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ORIGINAL PAPER

Assessment of construction and demolition waste leachate using column percolation test: effect of paint presence

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Abstract

Construction and demolition waste (CDW) are commonly disposed of in unlined landfills or inappropriately at irregular sites. Civil construction materials may contain hazardous substances that, if solubilized or leached, can negatively impact the environment and human health. Understanding the leaching behavior of CDW is essential for assessing its environmental performance and ensuring its safe reintegration into the construction supply chain. This study aimed to investigate the impact of paint presence on the leachate contamination potential. The method involved the UNE-EN 12457-3 compliance leaching test and column percolation tests conducted under both saturated and unsaturated conditions, using columns filled with CDW, with and without paint. The samples, regardless of the presence of the paint layer, were classified as non-hazardous according to the criteria established by the European Council. The results indicate that the presence of paint mainly influenced the apparent color, turbidity, and concentrations of Na^+ and K^+ in the leachate. Although various heavy metals are used in paints, especially as pigments, the presence of paint in CDW did not significantly influence the release of these metals into the leachate. The CDW leachates, regardless of the presence of paint, exhibited potential for groundwater contamination due to elevated levels of sulphate and total dissolved solids. Notably, CDW also demonstrated the capacity to remove Zn and Fe and CDW without paint was found to reduce water turbidity.

Keywords Environmental risk potential · Inert landfill · Lead-based paints · Leaching test · Demolition waste

Introduction

The annual production of construction and demolition waste (CDW) worldwide exceeds 10 billion tons (Wang et al. 2019). In Brazil, CDW consists mainly of materials such as concrete and masonry, which can be reintroduced into the construction industry as substitutes for natural aggregates. Recycled aggregates find applications in road subbases (Beja et al. 2020; Al-Ali and Eid 2023), landfills (Zhang et al. 2019), and nonstructural (López-Uceda et al. 2016; Valdés et al. 2018) and structural concrete (Xiao et al. 2022).

Despite the environmental benefits and cost savings associated with using recycled aggregates over natural ones (Zhang et al. 2023), it is estimated that over 35% of globally generated CDW still ends up in landfills (Menegaki and Damigos 2018). Additionally, irregular CDW disposal practices remain a global challenge (Yuan et al. 2023).

Disposing of CDW in irregular areas, placing non-inert CDW in unlined landfills, and indiscriminately using recycled aggregates can lead to environmental damage. CDW poses potential risks to the environment and health due to the presence of adhesives, paints, sealants, solvents, PCBs, asbestos and other potentially hazardous materials (Del-Rio et al. 2010). These risks are exacerbated by inadequate source segregation and the increasing use of chemical additives and organic polymers in the construction industry (Molla et al. 2021; Purchase et al.2022).

Concentrations of arsenic, copper, chromium, selenium, antimony, lead, zinc, and sulfate were detected in construction and demolition waste samples at levels exceeding

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local regulatory limits (Butera et al. 2014; Laadila et al. 2022). Studies have also reported elevated concentrations of heavy metals, such as cadmium, in soils from landfills designated for CDW (Zhou et al. 2022; Balali et al. 2023). Chromium and sulfate are commonly found in CDW leachate at concentrations exceeding the limit established for inert waste by the European Union (Barbudo et al.2012; Gálvin et al.2014, Vegas et al. 2015; Saca et al.2017; López-Uceda 2019; Agrela et al. 2021).

Identifying contaminant sources is essential for the effective management of CDW to enhance recycling efforts and ensure the prevention of environmental and health risks. Among the potentially hazardous materials in CDW, paints stand out because they often contain heavy metals, primarily in pigments and additives (Muehlethaler and Massonnet 2023).

Lead has historically been incorporated into paints for its properties that improve durability, surface adhesion, color enhancement, and gloss (O´Connor et al.2018; UNEP and WHO 2021). However, due to the health hazards posed by exposure to lead, especially in children, the international community, led by the United Nations Environment Programme and the World Health Organization, actively supports the global elimination of lead-based paints (UNEP and WHO, 2021). Despite these efforts, lead-based paints are still widely used in many developing countries (Ranjbar et al.2023), and CDW can contain paints manufactured before regulations.

In Brazil, a study examining paints sold prior to the enforcement of legislation that established a 600 mg/kg lead limit found average lead concentrations of 36,000 mg/kg, with maximum levels reaching 170,000 mg/kg (Clark et al.2014). Similarly, oil-based paints sold in Ethiopia exhibited lead concentrations ranging from 41.90 to 51,204.17 mg/kg, along with other heavy metals such as chromium, which ranged from 43.75 to 5450 mg/kg, and zinc from 179.08 to 1102.15 mg/kg (Megertu and Bayissa 2020). In Nigeria, water-based paints showed lead concentrations ranging from 170 to 3231 mg/kg and cadmium concentrations ranging from 98 to 1999 mg/kg (Apanpa-Qasim et al. 2016). Additionally, high concentrations of lead, zinc, cadmium, copper, manganese, nickel, cobalt, chromium, and vanadium were also found in paint chip samples (Mielke et al.2001; Ogilo et al. 2017).

Based on the presence and concentration of these metals in paints sold in various countries and in paint chips, this study aims to evaluate the influence of these paints on the contamination potential of leachates from construction and demolition waste. Although several studies have investigated the presence of hazardous substances in CDW and its leachates, research identifying the source of these contaminants is still limited. In particular, there are no studies assessing whether paints could act as a source of hazardous contaminants in CDW leachates.

Materials and methods

Sample collection and characterization

Samples of wall coating residues were collected from 15 demolition and renovation sites in cities in the southeastern region of Brazil between March and July 2022. Layers of coating corresponding to roughcast, plastering, and rendering were collected, excluding ceramic blocks or other structural components. Samples were sorted and separated into two groups based on the presence of paints. Using a plastic-wrapped hammer, the samples were ground to pass through a sieve with 9.5 mm openings.

Individual samples from each site, ground and segregated based on the presence of paints, were combined into composite samples. Approximately 2 kg of each sample was placed on a plastic tarp and homogenized. The total mass, approximately 30 kg, was reduced using the quartering method to obtain a sufficient quantity for the experiments (about 7.5 kg). The particle size distribution of each composite sample was characterized and is presented in Supplementary Material Figure SM-1.

Figure 1 summarizes the procedure used to obtain composite CDW samples for the experiments.

Compliance leaching test

A compliance leaching test was carried out in accordance with the UNE-EN 12457–3 (2022) standard to evaluate whether the construction and demolition waste samples, both with and without the paint layer, meet the criteria established by European regulations (Council Decision 2003/33/EC). The concentrations of Al, Ba, Cd, Co, Cu, Cr, Fe, Mn, Ni, Pb, and Zn in the leachates were determined using atomic absorption spectrometry (Varian AA240 FS), while Na and K were measured by flame photometry (Digimed DM 62). Sulfate was quantified by spectrophotometry (HACH DR/2010). Additionally, pH and electrical conductivity of the leachates were measured. The CDW samples, were classified according to the criteria of the Landfill Directive (Council Decision 2003/33/EC).

The compliance leaching tests were performed in triplicate. When the concentration of a given parameter was below the instrument's detection limit, a value corresponding to half of the detection limit was assigned to the sample for the purpose of calculating the mean and standard deviation.

Configuration and operation of the percolation columns

This study utilized six percolation columns developed by Córdoba (2014), with three columns simulating a saturated regime and the other three simulating an unsaturated regime. The columns were constructed from reinforced acrylic

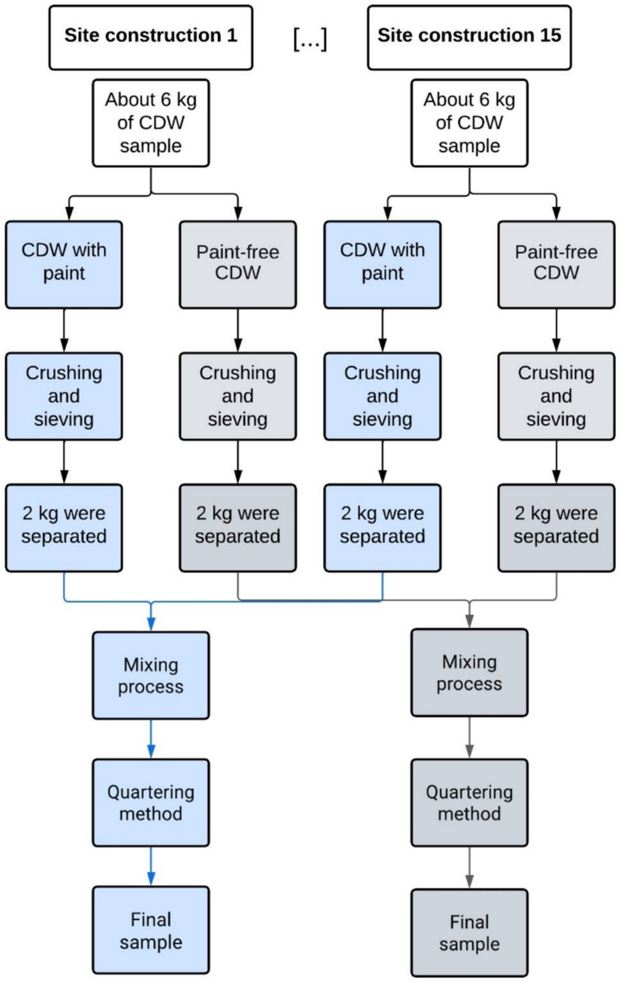

Fig. 1 Diagram of the process for obtaining composite CDW samples with and without the presence of paints

tubing, each with an internal diameter of 9 cm, a height of 100 cm, and a useful volume of 6300 cm^3. A non-woven geotextile was placed at the base of the columns to prevent potential clogging of the leachate collection ducts.

One column in each saturation regime was filled with 6.5 kg of CDW without paint, and another column in each regime was filled with 6.5 kg of CDW containing paint. To assess possible interferences with the equipment and the leaching solution, one column in each regime had no material inserted, constituting experimental controls, as shown in Table 1.

The leaching simulation systems under saturated and unsaturated conditions were fabricated using materials typical of domestic water supply systems, such as PVC pipes, fittings and tubing. The respective equipment comprising them is depicted in Fig. 2.

Table 1 Saturation regime and construction and demolition waste (CDW) filling of the percolation columns

Colunm*	Saturation regime	Sample
UF	Unsaturated	Paint-free CDW
UP		CDW with paint
UC		Not filled
SF	Saturated	Paint-free CDW
SP		CDW with paint
SC		Not filled

*UF: Unsaturated column with paint-free CDW; UP: Unsaturated column with CDW with paint; UC: Unsaturated column control; SF: Saturated column with paint-free CDW; SP: Saturated column with CDW with paint; SC: Saturated column control

The leaching solution used was extraction fluid No. 2 from Method 1312—Synthetic Precipitate Leaching Procedure (EPA, 1994), composed of a diluted solution of sulfuric and nitric acid (60/40 rate) in deionized water, suitable for leaching tests under slightly acidic precipitation conditions (pH = 5.0 ± 0.05), which are representative of urban areas in several Brazilian cities (Martins et al. 2019). The leaching solution was prepared weekly and stored in a common reservoir for both systems. In the unsaturated columns, approximately 533 ml of leaching solution was sprayed three times a week (Monday, Wednesday and Friday), continuously for a short period of time, until the desired volume reached, totaling approximately 1.6 L per week. In the saturated columns, the flow was upward; peristaltic pumps pumped approximately 230 mL of leaching solution per day at alternating intervals of 30 min, totaling approximately 1.6 L per week.

The columns were operated for a total period of six months. This duration was selected because the highest concentrations of metals in CDW leachates typically occur within the first 15 weeks, driven by the initial mobilization of highly soluble contaminants. After this period, a gradual

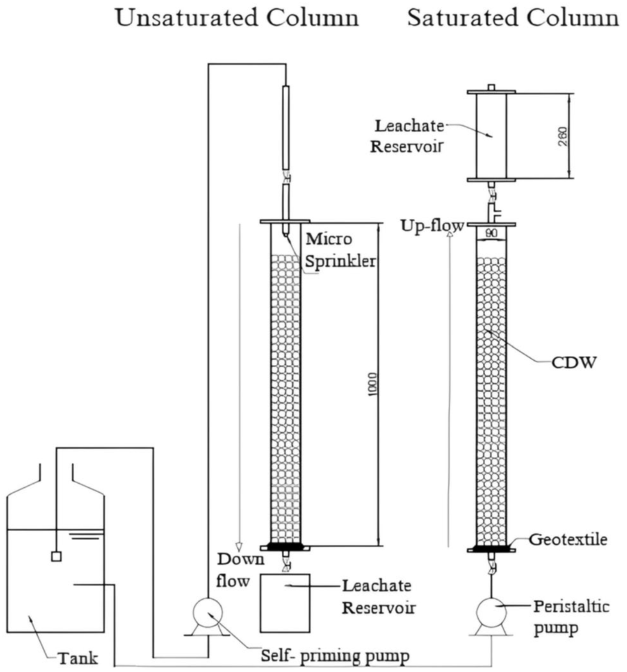

Fig. 2 Schematic diagram of the percolation columns (dimensions in mm)

decline in metal concentrations is observed, reflecting the transition to a continuous but less intense leaching phase (Diotti et al. 2021; Molla et al. 2025).

Each week, the leachate reservoirs of each column reached their capacity, and the leachate was then collected. During the first two months, leachates were collected and analyzed weekly; in the subsequent two months, leachate from alternate weeks was analyzed; in the final two months, analysis was conducted once a month. Table 2 presents the days of collection and their respective liquid-to-solid ratios (L/S), indicating the volume, in liters, of the leaching solution that permeated the columns relative to the mass of waste contained in them (kg).

Analytical methodology

The concentrations of metals Al, Ba, Cd, Co, Cu, Cr, Fe, Mn, Ni, Pb, and Zn in the leachate were analyzed by atomic absorption spectrometry (Varian AA240 FS), and Na and K were analyzed by flame photometry (Digimed DM 62). The limits of quantification of the methods are presented in Supplementary Material Table SM-1. The anions chloride, sulfate, and fluoride were analyzed by spectrophotometry (HACH DR/2010). pH, electrical conductivity, turbidity, apparent color, hardness, and total dissolved solids were also analyzed (APHA, AWWA, WEF 2023).

To identify potentially critical substances and assess the potential for alteration of groundwater quality, leachates were compared with the limit values for drinking water in Brazil (GM/MS 888/2021) (Brazil 2021) and the acceptance criteria of the European Union Landfill Directive for inert materials (2003/33/CE). The limit values for drinking water in Brazil were used because SPLP leachate concentrations are generally compared to drinking water standards.

Results and discussion

Compliance leaching test

UNE-EN 12457-3/(2002) standard is a compliance leaching test designed to assess whether granular recycled materials meet regulatory requirements. Table 3 presents the results obtained for the construction and demolition waste samples, both with and without the paint layer, tested using this procedure. The data were compared with the limit values established by the European criteria 2003/33/EC.

Table 2 Collection days and corresponding liquid-to-solid (L/S) ratios

Days	L/S (L/kg)	Days	L/S (L/kg)
7	0.24	56	1.96
14	0.49	70	2.45
21	0.74	84	2.94
28	0.98	98	3.43
35	1.23	112	3.92
42	1.47	140	4.90
49	1.72	168	5.88

According to the European regulatory criteria, all tested materials were classified as non-hazardous waste due to cadmium and lead concentrations exceeding the limits established for inert waste. Studies conducted in Europe have frequently reported chromium and sulfate levels above the thresholds for inert waste (Barbudo et al. 2012; López-Uceda et al. 2019; Del Rey et al. 2015; Diotti et al. 2021). In Brazil, research based on the leaching and solubilization tests adopted for waste classification has identified aluminum, barium, cadmium, and lead (Andrade et al. 2025), as well as cadmium, iron, and chromium (Cordoba 2014), at concentrations exceeding the maximum limits for inert waste. Although further studies are needed, cadmium stands out as a pollutant of concern leached from CDW generated in Brazil.

The presence of the paint layer in the CDW appears to have contributed to the higher concentrations of sulfate, sodium, and potassium in the leachates. These elements may originate from sodium polymaleate, used as a dispersant surfactant for inorganic fillers and pigments, sodium nitrite, used as a corrosion inhibitor, sodium or potassium dichromate, used to obtain zinc chromates as pigments, sodium silico-aluminate, used as a filler, barium sulfate, among others (Muehlethaler and Massonnet 2023).

Column percolation test

Physicochemical parameters

The collected leachate samples were analyzed for conventional water quality parameters. The leachate from the columns filled with CDW exhibited a slightly alkaline pH, while the unfilled columns showed a pH close to neutrality (Fig. 3a). The alkaline nature of the materials present in construction and demolition waste tends to increase the pH of the leachate. The pH values of the columns with CDW ranged from 6.81 to 10.14, values close to those reported by Gálvin et al. (2014) (7.26–11.55) and Diotti et al. (2021) (6.90–12.00) for mixed recycled aggregates.

The saturation regime had a significant influence on leachate pH. Saturated columns showed a more alkaline pH, with leachate from the column containing CDW with paint remaining around pH 9 throughout the experiment, while the pH of the column with CDW without paint exceeded 10. On the other hand, columns under the unsaturated regime initially presented a pH close to 7, which later increased to values above 8 (Fig. 3a). Townsend et al. (1999) also identified the influence of the regime on leachate pH, observing a stable pH around 11 in

Table 3 Leached concentrations (mg/kg) obtained with the European standard UNE-EN 12457-3

Parameters	Paint-free CDW		CDW with paint	
	L/S 2	L/S 10	L/S 2	L/S 10
EC(μS/cm)	1236.9 ± 46.96	193.5 ± 25.37	1716.5 ± 124	265.17 ± 13.22
pH	6.613 ± 0.289	8.953 ± 0.117	7.640 ± 0.272	9.437 ± 0.068
T(°C)	19.97 ± 0.058	21.37 ± 0.115	20.1 ± 0.100	21.01 ± 0.116
Al	< 0.01	< 0.01	< 0.01	< 0.01
Ba	< 0.005	< 0.005	< 0.005	< 0.005
Cd	0.016 ± 0.008	**0.217 ± 0.256**	0.026 ± 0.011	**0.247 ± 0.059**
Co	< 0.005	< 0.005	< 0.005	< 0.005
Cu	< 0.003	< 0.003	< 0.003	< 0.003
Cr	< 0.005	0.39 ± 0.180	< 0.005	0.134 ± 0.116
Fe	0.064 ± 0.020	0.967 ± 0.169	0.077 ± 0.019	0.703 ± 0.499
K	41.067 ± 1.921	70.667 ± 7.572	68.333 ± 10.263	81.333 ± 3.055
Mn	< 0.003	0.0177 ± 0.028	0.006 ± 0.008	< 0.003
Ni	< 0.008	< 0.008	< 0.008	< 0.008
Na	30.73 ± 1.716	38.0 ± 6.082	54.333 ± 9.504	48.0 ± 3.00
Pb	< 0.01	**1.3667 ± 0.321**	< 0.01	**0.535 ± 0.548**
Zn	0.051 ± 0.0166	0.337 ± 0.196	0.075 ± 0.015	0.583 ± 0.125
Sulfate	278.333 ± 25.66	290 ± 34.64	353.333 ± 50.33	350 ± 34.641

Values shown in bold exceeded the inert limit value.

saturated columns. In contrast, the pH in unsaturated columns dropped to approximately 7. Townsend et al. (1999) attributed this pH reduction in the unsaturated columns to the production of organic acids resulting from microbial activity.

Electrical conductivity (EC) and hardness exhibited a sharp decrease at the beginning of the experiment, followed by a stabilization trend from day 60 onwards (Fig. 3b, c). The high initial values are probably attributed to the presence of salts, such as calcium carbonate present in cement, mortars and paints. However, the maximum value found for hardness was 198 mg $CaCO_3$/L for the sample with paint under the unsaturated regime, which is below the maximum limit allowed for drinking water in Brazil, of 300 mg $CaCO_3$/L (Brazil 2021).

The leachate of CDW samples with paint (columns UP and SP) exhibited higher values of apparent color, turbidity, and total dissolved solids (Fig. 3d–f) compared to columns containing CDW without paint (columns UF and SF), considering the same operating regime. The apparent color and total dissolved solids values exceeded the maximum allowed limit for drinking water in Brazil (2021), which is 15 uH and 500 mg/L, respectively, in all columns containing CDW. The highest values were recorded in the initial weeks, followed by a gradual reduction and stabilization.

Turbidity values fluctuated throughout the experiment. This is probably due to variations in the turbidity of the leaching solution and interference from the experimental apparatus, as the turbidity values in column UC were generally higher than those in column SC. This underscores the importance of including a control column, an aspect often neglected in studies utilizing percolation columns. The control columns also generally presented higher turbidity values than columns with paint-free CDW, indicating a possible capacity of paint-free recycled aggregates to retain suspended solids.

Kuoppamäki et al. (2021) observed that a biofilter composed of recycled concrete aggregate achieved a total suspended solids removal efficiency of over 97% from roadside stormwater. Verma et al. (2023) evaluated filters composed of various proportions of natural and recycled aggregates and observed an increase in turbidity removal efficiency from raw water as the proportion of recycled aggregates increased. In the case of a filter composed exclusively of recycled aggregate, a 98% turbidity removal was achieved, along with a 33.40% removal of total solids, while the concentration of total dissolved solids increased by 146%.

According to Townsend et al. (1999), the main sources of dissolved solids in CDW leachates are calcium and sulfate. Sulfate stands out as one of the most critical compounds, as it is often present in CDW leachates at concentrations that exceed the limits established for inert waste by the European Union Landfill Directive, of 1500 mg SO_4^{2-}/L (Barbudo et al. 2012; Gálvin et al. 2014; Vegas et al.2015; Saca et al.2017; López-Uceda et al.2019; Agrela et al.2021). The primary origin of sulfate in CDW includes gypsum, ceramic particles, and mortar (Del Rey et al. 2015).

Sulfate levels in the control columns (UC and SC) remained close to zero throughout the experiment, demonstrating that the leaching solution was not a significant source of this compound (Fig. 4a). On the other hand, leachate from all CDW columns

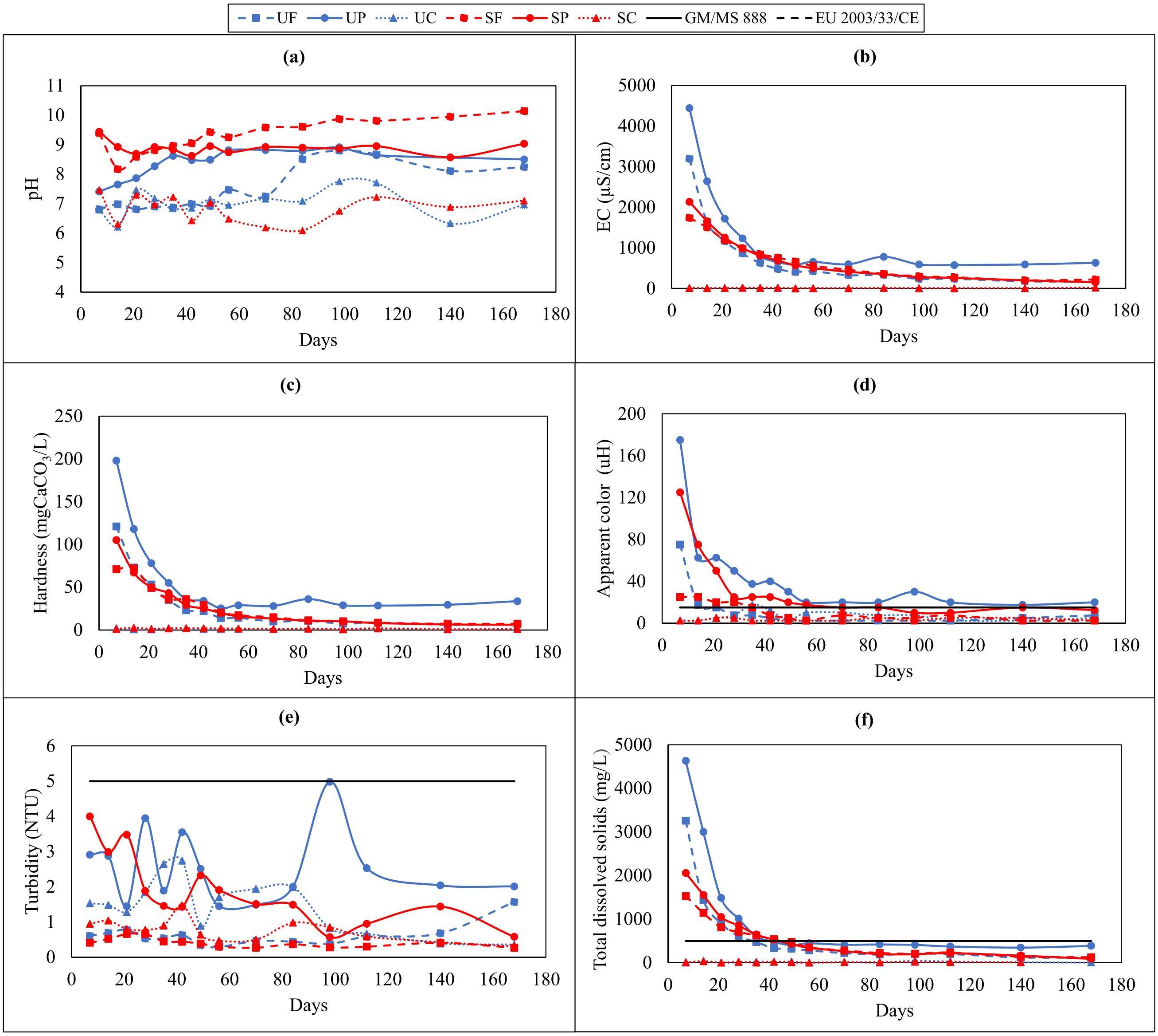

Fig. 3 Temporal evolution of the physicochemical parameters of leachates from the percolation columns. Columns in saturated regime and unsaturated regime, filled with material containing paint, paint free and control columns

exceeded 250 mg SO_4^{2-}/L during the first 35 days, exceeding the maximum allowed limit for drinking water in Brazil (Brazil 2021) and indicating the potential for groundwater contamination. According to Del-Rey et al. (2015), the main mechanisms governing sulfate release are solubility control in the initial stages and depletion in the final stages.

Gypsum, ceramic particles, and mortar present in CDW are the primary sources of sulfate in leachate. However, the presence of paint appears to have played a significant role in the leachate sulfate levels in the first month. In the paint industry, barium sulfate is frequently used due to its high whiteness, low oil absorption, and great covering power (Li et al. 2023). Older constructions may have been painted with coatings that used basic lead sulfate as a white pigment (Muehlethaler and Massonnet 2023). Although barium and lead sulfates have low solubility, their presence in house paints may have contributed to the higher sulfate values found in the leachates from columns UP and SP in the first month (Fig. 4a).

For chloride (Fig. 4b), the leachate of CDW did not exceed the limits established by the European Union Landfill Directive (2003/33/CE), which is 460 mg/L, nor GM/MS 888/2021 (Brazil 2021), which is 250 mg/L. Additionally, the chloride concentration in the leachate decreased significantly during the first month, especially in columns with an unsaturated regime. Fluoride concentrations (Fig. 4c) exceeded the maximum allowed limit for drinking water in Brazil (1.5 mg/L, according to GM/

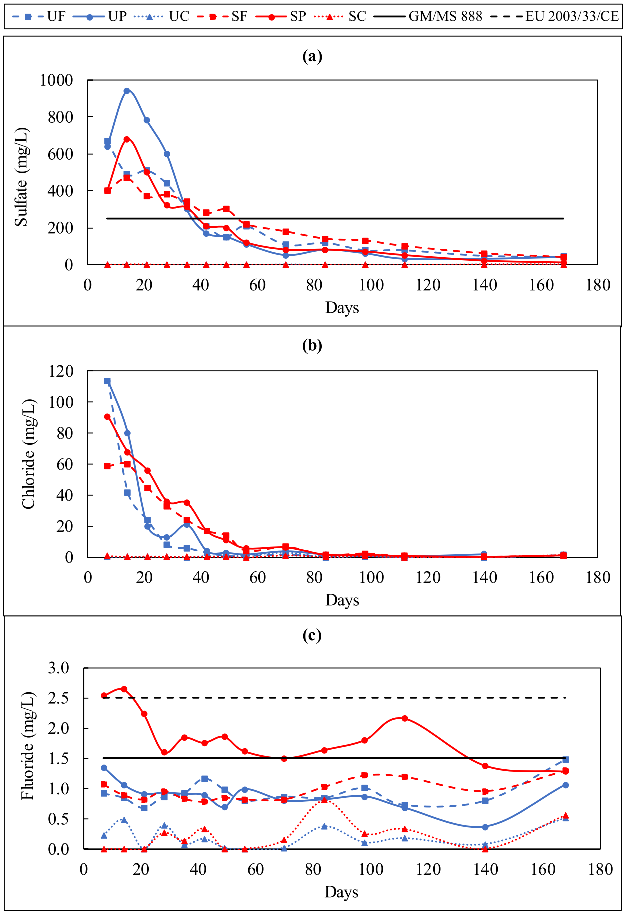

Fig. 4 Concentration of sulfate, chloride, and fluoride anions in leachates from the percolation columns. Columns in saturated regime and unsaturated regime (U, in blue), filled with material containing paint, paint free and control columns

MS 888/2021) and the limit for inert waste, according to the European Union Landfill Directive (2003/33/CE) (2.5 mg/L for L/S = 0.1) only in CDW leachate with paint and in the saturated regime (Column SP).

Metal leaching

Figure 5 presents the concentrations of metals in the collected leachates. It is important to note that the elements barium, cobalt, and copper, although analyzed, are not shown as their values consistently fell below the method's detection limit. Similarly, manganese and nickel are not presented in Fig. 5, as their concentrations remained well below the regulatory limits.

Cadmium and lead were the only elements that exceeded the values for inert waste, according to the European Union Landfill Directive (2003/33/EC). However, cadmium may have originated from the experimental apparatus, as the SC control column showed high cadmium values, especially during the first month.

In the first two samplings (L/S equal to 0.24 and 0.49), it was observed that leachates from CDW with paint (Columns UP and SP) showed higher lead concentrations than the columns without paint (Fig. 5e). However, in subsequent collections, the presence of paint did not exert a considerable influence. Roussat et al. (2008), conducting column percolation tests (CEN/TS 14 405/2004) on hazardous construction and demolition waste, including lead-based paints, reported a lead concentration of 0.031 mg/L in the leachate, which is lower than the maximum value of 0.19 mg/L observed in this study. The low concentration of lead in the leachate from CDW, despite the presence of paints with high lead concentrations, may be attributed to the effect of concrete and other materials that increase the pH of the leachate to a range that reduces the solubility of this metal (Wadanambi et al.2008). Additionally, the relatively small proportion of paints compared to the total mass of the waste contributes to the fact that lead-based paints do not render CDW hazardous (EPA 1993).

Although the columns UP and SP had a considerable proportion of paint relative to the total mass of the waste, as only samples with adhered paint were selected, the presence of paint did not significantly influence the concentration of metals in the leachate, except for potassium and sodium (Fig. 5f, g), as also observed in the compliance leaching test.

Regarding the Brazilian potability standard, it was found that the concentrations of the elements Al, Cd, Cr, Fe, and Pb exceeded the maximum allowable values. The presence of Cr was detected only in the first month, and the highest concentrations were observed in samples without paint and under the unsaturated regime (Column UF). This pattern differs from other studies that highlight chromium as one of the most critical elements, often found in leachates at concentrations exceeding the limits established for inert waste (Barbudo et al. 2012; Gálvin et al. 2014; Del -Rey et al. 2015).

Although the CDW leachates presented concentrations of Al and Cd above the evaluated normative limits in some samples, their presence was also verified in the control columns, indicating that, in those samples, contamination may be related to the experimental setup or the leaching solution.

Iron (Fig. 5d) and zinc (Fig. 5h), in general, showed higher concentrations in the control columns (Columns UC and SC) than in the CDW columns, indicating elution from the test apparatus. As this elution is expected to occur in all of the columns, the lower Fe and Zn concentrations observed in the columns filled with CDW suggests the occurrence of removal mechanisms associated with CDW. Córdoba (2014) also observed higher concentrations of zinc in columns without CDW, attributing the results to the sorption or precipitation mechanisms of zinc

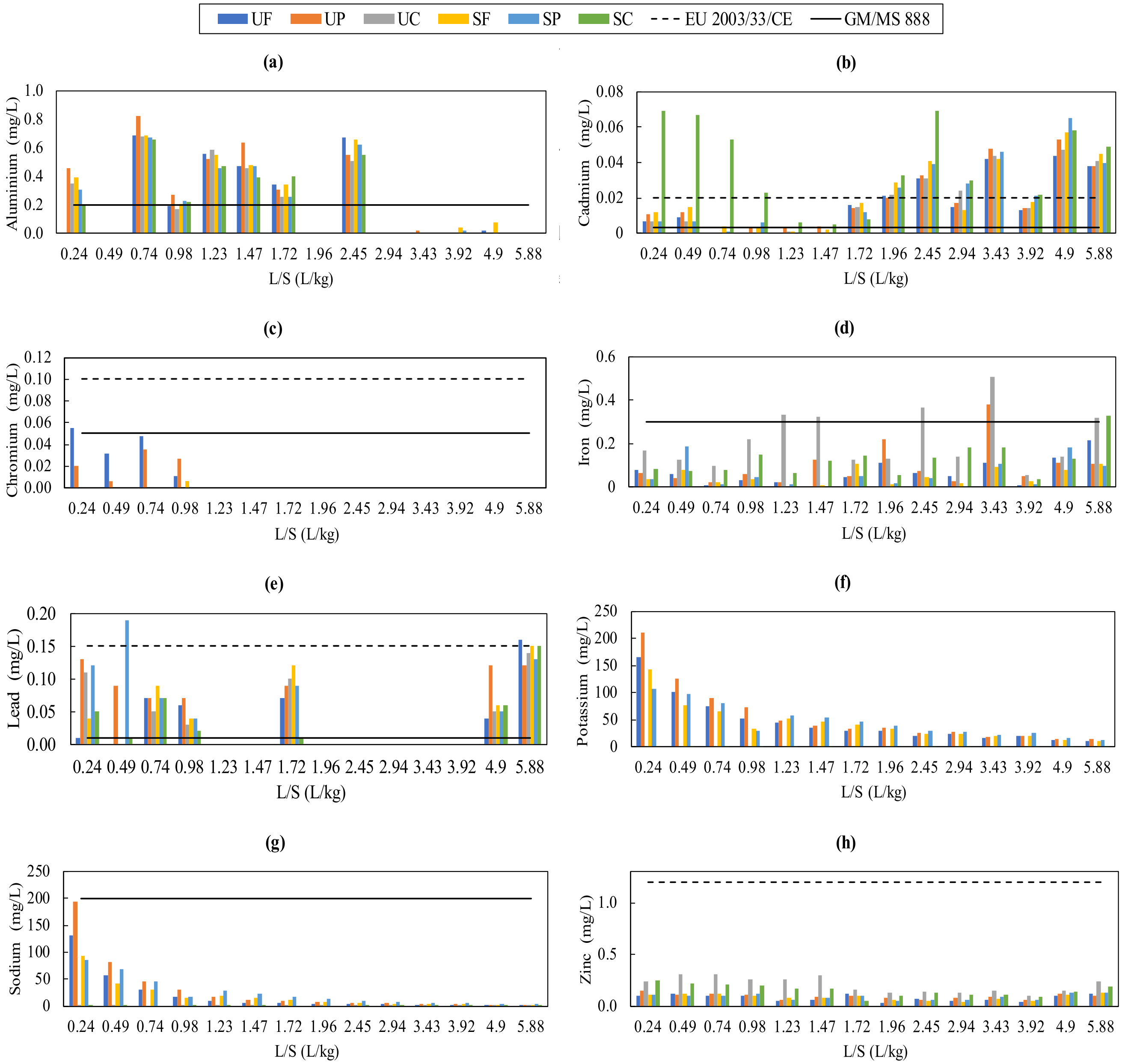

Fig. 5 Metal concentration in leachates and the limit value of inert waste according to the European Union landfill Directive (2003/33/EC, dashed horizontal line) for the percolation test (L/S = 0.1) and the maximum allowed value for drinking water in Brazil (GM/MS 888, 2021, continuous horizontal line)

contained in the water inside the columns. According to Coleman et al. (2005), the fine fractions of concrete waste can be effective sorbents of aqueous metal species due to their exchangeable ion phases and high pH. The authors evaluated the removal of Cu^{2+}, Pb^{2+}, and Zn^{2+} by the fine fraction of concrete waste and observed that the removal of Cu^{2+} and Zn^{2+} was mainly due to surface precipitation reactions, while the main removal mechanism of Pb^{2+} from the liquid phase was diffusion into the cement matrix. Vallini et al. (2023) observed that demolition waste is an efficient adsorbent of Cu^{2+}, Ni^{2+}, and Zn^{2+} from industrial effluents. Pallewatta et al. (2023) conducted a literature review and found that the main mechanism of removal of contaminants by CDW is chemisorption and that concrete-based adsorbents are the most efficient among the typical constituents of CDW. These results suggest that, for a comprehensive analysis of the contamination potential of CDW by metal species, it is necessary to consider the fraction retained in the solid phase, which could potentially be mobilized if the CDW is exposed to stronger eluents.

Supplementary investigation

A pink coloration was identified in column SP in the final weeks of the experiment (Fig. SM 2), possibly resulting from the prolonged exposure of a paint film to the leachate in a saturated environment, causing the degradation of one of the paints. However, such coloration was not observed in the routine monitoring samples of this column. Before the end of the experiment, a specific sampling procedure was performed, allowing the characterization of this colored fraction of the leachate (Table 4).

When comparing the results presented in Table 3 with the result of the last collection of leachate from column SP, a significant discrepancy is observed, particularly in the terms of pH, apparent color, and turbidity (Fig. 3a, d, e) and concentrations of aluminum and iron (Fig. 5a, d). The need for more comprehensive studies, with an extended duration, becomes evident, aiming to assess the dissolution of paint chips and the consequent release of contaminants contained within them.

Table 4 Concentration in the eluate of pink color extracted from the column operated under saturated conditions, filled with waste containing paint (Column SP)

Parameters	
pH	8.07
EC (µS/cm)	187.76
Turbidity (UNT)	124
Apparent color (uH)	120
Total dissolved solids (mg/L)	117
Hardness (mg $CaCO_3$/L)	8.4
Aluminum (mg/L)	3.800
Barium (mg/L)	nd
Cadmium (mg/L)	0.044
Total chromium (mg/L)	nd
Cobalt (mg/L)	nd
Copper (mg/L)	0.146
Total iron (mg/L)	2.611
Potassium (mg/L)	13.700
Manganese (mg/L)	0.074
Sodium (mg/L)	3.30
Nickel (mg/L)	nd
Lead (mg/L)	nd
Zinc (mg/L)	0.465
Chloride (mg/L)	0.800
Fluoride (mg/L)	1.080
Sulfate (mg/L)	10

nd: value below the equipment detection limit.

Limitations and recommendations

Construction and demolition waste (CDW) is frequently disposed of in irregular sites or in landfills lacking adequate lining systems (Seror and Portnov 2018; Thives et al. 2022; Defra, 2025). The leachates generated from this waste can pose environmental and human health risks, particularly due to the presence of hazardous substances in their composition.

Paints, widely used in the construction sector, are a significant source of heavy metals, primarily employed as pigments, as well as volatile organic compounds (Muehlethaler and Massonnet 2023). In this study, the influence of paint presence on the contamination potential of CDW leachates was assessed. However, organic compounds, some heavy metals (e.g. Hg, As) and microplastics were not investigated, despite their potential contribution to environmental contamination. Therefore, future studies are encouraged to incorporate advanced analytical techniques capable of improving the detection of trace contaminants and emerging pollutants in CDW leachates, as well as to assess the release dynamics of these pollutants over extended periods.

The findings of this work provide important insights into the contamination potential associated with CDW and reinforce the need for appropriate waste management practices. Most CDW can be reused as recycled aggregates, and such reuse should be encouraged; however, reuse strategies must be aligned with national drinking water protection policies to mitigate risks of groundwater contamination. Additionally, capacity-building and targeted training for construction-sector workers are essential to enhance awareness and promote proper waste segregation practices, prevent contamination of recyclable materials, and encourage construction practices that minimize waste generation and the use of hazardous materials.

Studies characterizing groundwater in areas surrounding CDW landfills and sites of informal disposal are also needed to deepen the understanding of associated risks and to support the development of regulations aimed at minimizing these impacts. Such measures may include, for instance, the requirement of impermeabilization systems in CDW landfills when technically warranted.

Finally, it is recommended that the assessment of contaminant presence in CDW be based on a standardized and robust protocol comprising (i) an initial screening to verify the presence of hazardous or potentially contaminating materials; (ii) chemical characterization of CDW and recycled aggregates; (iii) leaching tests performed under pH-controlled and scenario-relevant conditions to capture contaminant mobility; and (iv) comparison of the results with regulatory thresholds for inert waste classification. In addition, the protocol should be complemented by a tiered risk assessment framework, in which leaching results are integrated with contaminant toxicity and potential exposure pathways (Fig. 6), allowing the differentiation between

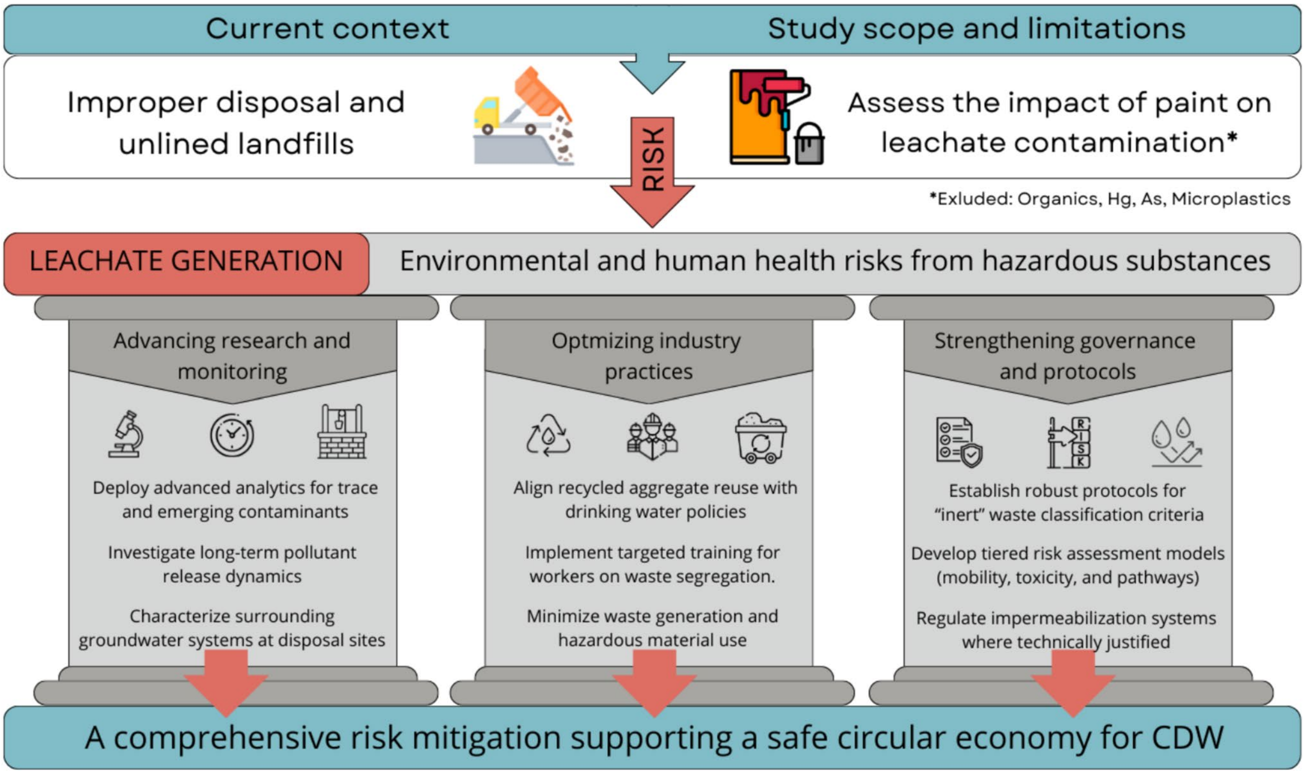

Fig. 6 Schematic overview of the scope of the present study, its limitations, and recommendations for future research

materials suitable for disposal in unlined inert landfills and those requiring additional management measures or restricted use as recycled aggregates. Such an approach would strengthen decision-making by linking standardized testing outcomes to environmental risk-based criteria rather than solely to concentration limits.

Conclusion

The leaching behavior of the construction and demolition waste (CDW) indicated that cadmium and lead were the critical elements according to the European Council criteria, leading to the classification of both with paint and paint-free samples as non-hazardous waste.

The percolation column tests with construction and demolition waste revealed that these wastes could potentially contaminate groundwater. The CDW leachate, with and without adhered paint, exhibited sulfate and total dissolved solids concentrations that exceeded the maximum allowed limits for drinking water in Brazil (GM/MS 888, 2021). The presence of paint on the CDW predominantly influenced the apparent color, turbidity, and concentrations of Na^+ and K^+ in the leachate. Furthermore, in saturated conditions, the presence of paint also influenced the fluoride concentration, surpassing the limits for inert waste, as per the European Union Landfill Directive (2003/33/CE), and the limit for drinking water in Brazil. Although lead is a contaminant historically incorporated into paints, columns containing CDW with paint leached higher lead concentrations compared to paint-free columns only in the initial weeks, suggesting that more studies on lead leaching mechanisms and potential environmental risks are warranted. In general, the paint presence did not significantly influence the release of heavy metals in the leachate. However, further studies are recommended on possible degradation of paint chips when subjected to prolonged saturated conditions and the release of contaminants contained therein.

The results of this study support findings from previous research, indicating that construction and demolition waste (CDW) can pose environmental risks if not properly managed. The leaching behavior of recycled materials from construction and demolition activities must be assessed and deemed acceptable before their use in civil infrastructure.

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Data availability The data can be availed by requesting to the corresponding author.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval Not applicable.

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