quality parameters in various environments [87]. Furthermore, the correlation matrix can be an essential tool for assessing human health and environmental risks. Particularly, correlations of heavy metals can contribute to environmental risk management by identifying the sources of these metals.

According to the results and findings gathered in the current study, we recommend taking the following actions during the operation of the Kakia Dumping Site:

- Reduce the quantity of respirable dust particles disturbed by the movement of compactors and trucks during unloading, and squeeze and compact sand cover deposits and MSW through the occasional wetting of the operational area and the pavement of the roads, where possible, with asphalt.
- Frequently spray water around the entry area of the dumping site and the weighing site for trucks.
- Conduct regular follow-ups and repairs of the entire road network and the operating cells of the dumping site.
- Regularly spray water to minimize and mitigate the potential for the resuspension of particulate matter to avert and minimize the risk of human exposure for workers in the landfill/dumping sites.
- Plant more trees and expand the green landscape in/around the landfill/dumping site to minimize the levels of ambient particulate matter by means of the dust retention capacity of the foliage of shrubs and trees.
- Generally, the studied site is in need of a plan for preserving the current natural resources (soil, groundwater, and air).
- Encourage the optimum scenario for the management of MSW with the 3Rs concept (reduce, reuse, and recycle) and conduct waste sorting and treatment before disposal.

The detection of pollution originating from open dumping sites and the initiation of rehabilitation efforts serve as a primary step towards mitigating various impacts on human settlements in the vicinity. These impacts affect different domains, including health, the environment, the economy, and society. Hazardous substances and pollution emitted from open dumping sites adversely affect the health of individuals residing in the vicinity, contributing to respiratory ailments due to air pollution and jeopardizing drinking water sources through water contamination. Additionally, the pollution surrounding dumping sites can negatively impact local economic activities such as agriculture, livestock farming, and tourism, leading to economic losses. From a societal perspective, pollution in the vicinity of dumping sites diminishes the quality of life of nearby residents, fostering societal unrest and a decline in community well-being. This study sheds light on the importance of identifying existing pollution levels and undertaking rehabilitation work to mitigate or prevent these adverse effects.

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