Impact of Landfill Leachate on Groundwater Quality and Health Risk Assessment in Mohammedia Prefecture, Morocco

Rachida El Morabet[1], Yasser Lamouadene[2], Mohamed Alouane[3],
Dhafer Ali Alqahtani[4], Roohul Abad Khan[5]*

[1]*Department of Geography, LADES-Lab, FLSH-M, Hassan II University of Casablanca, Mohammedia, Morocco*
https://orcid.org/0000-0003-4750-644X
[2]*Department of Geography, LADES-Lab, FLSH-M, Hassan II University of Casablanca, Mohammedia, Morocco*
[3]*Department of Geography, LADES-Lab, FLSH-M, Hassan II University of Casablanca, Mohammedia, Morocco*
[4]*Department of Civil Engineering, King Khalid University, Abha, Saudi Arabia*
https://orcid.org/0000-0003-1675-2947
[5]*Department of Civil Engineering, King Khalid University, Abha, Saudi Arabia*
https://orcid.org/0000-0002-2329-4123

**corresponding author's e-mail: rakhan@kku.edu.sa*

Abstract: Several studies have been conducted to identify the potential impact of landfills on groundwater resources. This study evaluates the impact of landfills on groundwater resources in Mohammedia prefecture, Morocco. The groundwater was analysed from 2015 to 2022. The groundwater quality was evaluated based on electrical conductivity, pH, biological oxygen demand, chemical oxygen demand, total Kjeldahl nitrogen, phosphate, suspended solids, dissolved oxygen, ammonia, and total hydrocarbon, aluminium, iron, cadmium, chromium, copper, iron-nickel, zing, and mercury. The assessment was based on the water quality index, leachate pollution index, non-carcinogenic risk assessment, and carcinogenic risk assessment. A leachate pollution index <5 indicates that it poses a severe risk to groundwater resources. The non-carcinogenic risk HQ was determined to be <1, which infers no potential risk. The carcinogenic risk index value of 10^{-4} indicated that it is within the threshold of acceptable limit. The current study concludes that leachate from the analysed landfills does not infiltrate the groundwater resources of Mohammedia prefecture. However, the leachate pollution, even though it varies, is increasing over time. This is validated by the fact that the landfill is protected with a membrane covering the ground, which inhibits any possible infiltration of soil or water resources. Hence, this study calls for continuous monitoring of groundwater resources in the region. Future studies are required to investigate the groundwater in Mohammedia prefecture in terms of emerging pollutants to identify any potential risk.

Keywords: landfill, groundwater, water quality, leachate pollution index, hazard quotient

1. Introduction

A designated area or pit for solid waste disposal has been used in one form or another. With the advent of technology and comprehension of solids waste decomposition, the pits were organised, and the term landfill was introduced (Hosseini Beinabaj et al. 2023). Globally, landfills are mainly employed owing to their economy, effectiveness, and straightforward approach to use for solid waste disposal (Hosseini Beinabaj et al. 2023). Landfill leachate is a combined product of solid waste decomposition, rainfall, and surface discharge of landfills. Its characteristics vary from seasonal variation, waste composition, and landfill ageLeaving aside its foul smell (Nyirenda & Mwansa 2022). Also, the primary concern about landfills is the potential for polluting groundwater, surface water, and soil, which calls for treating leachate in landfill facilities. If landfill leachate is not handled correctly or there is a lack of proper management, the leachate can seep through to the groundwater table, which will render the most fragile water resource existing on the planet Earth.

The contamination potential necessitates regularly monitoring water resources around landfills to analyse any potential threat. Several studies have been conducted to identify the potential risk for water resource contamination using chemical indicators, tracers, and several analytical techniques (Afolabi et al. 2022, Hosseini Beinabaj et al. 2023, Thyagarajan et al. 2021). The conventional parameters used in these studies comprise physicochemical parameters such as pH, ammonium (NH^+), chemical oxygen demand (COD), biological oxygen demand (BOD), and electrical conductivity (Asomaku 2023). The risk becomes much more severe when the landfill leachate is laden with heavy metals. Heavy metals have long shell life and are persistent in the environment. Hence, several studies associated with landfill and their surrounding water resources have also investigated heavy metal occurrence in landfill leachate and water resources to identify potential contamination (Hosseini Beinabaj et al. 2023, Uddh Söderberg et al. 2019). Morocco, the northwest country of the African continent, is no exception. Elmaghnougi et al. (2022) examined groundwater pollution from landfill leachate

in the Tangier landfill in Morocco for the years 2016-2019. Benaddi et al. (2022) evaluated the impact of three different landfills in Morocco on groundwater quality regarding age and their category as rural and urban landfills. El Mouine et al. (2021) studies the landfill plume pollution in the tadla plains of Morocco to assess its impact on agricultural activities. Nonetheless, there is a lack of literature and studies involving landfill leachate pollution and its impact on groundwater resources in Mohammedia prefecture in Morocco. This study is the first of its kind for the prefecture to evaluate the impact of landfill leachate on groundwater quality in Mohammedia prefecture. The objectives of the study are: i) Assess the groundwater quality in Mohammedia prefecture in the vicinity of a landfill, ii) evaluate the leachate pollution index, iii) estimate health risk from heavy metal contamination of groundwater and iv) analyse the groundwater quality variation for period of eight years.

2. Methods and Data Used

2.1. Study Area

The landfill under investigation in this study is located in Morocco, Casa-Setat-region, Mohammedia prefecture. The landfill is situated on the western border of the prefecture. The nearest surface water body was in the form of a river, Nfifikh. Two river samples, S1 and S2, are the surface water bodies passing near the landfill site. However, since the surface water body does not have continuous water flow every year as it depends on the rainfall received in the watershed, the primary focus of this study is groundwater samples. Groundwater was investigated at three sampling locations: P1, P2, and P3. Sample location P3 was chosen near the landfill area to identify potential landfill leachate contamination. The study area and groundwater sample locations are presented in Figure 1.
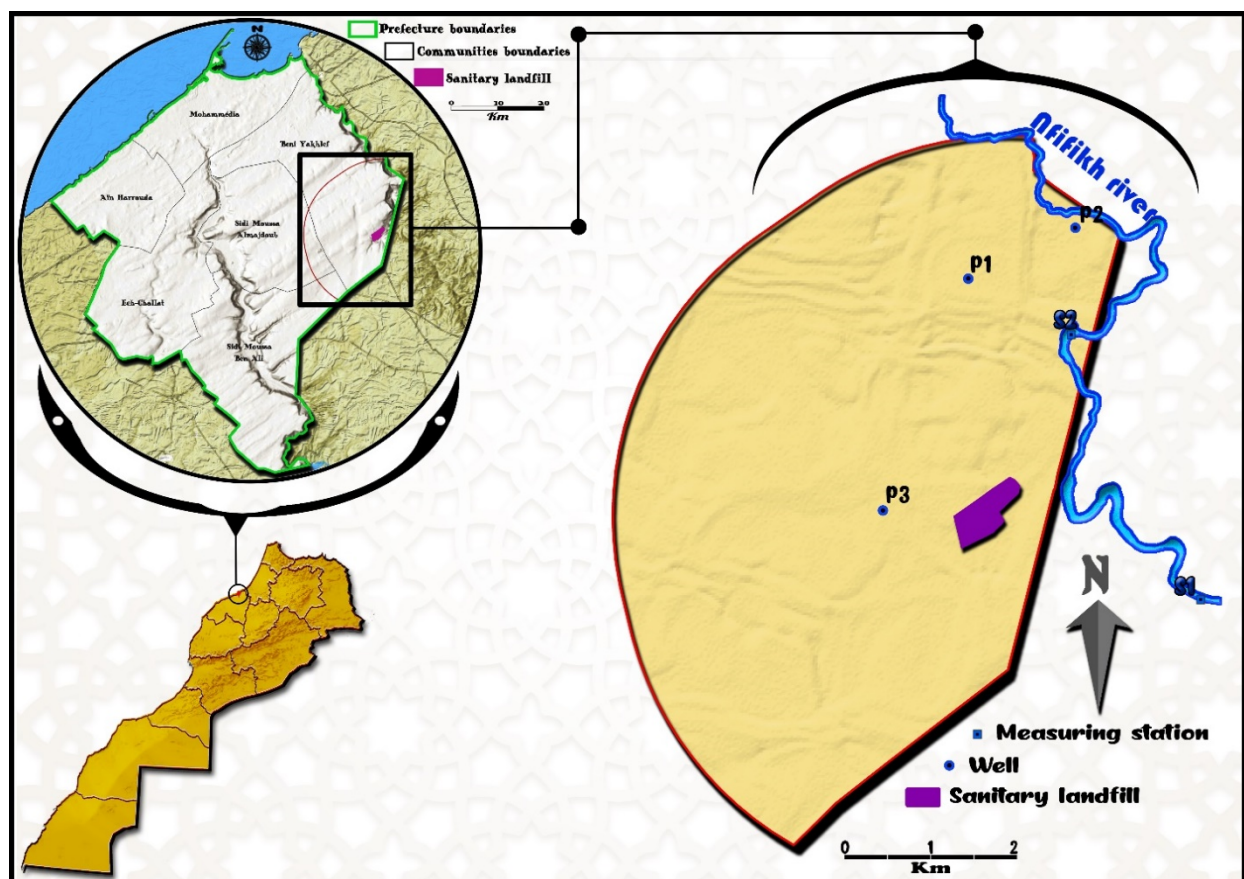

Fig. 1. Landfill location in Mohammedia prefecture Morocco and sample location of wells for groundwater quality assessment (P1, P2, P3 = groundwater sample location and S1, S2 = surface water sampling location)

2.2. Landfill Description

The Beni Yakhlef landfill is a controlled landfill (Fig. 2), which has been delegated to a private company to manage and treat waste in a way that will preserve the surrounding environment. The total area of the project is 47 hectares. The landfill consists of buildings for sorting waste and 4 landfills containing a network of pipes to withdraw leachate and toxic gases, basins to collect the leachate resulting from the accumulation of garbage,

and another basin to collect polluted rainwater. In addition to a basin for biological leachate treatment, a physicochemical treatment station, and a biogas incinerator. Annually, the landfill receives 180,000 tons of waste at a rate of 493 tons daily. All of this waste is household waste.
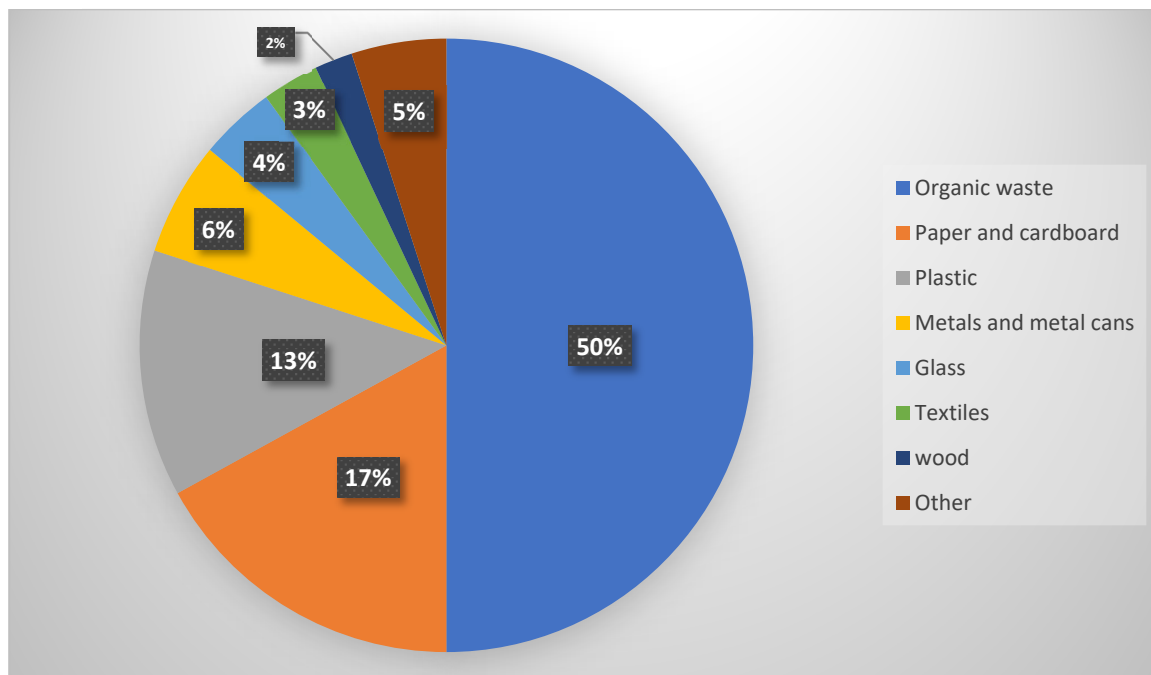

Fig. 2. Mohammedia Landfill waste composition in percent

The landfill has been operational since 2012 and is still receiving waste daily. The first layer on top of the soil subgrade is the geosynthetic clay liner (GCL). The next layer is the secondary 60-mil high-density polyethene (HDPE) geomembrane liner rolled out on top of the GCL. The direction of water flow is northwest through gullies towards the Nfifikh River.

Agricultural lands that are characterised by various crops surround the landfill, and the agricultural livelihoods are only a few meters from the landfill site. This is in addition to the fact that it is only one kilometre from the ecological site of the Nfifikh River, which is characterised by diverse natural flora and fauna. It should also be noted that rural residential communities surround this landfill.

2.2.1. Landfill climatic conditions

The region in which the landfill is located is characterised by a semi-humid and semi-arid climate. Fluctuation and irregularity in precipitation rates between rainy and dry years, with an average annual precipitation of 404 mm. The seasonal distribution of precipitation shows that the climate is characterised by rainfall during the winter and dryness during the summer, which characterises the prevailing climate in the Mediterranean region. According to the Gaussen index, the dry period extends over six months (May, June, July, August, September, and October), while the wet period extends from November to April. As for temperature, the coldest month of the year is January, while the hottest is August, and the average temperature reaches 18.5 degrees Celsius.

2.2.2. Landfill vicinity Hydrogeological conditions

Morphologically, it is a hilly area whose surface is characterised by contortions, as it comes within the end of the central plateau unit, bordered by the Hamra gully, which pours its waters into the Nfifikh River in the event of precipitation. In terms of soil, the area is characterised by red silt soil. And from a geological standpoint, the landfill is located on layers of doleritic basalt, limestone sand, limestones, and red clays. Hydrologically, one kilometre from the landfill, we find the seasonal Nfifikh River, which empties into the Atlantic Ocean in Mohammedia. This is in addition to underground water, which residents use in their daily lives through wells.

2.2. Sampling and laboratory analysis

The sampling was done in cooperation with ECOMed, the agency responsible for assessing the impact of landfill leachate on water resources. A sample for each location was chosen in a replicate of three. The collected

samples were stored in amber-coloured glass bottles. Upon arrival at the laboratory, if samples were not scheduled to be tested immediately, they were stored at a temperature of -4°C. The parameters investigated in this study are chemical oxygen demand (COD), biological oxygen demand BOD_5, pH, Electrical conductivity, total Kjeldahl nitrogen, suspended solids, total phosphate, dissolved oxygen, total hydrocarbon, and ammonia, which are in lieu with the parameters currently used by the governing agencies for assessing the impact of landfill leachate on groundwater in Morocco. The heavy metals investigated in this study are chromium (Cr), cadmium (Cd), iron (Fe), zinc (Zn), nickel (Ni), aluminium (Al), mercury (Hg), copper (Cu), and silver (Ag). Standards for analysing targeted compounds were adopted from Moroccan drinking water standards and WHO guidelines.

2.3. Potential Ecological Risk

Fadlillah et al. (2023) and Mohajane & Manjoro (2022) have assessed ecological risk in water and surface water sources. This study has also adopted the same methodology to assess potential ecological risk to groundwater near the landfill area. Potential ecological risk is necessary because groundwater is used for irrigation and can impact agricultural land negatively. Also, if the landfill leachate permeates to the surface water body near the landfill, it can risk the aquatic ecosystem. However, there is a lack of assessment from this point of view regarding landfill leachate contamination of water sources. As presented in eq. 6, the potential ecological risk index PERI is calculated by combining contamination status (Sc) and toxicity factor (Ft) of each target parameter. The toxicity factors of the heavy metal taken in this study are as follows: Cd = 30, Cu and Ni = 5, Hg = 40, Cr, Fe, Zn = 1 (Fadlillah et al. 2023). Status of contamination is obtained by dividing the measured concentration (M_c) with standards (Std_c) for the target parameter.

$$E_r = F_t \cdot Sc \tag{1}$$

$$S_c = \frac{M_c}{Std_c} \tag{2}$$

$$PERI = \sum_r^i E \tag{3}$$

2.4. Leachate Pollution Index

The Leachate Pollution Index (LPI) is an indexing-based approach to evaluate water quality. This approach is similar to the water quality index (WQI). It exhibits the landfill and its associated pollution (Nyirenda & Mwansa 2022). LPI provides quantitative potential of landfill leachate pollution on a scale of 5 to 100. The higher values of LPI indicate a higher level of pollution caused by landfills (Afolabi et al. 2022). LPI was estimated using equation 4.

$$LPI = \frac{\sum_{i=1}^n w_i \cdot p_i}{\sum_i^n w_i} \tag{4}$$

$$w_i = \frac{1}{S_i} \tag{5}$$

$$W_i = \frac{w_i}{\sum w_i} \tag{6}$$

$$p_i = \frac{C_i}{S_i} \cdot 100 \tag{7}$$

$$LPI_i = W_i \cdot p_i \tag{8}$$

$$LPI_{total} = LPI_1 + LPI_2 + LPI_n \tag{9}$$

Where LPI = leachate pollution index w_i is the weight of ith parameter analysed in the study, p_i = sub-index of leachate parameter analysed in the study, n = a number of leachate pollutant parameters employed to estimate LPI. W_i is the weightage of each weight assigned to the pollutant against the total weight of pollutants analysed. S_i is the permissible limit of pollutants in water for drinking purposes. C_i is the parameter concentration in the sample. Since LPI is not estimated based on a single parameter but based on multiple parameters, it is termed a weighted additive leachate pollution index (Afolabi et al. 2022).

2.5. Health risk assessment

2.5.1. Non-carcinogenic risk assessment

Chemical exposure to humans is estimated for its potential and magnitude based on its significant routes and transport pathways leading to exposure (Epa and Risk Assessment 2002). Health risk of each parameter analysed in this study was estimated based on USEPA (2004). Pollutant exposure pathways have been described as ingestion and dermal contact. Ingestion comprises direct water intake, and dermal contact refers to

skin contact (bathing, swimming, etc.) (Afolabi et al. 2022). Non-carcinogenic risk is calculated based on average daily intake (ADI) and hazard quotient (HQ). The ADI is calculated based on equation 10, and HQ is calculated based on equation 11.

$$\text{Average Daily Intake }_{ADI} = \frac{C_w \cdot IR \cdot EF \cdot ED}{BW \ X \ AT} \tag{10}$$

Where C_w refers to the concentration of pollutants in the water sample, ingestion rate (IR) is per day consumption water taken as 2 litres in this study, ED is exposure duration in years for consumption of the water sample investigated in this study taken 70 years lifetime for an adult, (assessment for children was not conducted in this study) exposure frequency refers to the number of days per year which is taken as 365 days, BW is the body weight of the adult taken as 70 kg and average exposure time if ED · EF. These values adopted in this are subject to change with local parameters. For example, an individual's body weight varies from region to region, followed by lifespan, ingestion rate, and exposure frequency. For example, people tend to travel during vacation for 30-60 days, so exposure frequency will be reduced from 365 days to 335 days or 305 days accordingly. However, the adopted values are in coherence with those adopted in published literature (Long et al. 2021, Afolabi et al. 2022).

$$\text{Hazard Quotient}_{HQ} = \frac{ADI}{RfD} \tag{11}$$

The hazard quotient is obtained by dividing the average daily intake by each parameter's chronic reference dose (RfD). It is obtained as a ratio between ADI and RfD (Afolabi et al. 2022). The RfD values adopted in this study are given in Table 1 (Afshin Maleki 2021). The Hazard index is obtained as the summation of the hazard quotient from each pollutant.

Table 1. RfD and CSF values of heavy metals analysed in this study

Heavy Metal	Unit	RfD	CSF
Al	$mgkg^{-1}d^{-1}$	1	NA
Cd	$mgkg^{-1}d^{-1}$	0.0005	0.61
Cr	$mgkg^{-1}d^{-1}$	0.003	0.5
Cu	$mgkg^{-1}d^{-1}$	0.04	NA
Ni	$mgkg^{-1}d^{-1}$	0.02	1.7
Zn	$mgkg^{-1}d^{-1}$	0.2	NA
Fe	$mgkg^{-1}d^{-1}$	0.7	NA

Cancer risk among humans increases upon long-term intake of contaminated water. This necessitates the carcinogenic risk assessment. The carcinogenic risk is assessed based on average daily intake (ADI) and cancer slope factor (CSF). Carcinogenic risk is assessed based on equation 12.

$$CR = ADI \cdot CSF \tag{12}$$

3. Results and Discussion

To evaluate the change in groundwater quality variation, the concentration of the first year of occurrence was used to determine the increment or decrement in the concentration of the analysed parameters in this study. Figure 3. presents the variation of water quality parameters over eight years of investigation concerning variation in each year with the previous one and variation from the year of investigation starting, i.e., 2015, which will provide a reference to assess water quality variation after eight years. To present the overall change in characteristics of leachate and water samples, the difference in measurement in the years 2015 and 2022 was considered. Table 2 presents the typical landfill leachate characteristics observed in this study. pH in the landfill leachate sample ranged from 6.1 to 8.25 over eight years in leachate sample. The leachate was alkaline in 2015, with a pH of 7.26. In 2016 and 2017, it was changed to acidic, with a pH range of 6.2-6.8. In the 2018-2021, leachate exhibited an alkaline nature with a pH range of 7.05-8.25. Again, in 2022, pH was observed to be acidic, with a value of 6.1. Compared to 2015, pH in 2022 decreased by 22%, turning the sample nature from alkaline to acidic. The water sample analysis was comprised of only river Nfifikh in 2015, with one sample point before the river reached the landfill and one sample after the river crossed the landfill. pH was in the range of 7.25-7.8. In 2016, three groundwater samples with a pH range of 7.25-7.8 were also analysed. From the Year 2017 onwards, two water samples were analysed from river Nfifikh, and three groundwater samples
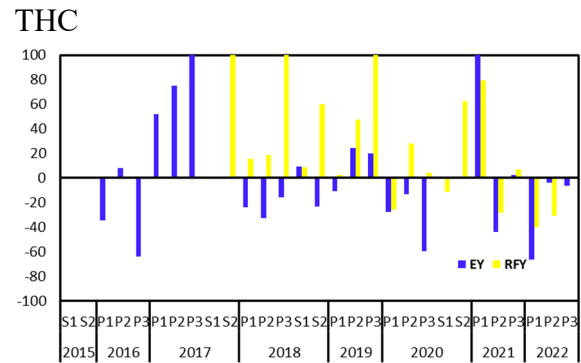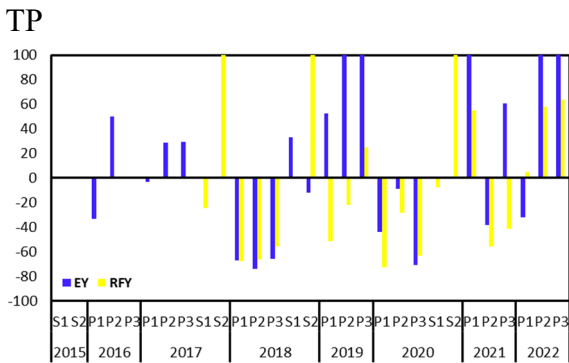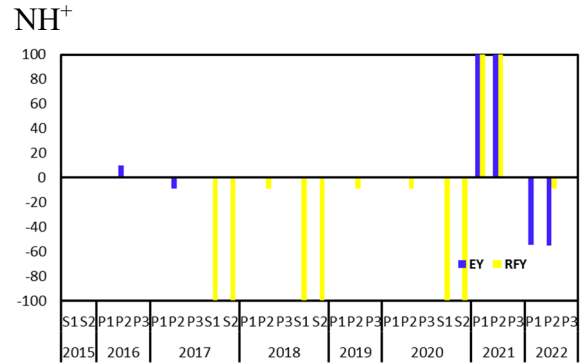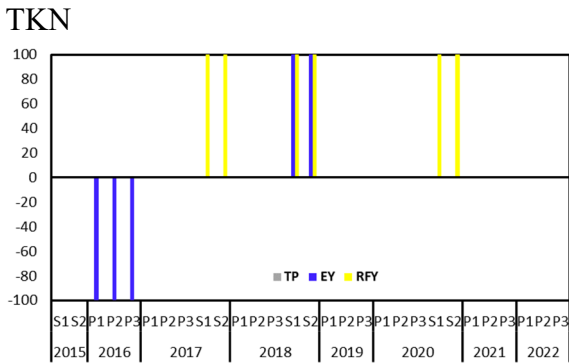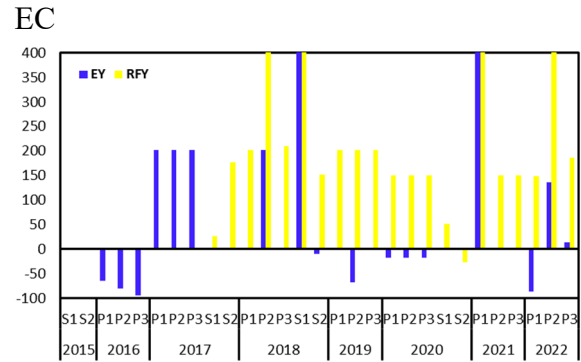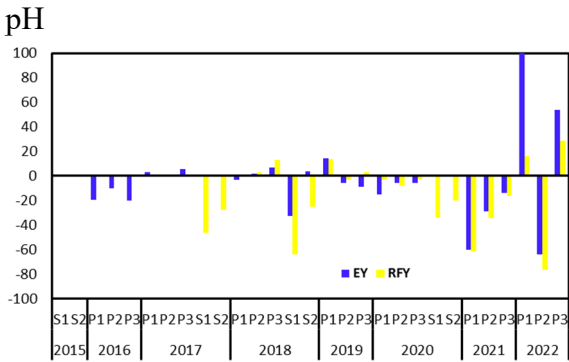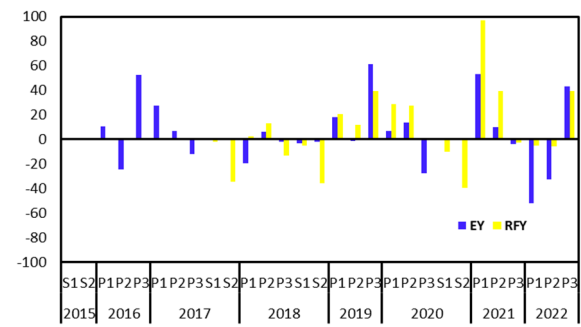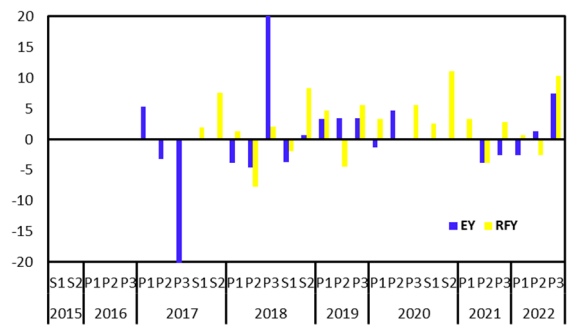
were selected to evaluate potential contamination reaching groundwater from landfill leachate reaching up to the river Nfifikh. In the groundwater sample at point P3, there was a significant decrease in pH, reaching 5.35, rendering it acidic.

Table 2. Landfill leachate sample characteristics

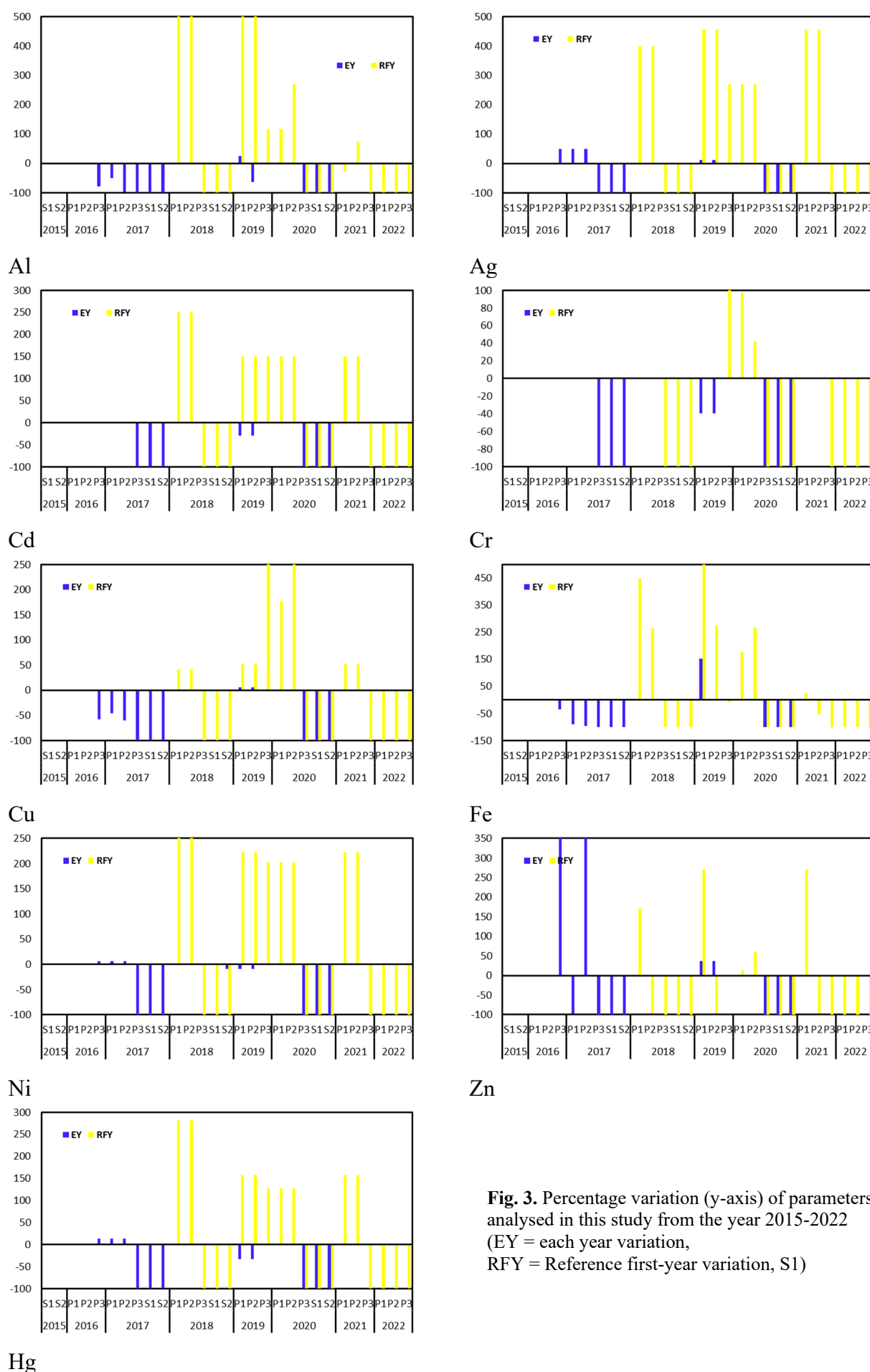| Parameter	Units	Min.	Max.	Avg.
pH	–	6.10	8.25	7.24
BOD5	mgL^{-1}	81.30	53,301.00	19,834.06
COD	mgL^{-1}	97.89	79,872.00	33,570.88
EC	mgL^{-1}	35,600.00	51,800.00	43,230.00
DO	mgL^{-1}	0.00	0.00	0.00
TKN	mgL^{-1}	4,592.00	7,302.00	5,958.00
NH4+	mgL^{-1}	3,220.00	6,989.00	4,947.20
TP	mgL^{-1}	32.60	84.90	57.74
SS	mgL^{-1}	220.00	2,084.00	881.30
TCH	mgL^{-1}	0.00	463.00	102.62
Al	mgL^{-1}	0.00	16.90	4.50
Ag	mgL^{-1}	0.00	0.04	0.01
Cd	mgL^{-1}	0.00	0.01	0.00
CrT	mgL^{-1}	0.00	2.01	0.70
Cu	mgL^{-1}	0.00	0.40	0.11
Fe	mgL^{-1}	0.00	69.50	20.64
Ni	mgL^{-1}	0.00	0.61	0.22
Zn	mgL^{-1}	0.00	2.40	0.75
Hg	mgL^{-1}	0.00	0.01	0.00

However, in 2018, it was observed to be 7.40, which indicates a one-time incidence or possible contamination of the sample upon collection. The pH values were in the range of 7-8 from 2018-2022 for samples of groundwater and river Nfifikh. The alkaline nature of the samples indicates the old age of the landfill. Mao et al. (2023) reported a pH range of 7.14-7.86 in groundwater samples tested near landfill areas in China and termed the water quality acceptable as pH values do not cross the permissible standard range of 6.5-8.5. Nyirenda & Mwansa (2022) have reported a pH range of 6.6 to 7.7 during the dry period and 6.9 to 7.8 during the wet period in groundwater samples near the Chunga landfill in Zambia. They also observed that water quality was acceptable regarding pH as it did not cross the standard pH limit. Asomaku (2023) has reported pH values in the range of 4.4 to 4.75 for abandoned landfills in Nigeria.

Landfill leachate's electrical conductivity (EC, µScm^{-1}) ranged between 35000-51800 µScm^{-1} for eight years. In 2016, EC increased by 17%, and decreased by 7% in 2017. In 2018 and 2019, the EC values increased by 4% and 19%, respectively. In 2020, EC values decreased to 42500 µScm-1 with a 12% decrease; in 2021, it again increased by 21% with an EC value of 51800. In 2022, it decreased by 12% with an EC value of 45500 µScm^{-1}. Compared to 2015, the EC value will increase by 27% in 2022. EC in all water samples analysed ranged from 1790 to 3620 µScm^{-1}. Compared to 2015, there was a decrease in EC values by 25% and 11% and sample points P1 and P2. While at sample point P3, there was an increase of 58% (Fig. 3 EC). Koda et al. (2023) reported an EC value of 1306 µScm^{-1} in a groundwater sample near a landfill in Warsaw, Poland, in 1996. Still, it decreased to 779 µScm^{-1} after installing a vertical barrier over 7 years. EC is directly dependent on total dissolved solids. EC is directly linked to dissolved earth materials (Afolabi et al. 2022). High EC values have been reported by Thyagarajan et al. (2021), from 680 µScm^{-1} to 3921 µScm^{-1} for groundwater samples around the landfill area in Coimbatore, India.

pH

EC

DO

SS

TKN

NH^+

TP

THC

BOD_5

COD

Al

Ag

Cd

Cr

Cu

Fe

Ni

Zn

Hg

Fig. 3. Percentage variation (y-axis) of parameters analysed in this study from the year 2015-2022 (EY = each year variation, RFY = Reference first-year variation, S1)
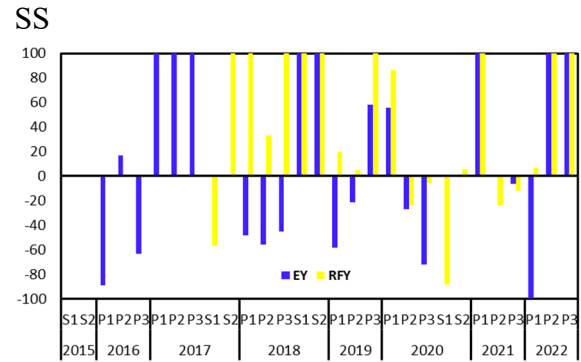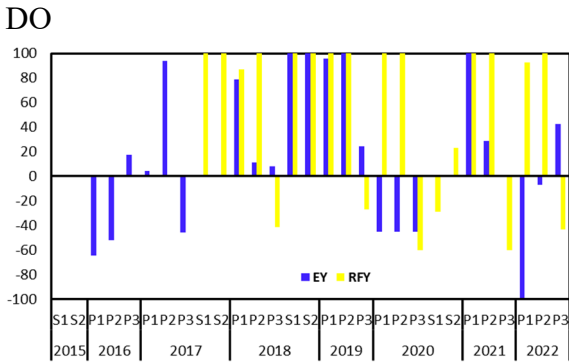
Dissolved oxygen in landfill leachate was observed to be zero in all samples from the year 2015-2022. The suspended solids in landfill leachate samples ranged between 220-2084 mgL^{-1}. All groundwater samples from 2015 to 2020 exhibited a DO range of 6-9 mgL^{-1}. In 2021, the groundwater sample was observed to be 3 mgL^{-1}, 5 mgL^{-1}, and 6 mgL^{-1} for points P1, P2, and P3, respectively. This indicated possible contamination of groundwater. In the year 2022, DO increase significantly at 9.12 mgL^{-1} at P1 and 9.6 mgL^{-1} at P3. This implies that a one-time or short-time pollution incidence affected the water quality. However, at point P2, DO was 1.92 mgL^{-1}, suggesting persistent or continuous groundwater contamination. Zeng et al. (2021) observed DO in groundwater samples near a landfill in the 5.11 to 7.38 mgL^{-1} range. Long et al. (2021) have reported 0.4 to 2.09 ppm DO in groundwater samples near landfills.

In 2016, there was a significant increase in suspended solids concentration, which increased by 113%. This was reduced to 223mgL^{-1} in the year 2017, which is a 16% reduction. In 2018, again, there was a significant increase in suspended solids concentration of 277%, with concentrations reaching up to 842 mgL^{-1}. In the following years, 2019 and 2020, the suspended solids were reduced by 23% and 41%, respectively. However, again, in 2021, there was a significant increase in suspended solids concentration, reaching up to 2082 mgL^{-1}, followed by a drastic reduction of 89% in 2022. Compared to 2015, the suspended solids in landfill leachate samples were reduced by 67% (Fig. 3 SS). Several studies have reported total dissolved solids concentration for evaluation of groundwater quality. However, this study is restricted to the parameters designated by agencies in Morocco responsible for evaluating groundwater quality. However, a study by Abd El-Salam & Abu-Zuid (2015) in Egypt, also among the North African countries like Morocco, has investigated TDS and SS in their study of groundwater quality assessment near landfill areas. They have observed the presence of suspended solids in groundwater in the range of 3278 to 14484 mgL^{-1}.

Total nitrogen concentration in landfill leachate was in the range of 4592-7302 mgL^{-1} for the year 2015-2022. For 2016 to 2018, there was an increase in total nitrogen concentration of 18%, 3%, and 20%, respectively. In the following years, 2019-2020, there was a decrease in total nitrogen by 2% and 23%. In 2021, the total nitrogen concentration increased to 7302 mgL^{-1} with a 42% increment. In the following year, 2022, there was a decrease in total nitrogen concentration of 18%. Compared to 2015, there was an increase of 29% in 2022 in total nitrogen concentration (Fig. 3 TKN). Abd El-Salam & Abu-Zuid (2015) observed a TKN value of 538 mgL^{-1} in groundwater in a landfill in Egypt.

Ammonium concentration in the Leachate sample ranged between 3000 and 7000 mgL^{-1} for 2015-2022. In 2016, there was a minor increase of 0.19% in NH$^+$ concentration, which decreased by 22% (3220 mgL^{-1}) in 2017. In 2018 and 2019, NH$^+$ concentration increased to 5136 mgL^{-1} and 6566 mgL^{-1}, respectively, which decreased in the year 2020 by 30%. In 2021, a 54% increase was observed, which decreased by 34%, and the concentration was 4564 mgL^{-1}. Compared to 2015, there was an overall increase of 11% in ammonium concentration in 2022. In the groundwater sample, NH$_4^+$ concentration ranged between 0.13 and 0.046 mgL^{-1} for 2015 (Fig. 3 NH$_4^+$). Abiriga et al. (2020) has reported Ammonium as N for concentration of 9-9.2 mgL^{-1}. Mao et al. (2023) have reported 0.4 to 1.4 mgL^{-1} of ammonia in groundwater samples of the Kaifeng City Landfill in China.

Total phosphate concentration ranged from 32 mgL^{-1} to 84 mgL^{-1} from 2015 to 2022. There was an increase in total phosphate concentration in 2016, 2017, and 2018 by 50%, 15%, and 16%, respectively. In 2019, there was a decrease of 41% with a total phosphate concentration of 38 mgL^{-1}. In the following year, 2020, there was a significant increase in total phosphate concentration by 119%, followed by a decrease of 11% and 23% in the years 2021 and 2022, respectively. Based on the year 2015, there was a 75% increment in total phosphate concentration in 2022 (Fig. 3 TP). In the groundwater sample, the phosphate concentration ranged from 0.04 to 0.13 mgL^{-1} in 2015. In the following years, 2016-2021, total phosphate concentration could not be detected in the groundwater samples. Asomaku has reported a phosphate concentration of 0.02 mgL^{-1} for groundwater samples near three different landfills. Afolabi et al. (2022) have also reported a similar phosphate concentration of 0.02 mgL^{-1} in groundwater samples in landfill areas in Nigeria.

Total hydrocarbon presence in water is detectable by taste and odour. Its concentration range in landfill leachate samples was 0 to 460 mgL^{-1} for the years 2015 to 2022. There was a significant increase in total hydrocarbon concentration in the years 2016 and 2017 as compared to 2015, with 428% and 957% increments, respectively. In 2018, it was not detectable, and the value increased to 1.71 mgL^{-1} in 2019. In 2020 and 2021, there was a significant increase in total hydrocarbon concentration of 225% and 8227%, respectively. In 2022, the results were contrary, with decreased total hydrocarbon values from 463 mgL^{-1} to 0.93 mgL^{-1}. Compared to 2015, there was an overall decrease of 37% in 2022 (Fig. 3 THC). The hydrocarbon in the groundwater sample had a concentration of 0.1 mgL^{-1} in 2015. In 2016, it was below the detection limit. However, from 2017 to 2020, it was observed to be in the range of 0.1 mgL^{-1}, which increased to 0.22 mgL^{-1} in 2021 but again decreased to the concentration of 0.1 in 2022. Preziosi et al. (2019) investigated groundwater in an Italian

landfill area and reported polycyclic aromatic hydrocarbons below the detection limit. However, benzene and dissolved organic carbon exceeded the permissible limit in a few samples with concentrations of 1.46 and 14 mgL^{-1}, respectively. The presence of hydrocarbons can be attributed to automobile-related contamination or atmospheric precipitation, which brings down hydrocarbon emissions from various industrial processes in the Mohammedia prefecture.

The presence of organic matter in landfill leachate samples was determined based on BOD$_5$ and COD. The BOD$_5$ range was 81 to 53301 mgL^{-1} from 2015 to 2022. In 2016 and 2017, the increase in BOD$_5$ value was observed to be 147% and 63%, respectively. In the following two years, 2018 and 2019, there was a decrease of 41% and 86%, respectively. In 2020, there was an increase in BOD$_5$ of 88%, which decreased by 69% and 96% in the following years, 2021 and 2022, respectively. Compared to 2015, in 2022, the BOD$_5$ decreased by 99% (Fig. 3 BOD$_5$). In groundwater samples, BOD$_5$ values were in the range of 0.4-1.2 mgL^{-1} in 2015, which increased to 1 mgL^{-1} in 2016, decreasing to 0.7 mgL^{-1} in 2017. There was a continuous decrease and increase in BOD and COD values over 8 years. In 2022, BOD$_5$ values were in the 0.84-0.95 mgL^{-1} range. Nyirenda and Mwansa (2022) observed COD and BOD values of 102-10378 mgL^{-1} and 67 to 1569 mgL^{-1} in groundwater samples near a landfill in Zambia. Thyagarajan et al. (2021) have reported BOD values in the range of 2-6 mgL^{-1} and 32-704 mgL^{-1} in groundwater in a landfill vicinity in Coimbatore, India. COD in landfill leachate range was 97 mgL^{-1} to 79872 mgL^{-1} from 2015 to 2022. Keeping with the trend of BOD$_5$, there was an increase of 92% and 82% in COD in 2016 and 2017. The following year, it decreased by 18% and 77% in 2018 and 2019, respectively. In 2020, COD values increased by 23%, but in 2021 and 2022, COD concentration decreased by 41% and 99%, respectively. There was a decrease in COD value by 99% in the year 2022 as compared to 2015 (Fig. 3 COD). Meanwhile, COD values in groundwater samples in 2015 ranged between 1700-2461 mgL^{-1}, reaching 2500-3500 mgL^{-1} in 2022. The variation in BOD and COD values is due to the change in the organic composition of waste in the landfill. Also, the change in the decomposition rate directly affects the amount available for leaching of organic waste.

3.1. Heavy metal occurrence in Leachate and groundwater

Aluminum was observed to be 1107% more in the year 2016 than in the year 2015 in landfill leachate. In the years 2017 to 2019, no Al was detected. In 2020, an Al concentration of 5 mgL^{-1} was observed; however, in the next two years, 2021 and 2022, again, no Al was detected in landfill leachate samples. Upon analysis of sliver occurrence in landfill leachate only in 2020, Ag was observed with a concentration of 0.04 mgL^{-1}. In groundwater samples, Al was found to be well below the permissible limit of 0.2 mgL^{-1} in all the years of analysis.

Fe, Cd, Cr, Ni, Zn, Cu and Hg were also observed in 2015, 2016 and 2020. Fe saw an increase of 281% in 2016 and 57% in 2020 compared to 2015. Cu concentration increased by 870% in 2016 and 202% in 2020 compared to 2015. Cr concertation increased by 193% and 128% in 2016 and 2020, respectively, compared to 2015. Cd concentration in 2016 and 2020 increased by 450% and 300%, respectively, compared to 2015. Fe is essentially required for metabolism activity in the human body. However, its overexposure is deemed undesirable. The Fe concentration in groundwater samples was 0.01-0.003 mgL^{-1} from 2015-2018, well below the permissible limit of 2 mgL^{-1}. Similarly, Cd, Cr, Cu, Ni, Zn, and Hg were also below permissible limits in all the years 2015-2022 in groundwater samples. Also, in 2021, heavy metals were below detection limits. Asomaku (2023) has also reported heavy metal concentrations below permissible limits in groundwater samples in landfill areas of Nigeria. Abiriga et al. (2020) analysed groundwater contamination from heavy metal leaching from Norway's landfills and reported results similar to this study, with heavy metals being within permissible standard limits.

The leachate pollution index in this study was determined as reported by Afolabi et al. (2022) and Nyirenda & Mwansa (2022). The LPI was developed on a scale of 5-100 to evaluate groundwater quality, almost similar to the water quality index of scale 0-100 (Afolabi et al. 2022). The LPI index value for each year is presented in Fig. 3. In 2015, the leachate sample exhibited an LPI value of 63, which increased to 329 in 2016. Again, in 2017, it increased by tenfold to reach a value of 3466, which is mainly attributed to THC, BOD$_5$, and NH^{4+}. Nonetheless, the LPI value decreased to 2.21 in 2018. In 2019, the LPI value of 72 was observed, which increased to 234 in 2020; LPI further increased to 19393 in 2021. However, in 2022, this value decreased to 39. There was great variation in LPI values of leachate samples over 8 years. However, the drastic increase and decrease yearly suggests a sudden change in solid waste composition arising from a sudden increase in waste from a particular industry. Industrial activities are identified based on the impact of THC on LPI. Also, this sudden change in LPI results from solid waste from a similar source. As in all sudden rise of LPI over eight years is coming from THC, BOD$_5$ and NH^{4+}. If other parameters were involved, they would also exhibit changes not observed in this study.

Nonetheless, the groundwater LPI index was <10 in all eight years of evaluation. Afolabi et al. (2022) have cited another study where an LPI greater than 10 may pose a risk to plants. However, in this study, the LPI value of the leachate sample in 2022 was 39, which is similar to the studies carried out by Afolabi et al. (2022) (LPI = 18-19) and Nyirenda & Mwansa (2022) (LPI = 30.17). The geospatial distribution of Leachate Pollution Index is presented in Figure 4.
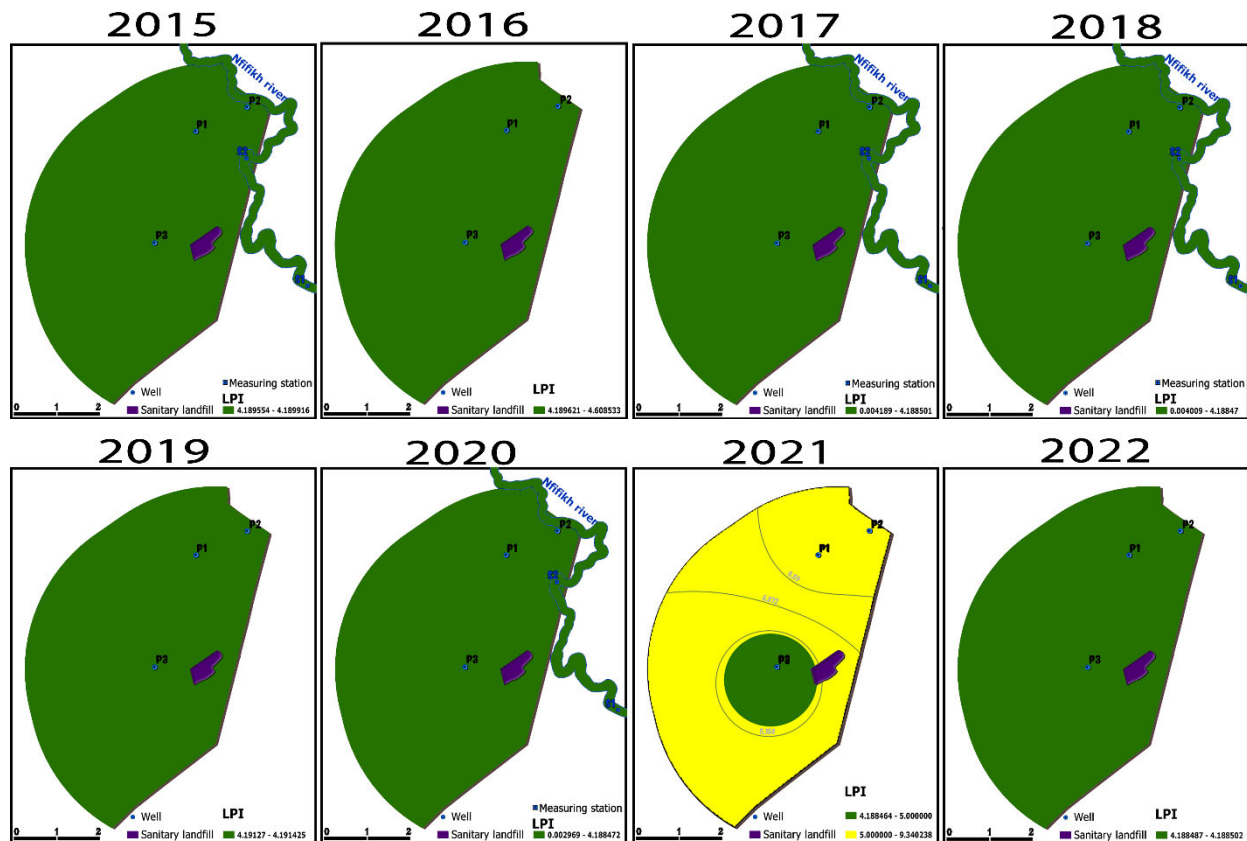

Fig. 4. Geospatial distribution (using IDW approach) of Lechate pollution index from year 2015-2021, (0-5 (green) no risk, 5-10 (yellow) moderate risk and >10 red high risk

From 2015-2020, the LPI value for all sample points was <5, which inferred no potential leachate contamination or risk to the aquatic environment. In 2021, groundwater samples exhibited LPI values of 4.18 to 9.34. Also, in 2021 and 2022, heavy metal concentration was below the detection limit, rendering groundwater free from trace element contamination.

### 3.2. Source identification of heavy metal occurrence in groundwater

The source apportionment of groundwater pollutants is validated using principal component analysis and correlation matrix (Fadlillah et al. 2023). The two assessment tools provide insight into the interrelationship of parameters investigated for groundwater quality analysis (Vijaya Kumar et al. 2022). Table 3 presents the correlation matrix of pollutants in this study. Figure 5 presents a principal component analysis in this study. BOD_5 and COD depicted a high correlation; TKN, TP, NH_4^+, and EC were also significantly correlated. Heavy metals Al, Cd, Cr, Fe, Ni, Zn, Hg, and Cu correlate significantly. This infers that heavy metals have similar origins (Vijaya Kumar et al. 2022). From principal component analysis, EC (PC1), pH (PC2), BOD_5 (PC3) and COD (PC4) were identified as primary parameters affecting the total variance by 99.25%. However, EC accounted for 99% of covariance individually. Hence, another PCA was performed, and it revealed that pH accounted for 67% variance, followed by BOD_5 with 15% and COD 10%. The three principal components accounted for a cumulative 93.41% of the total variance. This indicates that the source of pollution is the same for all water samples (Fadlillah et al. 2023).
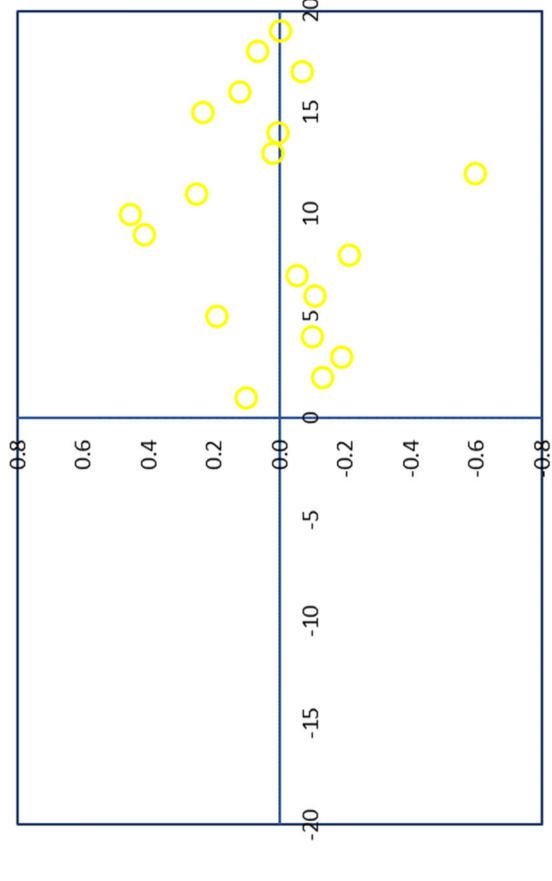
Table 3. Correlation matrix between the parameters analysed for groundwater quality evaluation
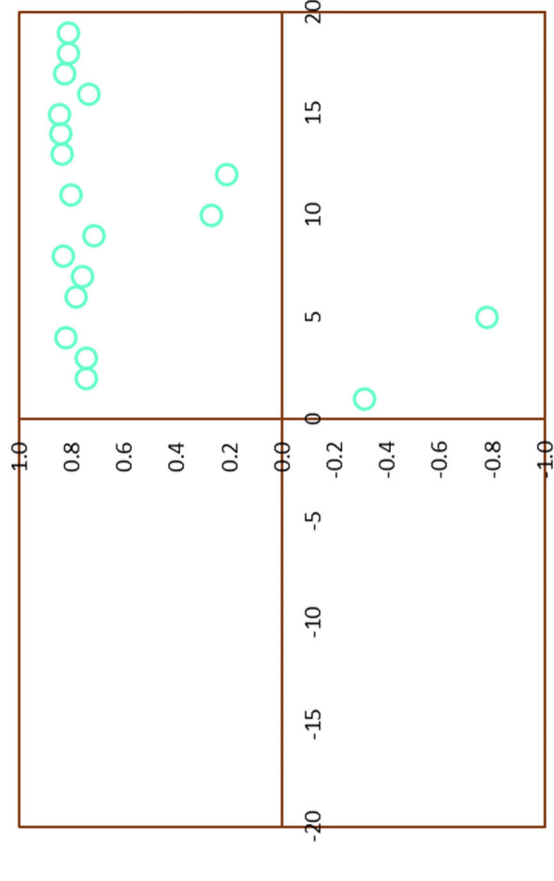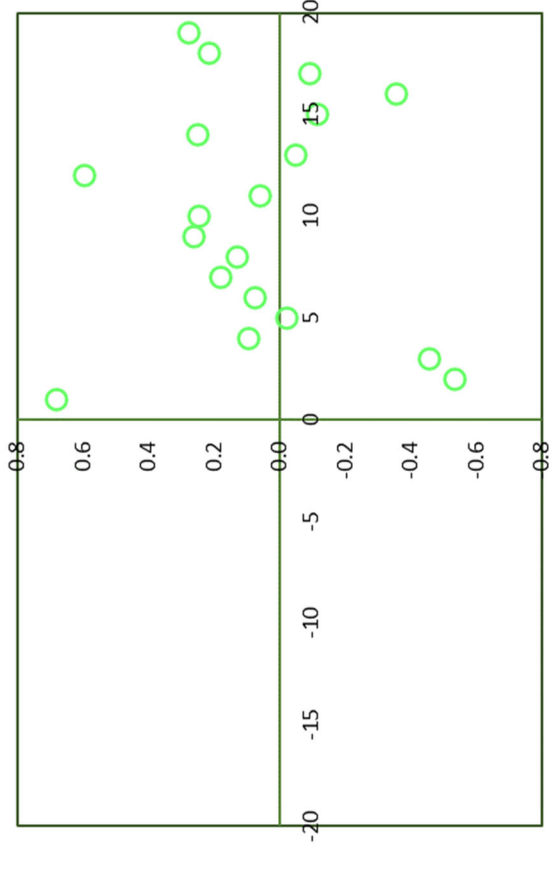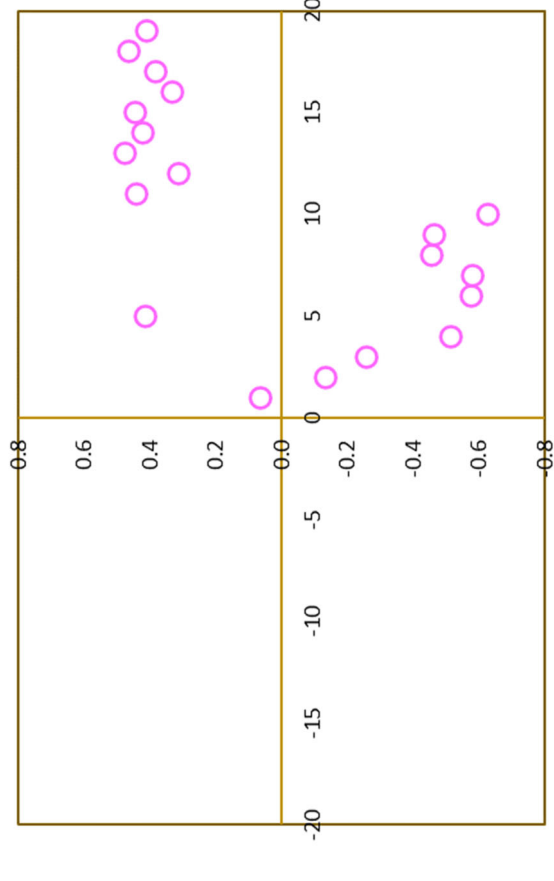
Fig. 5. Principal Component Analysis of groundwater parameters analysed in this study

3.3. Health risk assessment

The health risk assessment enables the decision-makers and policy developers to identify potential health risks of water resources. This study considered Al, Cd, Cr, Cu, Fe, Ni, Zn and Hg for health risk assessment. Individual HQ for each heavy was estimated for each year of study. The cumulative hazard from heavy metals termed HI is presented in Figure 6 for 2015-2022. Heavy metals in 2017, 2020, 2021 and 2022 were undetected in water samples. The heavy metal concentration was evaluated based on the first year of readings, i.e., 2015. In 2016, health risk increased by 1.89% to 20.8% for Al, 98% for Cd, 39% to 54% for Cu, 3%-66% for Fe, 106% for Ni and 113% for Hg. The hazard index values for 2015 were 0.02, 0.06 and 0.03 for sample points P1, P2 and P3, respectively. In 2016, the hazard index increased by 358% for point P1, 124% for point P2 and 215% for point P3. In 2018, again, it was observed that HI values increased significantly. HI value increased to 0.11 at P1 and 0.10 at P2, and at sample P3, the heavy metals were not detected. In the following year, 2019, non-carcinogenic risk further increased with HI values of 0.12 at sample point P1, 0.18 for P2 and 0.11 at sample point P3. The overall increase in non-carcinogenic risk compared to 2015 till 2019 was 626% at P1, 268% at P2 and 394% at P3. For all the years of investigations, viz. 2015-2022, based on the estimation of hazard quotient, it was observed that the HQ value was not >1. Therefore, as of the current scenario, there is no potential non-carcinogenic risk from groundwater near the landfill upon consumption to human health. However, continuous increase in non-carcinogenic risk is a concern for the future.
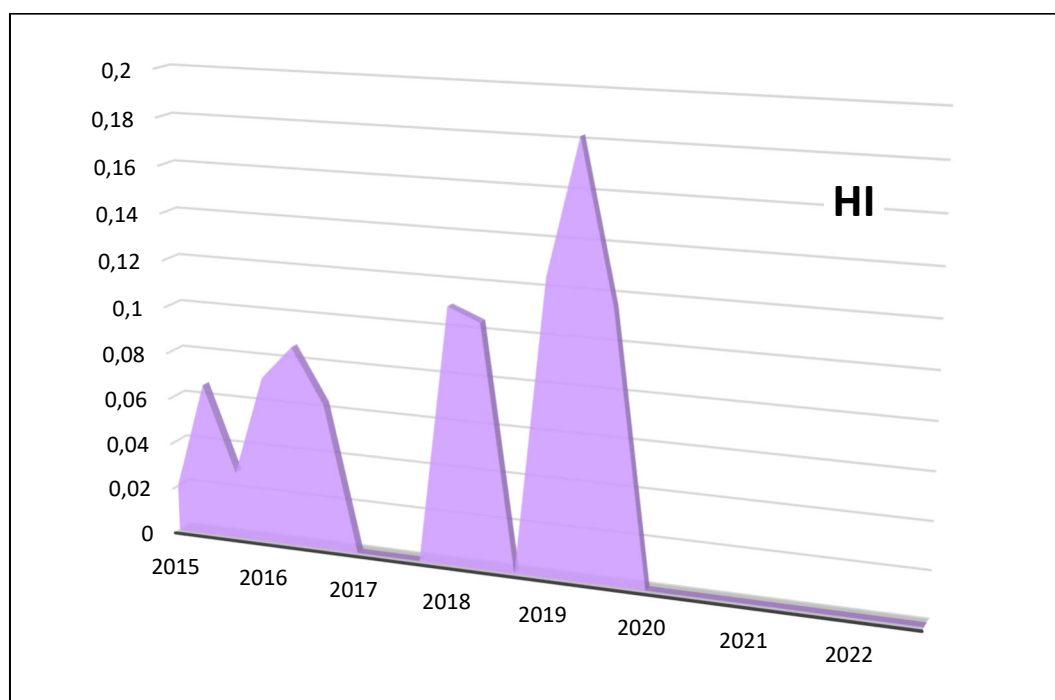

Fig. 6. Non-carcinogenic risk from groundwater samples in the vicinity of landfill area in Mohammedia prefecture, Morocco, for the years 2015-2022

The carcinogenic risk from groundwater samples in Mohammedia prefecture in the vicinity of the landfill for 2015-2016 is presented in Figure 7. Carcinogenic risk assessment was carried out based on Cd, Cr and Ni. Each year, the carcinogenic risk (CR) of individual heavy metal was estimated. Cumulative risk, i.e., was calculated as CRI (carcinogenic risk index). The carcinogenic risk acceptable value range is 10^{-4} to 10^{-6}, which infers that 1 in every 10000 people is susceptible to cancer risk, which is the lower boundary limit, and 1 in every 1000000 is susceptible to cancer risk, which is upper boundary risk. If the CR value is lower, there is no potential risk. In 2015 and 2016, the carcinogenic risk from sample points P2 and P3 was within acceptable limits. However, in 2016, risk increased by 29% for sample point P2 and 72% for P3. At sample point P1, the carcinogenic risk was high due to Cr and Ni concentrations in the groundwater sample. Cr posed a risk to 1 in every 1000 people, while Ni posed a risk to 1 in every 100. In 2016, risk increased by 140%. Nonetheless, in 2018 and 2019, the carcinogenic risk was reduced by 3% at point P1, and the CRI was within the limit of 1 in every 10000 persons.

On the contrary, in the year 2020, the carcinogenic risk increased significantly, rendering 1 in every 100 persons susceptible to cancer over 70 years upon consumption of contaminated groundwater. In the years 2021 and 2022, heavy metal was not detected in groundwater samples as it was not detected in 2017. From these results, it can be inferred that heavy metals in groundwater are not attributed to landfill leachate. This is derived from the fact that if their landfill leachate reaches groundwater, heavy metals will be detected in every water sample each year. Also, upon analysis of landfill leachate for carcinogenic risk, it was estimated that the risk posed by landfill leachate is within acceptable range. This is not the same as in the case of groundwater samples, which have varied significantly over 8 years.
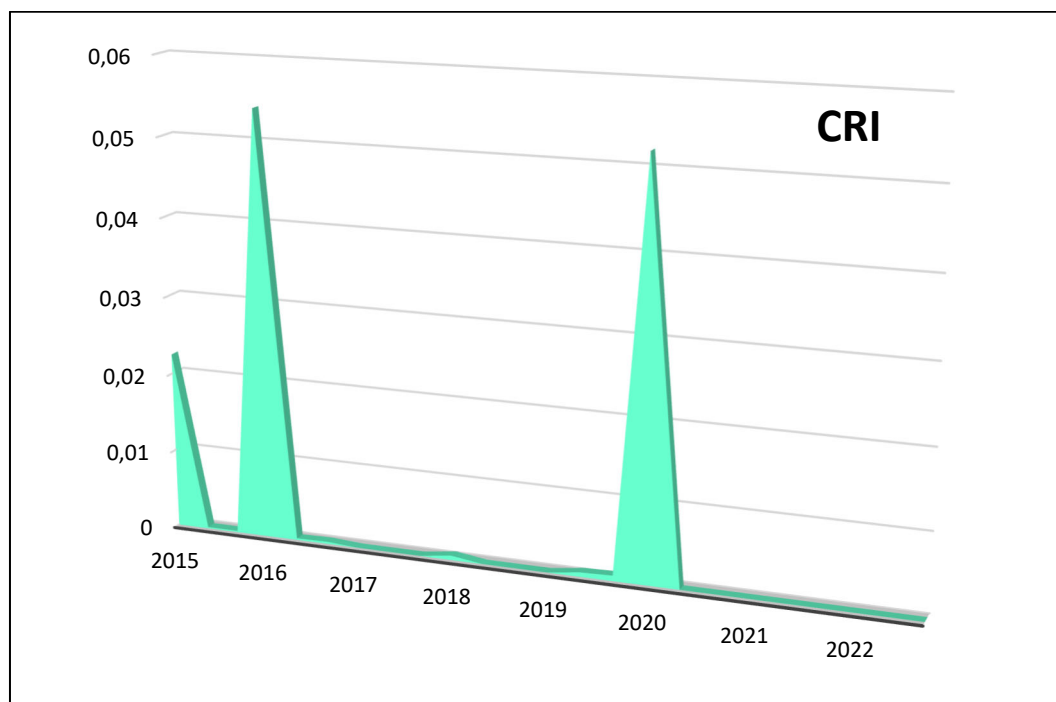

Fig. 7. Carcinogenic risk index for groundwater samples in the vicinity of landfill area in Mohammedia prefecture, Morocco, for years 2015-2022

4. Conclusion

This study investigated water quality near a landfill in Mohammedia prefecture of Morocco for eight years, 2015-2022. The study was conducted based on physio-chemical parameters and the occurrence of heavy metals in groundwater. The investigation revealed the concentration of water parameters varies significantly over the years. The water quality index was observed to be <10, rendering the area's groundwater excellent for drinking purposes. The increase in the leachate pollution index indicates that they can pose a future risk to water resources, which calls for continuous monitoring. The non-carcinogenic risk health assessment of groundwater samples revealed currently no risk from direct groundwater consumption with HI values <0.11 for all eight years of analysis. However, the leachate samples from the landfill revealed a very high non-carcinogenic health risk with HI values of 7-24 over eight years. The acceptable carcinogenic risk values lie between 10^{-4} and 10^{-6}; in this study, the groundwater samples met the minimum acceptable carcinogenic risk standard. For the current situation, the groundwater sample does not pose any carcinogenic severe risk, but continuous monitoring is required to evaluate the groundwater quality.

The limitation of the study is restricted to the parameters investigated by government agencies. The number of sampling locations is also minimal. The potential pollution of the Nfifikh River was not feasible as the river runs dry every other year or consecutive year, which restricts the scope of study to groundwater quality assessment only. Future studies are required with higher numbers of water samples from different locations based on the distance, slope, and depth of the groundwater aquifer in Mohammedia prefecture. Also, the parameters to be investigated should be increased to include emerging pollutant categories to identify any potential risk to groundwater resources in the region. Overall, the study concludes that in the current scenario, groundwater samples are fit for consumption, do not pose any potential health risks to their consumers, and landfill leachate is not contaminating the groundwater resources in Mohammedia prefecture in Morocco.

Statements and Declarations

Reference

Abd El-Salam, M.M., Abu-Zuid, G.I. (2015). Impact of landfill leachate on the groundwater quality: A case study in Egypt. *J. Adv. Res.*, *6*, 579-586. https://doi.org/10.1016/j.jare.2014.02.003

Abiriga, D., Vestgarden, L.S., Klempe, H. (2020). Groundwater contamination from a municipal landfill: Effect of age, landfill closure, and season on groundwater chemistry. *Sci. Total Environ.*, *737*, 140307. https://doi.org/10.1016/j.scitotenv.2020.140307

Afolabi, O.O., Wali, E., Ihunda, E.C., Orji, M.C., Emelu, V.O., Bosco-Abiahu, L.C., Ogbuehi, N.C., Asomaku, S.O., Wali, O.A., 2022. Potential environmental pollution and human health risk assessment due to leachate contamination of groundwater from anthropogenic impacted site. *Environ. Challenges*, *9*, 100627. https://doi.org/10.1016/j.envc.2022.100627

Afshin Maleki, H.J. (2021). Evaluation of drinking water quality and non-carcinogenic and carcinogenic risk assessment of heavy meatls in rural areas of Kurdistan. *Iran. Environ. Technol. Innov*. 23.

Asomaku, S.O. (2023). HydroResearch Quality assessment of groundwater sourced from nearby abandoned land fi lls from Industrial City in Nigeria : Water pollution indices approach. *HydroResearch*, *6*, 130-137. https://doi.org/10.1016/j.hydres.2023.03.002

Benaddi, R., Ferkan, Y., Bouriqi, A., Ouazzani, N. (2022). Impact of Landfill Leachate on Groundwater Quality – A Comparison Between Three Different Landfills in Morocco. *J. Ecol. Eng.*, *23*, 89-94. https://doi.org/10.12911/22998993/153006

El Mouine, Y., El Hamdi, A., Morarech, M., Kacimi, I., Touzani, M., Mohsine, I., Tiouiouine, A., Ouardi, J., Zouahri, A., Yachou, H., Dakak, H. (2021). Article landfill pollution plume survey in the moroccan tadla using spontaneous potential. *Water* (Switzerland), *13*, 1-11. https://doi.org/10.3390/w13070910

Elmaghnougi, I., Tribak, A.A., Maatouk, M. (2022). Leachate Monitoring and an Assessment of Groundwater Pollution from the Tangier Landfill. *Geomatics Environ. Eng.*, *16*, 111-130. https://doi.org/10.7494/geom.2022.16.3.111

Epa, U.S. Environmental Protection Agency (2002). Risk Assessment Guidance for Superfund Volume I: Human Health Evaluation Manual (Part E, Supplemental Guidance for Dermal Risk Assessment).

Fadlillah, L.N., Utami, S., Rachmawati, A.A., Jayanto, G.D., Widyastuti, M. (2023). Ecological risk and source identifications of heavy metals contamination in the water and surface sediments from anthropogenic impacts of urban river, Indonesia. *Heliyon*, *9*(4), e15485. https://doi.org/10.1016/j.heliyon.2023.e15485

Hosseini Beinabaj, S.M., Heydariyan, H., Mohammad Aleii, H., Hosseinzadeh, A. (2023). Concentration of heavy metals in leachate, soil, and plants in Tehran's landfill: Investigation of the effect of landfill age on the intensity of pollution. *Heliyon*, *9*(1), e13017. https://doi.org/10.1016/j.heliyon.2023.e13017

Koda, E., Osiński, P., Podlasek, A., Markiewicz, A., Winkler, J., Vaverková, M.D. (2023). Geoenvironmental approaches in an old municipal waste landfill reclamation process: Expectations vs reality. *Soils and Foundations*, *63*(1). https://doi.org/10.1016/j.sandf.2023.101273

Long, X., Liu, F., Zhou, X., Pi, J., Yin, W., Li, F., Huang, S., Ma, F. (2021). Estimation of spatial distribution and health risk by arsenic and heavy metals in shallow groundwater around Dongting Lake plain using GIS mapping. *Chemosphere*, *269*, 128698. https://doi.org/10.1016/j.chemosphere.2020.128698

Mao, X., Zhang, S., Wang, S., Li, T., Hu, S., Zhou, X. (2023). Evaluation of Human Health Risks Associated with Groundwater Contamination and Groundwater Pollution Prediction in a Landfill and Surrounding Area in Kaifeng City, China. *Water* (Switzerland), *15*. https://doi.org/10.3390/w15040723

Mohajane, C., Manjoro, M. (2022). Sediment-associated heavy metal contamination and potential ecological risk along an urban river in South Africa. *Heliyon*, *8*, e12499. https://doi.org/10.1016/j.heliyon.2022.e12499

Nyirenda, J., Mwansa, P.M. (2022). Impact of leachate on quality of ground water around Chunga Landfill, Lusaka, Zambia and possible health risks. *Heliyon*, *8*, e12321. https://doi.org/10.1016/j.heliyon.2022.e12321

Preziosi, E., Frollini, E., Zoppini, A., Ghergo, S., Melita, M., Parrone, D., Rossi, D., Amalfitano, S. (2019). Disentangling natural and anthropogenic impacts on groundwater by hydrogeochemical, isotopic and microbiological data: Hints from a municipal solid waste landfill. *Waste Manag.*, *84*, 245-255. https://doi.org/10.1016/j.wasman.2018.12.005

Thyagarajan, L.P., Jeyanthi, J., Kavitha, D. (2021). Vulnerability analysis of the groundwater quality around Vellalore-Kurichi landfill region in Coimbatore. *Environ. Chem. Ecotoxicol.*, *3*, 125-130. https://doi.org/10.1016/j.enceco.2020.12.002

Uddh Söderberg, T., Berggren Kleja, D., Åström, M., Jarsjö, J., Fröberg, M., Svensson, A., Augustsson, A. (2019). Metal solubility and transport at a contaminated landfill site – From the source zone into the groundwater. *Sci. Total Environ.*, *668*, 1064-1076. https://doi.org/10.1016/j.scitotenv.2019.03.013

Vijaya Kumar, V., Rimjhim, S., Achary Garagu, S., Nayakkam Valappil, N., Prasanna Rakhavan, R. (2022). Heavy metal contamination, distribution and source apportionment in the sediments from Kavvayi Estuary, South-west coast of India. *Total Environ. Res. Themes*, *3-4*, 100019. https://doi.org/10.1016/j.totert.2022.100019

Zeng, D., Chen, G., Zhou, P., Xu, H., Qiong, A., Duo, B., Lu, X., Wang, Z., Han, Z. (2021). Factors influencing groundwater contamination near municipal solid waste landfill sites in the Qinghai-Tibetan plateau. *Ecotoxicol. Environ. Saf.*, *211*, 111913. https://doi.org/https://doi.org/10.1016/j.ecoenv.2021.111913