Prepublished copy

Nature Environment & Pollution Technology

This is a peer-reviewed prepublished version of the paper

Original Research

Diagnosis of the presence of total Cr in soil and groundwater due to urban solid waste in Veracruz, Mexico

I. Galaviz-Villa[1], A. García-Saldaña[1], I.D. Pérez-Landa[1†], F. Lango-Reynoso, L[1]. Martínez-Cárdenas [2]

[1]División de Estudios de Posgrado e Investigación, Tecnológico Nacional de México/Instituto Tecnológico de Boca del Río. Km. 12 carr. Veracruz-Córdoba. Boca del Río, Ver. C.P.94290
[2]Secretaría de Investigación y Posgrado, Universidad Autónoma de Nayarit, Ciudad de la Cultura Amado Nervo s/n. Tepic, Nayarit. México. C.P. 63190
†Corresponding author: irvingperez@bdelrio.tecnm.mx
0000-0002-8404-1365 I. Galaviz Villa
0000-0002-5213-0443 A. García Saldaña
0000-0001-8359-434X F. Lango Reynoso
0000-0002-8705-8146 L. Martínez Cárdenas
0000-0002-5240-5371 I.D. Pérez-Landa

Key Words	heavy metals, leachates, urban solid waste, groundwater
DOI	https://doi.org/10.46488/NEPT.2025.v24i04.D1757 (DOI will be active only after the final publication of the paper)
Citation of the Paper	Galaviz-Villa, I., García-Saldaña, A., Pérez-Landa, I. D., Lango-Reynoso, F. and Martínez-Cárdenas, L., 2025. Diagnosis of the presence of total Cr in soil and groundwater due to urban solid waste in Veracruz, Mexico. *Nature Environment and Pollution Technology*, 24(4), p. D1757. https://doi.org/10.46488/NEPT.2025.v24i04.D1757

Abstract: Chromium (Cr) is one of the 20 most abundant elements on Earth and is a heavy metal frequently found in leachates. This study aimed to diagnose the presence of total Cr in the soil and groundwater of the Cotaxtla aquifer, resulting from the improper disposal of urban solid waste (USW) in Veracruz, Mexico. Composite soil and groundwater samples were collected from three deep wells adjacent to the study area. The total Cr concentration was determined following the procedure established in the NMX-AA-051-SCFI-2001 standard. The mean concentration of total chromium in groundwater was 0.0438 mg L^{-1}, with a maximum of 0.0585 mg L^{-1}. The average chromium concentration in the soil samples was 0.527 mg kg^{-1}, with a maximum of 0.558 mg kg^{-1}. No correlation was observed between the concentration of Cr in water and soil. However, the total Cr concentrations in groundwater exceeded the maximum permissible limits (0.05 mg L^{-1}) established in NOM-127-SSA-1994 for human consumption and the drinking water quality parameters of international standards. The effects of Cr on human health, due to exposures exceeding established limits, include respiratory tract problems and skin lesions.

1. INTRODUCTION

Groundwater constitutes only 0.06% of the Earth's total available water, yet this relatively small volume represents 98% of the freshwater easily accessible to humans (Schwartz & Zhang 2024). In Mexico, 40.3% of agricultural, industrial, and public supply activities rely on groundwater (CONAGUA 2022). Concerns about this resource have grown due to its limited availability and declining quality. The susceptibility of surface waters to contamination makes groundwater a more attractive and viable option, as it is less vulnerable (Mukhopadhyay et al. 2022). However, population growth, the

significant generation of waste, and inadequate final disposal practices have negatively impacted this vital water source (Abubakar et al. 2022).

Solid waste deposited in open-air dumps generates leachates, resulting from the molecular biodegradation of organic matter and containing various heavy metals such as chromium (Cr), iron (Fe), nickel (Ni), lead (Pb), and cadmium (Cd). These metals directly affect the subsoil and groundwater (Naeem & Asam 2024). The distance from the landfill influences the concentrations of these heavy metals, the composition of the leachate, and seasonal variations, in addition to other polluting effects on the ecosystem and human health (Essien et al. 2022). Among the compounds present in leachates, heavy metals are particularly significant due to their high toxicity, even when found in very low concentrations.

Chromium (Cr) is among the 20 most abundant elements on Earth and is one of the heavy metals frequently found in leachates. It is one of the 13 trace elements identified by the U.S. Environmental Protection Agency (US EPA) as priority contaminants, alongside antimony, arsenic, beryllium, cadmium, copper, mercury, nickel, silver, lead, selenium, thallium, and zinc (Das & VishnuRadhan 2024). This metal can be present in groundwater due to both natural and anthropogenic sources (Vijayakumar et al. 2022). Chromium is primarily extracted in the form of chromite ($FeCr_2O_4$). During this process, hexavalent Cr (VI) compounds, such as chromates and dichromates, are generated and used in metallurgical, insulating, and chemical industries. Potassium dichromate ($K_2Cr_2O_7$) and chromium oxide (CrO_3) are utilized in the production of metallic pigments, paints, and plastic coatings. Sodium dichromate ($Na_2Cr_2O_7$) and basic chromium sulfates are employed in leather tanning, catalysts, and wood preservatives (Sicius 2024). Given that the groundwater in the area supports regional productive activities and serves as a public water supply for human consumption, it is essential to identify the concentrations of chromium present in the water. This will help determine whether there are risks to public health and the environment due to the improper disposal of urban solid waste at the recycling center in Cuitláhuac, Veracruz, Mexico.

Although the State of Veracruz has a total of 149 final disposal sites for urban solid waste, 131 of these lack a leachate collection and extraction system, and 115 also lack a waterproofing system to prevent leachate from contaminating groundwater (INECC 2022). One such site is the solid waste disposal and recycling center in the municipality of Cuitláhuac, Veracruz, Mexico, which also receives waste from neighboring communities such as Tamarindo, La Gloria, Palo Verde, Mata Naranjo, and occasionally from neighboring municipalities that request the service. This situation has led to the site exceeding its capacity, creating an imminent risk of ecological imbalance due to inadequate management of urban and special solid waste, as well as improper final disposal practices (SEDEMA 2022). According to the State Program for the Prevention and Comprehensive Management of Urban Solid Waste and Special Waste in the State of Veracruz, Mexico, the per capita generation of solid waste in Cuitláhuac is 0.874 kg/day. This amounts to 26,220 kg of urban solid waste discarded daily without proper disposal, of which 45.8% is organic matter, 23.7% is recyclable, and 28.3% is confinable. In contrast, 2.2% constitutes hazardous waste (PEPGIR-Ver 2016).

Despite these figures and the critical importance of preserving water resources, there is a notable lack of research diagnosing the degree of contamination in Mexican soils and aquifers caused by heavy metals in regions geographically close to final disposal sites for urban solid waste. In these areas, the rural population often perceives groundwater as a clean and safe source of drinking water and relies on it for various daily needs, especially during interruptions in regular water supplies caused by droughts and natural disasters. The objective of this study was to diagnose, for the first time, the impact of prolonged use of an uncontrolled urban solid waste disposal site located at the Cuitláhuac recycling center in Veracruz on environmental contamination by chromium (Cr) in groundwater and soil. This research aims to generate knowledge about the potential risks to public health and, potentially, to crops in the region.

2. MATERIALS AND METHODS

2.1 Study Area

In the municipality of Cuitláhuac, located in the state of Veracruz, Mexico, lies the Cotaxtla aquifer, which is situated between parallels 18° 42' and 18° 51' north latitude and meridians 96° 28' and 96° 47' west longitude, at an altitude ranging from 140 to 500 m. It is bounded to the north by the municipalities of Atoyac, Yanga, Carrillo Puerto, and Paso del Macho; to the south by the municipalities of Omealca, Tierra Blanca, and Cuichapa; to the east by the municipalities of Cotaxtla,

Carrillo Puerto, and Tierra Blanca; and to the west by the municipalities of Yanga and Cuichapa (INEGI, 2010). The predominant soil types in the study area are Phaeozem and Vertisol (Tun-Canto et al., 2017).

2.2 Sampling

Groundwater and soil sampling were conducted in January 2019, during the north wind season (November to February).

2.2.1 Groundwater

Groundwater samples were obtained in duplicate from three shallow wells (10-30 m deep) nearest to the landfill (Table 1, Fig. 1); the distance between wells P1 and P2 and the landfill was 1640 m, while well P3 was located 259 m from the landfill. One liter of sample was collected from each sampling site, and its replicate was preserved at a pH < 2 and refrigerated at 4º C. The samples were properly labeled and stored in hermetically sealed plastic containers to prevent contamination.

Table 1: Location of groundwater sampling sites.

Code	Location	Coordinates	
		Latitude (N)	Longitude (W)
P1	R.d. Córdoba-Boca del Río	18.745479	-96.5747750
P2	R.d. Córdoba-Boca del Río	18.743871	-96.5757590
P3	Rd. Cuitláhuac	18.748820	-96.5927194

2.2.2 Soil

For soil sampling, the "five golds" method was used. Samples were collected from four different sites around the landfill, covering an area of nine hectares (Fig. 1, Table 2). Five 1 kg samples were collected in hermetically sealed bags from each site to obtain a composite sample. Sampling was conducted in accordance with the NMX-AA-132-SCFI-2016, which specifies the criteria for obtaining and handling samples that facilitate soil characterization through the identification and quantification of metals and metalloids. The samples were properly labeled and stored in hermetically sealed plastic bags to prevent contamination.

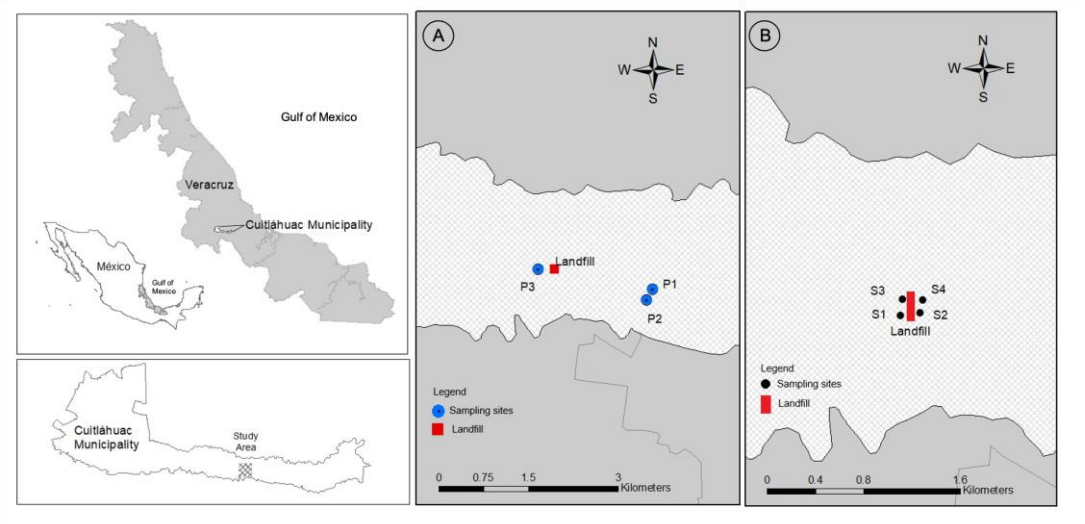

Fig. 1: Geographical distribution of groundwater (A) and soil (B) sampling sites.

Table 2: Location of soil sampling sites around the landfill.

Code	Coordinates	
	Latitude (N)	Longitude (W)
S1	18.74861	-96.59108

S2	18.74883	-96.58956
S3	18.74986	-96.59095
S4	18.74978	-96.58935

2.3 Laboratory Analysis

The analysis of the samples was conducted at the facilities of the Boca del Río Technological Institute in the Aquatic Resources Research Laboratory. The water and soil samples were refrigerated at 4 °C for subsequent analysis. The soil samples were placed in aluminum trays in a drying oven at 40 °C for 48 hours. They were then allowed to cool to room temperature and stored in hermetically bags. The preparation of laboratory materials was carried out in accordance with the specifications of the NMX-AA-051-SCFI-2001 standard, which establishes the analytical protocol for determining metals by atomic absorption in natural water, drinking water, wastewater, and treated wastewater.

The glassware used for the digestion process was thoroughly washed with a 10% neutral soap solution free of phosphates to prevent ionic interference during spectrophotometric readings. The glassware was then rinsed with potable water and immersed in a 20% nitric acid solution for 24 hours to ensure complete removal of the acid. Subsequently, the glassware was immersed in heavy metal-free Milli-Q quality water for an additional 24 hours. Finally, the glassware was drained and dried in a forced-air oven (Riossa CF-102) at 100 °C for 24 hours.

2.3.1 Sample Digestion

2.3.1.1 Groundwater samples

The digestion of the samples was carried out according to the method of the NMX-AA-051-SCFI-2001 standard, which establishes the determination of metals by atomic absorption in natural water, drinking water, wastewater, and treated wastewater. Water samples were collected in clean, pre-washed plastic bottles and stored at a temperature of 4 °C until analysis. For sample preparation, 45 mL of the water sample were measured and transferred to a Teflon® container (HP-500), along with 5 mL of 70% nitric acid (reagent grade). A reference blank was included, containing 0.5 mL of double-distilled water and 10 mL of 70% nitric acid. The digestion process followed the CEM-EPA-3015H method. At the end of the digestion, the samples were vacuum-filtered into a Nalgene® bottle using 0.45 µm nitrocellulose Millipore® filters. The filtrate was diluted in a volumetric flask to a volume of 25 mL with Type II water (obtained with a Milli-Q membrane), after which the diluted samples were transferred to polypropylene flasks and stored at a temperature of 4 °C for analysis by atomic absorption spectrometry.

2.3.1.2 Soil samples

For digestion, 0.5 g of each sample were placed in a Teflon® container (HP-500), to which 9 ml of 70% reagent-grade nitric acid was added. A reference blank was included, containing 0.5 ml of double-distilled water and 10 ml of 70% nitric acid. The digestion process was programmed using the Soil-3051 HP500 Method. After digestion, the samples were vacuum filtered into a Nalgene bottle using 0.45 µm nitrocellulose filters (Millipore®). The filtrate was then diluted in a volumetric flask to a total volume of 25 ml with Type II water. Finally, the samples were transferred to polypropylene bottles and refrigerated at 4 °C for subsequent analysis in triplicate.

2.3.2 Atomic absorption spectrometry

The total chromium concentration was determined in triplicate using a Thermo-Scientific Model Ice 3500 AA System spectrophotometer, employing flame spectrophotometry according to the specifications of the NMX-AA-051-SCFI-2001 standard. A certified High Purity Standard Thermo Fisher Scientific® was used to prepare the standard curve for chromium (Cr), utilizing five concentrations: 0.5, 2, 4, 6, and 8 ppm, which resulted in an R value of 0.99829 and an R^2 value of 0.9966, with the equation $Y = 0.004406x - 0.0006$. A blank reference was analyzed to ensure data quality. The

operating conditions for the spectrophotometer were a wavelength of 357.9 nm, a lamp current of 100%, an N2O-C2H2 flame type, a burner height of 4.0 nm, and a continuous signal type.

2.4 Statistical analysis

Initially, a Ryan-Joiner normality test was performed on the groundwater and soil datasets. Based on the test results, a parametric analysis (one-way ANOVA) was conducted to identify differences in total Cr concentrations across each sampling site. Prior to this, a Bartlett test was performed to confirm the homoscedasticity of the data. Tukey's multiple range test ($\alpha = 0.05$) was used to demonstrate the existence of homogeneous groups among the sampling sites. Additionally, Pearson's correlation test was used to evaluate the relationship between total Cr concentrations in groundwater and soil. Descriptive statistics, graphical representations, and statistical analyses were performed using Minitab® software version 18.1.

3. RESULTS

3.1 Total Chrome on soil samples

The maximum concentration of total Cr in soil was identified at site S3, followed by sites S1 and S2 (Table 3).

Table 3: Basic statistics of total Cr results obtained from soil samples.

Code	Total Chrome [mg Kg^{-1}]	Confidence Interval (95%)
	Mean* ± SD	
S1	0.532^{A} ± 0.015	(0.5026, 0.5607)
S2	0.517^{A} ± 0.023	(0.4878, 0.5459)
S3	0.533^{A} ± 0.022	(0.5039, 0.5621)
S4	n.d.	--

n.d.: not detectable. *Averages that do not share a letter are significantly different (ANOVA-Tukey; $p<0.05$).

The normality test indicated that the total Cr data in soil followed a normal distribution ($\rho > 0.100$). After confirming the homoscedasticity of the data using Bartlett's test ($\rho = 0.854$; $\alpha = 0.05$), a one-way ANOVA test was performed to compare the mean concentrations of Cr in soil samples from the sampling sites. The results revealed no significant differences among the sites (Table 4). Additionally, Pearson's correlation test indicated no significant correlation ($\rho = 0.670$, $r^2 = 0.0275$) between the concentrations of total Cr in groundwater and soil in the vicinity of the urban waste disposal site.

Table 4: Analysis of variance for the total Cr concentration in soil.

Source of Variation	Df	Sum of Squares	Mean Square	F	p-Value	F-crit
Site	2	0.000483	0.000242	0.57	0.593*	5.143
Error	6	0.002540	0.000423			
Total	8	0.003024				

* No significant at 0.05 level of significance.

3.2 Total chromium in groundwater samples

The maximum concentration of total chromium in groundwater was recorded in well 3 (P3), followed by well 1 (P1) and well 2 (P2) (Table 5).

Table 5: Physicochemical parameters and total Cr concentrations by groundwater sampling site.

Code	Temperature °C	pH	Cr Total [mg L^{-1}]	Confidence Interval (95%)
			Mean* ± SD	
P1	25.0 ± 0.8	7.0 ± 0.01	0.0491^{A} ± 0.0100	(0.0378, 0.0602)
P2	26.0 ± 0.4	6.0 ± 0.02	0.0270^{B} ± 0.0087	(0.0158, 0.0381)

P3	25.0 ± 0.5	7.0 ± 0.02	0.0553^{A} ± 0.0035	(0.0441, 0.0665)

*Averages that do not share a letter are significantly different (ANOVA-Tukey; p<0.05).

The normality test indicated that the total Cr data in groundwater followed a normal distribution ($\rho > 0.100$). After confirming the homoscedasticity of the data using Bartlett's test ($\rho = 0.452$; $\alpha = 0.05$), a one-way ANOVA test was performed to compare the mean concentrations of Cr in groundwater samples from the sampling sites. The analysis of variance (Table 6) revealed that total Cr concentrations were significantly different among the three sampling wells.

Table 6: Analysis of variance for the total Cr concentration in groundwater.

Source of Variation	Df	Sum of Squares	Mean Square	F	p-Value	F-crit
Well	2	0.001329	0.000664	10.58	0.011*	5.143
Error	6	0.000377	0.000063			
Total	8	0.001706				

*Significant at 0.05 level of significance.

3.3 Regulations and permissible limits

Within the international legal framework for the detection and maximum permissible limits of heavy metals, the United States Environmental Protection Agency (US-EPA 1998) establishes a maximum concentration of 0.1 mg L^{-1} for chromium (Cr) in natural waters intended for agricultural and urban public use, as well as a maximum concentration of 0.1 mg L^{-1} in agricultural-irrigated soils and natural wetlands. In Mexico, the applicable standards for heavy metals establish maximum permissible concentrations for different types of water (Table 7).

Table 7: Mexican legal framework for permissible limits of total Cr in water and soil.

Standard	Description	Maximum permissible limit
NOM-001-SEMARNAT-2021	Establishes the maximum permissible limits of contaminants in wastewater discharges into national waters and assets.	0.5 -1.5 mg L^{-1}
	Permissible limits for metals and cyanides (in infiltration soil and other irrigation).	0.5- 1.0 mg L^{-1}
NOM-127-SSA1-1994	Water for human use and consumption - quality limits and treatments to which the water must be subjected for purification.	0.050 mg L^{-1}

4. DISCUSSION

4.1 Total Cr in soil

The range of total Cr concentrations in soil reported in this study is consistent with that documented by Amaro-Espejo et al. (2020) for soils in the municipality of Cotaxtla, located in the same region and less than 50 km from Cuitláhuac. However, these concentrations are lower than those reported in soils within municipal waste disposal sites in other regions of the world, such as Assam, India (2.4 to 9.4 mg kg^{-1}) (Choudhury et al. 2022); Warsaw, Poland (17 to 99 mg kg^{-1}) (Gworek et al. 2016); and Lopburi, Thailand (21.7 to 81.1 mg kg^{-1}) (Aendo et al. 2022). This difference in soil Cr concentrations compared to those reported in other parts of the world can be attributed to the fact that, in these studies, samples were collected within the disposal site facilities rather than in adjacent areas. Additionally, the authors of these studies reported that the landfills where soil sampling was conducted had operational ages ranging from 15 to 36 years, whereas the disposal site in this study had been operational for less than 10 years at the time of sample collection.

According to the results obtained in this study, there is no correlation between the concentrations of total Cr found in groundwater and soil. This observation could vary in different climatic seasons or as the waste disposal site operates for a

longer period (Aendo et al. 2022). The presence of Cr in this matrix can be attributed to the widespread use of Cr (VI) compounds in fertilizers, metallic pigments, paints, and plastic coatings, primarily in the form of potassium dichromate ($K_2Cr_2O_7$) and chromium oxide (CrO_3). Additionally, Cr is used in leather tanning, catalysts, and wood preservatives as sodium dichromate ($Na_2Cr_2O_7$) and basic Cr sulfates (Rangel et al. 2015). According to the State Program for the Prevention and Comprehensive Management of Urban Solid Waste and Special Handling of the State of Veracruz (PEPGIR-Ver 2016), this type of solid waste represents 30.5% of the material received at the landfill, which, in this case, is the recycling center in the municipality of Cuitláhuac, Veracruz, Mexico, and is not properly disposed of.

Soil type plays a significant role in the low percolation of leachate into the saturated zone (Zuñiga 1999). The soil types in the study area are Feozem and Vertisol, with the latter characterized by its formation from clayey sediments dominated by highly dispersed clay minerals (SEMARNAT 2024). These clay minerals can act as natural adsorbents for metal cations in solution upon contact. However, the texture profile of Vertisol can also facilitate the faster mobility of dissolved metals in infiltrating liquids (Tun-Canto et al. 2017). Additionally, the desorption of certain metals can be influenced by anaerobic conditions resulting from water saturation (Rodríguez et al. 2019).

Hexavalent Cr (VI) is a relatively mobile and toxic anion, exhibiting higher solubility in soils compared to trivalent Cr (III), which is less toxic, insoluble, and strongly adsorbable on surfaces. As a result, Cr (III) is considered relatively immobile and is the predominantly present form in most soils. Perraki et al. (2021) found that fertilizers could be a significant anthropogenic source of Cr (III) in soils, as well as Cr (VI) if an oxidizing agent is present. Additionally, the reduction of Cr (VI) to Cr (III) occurs more readily compared to the oxidation of Cr (III) to Cr (VI) by oxidizing agents in soils. However, factors such as solubility, the presence of manganese oxides, and high soil pH values favor the oxidation of Cr (III) to Cr (VI) (Dhal et al. 2013). Hexavalent chromium is the only metal that remains highly mobile in alkaline soils, and its behavior is directly influenced by changes in the soil's redox potential (McLean & Bledsoe 1992). Remediation measures for chromium-contaminated soils should consider the conditions under which Cr (III) can be most readily oxidized to Cr (VI). In this context, determining the Potential Chromium Oxidation Score (PCOS), developed by James et al. (1997), is highly useful. For the remediation of Cr (VI)-contaminated soils, several innovative strategies have been proposed, including permeable reactive barriers, liquid injections of Na-dithionite, and bioremediation using natural microorganisms. Bioremediation, along with monitored natural attenuation, is reported as one of the most cost-effective options (Dhal et al. 2013; Ye et al. 2019).

4.2 Total Cr in groundwater

It is observed that the highest concentration of total chromium was recorded in wells P1 and P3, with P3 located 259 m from the waste disposal site and P1 at 1,640 m. This fact is directly related to the proximity of both wells to the source of contamination or origin of the deposit, which may be mining, industrial facilities, or dumps, as in this case (IMM 2009). However, other factors are involved in the dispersion of contaminants in the soil, such as the hydrographic regime of the groundwater and the vertical permeation of leachates (Aendo et al. 2022). These chromium concentrations in groundwater are higher than those reported in aquifers not located near landfills in other regions of Mexico, such as Huejutla de Reyes, Hidalgo, with an average value of 0.031 mg L^{-1} (Rivera-Rodríguez et al. 2019), and Guamúchil, Sinaloa, where concentrations range between 0.00012 and 0.00052 mg L^{-1} during the rainy and dry seasons, respectively (Rivera-Hernández et al. 2021). Furthermore, when compared to studies conducted in other parts of the world, the Cr concentrations in groundwater obtained in this study fall within the range of average concentrations reported for groundwater adjacent to landfills in Poland (0.044 mg L^{-1}) (Gworek et al. 2016), Turkey (0.03 and 0.04 mg L^{-1} in winter and summer, respectively) (Bakis & Tuncan 2011), and Egypt (0.062 mg L^{-1}) (Abd El-Salam & Abu-Zuid 2015). Lower average concentrations have been reported in India (0.01 mg L^{-1}) (Choudhury et al. 2022), while higher concentrations have been documented in Thailand (0.22 mg L^{-1}) (Aendo et al. 2022).

The results show that the maximum concentration of total Cr detected in groundwater well P3 (0.0553 mg L^{-1}) exceeds the maximum permissible limits established by Mexican standards for human use and consumption (Table 5). This poses a risk to flora and fauna, including microbes, invertebrates, rodents, and cattle (Aendo et al. 2022; Amaro-Espejo et al. 2020), and can cause ulcers and irritation in the small intestine. Although Cr (III) is an essential element for human health, playing a role in the metabolism of sugars, proteins, and fats, regular ingestion can lead to respiratory and dermatological damage (ATSDR 2006). Hexavalent chromium is less common in urban solid waste but can be present in industrial waste

mixed with municipal waste. According to Tapia & Iribarren (2021), municipal waste can be considered ecotoxic due to the presence of substances such as Cr (VI) from chemical, pharmaceutical, photographic, and metallurgical industries, as well as waste from fertilizer and pigment manufacturing, pesticide residues, and ceramic industry waste, among others.

Ceballos et al. (2016) studied the speciation and mobility of chromium in groundwater and concluded that the highest concentrations of Cr (VI) are found close to and downstream of the contamination source, as observed in this study. At higher elevations of the Cotaxtla aquifer, the intensity of Cr (VI) could be controlled by adsorption processes. However, the influx of uncontaminated groundwater can lead to the desorption of adsorbed Cr (VI), indicating non-specific adsorption. The presence of other compounds, such as sulfate and phosphate, can also inhibit chromium adsorption (Stollenwerk & Grove 1985).

4.3 Health risks

The maximum concentration of total Cr recorded in groundwater (0.0553 mg L^{-1}) in the present work does not exceed the maximum permissible limits of NOM-001-SEMARNAT-2021 but does exceed those established in NOM-127-SSA1-1994, which establishes the permissible limits of quality and water purification treatments for human use and consumption throughout the national territory. Since the groundwater use in this area is mainly livestock, agricultural, and domestic, it represents a risk to public health and the agroecosystem. The regulations of the European Economic Community (Abdul Jabar & Thabit 2021) regarding the quality of water for human consumption establish 0.050 mg L^{-1} as a mandatory limit, which is exceeded in this case since it is recorded as a maximum of 0.0553 mg L^{-1} in groundwater intended for human consumption.

Exposure to Cr and its possible health risks occur by ingesting food and/or water with high levels of this metal or by exposure to high air concentrations, mainly in the workplace (ATSDR 2006). The health risks associated with the chromium concentrations reported in this work and the domestic use of groundwater are related to skin irritations or nasal, throat, or respiratory allergies. Ingestion of water with high amounts of Cr (VI) can lead to intestinal problems and gastric and liver diseases; it is also considered a genotoxic and cytotoxic element for bacteria and eukaryotic organisms, while Cr (III), due to precipitating at neutral pH, is significantly less toxic than Cr (VI) (Covarrubias & Peña 2017). However, according to the OEHHA (2016), there is a risk of cancer associated with continuous exposure to Cr (VI); a concentration of 0.045 mg m^{-3} for 30 years can increase the risk of cancer to 25 in a million. The oral reference dose (RfD) that establishes the concentration of xenobiotics that can be consumed daily without harmful health effects due to Cr (VI) is 0.003 mg kg^{-1} day^{-1} (US-EPA 2024).

5. CONCLUSIONS

There is no correlation between the total Cr concentrations identified in groundwater and soil. The concentrations of total Cr registered in groundwater do not exceed the maximum permissible limits established by NOM-001-SEMARNAT-2021, which sets the maximum permissible limits for contaminants in wastewater discharges into national waters and assets, as well as the permissible limits for metals and cyanides in infiltration soil and other irrigation. However, they do exceed the maximum permissible limits (0.05 mg L^{-1}) established in NOM-127-SSA1-1994 for human consumption and the drinking water quality parameters of the World Health Organization and the European Economic Community.

The groundwater of the Cotaxtla aquifer could pose a risk to public health and the development of domestic and agricultural activities. Exposure to Cr at concentrations higher than those established in national and international regulations could cause respiratory problems, skin lesions, and even cancer. Environmental authorities should focus on reducing the risks associated with public health and ensure continuous monitoring of heavy metals in leachates generated at final disposal sites for urban solid waste, as well as in groundwater and soils near these sites. Additionally, supervision and prevention measures should be implemented to protect workers and residents of Cuitláhuac and neighboring municipalities who could be exposed to these contaminants.

This research highlights the urgent need for solid waste recycling centers to avoid becoming open-air dumps. Instead, they should function as appropriate facilities for sorting, separating, and analyzing waste to identify sources that contribute to heavy metal leaching into soil and groundwater. Furthermore, sufficient and properly designed sanitary landfills must be constructed, incorporating sustainable procedures to help mitigate soil and aquifer contamination. Future research could

focus on diagnosing contamination by other heavy metals associated with the uncontrolled disposal of solid waste in this area, as well as evaluating the effectiveness of implementing remediation or bioremediation strategies for contaminated soils over extended periods.

Author Contributions: Conceptualization, Galaviz V.I. and Pérez-Landa I.D.; methodology, Galaviz V.I.; software, Pérez-Landa I.D.; validation, García-Saldaña A., Galaviz V.I. and Pérez-Landa I.D.; formal analysis, Galaviz V.I., García-Saldaña A., Pérez-Landa I.D., investigation, Lango-Reynoso F.; data curation, Pérez-Landa I.D., Martínez-Cárdenas L.; writing—original draft preparation, Galaviz V.I., García-Saldaña A., Pérez-Landa I.D., Lango-Reynoso F., Martínez-Cárdenas L.; writing—review and editing, Galaviz-Villa I., Pérez-Landa I.D., Martínez-Cardenas L. All authors have read and agreed to the published version of the manuscript. Authorship should be restricted to individuals who have contributed significantly to the research.

Funding: This research received no external funding.

Informed Consent Statement: Not applicable

Conflicts of Interest: The authors declare no conflicts of interest.

REFERENCES

Abd El-Salam, M. M., and Abu-Zuid, G. I., 2015. Impact of landfill leachate on the groundwater quality: A case study in Egypt. *J. Adv. Res.*, 6(4), 579–586. https://doi.org/10.1016/j.jare.2014.02.003

Abdul Jabar, M.A.B. and Thabit, J.A., 2021. Chemical pollution risks for many drinking water sources in Baghdad City, Iraq. Pol. J. Environ. Stud., 30(2), pp.1203–1214. https://doi.org/10.15244/pjoes/120767.

Abubakar, I. R., Maniruzzaman, K. M., Dano, U. L., AlShihri, F. S., AlShammari, M. S., Ahmed, S. M. S., Al-Gehlani, W. A. G., and Alrawaf, T. I., 2022. Environmental Sustainability Impacts of Solid Waste Management Practices in the Global South. *Int. J. Environ. Res. Public Health*, 19(19). https://doi.org/10.3390/ijerph191912717

Aendo, P., Netvichian, R., Thiendedsakul, P., Khaodhiar, S., and Tulayakul, P., 2022. Carcinogenic risk of Pb, Cd, Ni, and Cr and critical ecological risk of Cd and Cu in soil and groundwater around the municipal solid waste open dump in central Thailand. *J. Environ. Public Health*, 2022. https://doi.org/10.1155/2022/3062215

Agency for Toxic Substances and Disease Registry (ATSDR), 2016. ToxFAQs: Cromo (Chromium). Available online: https://www.atsdr.cdc.gov/es/toxfaqs/es_tfacts7.html (Accessed on 29 December 2024).

Amaro-Espejo, I. A., Del Refugio Castañeda-Chávez, M., Murguía-González, J., Lango-Reynoso, F., Patricia Bañuelos-Hernández, K., and Galindo-Tovar, M. E., 2020. Geoaccumulation and ecological risk indexes in papaya cultivation due to the presence of trace metals. *Agronomy*, 10(2). https://doi.org/10.3390/agronomy10020301

Bakis, R., and Tuncan, A., 2011. An investigation of heavy metal and migration through groundwater from the landfill area of Eskisehir in Turkey. *Environ. Monit. Assess*., 176(1–4), 87–98. https://doi.org/10.1007/s10661-010-1568-3

Ceballos, E., Bea, S., García Einschalg, F., and Sanci, R., 2016. Especiación y movilidad del cromo en aguas subterráneas contaminadas de un sector de la cuenca Matanza-Riachuelo, Buenos Aires, Argentina. In: Actas IX Congreso Argentino de Hidrogeología y VII Seminario Hispano-Latinoamericano Sobre Temas Actuales de la Hidrología Subterránea. Catamarca, Argentina.

Choudhury, M., Jyethi, D. S., Dutta, J., Purkayastha, S. P., Deb, D., Das, R., Roy, G., Sen, T., and Bhattacharyya, K. G., 2022. Investigation of groundwater and soil quality near to a municipal waste disposal site in Silchar, Assam, India. *IJEWR*, 6(1), 37–47. https://doi.org/10.1007/s42108-021-00117-5

Comisión Nacional del Agua (CONAGUA)., 2022. NumeraguA 2022. Secretaría de Medio Ambiente y Recursos Naturales. Available online: www.gob.mx/conagua (Accessed on 13 January 2025)

Covarrubias, S. A. and Peña Cabriales, J. J., 2017. Contaminación ambiental por metales pesados en México: problemática y estrategias de fitorremediación. *Rev. Int. Contam. Ambient.*, *33*, 7–21. https://doi.org/10.20937/RICA.2017.33.esp01.01

Das, S., and VishnuRadhan, R., 2024. Effect of trace metals on aquatic invertebrates: dynamics and repercussions. In *The Handbook of Environmental Chemistry*. (pp. 1–40). Springer Berlin Heidelberg. https://doi.org/10.1007/698_2024_1185

Dhal, B., Thatoi, H. N., Das, N. N., and Pandey, B. D., 2013. Chemical and microbial remediation of hexavalent chromium from contaminated soil and mining/metallurgical solid waste: A review. In *Journal of Hazardous Materials* (Vols. 250–251, pp. 272–291). https://doi.org/10.1016/j.jhazmat.2013.01.048

Essien, J. P., Ikpe, D. I., Inam, E. D., Okon, A. O., Ebong, G. A., and Benson, N. U., 2022. Occurrence and spatial distribution of heavy metals in landfill leachates and impacted freshwater ecosystem: An environmental and human health threat. *PLOS ONE*, 17(2), e0263279-. https://doi.org/10.1371/journal.pone.0263279

Gworek, B., Dmuchowski, W., Koda, E., Marecka, M., Baczewska, A. H., Bragoszewska, P., Sieczka, A., and Osiński, P., 2016. Impact of the municipal solid waste Lubna landfill on environmental pollution by heavy metals. *Water (Switzerland)*, 8(10). https://doi.org/10.3390/w8100470

Instituto Nacional de Ecología y Cambio Climático (INECC), 2022. Atlas Nacional de Residuos Sólidos Urbanos. pp. 311. From https://www.gob.mx/cms/uploads/attachment/file/693803/125_2022_Atlas_Nacional_Residuos_Solidos.pdf

Instituto Nacional de Estadística and Geografía (INEGI), 2010. Compendio de información geográfica municipal. Cuitláhuac, Veracruz de Ignacio de la Llave. From https://www.inegi.org.mx/contenidos/app/mexicocifras/datos_geograficos/30/30053.pdf

Intendecia Municipal de Montevideo (IMM), 2009. Informe 2001-2009 de la contaminación de suelo por metales pesados (plomo, cromo y cadmio) en el departamento de Montevideo. Desarrollo Ambiental. Servicio Laboratorio de Calidad Ambiental (LCA). From https://montevideo.gub.uy/sites/default/files/monitoreo_metales_suelos_2001-2009.pdf

James, B. R., Petura, J. C., Vitale, R. J., and Mussoline, G. R., 1997. Oxidation-reduction chemistry of chromium: Relevance to the regulation and remediation of chromate-contaminated soils. *Soil Sediment Contam*., 6(6), 569–580. https://doi.org/10.1080/15320389709383590

McLean, J. E., and Bledsoe, B. E., 1992. Ground Water Issue Behavior of Metals in Soils. *EPA/540/S-92/018*. From http://nyackcommunitygarden.info/pdf/Behaviour_of_Metals_in_Soil.pdf

Mukhopadhyay, A., Duttagupta, S., and Mukherjee, A., 2022. Emerging organic contaminants in global community drinking water sources and supply: A review of occurrence, processes and remediation. *J. Environ. Chem. Eng.*, 10(3), 107560. https://doi.org/10.1016/J.JECE.2022.107560

Naeem M., Asam Z.u.Z., 2024. Contaminant transport from solid waste dumps: Implications for environmental degradation with a focus on capital territory regions. *Environ. Res.*, 247(15):118152. https://doi.org/10.1016/j.envres.2024.118152

Norma Mexicana-AA-051-SCFI-2016. Análisis de agua - determinación de metales por absorción atómica en aguas naturales, potables, residuales y residuales tratadas. Diario Oficial de la Federación, México. From https://www.dof.gob.mx/normasOficiales/6280/seeco3a12_C/seeco3a12_C.html

Norma Oficial Mexicana NOM-127-SSA1-1994. Salud Ambiental, agua para uso y consumo humano. Límites permisibles de calidad y tratamientos a que debe someterse el agua para su potabilización. Diario Oficial de la Federación, México. From https://www.dof.gob.mx/nota_detalle.php?codigo=5650705&fecha=02/05/2022

Norma Oficial Mexicana NOM-001-SEMARNAT-2021. Límites máximos permisibles de contaminantes en las descargas de aguas residuales en aguas y bienes nacionales. Diario Oficial de la Federación, México. From https://www.dof.gob.mx/nota_detalle.php?codigo=5645374&fecha=11/03/2022

Norma Oficial MexicanaAA-132-SCFI-2016. Muestreo de suelos para la identificación y la cuantificación de metales y metaloides, y manejo de la muestra. Diario Oficial de la Federación México. From https://www.dof.gob.mx/nota_detalle.php?codigo=5475373&fecha=06/03/2017

Office of Environmental Health Hazard Assessment (OEHHA), 2016. Efectos del Cromo Hexavalente Sobre la Salud. From https://oehha.ca.gov/media/downloads/faqs/sphexchromiumairfact111616.pdf

Perraki, M., Vasileiou, E., & Bartzas, G., 2021. Tracing the origin of chromium in groundwater: Current and new perspectives. *Curr. Opin. Environ. Sci. Health*, *22*, 100267. https://doi.org/10.1016/j.coesh.2021.100267

Programa Estatal para la Prevención y la Gestión Integral de los Residuos Sólidos Urbanos y de Manejo Especial del Estado de Veracruz (PEPGIR-Ver), 2016. From https://www.gob.mx/cms/uploads/attachment/file/187445/Veracruz.pdf

Rangel, C. A. A., Isarain Ch. E., and Maldonado V. M., 2015. Caracterización y recuperación de sales de cromo hexavalente de un pasivo ambiental. *Rev. Int. Contam. Ambient.*, 31(4), 427-437.

Rivera-Hernández, J. R., Green-Ruiz, C. R., Pelling-Salazar, L. E., and Flegal, A. R., 2021. Monitoring of As, Cd, Cr, and Pb in groundwater of Mexico's agriculture Mocorito river aquifer: Implications for risks to human health. *Water Air Soil Pollut.*, 232(7). https://doi.org/10.1007/s11270-021-05238-5

Rivera-Rodríguez, D. A., Beltrán-Hernández, R. I., Lucho-Constantino, C. A., Coronel-Olivares, C., Hernández-González, S., Villanueva-Ibáñez, M., Nolasco-Arizmendi, V., and Vázquez-Rodríguez, G. A., 2019. Water quality indices for groundwater impacted by geogenic background and anthropogenic pollution: case study in Hidalgo, Mexico. *IJEST*, 16(5), 2201–2214. https://doi.org/10.1007/s13762-018-1852-2

Rodríguez, E. N., McLaughlin M., and Pennock D., 2019. La contaminación del suelo: Una realidad oculta. Roma, FAO. From https://openknowledge.fao.org/server/api/core/bitstreams/7d70ca8d-7503-4839-8d6b-8250e9add8ac/content

Schwartz, F. W., and Zhang, H., 2024. Fundamentals of groundwater (2nd ed.). John Wiley & Sons, Inc. https://books.google.com/books/about/Fundamentals_of_Groundwater.html?hl=es&id=PXzmEAAAQBAJ

Secretaría de Medio Ambiente del Estado de Veracruz (SEDEMA)., 2022. PRIMER AVANCE DEL PLAN DE GESTIÓN ESTATAL DE RESIDUOS SÓLIDOS URBANOS Y DE MANEJO ESPECIAL. https://www.pmaver.gob.mx/wp-content/uploads/2022/04/Plan-de-gestion-Gaceta-Oficial.pdf

Secretaria de Medio Ambiente y Recursos Naturales (SEMARNAT), 2024. Suelos dominantes. Atlas Digital Geográfico. From https://gisviewer.semarnat.gob.mx/aplicaciones/Atlas2015/suelos.html

Sicius, H., 2024. Chromium Group: Elements of the Sixth Subgroup. In H. Sicius (Ed.), *Handbook of the Chemical Elements* (pp. 581–631). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-662-68921-9_11

Stollenwerk, K. G., and Grove, D.B., 1985. Adsorption and desorption of hexavalent chromium in an alluvial aquifer near Telluride, Colorado. *J. Environ. Qual*. 14:150-155. https://doi.org/10.2134/jeq1985.00472425001400010030x

Tapia, C.C., and Iribarren C. I., 2021. *Guía técnica para la clasificación de los residuos*. Ministerio para la Transición Ecológica y el Reto Demográfico. (2021). From https://www.miteco.gob.es/content/dam/miteco/es/calidad-y-evaluacion-ambiental/temas/prevencion-y-gestion-residuos/guiatecnicaclasificacionderesiduosnov_21_tcm30-509157.pdf

Tun-Canto, G. E., Álvarez-Legorreta, T., Zapata-Buenfil, G., and Sosa-Cordero, E., 2017. Metales pesados en suelos y sedimentos de la zona cañera del sur de Quintana Roo, México. *Rev. Mex. Cienc. Geol., 34*(3), 157-169. https://doi.org/10.22201/cgeo.20072902e.2017.3.433

United States Environmental Protection Agency (US-EPA), 1998. Toxicological Review of Hexavalent Chromium. From https://cfpub.epa.gov/ncea/iris2/chemicalLanding.cfm?substance_nmbr=144

United States Environmental Protection Agency (US-EPA), 2024. IRIS Toxicological review of hexavalent chromium [Cr (VI)]. Integrated Risk Information System Center for Public Health and Environmental Assessment. From https://iris.epa.gov/static/pdfs/0144tr.pdf

Vijayakumar, C. R., Balasubramani, D. P., and Azamathulla, H. M., 2022. Assessment of groundwater quality and human health risk associated with chromium exposure in the industrial area of Ranipet, Tamil Nadu, India. *J. Water Sanit. Hyg. Dev.*, 12(1), 58–67. https://doi.org/10.2166/washdev.2021.260

Ye, J., Chen, X., Chen, C., and Bate, B., 2019. Emerging sustainable technologies for remediation of soils and groundwater in a municipal solid waste landfill site – A review. *Chemosphere*, 227, 681–702. https://doi.org/10.1016/j.chemosphere.2019.04.053

Zuñiga, F. B. 1999. Introducción al estudio de la contaminación del suelo por metales pesados. 1st ed. Ediciones de la Universidad Autónoma de Yucatán: Yucatán, México. pp. 1-20.