Geochemical-hydrological assessment of municipal solid waste disposal site to identify environmental risk areas †

[Evaluación geoquímica-hidrológica de sitio de disposición de residuos sólidos urbanos para identificar zonas de riesgo ambiental]

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SUMMARY

Background: Municipal solid waste landfills represent significant sources of environmental contamination due to leachate production and the mobilization of heavy metals into surrounding soils and aquatic systems. In rural regions of Mexico, the close spatial interaction between disposal sites and agricultural land increases vulnerability of water resources, food production systems, and local communities. Integrated environmental assessments combining soil, water, and hydrological analyses remain limited for small-scale landfills. This study addresses this gap by evaluating contamination dynamics at the Reforma de Pineda landfill in Oaxaca through a multidisciplinary approach. **Objective:** To assess the environmental impact of the municipal landfill on soil and water quality, quantify the occurrence and distribution of heavy metals, and identify priority monitoring zones using rainfall–runoff hydrological simulations. **Methodology:** Physical, chemical, and mineralogical analyses were conducted on soils collected from the landfill area and from a neighbouring mango orchard, together with the characterization of groundwater and surface runoff. Soil physicochemical properties, heavy metal concentrations, and mineral phases were determined using standardized analytical protocols. Hydrological modelling based on rainfall–runoff scenarios was implemented to delineate recharge zones and potential contaminant transport pathways under different precipitation conditions. **Results:** Landfill soils exhibited statistically significant differences relative to agricultural soils, particularly in pH**,** organic matter content, electrical conductivity, and field capacity. Elevated concentrations of V, Ba, Ni, Cr, and Pb were detected in landfill soils, whereas Cd remained below detection limits. Mineralogical characterization revealed quartz, kaolinite, microcline, and iron oxides as dominant phases influencing metal retention processes. Water analyses showed that Fe, Mn, V, Pb, and Cr exceeded regulatory thresholds in samples from an artisanal well and from landfill runoff. Hydrological simulations identified high recharge potential zones associated with preferential contaminant migration pathways. **Implications:** The observed contamination patterns indicate potential risks to groundwater quality, agricultural productivity, and human health, emphasizing the need for strengthened monitoring frameworks and

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improved landfill management practices. **Conclusion:** The Reforma de Pineda landfill represents a source of pollution that requires environmental mitigation management.

Key words: environmental risk assessment; heavy metals; leachate; municipal solid waste; soil contamination.

RESUMEN

Antecedentes: Los vertederos de residuos sólidos urbanos constituyen una fuente relevante de contaminación ambiental debido a la generación de lixiviados y al transporte de metales pesados hacia suelos agrícolas y cuerpos de agua. En zonas rurales de México, la cercanía entre sitios de disposición final y áreas productivas incrementa el riesgo para la salud pública y la seguridad alimentaria. Este estudio integra análisis edáficos, calidad del agua y modelación hidrológica para evaluar estos impactos en el vertedero de Reforma de Pineda, Oaxaca. **Objetivo**: Evaluar el impacto ambiental del vertedero de residuos sólidos urbanos sobre la calidad del suelo y el agua, determinar la presencia y distribución de metales pesados e identificar zonas prioritarias para el monitoreo ambiental mediante simulaciones hidrológicas. **Metodología**: Se realizaron análisis físicos, químicos y mineralógicos en suelos del vertedero y en una parcela agrícola de mango adyacente, así como la caracterización de aguas (subterráneas y de escorrentía). Se determinaron propiedades edáficas, concentraciones de metales pesados y minerales mediante técnicas analíticas estandarizadas. Adicionalmente, se aplicó modelación hidrológica basada en escenarios lluvia-escorrentía para identificar áreas de recarga hídrica y posibles rutas de transporte de contaminantes. **Resultados**: Los suelos del vertedero mostraron diferencias significativas respecto a la parcela agrícola, principalmente en pH, contenido de materia orgánica, conductividad eléctrica y capacidad de campo. Se detectaron concentraciones elevadas de V, Ba, Ni, Cr y Pb en suelos del vertedero, mientras que Cd no fue detectado. El análisis mineralógico identificó cuarzo, caolinita, microclina y óxidos de hierro como fases dominantes. En agua, las concentraciones de Fe, Mn, V, Pb y Cr superaron los límites permisibles en muestras provenientes de un pozo artesanal y de la escorrentía superficial del vertedero. La modelación hidrológica permitió identificar zonas con mayor potencial de recarga hídrica asociadas a trayectorias preferenciales de transporte de contaminantes. **Implicacione**s: Los resultados evidencian riesgos potenciales para la salud humana, los recursos hídricos y la producción agrícola local, y destacan la necesidad de fortalecer estrategias de monitoreo y gestión ambiental en sitios de disposición final. **Conclusión**: El vertedero de Reforma de Pineda representa una fuente de contaminación que requiere gestión de mitigación ambiental.

Palabras clave: contaminación del suelo; lixiviados; metales pesados; residuos sólidos urbanos; riesgo ambiental.

INTRODUCTION

Municipal solid waste (MSW) management is a priority issue for many countries, particularly those committed to the 2030 Agenda. In this context, countries such as Mexico have implemented strategies to mitigate or reduce the impacts of MSW, moving toward sustainable cities (Del Carmen-Niño *et al.,* 2023). However, despite these efforts, significant problems persist in several regions, largely attributable to deficiencies in integrated waste management, especially in monitoring contaminants and their relationship with the socioeconomic conditions of local populations (Cuenca *et al.,* 2018).

The variability in municipal solid waste (MSW) composition across regions complicates its efficient management (Escobar, 2002). In highly urbanized areas with rapid population growth and demographic variations, MSW generation rates may exceed 0.6 kg per capita per day, increasing pressure on disposal sites that often surpass their design capacity (Küfeoğlu, 2024).). This overloading not only accelerates waste accumulation but also promotes the generation of leachates, which can infiltrate soils and migrate through hydrological pathways, affecting surface and groundwater systems, particularly in low-lying areas (Jagaba *et al.,* 2024). This process contributes to the progressive degradation of water quality, as leachate often carries heavy metals and other toxic substances that can accumulate and persist in aquatic environments. Such contamination has been widely documented in areas surrounding open dumps and landfills, where the interaction between leachate and groundwater represents a significant risk for both ecosystem integrity and human health (Drall *et al.,* 2025). In contrast, regions with more controlled population growth and adequate infrastructure still face challenges in waste collection, treatment, and final disposal. In some cases, waste remains exposed, leading to impacts on surrounding areas due to wildlife activity, surface runoff, and leachate dispersion (Ceballos-Perez *et al.,* 2022, Herrera-Uchalin *et al.,* 2023).

In small communities, although less waste is generated, similar challenges arise in collection and disposal, often resulting in open-air incineration or dumping in unprotected pits, which promotes contaminant dispersion across different environmental matrices. A recurrent issue is leachate generation in sites where MSW is disposed of in the open (Cervantes and Castellanos, 2022, Del Carmen-Niño *et al.,* 2023). Leachates, produced during MSW degradation, contain diverse components such as heavy metals, organic compounds, salts, and pathogenic microorganisms, which are considered toxic and pose risks to the health of communities near disposal sites (Nava-Ruiz *et al.,* 2017). Some studies indicate a higher risk in socioeconomically disadvantaged communities, where most residents consume untreated water (artisanal wells) and rely on backyard food production (Cervantes and Castellanos, 2022, García-Mondragón *et al.,* 2023).

In southern and southeastern Mexico, particularly in Oaxaca, cultural richness coincides with socioeconomic marginalization and inadequate solid waste management. In urban areas, such as the Central Valleys and the state capital, confinement sites face overfilling issues, whereas in the Isthmus region, such as Reforma de Pineda, waste is disposed of directly in open-air sites (Lucas, 2001, García and Salazar, 2024). Open-air dumping presents a significant challenge, as MSW composition varies according to predominant activities in each area (Jiménez, 2015, Gobierno del Estado de Oaxaca, 2022). For example, in Reforma de Pineda, there are no specific reports on per capita waste generation or MSW composition. Municipal and government development plans emphasize the urgency of generating information to support proper waste management, particularly in areas where waste is openly disposed of, incinerated, or deposited in unlined pits. This situation is especially relevant given the region's high agricultural production (Gobierno del Estado de Oaxaca, 2022).

The environmental impact of these dumps on agricultural areas in Oaxaca has been scarcely studied, highlighting the need for targeted research. This is particularly critical in the Isthmus of Tehuantepec, where the local economy depends on crops such as mango, agave, and various vegetables (Hernández-Nolasco, 2023), and where neoarctic-neotropical transition ecosystems host endemic species at risk of extinction (Gobierno del Estado de Oaxaca, 2022). Improper MSW management can affect soil and water quality, directly impacting agriculture and biodiversity.

In this context, the objective of the present study was to evaluate heavy metal concentrations in soils and waters of an open-air dump in Reforma de Pineda, Oaxaca, and assess potential accumulation in adjacent agricultural areas. Additionally, geochemical and hydrological parameters of the site were established to identify high-risk areas, providing essential information for decision-making in remediation projects and the implementation of civil works aimed at mitigating the environmental impacts of inadequate MSW disposal, especially in economically marginalized and culturally important zones.

MATERIALS AND METHODS

An exploratory study was conducted through quantitative and qualitative analyses of the municipal landfill in Reforma de Pineda, Oaxaca, Mexico, and an adjacent mango cultivation plot. At the landfill, two cells were identified: T1 or "Tiradero", containing municipal solid waste (MSW) that had been incinerated and mixed with local soil, and T2, containing both incinerated and non-incinerated (Figure 1). In the agricultural plot, mango trees of the varieties *Mangifera indica* I. and *Mangifera indica* L. were observed (Hernández-Nolasco, 2023).

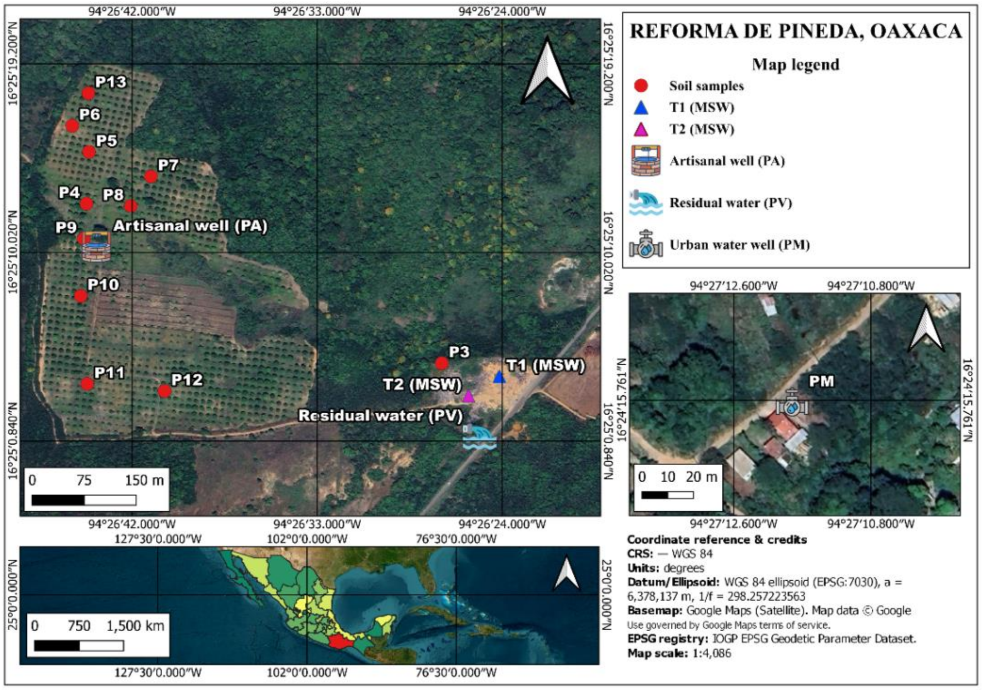

Figure 1. Study area in Reforma de Pineda, Oaxaca, Mexico, showing the location of soil and water sampling points in municipal solid waste disposal sites and surrounding areas. Source: Prepared by the authors

Soil sampling was conducted using a targeted approach, considering variations in texture (by touch) and site slope (Cruz-Roblero *et al.,* 2024). Thirteen soil samples (~30 cm depth) were collected: 10 from the cultivated area (P4 to P13) and 3 from the landfill area (P3, T1, and T2) (DOF, 2002). Additionally, three water samples were collected: one from residual water in the lower area of the landfill (PV), one from an artisanal well within the plot (PA), and another from a well in the urban zone (PM) (DOF, 1980). A rock fragment (Ro) was also collected at the same location as P7 (T 1).

Qualitative analysis comprised two studies: 1) petrographic analysis of the rock sample (Ro) and 2) mineralogical analysis of samples T1, P12, and P13. These analyses aimed to assess the relationship between the parent rock components, and the minerals present in natural and anthropogenically modified soils. Petrographic analysis was performed using thin-section microscopy with a Leica DM750 P polarizing light microscope, employing a 10× objective to describe mineral phase properties under both natural and polarized light (Stoops *et al*., 2018). Mineralogical analysis was conducted using a second-generation Bruker D2 Phaser X-ray diffractometer (XRD) (Vázquez-Vázquez *et al.,* 2023).

Quantitative analysis was performed in two parts. First, soil samples were air-dried, ground, and sieved using a #10 mesh. Physical and chemical properties were subsequently determined following NOM-021-SEMARNAT-2000 protocols (DOF, 2002), including Bulk Density (BD, $g \cdot cm^{-3}$), Particle Density (PD, $g \cdot cm^{-3}$), Field Capacity (%FC), pH (2:1 in water), Electrical Conductivity (EC of saturated extract, $dS \cdot m^{-1}$), Porosity (%Po), Textural fractions (Sand (%A), Clay (%R), Silt (%L)), and Organic Matter (%OM). Irrigation depth (ID) and permanent wilting point (PWP) were calculated based on the measured FC, BD, and texture (García Benavidez and Pérez Jirón, 2020).

Second, soil samples from T1, T2, P3, P12, and P13, along with all other samples, were analysed for heavy metals (Vanadium (V), Barium (Ba), Nickel (Ni), Lead (Pb), Chromium (Cr), and Cadmium (Cd)) using flame atomic absorption spectrophotometry (FAAS, Varian AA240FS), following NMX-AA-051-SCFI-2001 (DOF, 2001) and NOM-147-SEMARNAT/SSA1-2004 (DOF, 2007). Significant differences among mean values of physical, chemical, and metal concentrations were assessed using ANOVA-Tukey tests in R-project (Okoye *et al.,* 2020).

Finally, runoff directions and water storage areas were determined by dividing the site into polygons based on tactile soil texture. These data were compared with a two-dimensional rainfall-runoff numerical model (2D-RR), using digital elevation models (DEMs) and rainfall data obtained from the National Meteorological Service stations (Andrades *et al.,* 2020, CONAGUA, 2024).

RESULTS AND DISCUSSION

Mineralogy

The main mineral phases identified in the samples are quartz (Qz), plagioclase (Pl), and pyroxene, including both clinopyroxene (Cpx) and orthopyroxene (Opx) (Figure 2). The Opx and Cpx phases appear as subhedral crystals developing an acicular habit, whereas the plagioclase (Pl) and quartz (Qz) phases are observed as anhedral to subhedral minerals with tabular and granular habits, respectively (Figure 2). Previous studies conducted in localities of the Sierra Madre del Sur have reported these minerals; although not specifically from Reforma de Pineda, the geographical proximity and inclusion within the same geological unit suggest that the analysed samples could exhibit similar mineralogical characteristics (González-Torres *et al.,* 2007).

Additionally, in the photomicrographs (Figure 2), secondary minerals such as sericite (Ser) and iron oxides were observed, developing as anhedral crystals because of secondary processes in the rock. The mineral alteration observed in these specimens indicates a high degree of rock weathering (Stoops *et al.,* 2018, Loaiza-Usuga *et al.,* 2023). It has been reported that sericite and iron oxides can be associated with the weathering of the parent rock (Kanhaiya *et al.,* 2024). The mineralogical composition suggests that the studied rock belongs to a mafic segment of a gneiss, corroborated by other studies (Culí *et al.,* 2021a, Acevedo-Sandoval *et al.,* 2022).

On the other hand, the results obtained from the diffractograms corresponding to the landfills (T1 or Tiradero) show mineral phases such as quartz, kaolinite, and microcline. In the soil samples from the agricultural plot (P12, P13), quartz, kaolinite, albite, microcline, and aluminosilicate oxides were identified (Figure 3). The soils also exhibit a high degree of weathering and pedogenetic evolution, as indicated by the presence of stable secondary minerals, such as residual quartz, clays, and metal oxides, reflecting a mature and well-developed profile (Chang *et al.,* 2022). These diffractograms are consistent with the minerals observed in the rock petrography, particularly the high quartz content, which is the most common mineral in metamorphic and acidic intrusive rocks derived from sediments such as sandstones and schists (Beaumont *et al.,* 2023).

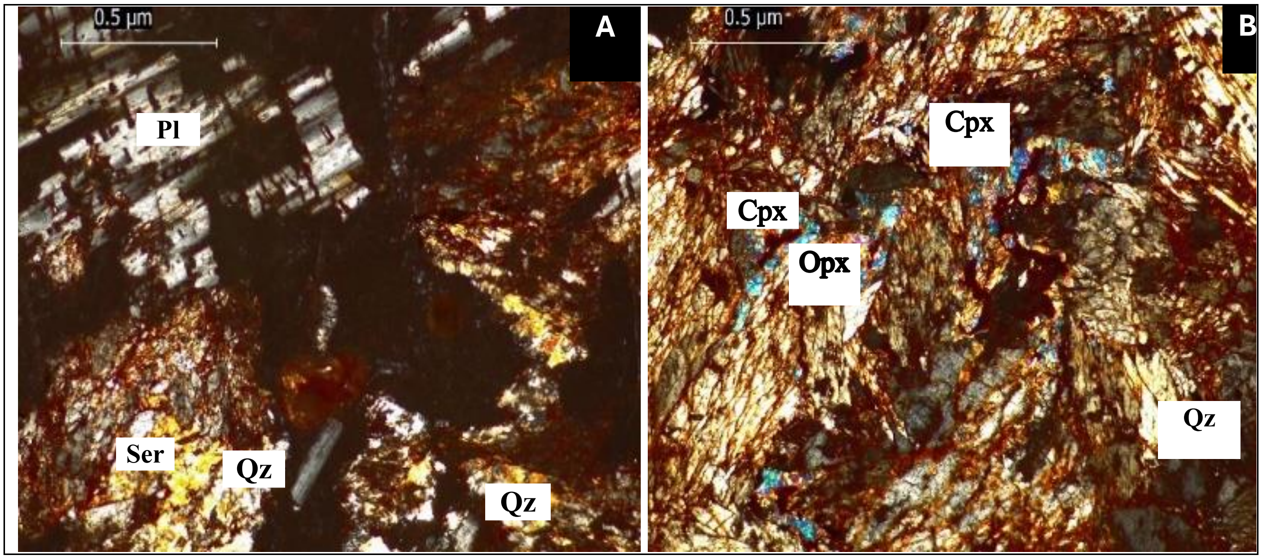

Figure 2. Photomicrographs of rock samples collected in the study area, illustrating mineralogical composition and textural features. Source: Prepared by the authors.

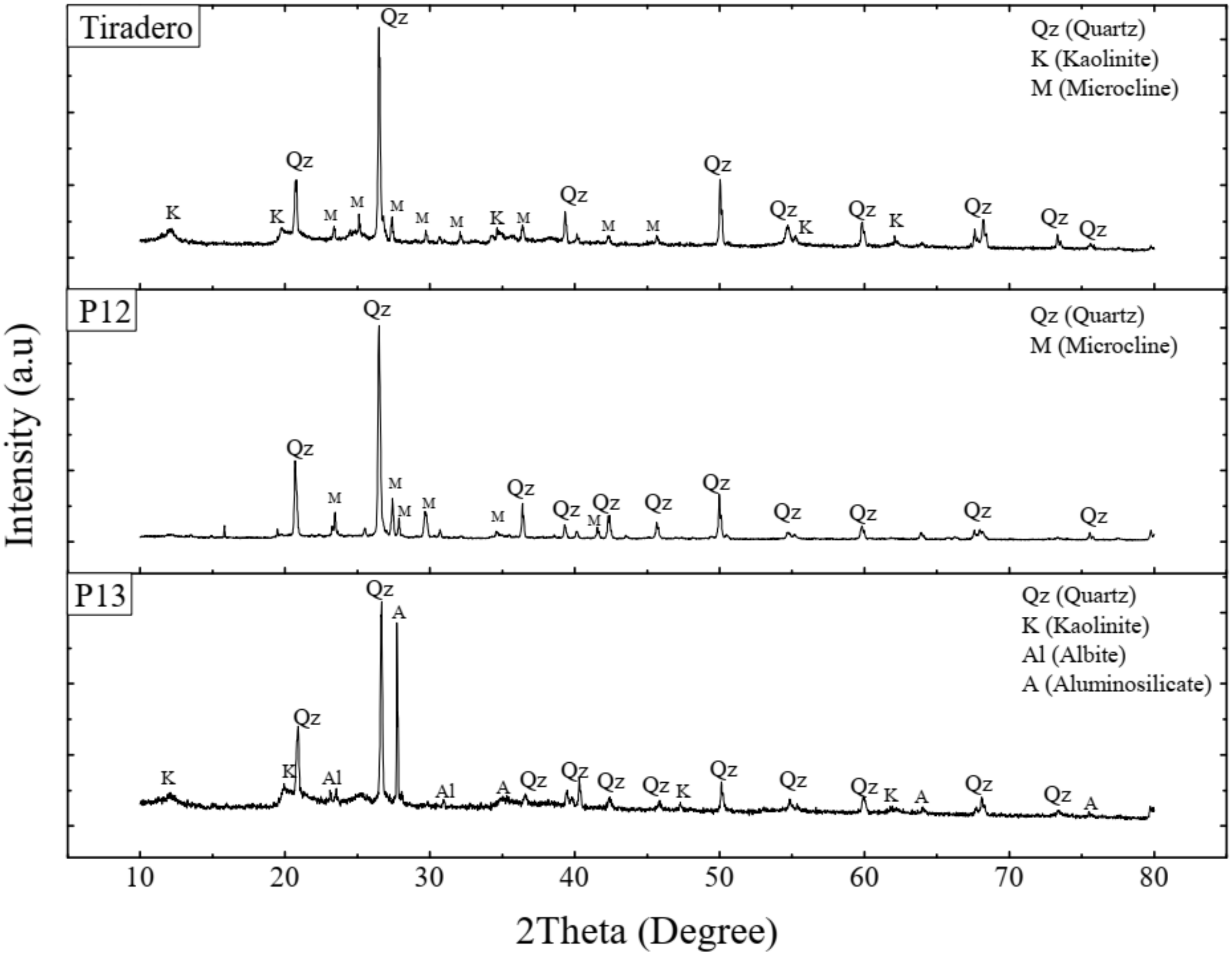

Figure 3. DRX of the soil samples. Crystallographic cards: Quartz (Qz) PDF 01-070-7344, Kaolinite (K) PDF 00-014-0164, Microcline (M) PDF 00-019-0932, Albite (Al) PDF 01-072-8434, Aluminosilicate oxide.

From an environmental standpoint, the mineralogical composition identified in both the landfill and surrounding soils provides important insights into the behavior of contaminants in the study area. The presence of secondary minerals such as kaolinite and iron oxides suggests that these materials may act as active surfaces for the adsorption of heavy metals, temporarily limiting their mobility but also favoring their gradual accumulation in the soil matrix over time. This interaction is particularly relevant in open dumps, where continuous leachate production can enhance the incorporation of potentially toxic elements into the soil system (Tao *et al.,* 2023).

At the same time, the advanced degree of weathering observed in the materials indicates a well-developed porous structure, which may facilitate water infiltration and promote the vertical transport of dissolved contaminants toward deeper horizons and groundwater. In this sense, the coexistence of relatively inert minerals such as quartz with more reactive phases such as clays and oxides suggests a complex environmental dynamic, in which both retention and mobilization processes can occur simultaneously depending on local geochemical conditions. Therefore, these mineralogical characteristics are directly linked to the environmental assessment of the landfill, as they help explain the potential dispersion, accumulation, and long-term environmental risk associated with heavy metals in the area (Tedoldi *et al.,* 2017).

Physical and chemical properties of soils

Soil samples were classified according to their textural class as sandy loam (T1, T2, P5, P6, P7, and P11) and loamy sand (P3, P4, P8, P9, and P10) (Table 1). Samples T1 and T2 correspond to the municipal solid waste landfill, whereas samples P3–P11 were collected from the adjacent mango orchard. Distinguishing between these two settings is essential, since it enables a clearer comparison between soils directly affected by waste disposal and those under agricultural use. When compared with the reference ranges established by the Mexican Standard NOM-021-SEMARNAT-2000, significant differences were observed in pH, electrical conductivity (EC), organic matter content (%OM), and field capacity (%FC) between landfill soils and those from the agricultural plot (DOF, 2002).

Electrical conductivity (EC)

Clear differences were observed between landfill soils (T1 and T2) and agricultural soils (P3–P11). Overall, salinity levels remained low (<1 $dS{\cdot}m^{-1}$); however, landfill samples exhibited comparatively higher EC values, approaching the boundary between non-saline and slightly saline conditions (1.1-2.0 $dS{\cdot}m^{-1}$). In contrast, soil from the mango orchard showed consistently lower EC values, reflecting limited salt accumulation under agricultural conditions.

The relatively higher EC in landfill soils may be associated with the presence of soluble salts derived from ash residues following waste combustion. In this regard, Arunrat *et al.* (2022) reported that ash inputs can increase soil EC, while Agbeshie *et al.* (2022) documented post-fire increases in both pH and EC, along with reductions in field capacity (%FC), which may negatively affect vegetation growth (Hinojosa *et al.,* 2021).

It is worth noting that, during fieldwork, signs of open-air burning of municipal solid waste were observed at the site, mainly to reduce waste volume and recover metals from materials such as tires and other residues. Similar practices have been reported in unmanaged disposal sites, where informal recycling activities often involve waste combustion (Ferronato and Torretta, 2019). In this context, it is reasonable to assume that combustion-derived residues are contributing to the EC patterns observed in landfill soils.

Organic Matter (%OM) and Soil pH

Landfill soils (T1 and T2) exhibited very low organic matter (<0.5%), whereas soils from the mango orchard (P3-P11) showed slightly higher values, ranging from 0.5 to 1.5%. In terms of pH, the landfill samples were moderately alkaline (7.4-8.5), while orchard soils were predominantly moderately acidic, except for P7, which was neutral. The soil sample closest to the landfill (P3) displayed pH and EC values like those of other orchard soils, suggesting limited influence of the adjacent landfill in this area.

The observed higher pH and reduced organic matter in landfill soils are consistent with the effects of municipal solid waste combustion. Previous studies have reported that MSW fires can reach temperatures between 700 and 1000 °C, leading to the formation of calcium and magnesium carbonates and, consequently, an increase in pH and a reduction in organic matter content (Badía and Martí, 2003, Ni *et al.,* 2021).In the present study, these patterns are likely linked to the recurrent waste burning observed during sampling, which provides a plausible explanation for the physicochemical differences between landfill and orchard soils.

Field Capacity (%FC), Texture, and Soil Water Dynamics

A significant reduction in field capacity (%FC) was observed in landfill soils (T1 and T2: 25-30%) compared to orchard soils (P5, P6, P7, P11: 31-36%). Despite these differences, the textural classification of upper horizons remained similar (predominantly sandy loam), suggesting that the reduced water retention in landfill soils is likely linked to horizon homogenization caused by excavation and compaction, whereas natural pedogenesis and agricultural management maintain slightly higher water retention in the orchard (Cruz-Roblero *et al.,* 2024).

Relationships among bulk density (BD), porosity (%Po), irrigation depth (ID), and %FC revealed inversely proportional trends, indicating that higher BD corresponds to lower microscopic porosity, reduced %FC, and limited root-zone water storage. For example:

a) $\%Po = (-48.758\,(BD)) + 105.4$; $R^2 = 0.863$

b) $ID = 6.5852e(1.1023 \cdot BD)$; $R^2 = 0.8698$

c) $\%FC = -20.54 \cdot \text{Ln}\,(BD) + 29.997$; $R^2 = 0.5373$

These results suggest a reduction in microscopic porosity, negatively affecting soil aeration, moisture retention, and plant rooting (Stover and Verrelli, 2020). Additionally, variability in irrigation depth (ID) was associated with soil texture. Sandy-loam soils exhibited lower values (15-19 mm) and higher values up to 26 mm, reflecting greater heterogeneity in water infiltration and storage. In contrast, loam-sandy samples showed more stable values (19-21 mm), close to the mean, suggesting a more uniform behaviour in moisture retention.

These observations are consistent with reports highlighting the effect of slight variations in the proportions of sand, silt, and clay on soil water dynamics and irrigation efficiency. For example, Candeias *et al.* (2011) found that irrigation increased peach fruit diameter by ~5% in sandy-loam soils and by ~18% in clay-loam soils. Moreover, García *et al.* (2014) reported that soil texture and chemical composition affect pulp firmness and titratable acidity of fruits. In mango cultivation, this heterogeneity emphasizes the importance of considering texture as a management criterion, adjusting irrigation scheduling according to local conditions to avoid water deficit or excess in different sectors of the plot (Culí *et al.,* 2021b).

Water Repellence and Contaminant Migration

Moreover, landfill soils may present additional environmental risks due to the potential development of water repellence, a phenomenon observed in soils contaminated by hydrocarbons or exposed to high-temperature events such as landfill fires. During combustion, petroleum derivatives and other organic residues can transform into hydrophobic aggregates, reducing water infiltration in upper horizons while promoting vertical migration of contaminants toward deeper layers and groundwater. Although this study focused primarily on heavy metals as indicators of health risk, the presence of water-repellent layers highlights the complex interplay between soil physical properties, contaminant mobility, and long-term environmental impacts. These processes underscore the importance of monitoring landfill soils not only for chemical pollutants but also for changes in hydrological behavior that could exacerbate contaminant dispersion over time (Travis and Hester, 1991, Samburova *et al.,* 2018, Stelzer, 2019, Alabi *et al.,* 2023).

Metals in soil and water

The presence of metals in the study area is likely linked to a combination of interacting factors. On one hand, agricultural practices in the mango orchard may contribute to the input of certain elements using agrochemicals, such as fertilizers, pesticides, and irrigation have been widely recognized as potential sources of metal accumulation in soils. On the other hand, the proximity to the municipal solid waste landfill represents an additional source of contamination, particularly considering the open disposal conditions and the recurrent burning of waste observed during fieldwork. Moreover, the heterogeneous composition of the waste including materials such as batteries, tires, and other metal-containing residues-can promote the release of heavy metals through leaching and weathering processes. In this sense, the distribution of metals observed in the study area likely reflects the combined influence of agricultural inputs and landfill-related processes, such as leachate generation, ash deposition, and subsequent environmental transport (Xu *et al.,* 2024, Oluyinka et al., 2024, Mkhonza *et al.,* 2026).

The results for metals indicate that the concentrations of V, Ba, Ni, Pb, and Cr do not exceed the Maximum Permissible Limits (MPL) established by the Mexican standard NOM-147-SEMARNAT-SSA1-2004 for agricultural soils (DOF, 2007; MPL: V < 78, Ba < 5400, Ni < 1600, Pb < 400, and Cr < 280 $mg \cdot kg^{-1}$). Although all metal concentrations in the samples showed significant differences among them ($x_1 – x_2 >$ HSD), V, Ba, Ni, and Cr were detected in landfill soils (P3, T1, and T2) and in the lower part of the agricultural plot (P13). In contrast, only V and Ba were observed in the upper part of the plot (P12) at lower concentrations than in the lower zone. This pattern suggests downward migration of these elements, with Ni and Cr likely of anthropogenic origin. Notably, Pb was only detected in the landfill area (T1 and T2), and Cd was below the detection limit in all samples (<DL). Regarding metals, 14 elements were analysed: Ca, Mg, Na, Fe, Cu, Mn, Zn, V, Ba, Ni, Pb, Cr, and Cd, of which only Cd was below its detection limit (Table 2).

Table 1. Physical and chemical properties of soil samples collected from municipal solid waste disposal sites and surrounding areas.

		pH	EC (dS·m^{-1})	%OM	%FC	BD (g·cm^{-3})	PD (g·cm^{-3})	%A	%R	%L	%Po	PWP	ID
Sandy loam	**T1**	7.4 ± 0.11	$0.99 \pm 2\cdot10^{-3}$	0.14 ± 0.10	25 ± 1	1.18 ± 0.01	2.26 ± 0.01	48 ± 1.15	7 ± 0.10	45 ± 1.15	48	28	26
	T2	7.8 ± 0.10	$0.77 \pm 1\cdot10^{-3}$	0.39 ± 0.11	23 ± 2	1.14 ± 0.01	2.23 ± 0.02	62 ± 0.76	4 ±1.38	34 ± 0.61	49	19	23
	P5	6.1 ± 0.13	$0.01 \pm 1\cdot10^{-3}$	1.33 ± 0.02	33 ± 1	0.77 ± 0.01	2.47 ± 0.07	59± 1.41	3 ± 0.13	38 ± 1.41	69	19	15
	P6	6.3 ± 0.10	$0.01 \pm 1\cdot10^{-4}$	1.27 ± 0.11	31 ± 2	0.92 ± 0.02	2.33 ± 0.04	54 ± 0.7	1 ± 0.05	45 ± 0.7	60	18	18
	P7	6.6 ± 0.14	$0.02 \pm 1\cdot10^{-4}$	1.39 ± 0.10	36 ± 1	0.87 ± 0.02	2.15 ± 0.03	69 ± 0.7	3 ± 0.02	29 ± 0.7	60	22	19
	P11	6.0 ± 0.11	$0.09 \pm 1\cdot10^{-3}$	1.21 ± 0.12	30 ± 2	1.15 ± 0.03	2.09 ± 0.02	50 ± 2.12	1 ± 0.03	50 ± 2	45	17	22
Loamy sand	**P3**	6.2 ± 0.12	$0.01 \pm 2\cdot10^{-4}$	1.34 ± 0.10	31 ± 2	1.03 ± 0.01	2.48 ± 0.06	84 ± 1	2 ± 0.01	14 ± 1	59	18	20
	P4	5.5 ± 0.11	$0.01 \pm 1\cdot10^{-3}$	1.34 ± 0.09	27 ± 1	1.08 ± 0.01	2.54 ± 0.01	74 ± 2	3 ± 0.01	23 ± 1	57	15	20
	P8	5.9 ± 0.10	$0.03 \pm 1\cdot10^{-3}$	1.32 ± 0.11	32 ± 2	1.07 ± 0.02	2.39 ± 0.02	86 ± 0.42	5 ± 0.02	9 ± 0.42	55	19	21
	P9	5.6 ± 0.11	$0.09 \pm 2\cdot10^{-3}$	1.36 ± 0.10	30 ± 1	0.97 ± 0.02	2.21 ± 0.04	77 ± 1.41	1 ± 1.41	22 ± 1	56	17	19
	P10	6.1 ± 0.13	$0.09 \pm 1\cdot10^{-3}$	1.40 ± 0.08	36 ± 2	1.19 ± 0.02	2.22 ± 0.04	81 ± 0.7	2 ± 0.02	18 ± 0.7	47	22	26
	p-valor					< 0.05					-	-	-
	HSD	0.210	0.015	0.002	3.70	0.053	0.122	4.27	3.57	4.90	-	-	-

Where **EC** is electrical conductivity, **BD** is bulk density, **PD** is particle density, **%Po** is porosity, **%FC** is field capacity, **%OM** is organic matter, **%A** is sand, **%R** is clay, and **%L** is silt. **PWP** represents the permanent wilting point, and **ID** is the irrigation depth. Additionally, *, **, and *** indicate no significant differences among the samples within the same column. Values are expressed as mean ± standard deviation (n = 3).

Table 2. Metal concentrations in water.

	Water (mg·L^{-1})													
ID	**K**	**Ca**	**Mg**	**Na**	**Fe**	**Cu**	**Mn**	**Zn**	**V**	**Ba**	**Ni**	**Pb**	**Cr**	**Cd**
PA	2.302 ± 0.003	2.282 ± 0.001	1.683 ± 0.002	2.154 ± 0.001	58.701 ± 0.007	0.013 ± 0.001	0.150 ± 0.001	0.055 ± 0.001	0.163 ± 0.002	0.043 ± 0.002	0.320 ± 0.003	0.001 ± 0.001*	<LD	<LD
PV	1.585 ± 0.001	2.535 ± 0.003	2.921 ± 0.004	4.159 ± 0.002	356.411 ± 0.004	0.051 ± 0.001	0.466 ± 0.001	0.069 ± 0.001	0.269 ± 0.005	0.081 ± 0.003	0.257 ± 0.001	0.002 ± 0.001*	0.641 ± 0.001	<LD
PM	8.435 ± 0.002	4.461 ± 0.004	4.342 ± 0.004	5.776 ± 0.007	247.521 ± 0.002	<LD	0.003 ± 0.001	<LD	<LD	<LD	<LD	<LD	<LD	<LD
p-value						< 0.05							NA	
HSD	0.67	0.98	0.35	1.01	23.01	0.002	0.012	0.003	0.021	0.016	0.030	0.001		
LD	0.662	0.012	0.001	0.001	0.988	0.023	0.001	0.030	0.001	0.001	0.001	0.001	0.001	0.015

For micronutrients (K, Na, Ca, Mg), comparison with NOM-021-SEMARNAT-2000 revealed different classifications (DOF, 2002). For example, P12 and P13 were medium (0.3-0.6 Cmol·kg^{-1}), while P3, T1, and T2 were high (>0.6 Cmol·kg^{-1}). For Ca, samples T2, P3, P12, and P12 were very low (<2 Cmol·kg^{-1}), and T1 was low (2–5 Cmol·kg^{-1}). Mg was medium in P12 and P13 (1.3-3 Cmol·kg^{-1}), and high in P3, T1, and T2 (>3 Cmol·kg^{-1}). All Na values were below 15 Cmol·kg^{-1}, considered non-toxic for crops. Micronutrients (Fe, Mn, Zn, Cu) were within adequate ranges (Fe > 4.5, Mn and Zn > 1, Cu > 0.2 mg·kg^{-1}) according to NOM-021-SEMARNAT-2000 (Table 2). Significant differences among sample values were observed for all elements (x_1–x_2 > HSD).

Although some samples showed similar classifications, it is noteworthy that P3, T1, and T2 consistently exhibited higher metal concentrations. This pattern is consistent with processes commonly observed in soils influenced by waste disposal and burning. Previous studies indicate that repeated waste incineration increases the inorganic content of ash, thereby enriching soils with metals and other mineral components (Badía and Martí, 2003). In addition, thermal processes can reduce particle size and density, enhancing the mobility of these elements in the environment (Monib *et al.,* 2024). Local environmental conditions may further influence this behavior. The study area, located in the Isthmus of Tehuantepec, is subject to frequent wind gusts (Martínez-Reyes *et al.,* 2023), which can facilitate the dispersion of ash particles, while the predominantly acidic soils in the agricultural plot may favor metal mobilization (Contreras-De la Cruz *et al.,* 2023). Together, these factors help explain the observed distribution patterns and suggest an increased potential for contaminant dispersion and exposure (Muimba-Kankolongo *et al.,* 2018, Kicińska *et al.,* 2022).

Though multiple sources may contribute to the presence of metals in the soil, the spatial distribution observed in this study provides useful insights into their behavior. Higher concentrations of Ni and Cr were detected in the lower zone compared to the landfill, which may be associated with processes of transport and accumulation across different environmental compartments (Chen *et al.,* 2020, Gao *et al.,* 2020). In contrast, Pb was only detected in the landfill area, suggesting a more localized source. This element may be linked both to the composition of disposed waste—such as batteries and metallic residues and to natural background levels reported in the region (Solari *et al.,* 2021, Abdul-Rashid *et al.,* 2023).

Analysis of water samples from the artisanal well (PA) in the plot revealed the same 13 elements present in soils, with Cd remaining undetected in all samples (Table 2). Pb was only found in PA and PV, with no significant differences between them (x_1-x_2 < HSD). In contrast, the mean values of the other metals showed significant differences among samples (x_1-x_2 > HSD).

Regarding regulatory values in Mexico, the standard NOM-127-SSA1-1994 for water intended for human use and consumption establishes the maximum permissible limits (MPL) as follows: Na < 200, Ba < 0.70, Cu < 2, Cr < 0.05, Fe < 0.30, Mn < 0.15, Pb < 0.025, Zn < 5, all in mg·L^{-1} (DOF, 2000). Likewise, the standard NOM-001-SEMARNAT-2021 sets Ni < 5 mg/L as the MPL for the monthly average discharge (PM) in rivers and streams (DOF, 2007). No regulatory references were found for Calcium, Magnesium, Potassium, and Vanadium; however, some studies recommend, for human use and consumption, limits of Ca < 100, Mg < 30, K < 10, and V < 0.1 mg·L^{-1} (Filler *et al.,* 2021, Jomova *et al.,* 2022, Kowalczyk *et al.,* 2022, Zhang *et al.,* 2023).

Considering the above, it was observed that water samples from plots and MSW landfills (PA and PV) exhibited concentrations above the MPL for Fe, Mn, V, and Pb, as well as Cr, although the latter was only detected in PV. In contrast, well water from the municipality (PM) only exceeded the MPL for Fe. In all cases, concentrations were higher in the landfill samples. On one hand, Ca, Fe, and Mn have been reported as elements posing challenges during water treatment and distribution in the area, as they contribute to high water hardness due to their presence in the bedrock (Preethi *et al.,* 2025). On the other hand, the detection of V and Cr in both soil and water has been associated in the literature with increased mobility in the environment and, consequently, elevated health risks. Likewise, Pb, which was only detected in landfill and plot samples for both matrices, poses potential risks to crops (Lorenzo-Márquez *et al.,* 2016, Hernández *et al.,* 2019).

Two-Dimensional Rainfall-Runoff Model (2D-RRM)

The rainfall-runoff modelling allowed the identification of water flow directions and areas with the highest groundwater recharge at the study site (blue zones in Figures 4a and 4b), representing the most promising locations for groundwater exploration and guiding assisted irrigation strategies according to the calculated irrigation depth. The results indicate that sandy-loam soils, predominantly found in the northern area, exhibit higher field capacity (%FC: 27-36%) and lower permanent wilting point (15-22%), which enhances both moisture retention and infiltration. In contrast, loamy-sand soils display a more uniform behaviour but with lower water storage capacity, suggesting reduced water availability for crops.

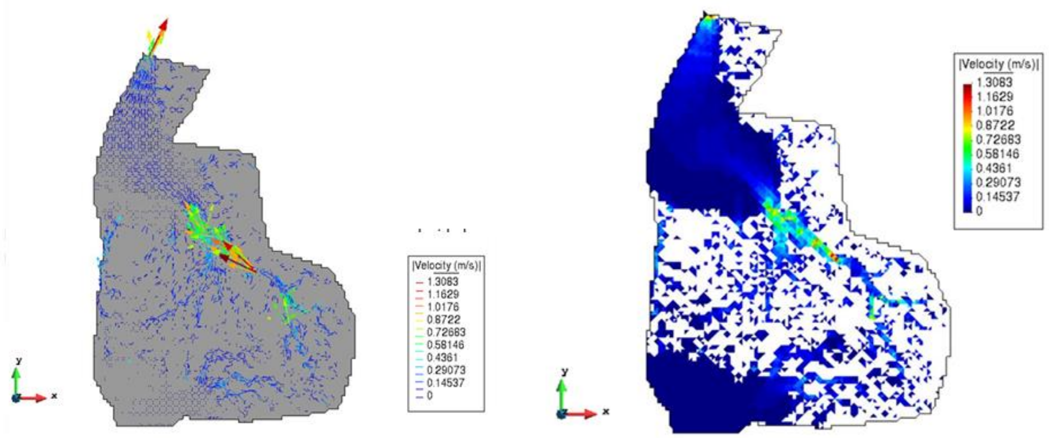

Figure 4. Runoff direction with velocity vectors (m/s) (a). Distribution of areas with higher water potential (in blue) (b).

When correlating the physical and chemical properties with the detected metals, it was observed that elements such as Ni, Cr, V, and Ba showed higher concentrations in the landfill (T1, T2, P3) and in the lower section of the plot (P13), whereas Pb was detected exclusively in the landfill. This indicates that the combination of water flow, soil texture, and porosity promotes metal displacement toward lower areas, making them the most vulnerable to contamination. For example, soils with higher porosity and field capacity facilitate metal leaching and transport, whereas finer soils partially retain metals in the upper horizons (Chen *et al.,* 2020. Gao *et al.,* 2020). Likewise, soils from the landfill (T1 and T2), characterized by lower %OM and %FC due to the combustion of municipal solid waste, exhibited higher pH and reduced adsorption capacity, which increases the mobility of metals such as Ni, Cr, and Pb (Badía and Martí, 2003, Ni *et al.,* 2021). Therefore, low-lying areas with sandy-loam soils and high runoff constitute the most critical zones for metal accumulation.

On the other hand, sandy-loam soils in the northern sector, with greater water retention capacity and lower bulk density, represent the most promising locations for groundwater extraction and assisted irrigation, as they combine higher infiltration with lower risk of metal contamination. This pattern highlights that the integration of texture, field capacity, and runoff dynamics is essential for water management and environmental control within the plot.

Finally, modelling results indicate that areas with greater infiltration coincide with sandy-loam soils exhibiting lower bulk density, consistent with the higher metal presence in the lower part of the site. This pattern suggests that the interplay of soil texture, water retention capacity, and runoff flow directly influences the spatial distribution of metals, constituting a critical factor for environmental risk management and assisted irrigation planning in the study area.

CONCLUSIONS

The open-air landfill of Reforma de Pineda represents a significant source of soil alteration and heavy metal contamination, particularly Vanadium, Barium, Nickel, Chromium, and Lead, which are found at higher concentrations in landfill soils and in some surrounding agricultural areas. The physicochemical properties of the soil indicate degradation, with decreased organic matter, alkalinization, and increased salinity in zones affected by waste burning. In nearby waters, elevated levels of toxic elements exceeding permissible limits for human consumption were detected, posing a potential health risk for local communities dependent on groundwater. Mineralogical analysis revealed the presence of alteration-derived phases, such as kaolinite and iron oxides, and a high degree of soil weathering. Additionally, areas of greater water accumulation were identified through runoff modelling, providing tools for risk management and mitigation. This environmental assessment establishes a solid technical foundation for designing remediation strategies, monitoring programs, and territorial planning. It is recommended to implement comprehensive waste management plans and periodic monitoring of soils and waters to protect public health and agricultural ecosystems in the Istmo of Tehuantepec.

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Conflict of Interest. The authors declare that they have no known competing financial interests or personal, academic, or institutional relationships that could have appeared to influence the work reported in this paper.

Ethical Approval. This study did not involve human participants or experimental animals and therefore did not require approval from an institutional or national ethics committee. All sampling and analytical procedures were conducted in accordance with applicable national environmental regulations and internationally accepted ethical standards for environmental research.

Data availability. The data that supports the findings of this study are available from the corresponding author upon reasonable request.

Statement on the Use of Artificial Intelligence. Artificial intelligence–based tools were used exclusively for language editing, clarity enhancement, and stylistic improvement. These tools were not used for data generation, data analysis, interpretation of results, or scientific decision-making. The authors take full responsibility for the originality, scientific content, and ethical integrity of this manuscript.

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