

INVESTIGATION OF AREAS CONTAMINATED BY SANITARY LANDFILLS IN BRAZIL: A BIBLIOGRAPHIC REVIEW

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Abstract: Sanitary landfills are considered a solution to the problem of increasing solid waste generation. However, these places can become sources of active contamination through leachate leakage. Investigating these locations is necessary to identify contaminated areas and carry out remediation processes. Therefore, the objective of this study was to identify areas contaminated by the disposal of solid waste in sanitary landfills in Brazil, as well as the analyzed environmental matrices, the investigation techniques used, and the parameters evaluated. The selection of articles was based on a systematic review in peer-reviewed scientific article databases (Scopus, ScienceDirect, Springer, and Scielo). Eleven studies were selected, from which the use of indirect (4) and direct (7) methods were verified; analyses were performed on soil (2), surface water (3), and groundwater (4) matrices. The main parameters evaluated were physicochemical and metal concentration. Despite the confirmation of contamination, it was found that there is no protocol used for the investigation of areas contaminated by the disposal of solid waste in these studies. The method of collection and depth of the samples may imply significant differences in the results of the physical-chemical analyses. Therefore, geophysical methods are recommended to assist in sampling planning, following sampling standards and protocols, and the inclusion of new parameters to be analyzed.

Keywords: Pollution; Leachate; Sanitary landfill; Direct methods; Indirect methods.

INTRODUCTION

Concerns and discussions about solid waste have grown in recent years, especially regarding the increase in generation and final disposal. In 2019, more than 79 million tons of urban solid waste were generated, with a per capita average of 379.2 kg/inhabitant. Of this amount, more than 43 million tons were

destined to landfills, representing an increase of 2.7% compared to 2010 data (BRAZILIAN ASSOCIATION OF PUBLIC CLEANING AND SPECIAL WASTE COMPANIES - ABRELPE, 2020). In addition, the amount of waste sent to inappropriate units (dumps and controlled landfills) increased from 25 million tons per year to more than 29 million tons per year (ABRELPE, 2020).

The disposal of waste in inappropriate units is not only an environmental but also a public health issue. Inadequate final disposal has the potential to intensify soil, air, groundwater, and surface water pollution. In addition, it is favorable to the emergence of vectors, which acts as transmitters of human diseases, such as leptospirosis (COSTA, 2004).

Minimizing the impact of contamination from solid waste is a concern that led to the concept of sanitary landfills. Landfills are an essential part of an integrated waste management strategy, mainly because they provide the only terrestrial sink for hazardous substances that would otherwise be dispersed into the environment (TOUZE-FOLTZ; XIE; STOLTZ, 2021). Therefore, the base and sides of the embankment must consist of an impermeable layer that satisfies hydraulic conductivity and thickness parameters, which have a combined effect on protecting soil, groundwater, and surface water (TOUZE-FOLTZ; XIE; STOLTZ, 2021).

Despite being considered an adequate method for the destination and treatment of urban solid waste (USW), sanitary landfills can also be potential sources of contamination. The lack of planning in the structuring of a landfill, a failure in the drainage system, or the sealing barrier can cause the leakage of leachate, a substance resulting from a complex mixture of toxic metals, water, salts, and organic matter (TOUZE-FOLTZ; XIE; STOLTZ, 2021; ZENG *et al.*, 2021). The leachate permeates through the bottom layers

and can contaminate the soil and groundwater. The evolution of contamination to the aquifer zone depends on local conditions such as the hydraulic conductivity, the thickness of the aeration zone, and the concentration of pollutants present in the leachate (CHOFQI *et al.*, 2004; ZENG *et al.*, 2021).

Contamination can remain active even after the activities of the landfill have ceased since the waste decomposition process is time-consuming, so leachate generation remains active even if the landfill operation has finished (KIM; LEE, 2009; NAI *et al.*, 2021).

Han *et al.* (2016) identified 96 different pollutants in groundwater in areas close to solid waste landfills. These pollutants include inorganic salts, such as sulfate (SO_4^{2-}) and nitrate; metal ions such as aluminum (Al) and calcium (Ca); potentially toxic metals such as zinc (Zn) and mercury (Hg); bacteriological pollutants such as total coliforms and bacterial counts; and xenobiotic organic compounds such as benzene and trichloroethane. Zeng *et al.* (2021) found high levels of nitrate, nitrite, and metals, including arsenic (As) and hexavalent chromium (Cr) in groundwater near six landfill sites in the Qinghai-Tibetan Plateau.

Understanding the biogeochemical processes is essential to proposing intervention measures for the management of contaminated areas (ALVES; BERTOLO, 2012). Thus, there is a need to use efficient methods and techniques to identify: the potential risks in areas subject to contamination, the contaminants, and their respective concentrations in contaminated sites, and to delimit the contamination plume in areas with confirmed contamination.

In this context, there are different techniques for investigating contaminated areas, which can be classified as geophysical (indirect methods) or geotechnical (direct methods) (GIACHETI; ELIS; RIYIS, 2015).

The investigation of an area depends on the knowledge of the spatial distribution of geological materials and their properties. Thus, geophysical tests are recommended to be carried out in advance to estimate the distribution of geological materials in the site, and to determine the location of the direct studies (GIACHETI; ELIS; RIYIS, 2015). Soil sampling with auger, direct-push, and Standard Penetration Test (SPT) are commonly used direct methods for contaminated or potentially contaminated area investigation.

Monitoring groundwater contamination is mandatory for sanitary landfill and aims to ensure that environmental protection systems are working (BRAZILIAN TECHNICAL STANDARDS ASSOCIATION - ABNT NBR 8419:1992; ABNT NBR 15849:2010). In this context, the installation of monitoring wells is recognized worldwide and highly recommended by environmental agencies, as it is a resource for direct access to the existing aquifer in the study area and through its results, it is possible to identify physical-chemical patterns of the aquifer (MONDELLI; GIACHETI; HAMADA, 2016). In Brazil, all environmental agencies require that groundwater be evaluated using the installation of monitoring wells and subsequent sampling (GIACHETI; ELIS; RIYIS, 2015).

Although sanitary landfill is regulated by legislation and technical standards aimed at environmental protection, these systems are subject to failures and the generation of contamination. In this context, monitoring is essential to evaluate environmental quality standards. If contamination is encountered, it is necessary to manage the area, as recommended by the Board Decision N° 038/2017/C (SAO PAULO STATE ENVIRONMENTAL COMPANY - CETESB, 2017). Therefore, the objective of this study

was to survey studies carried out in sanitary landfills in Brazil, in which contamination was verified, to identify the investigation methods (indirect or direct) used, the environmental matrices investigated, and the parameters evaluated.

MATERIALS AND METHODS

The databases used for the search were Scopus, ScienceDirect, Springer, and Scielo. The choice of the Scopus, ScienceDirect and Springer databases is because they are important databases of abstracts and citations of the literature with peer review. Scielo was selected since it is the largest database of periodicals published in Portuguese.

In all databases, a combination of the following search terms was used: “Brazil”, “sanitary landfills” or “solid waste landfill”, and “contamination”. Searches were carried out in English and Portuguese. With the use of the search terms, several publications were obtained. These publications were screened by reading the titles and abstracts.

Scientific articles that analyzed contamination in landfills in Brazil in the last 5 years (2017-2022) were selected. The selected articles were read completely to verify if they met the inclusion criteria of the research (analysis of contamination in areas surrounding sanitary landfills in Brazil using direct and/or indirect methods).

From the selected studies, information regarding the profile of the studies (title, first author, year of publication, geographic location of the study area, characteristics of the studied area - area and age of the landfill), research methodology used, environmental matrix analyzed (soil, groundwater, or surface water) and parameters evaluated were extracted. The data extracted from the articles were analyzed descriptively.

RESULTS AND DISCUSSION

PROFILE OF THE EVALUATED STUDIES

Using the defined criteria, 11 publications related to 9 different sanitary landfills in Brazil were selected. Studies involving analyses in dumps or controlled landfills were disregarded. The studies were published between 2017 and 2021. In Table 1 below, information about the selected studies is presented.

The location of landfills represents about 1.4% of the 621 active landfills in 2019 according to the Diagnosis of Urban Solid Waste Management (BRAZILIAN SANITATION INFORMATION SYSTEM - SNIS, 2020). As for the representativeness of the geographic location of the solid waste disposal units, it is observed that the studies are concentrated in the South ($n = 6$), Southeast ($n = 4$), and Northeast ($n = 1$). It was expected to find a greater number of studies and a better distribution between the regions of the country. In addition, it was expected that the Southeast region would present greater numbers of studies since it is the region that generates the most USW.

According to the Diagnosis of Urban Solid Waste Management, sanitary landfills in the Southeast region received more than 23 million tons of waste, equivalent to 54.4%. The Northeast region occupies the second position in the ranking of macro-regions and sends about 8.6 million tons of waste mass to sanitary landfills, or 19.9% of the total. Following the South region, with an amount of 5.8 million tons, or 13.5% of the total. Next, there is the Midwest region, with 3.8% million tons (8.7%), and finally, the North region, with approximately 1.5 million tons (3.5%) (SNIS, 2020).

The numbers provided by the SNIS are similar to those exposed by Abelpre (2020). According to the Panorama of Solid Waste in Brazil, the Southeast region sends the most

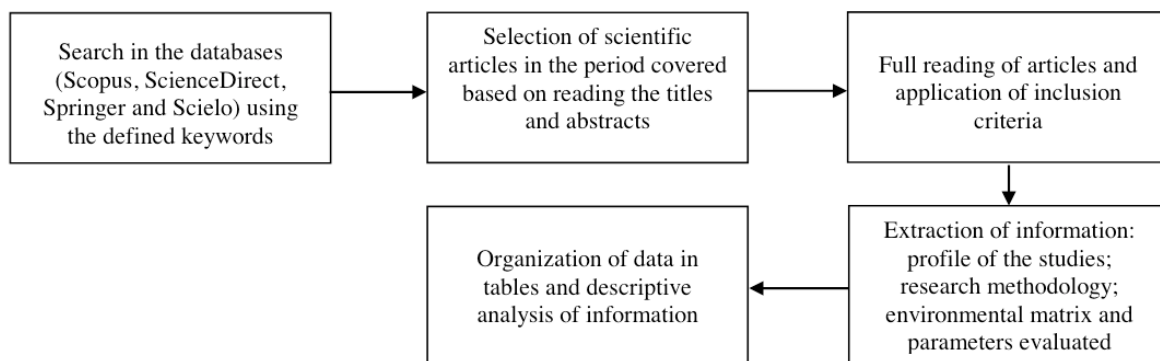


Figure 1. Flowchart of the activities performed

Study	Authors	Year of Publication	Location of the study area	Area (m ²)	Landfill age (years)
Impacts of the urban solid waste disposal on the quality of surface water in three municipalities of Minas Gerais – Brazil	Marques <i>et al.</i>	2021	Campo Belo - MG	105300	NI
Hydrogeophysical characterization of the Marizal–São Sebastião aquifer system in the surroundings of the Limpec sanitary landfill, Camaçari, Bahia, Brazil	Porciúncula and Leal	2021	Camaçari - BA	NI	NI
Analysis of leachate generation dynamics in a closed municipal solid waste landfill by means of geophysical data (DC resistivity and self-potential methods)	Helene and Moreira	2020	Vila Nova do Sul - RS	44650	13
Analysis of chemical features of a soil used as landfill: using the X-Ray Fluorescence (XRF) technique	de Borba <i>et al.</i>	2020	Seberi - RS	NI	NI
Temporal behavior analysis of leachate contamination in a tropical landfill	Faria and Mondelli	2020	Bauru - SP	268985	29
Analysis of heavy metals and aromatics compounds in soil layers of a sanitary landfill	Forti <i>et al.</i>	2019	Rubiácea - SP	24200	12
Integration of geophysical methods of resistivity, induced polarization and electromagnetic landfill Guaratuba-PR	Canata <i>et al.</i>	2018	Guaratuba - PR	NI	NI
Analysis of leaks from geomembrane in a sanitary landfill through models of electrical resistivity tomography in South Brazil	Moreira <i>et al.</i>	2018	Vila Nova do Sul - RS	44650	NI
Environmental monitoring of a landfill area through the application of carbon stable isotopes, chemical parameters and multivariate analysis	Engelmann <i>et al.</i>	2018	Osório - RS	NI	NI
Environmental monitoring of water resources around a municipal landfill of the Rio Grande do Sul state, Brazil	Engelmann <i>et al.</i>	2017	Osório - RS	NI	NI
Interaction between municipal solid waste leachate and Bauru aquifer system: a study case in Brazil	Faria and Mondelli	2017	Bauru - SP	268985	29

NI – Not informed

Table 1. Description of studies included in the literature review

considerable amount of USW to landfills (over 28 million tons); followed by the Northeast region (5.6 million tons); the South region (5.5 million tons); the Midwest region (2.2 million tons), and finally the North region (1.6 million tons) (ABELPRE, 2020). However, inappropriate processing units such as dumps are still the majority in the Northeast region, which receives about 4.2 million tons of waste, or 57.7% of the total.

The concentration of studies verified between the Southeast and South regions in the present study was also noted in the study by Morita *et al.* (2021). In addition, the authors analyzed the scientific contributions of the studies and concluded that the contributions are limited since most were published in Portuguese or low-impact journals. In the present study, it was found that 10 studies were published in English and 1 in Portuguese.

Of the studies identified in this literature review, only six studies surveyed the total area of the landfill. According to Mondelli, Giacheti, and Hamada (2016), the variables extension of the landfill and the amount of leachate generated are important to identify flaws in the waterproofing system, and possibly in the drainage system.

A second important topic that was also little considered in the selected studies is the landfill operation period. Through this information, it is possible to understand the predominant metabolic phase inside the landfill at that moment and thus verify the level of influence of this factor on the concentrations found. Of the selected studies, only four studies raised information about the landfill operation period.

INVESTIGATION METHODS AND INVESTIGATED ENVIRONMENTAL MATRICES

The investigations carried out were divided into two groups: indirect methods,

which include geophysical studies such as electroresistivity, induced polarization, and electromagnetic; and direct methods, where groundwater, surface water, or soil sampling are included. Of the publications analyzed, 63.6% (n = 7) involved direct methods in their investigations, and 36.7% (n = 4) involved geophysical methods.

The geophysical methods used in the investigations were electroresistivity (n = 4) and electromagnetic (n = 1). Despite electroresistivity methods being more applied to contaminated areas, Canata *et al.* (2018) suggest that the integration of electroresistivity and electromagnetic methods enabled a better understanding of the contaminated area. However, these studies did not validate the geophysical results with the direct methods.

Despite the high investment required, geophysical studies are assertive, as they detect anomalies in the subsoil, and reduce the need to obtain direct data. However, what is perceived is the carrying out of soil sampling and installation of monitoring wells without a preliminary investigation, not knowing the location of the contamination plume, which can lead to erroneous interpretations (MORITA *et al.*, 2021).

The environmental matrix most frequently evaluated in studies involving direct methods was groundwater (n = 4), followed by surface water (n = 3) and soil (n = 2). The environmental matrix evaluated in the geophysical studies is the subsurface, to identify the contamination plume. In studies involving groundwater analysis, all collections were performed using existing monitoring wells in the surroundings of the sanitary landfill, and two of these studies used secondary data for analysis. Information about the year and form of installation of the monitoring well is only available in one study. Groundwater collections were performed using a groundwater sampler (bailer).

In studies with surface water analysis,

samples were collected directly using polyethylene bottles ($n = 2$) and according to the specifications of Standard Methods for the Examination of Water and Wastewater (APHA, 1998) ($n = 1$). In the case of studies involving soil analysis, samples were collected in three 2-meter soil profiles ($n = 1$) and a 4-meter trench open with a backhoe ($n = 1$).

The choice of sampling methodology and collection depth can directly influence the results of chemical analyses. In terms of the sampling methodology, this information is well defined in technical standards and the literature. For soils, procedures for collecting, transporting, and preserving soil samples are described in the technical standards: ABNT NBR 15492:2007 – Borings in order to analysing environmental quality - Procedure, ABNT NBR 16435:2015 – Quality control in sampling of contaminated areas for research purposes - Procedure, and ABNT NBR 9603:2015 – Hand drilling auger - Procedure. For surface water, sampling procedures are described in the technical standards ABNT NBR 9897/1987 – Panning of liquid effluent sampling and receptor bodies - Procedure, ABNT NBR 9898/1987 – Preservation and sampling techniques of liquid affluents and receptor bodies - Procedure, and in the National Guide to the Collection and Preservation of Samples (BRAZILIAN WATER AGENCY - ANA, 2011). In the case of groundwater sampling, the sampling method is described in ABNT NBR: 15847/2010 – Groundwater sampling in monitoring wells – purging methods.

In the case of determining the location and depth of sampling points, the use of geophysical methods can help in choosing the location of the sampling spots to determine parameters of interest.

EVALUATED PARAMETERS

From the selected studies, the parameters

evaluated in direct investigation methods were verified. The description of the parameters can be seen in Table 2.

In studies involving the analysis of groundwater, it was verified the determination of the concentration of metals ($n = 4$), of physical-chemical parameters (pH, EC, DO, and Eh) ($n = 3$), organic carbon ($n = 3$), BOD and COD ($n = 2$), among others. The identification and characterization of leachate leaks are difficult because groundwater is complex, and there are hardly any signs in surface water (FARIA; MONDELLI, 2020). Thus, the determination of physical-chemical parameters, metals and semi-metals, ions, BOD, and COD can help to determine changes in quality standards. In addition, the behavior and characteristics of the leachate are related to several factors such as climate, landfill age, landfill construction project, waste disposal, and waste moisture, among others (FARIA; MONDELLI, 2020). Finally, hydrogeological parameters such as flow, hydraulic conductivity, and groundwater direction are important for understanding the dynamics of contaminants. Thus, such information is important to be included in studies of this type.

In surface water studies, the determination of the concentration of metals ($n = 2$) and physical-chemical parameters (pH, EC, and DO) ($n = 2$) was verified, among others. In addition, parameters related to surface water dynamics not raised in the analyzed studies, such as flow and reaeration rate, are important for understanding the dynamics of contaminants in lotic environments and may vary seasonally. Therefore, it is recommended to determine these parameters in different periods.

Finally, in studies involving soil analyses, the choice of parameters such as pH, CEC, the concentration of metals, and organic matter is noted. The determination of

Authors	Investigation method	Evaluated environmental matrix	Evaluated parameters
Marques <i>et al.</i> (2021)	Direct	Surface water	T, pH, EC, DO, BOD, COD, turbidity, dissolved solids, color, chloride, total solids, fixed solids, volatile solids, total suspended solids and fecal coliforms
Porciúncula and Leal (2020)	Indirect	-	-
Helene and Moreira (2020)	Indirect	-	-
de Borba <i>et al.</i> (2020)	Direct	Soil	pH, CEC, metals, organic matter
Faria and Mondelli (2020)	Direct	Groundwater	pH, EC, DO, BOD, COD, Eh, total organic carbon, metals and semi-metals, nitrogen compounds, sulfur compounds, total phosphate
Forti <i>et al.</i> (2019)	Direct	Soil	pH, CEC, metals, aromatic hydrocarbons, organic matter, macro and micronutrients
Canata <i>et al.</i> (2018)	Indirect	-	-
Moreira <i>et al.</i> (2018)	Indirect	-	-
Engelmann <i>et al.</i> (2018)	Direct	Surface and groundwater	Metals, ions, dissolved organic and inorganic carbon
Engelmann <i>et al.</i> (2017)	Direct	Surface and groundwater	T, pH, EC, DO, Eh, salinity, metals, ions
Faria and Mondelli (2017)	Direct	Groundwater	T, pH, EC, DO, BOD, COD, Eh, total organic carbon, metals and semi-metals, selenium, nitrogen compounds, sulfur compounds, cyanide, total phosphate

Where: T = temperature; pH = hydrogenionic potential, EC = electrical conductivity; DO = dissolved oxygen; BOD = biochemical oxygen demand; COD = chemical oxygen demand; CEC = cation exchange capacity, Eh = redox potential

Table 2. Description of the parameters evaluated in the studies included in the literary review

physicochemical parameters is important to determine the mobility of the metal in a given environment. Changes in pH, Eh, and organic matter content can influence the mobility of metals. In addition, tests that aim to determine the availability of the metal in the environment, such as sequential extraction (TESSIER; CAMPBELL; BISSON, 1979; RAURET, 1998) and bioavailability tests (UNITED STATES ENVIRONMENTAL PROTECTION AGENCY – USEPA, 2007), can be useful to assist in the interpretation of information. Waste characterization tests, such as solubility and leaching tests, both standardized by ABNT (ABNT 10.005:2004 and 10.006:2004), can help to characterize the contaminated environment. In addition, the application of indices such as the geoaccumulation index (MÜLLER, 1986) and potential ecological risk (HÅKANSON, 1979) can be useful to assess the contaminated area. To avoid risk, the concentrations of metals are limited by environmental organizations and health authorities based on ecotoxicology assays. A contamination assessment must be conducted in an integrative form, including geochemical, geotechnical, physicochemical and ecological parameters to fully understand the scenario. Thus, in cases of determination of the concentration of metals and other contaminants, it is recommended to include these tests and indices.

CONCLUSION

From the systematic review, it was possible to identify 11 studies that determined contamination of areas surrounding sanitary landfills in Brazil. In these studies, the predominant use of direct methods compared to geophysical methods was noted. The combination of direct and geophysical methods was not observed in any of the selected studies.

Of the selected studies, analyses were

conducted in groundwater (4), surface water (3), and soil (2). The choice of parameters to be evaluated in the matrices evaluated in the studies were divergent, especially in the soil matrix. For contamination analysis, additional parameters, such as chemical fractionation and the use of contamination indices (such as geoaccumulation index and potential ecological risk), can assist in data analysis.

Despite reaching the established objectives, the present review has limitations due to the small number of selected studies. In addition, the following gaps were identified in the studies analyzed in this review: lack of information on the sanitary landfills studied and on the monitoring wells used in the studies, absence of a conceptual model, and determination of the sampling location and method used in the studied area.

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