



Hazardous Waste Landfills: Best Practices and Challenges in the Face of a Circular Economy

Aterros de Resíduos Perigosos: Boas Práticas e Desafios Frente à Economia Circular

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ABSTRACT

The inadequate management of hazardous solid waste poses environmental and public health risks, demanding sustainable alternatives. This study aims to evaluate operational practices in Class 1 Landfills and analyze the potential of Landfill Mining as a circular economy strategy for the remediation and recovery of raw materials in disposal sites. The central case study is the Caieiras Landfill, in São Paulo (SP), Brazil. The methodology employed a bibliographic review, documentary analysis, and field inspections to assess the aspects of the landfill's design, construction, operation, and closure, verifying compliance with current regulations for Class 1 Landfills. The results confirm that Caieiras Landfill adopts management and engineering practices compatible with legislation. The analysis of the Landfill Mining process indicates the possibility of revenue generation, job creation, and reduction of environmental liability. However, the study highlights the need for in-depth evaluations on the economic viability and socio-environmental impacts of its application to hazardous waste. It is concluded that Landfill Mining represents an opportunity for more advanced management of hazardous waste,

requiring investment in research and development of technologies to optimize this valorization process.

Keywords: Hazardous waste, Landfill Mining, Class 1 Landfill, Solid Waste Management.

RESUMO

A gestão inadequada de resíduos sólidos perigosos impõe riscos ambientais e de saúde pública, demandando alternativas sustentáveis. Este estudo objetiva avaliar as práticas operacionais em Aterros Classe 1 e analisar o potencial da Mineração de Aterro como estratégia de economia circular para a remediação e a recuperação de matéria-prima em locais de disposição final. O caso de estudo central é o Aterro Caieiras, em São Paulo (SP), Brasil. A metodologia empregou revisão bibliográfica, análise documental e inspeções de campo para avaliar os aspectos de projeto, construção, operação e encerramento do aterro, verificando a conformidade com as regulamentações vigentes para Aterros Classe 1. Os resultados confirmam que o Aterro Caieiras-SP adota práticas de gestão e engenharia compatíveis com a legislação. A análise do processo de Mineração de Aterro indica a possibilidade de geração de receita, criação de postos de trabalho e redução do passivo ambiental. Contudo, o estudo ressalta a necessidade de avaliações aprofundadas sobre a viabilidade econômica e os impactos socioambientais da aplicação em resíduos perigosos. Conclui-se que a Mineração de Aterro representa uma oportunidade para uma gestão mais avançada de resíduos perigosos, requerendo-se o investimento em pesquisa e desenvolvimento de tecnologias para a otimização desse processo de valorização.

Palavras-chave: Resíduos perigosos, Landfill Mining, Aterro Classe 1, Gestão de Resíduos.

1. INTRODUCTION

Increasing industrial production, driven by rising demand and the rapid obsolescence of products, generates ever-larger volumes of waste. Among them, those classified as hazardous stand out, originating from various sectors such as metallurgy, chemicals, and petrochemicals, whose mismanagement represents a serious and continuous threat to human health and the environment (Le-Khac et al., 2024). Data from Eurostat (2023) reinforces the magnitude of the



problem by revealing that, in 2020, approximately 4.4% of the 95 million tons of waste produced in Europe was classified as hazardous, underlining the need for rigorous management.

The expansion of the chemical industry, characterized by the continuous emergence of new substances (estimated to be in the millions annually), presents critical risk management imperatives for occupational health and environmental integrity. This situation is exacerbated by the time disparity between the accelerated pace of molecular development and the inertia of regulatory and toxicological assessment frameworks, resulting in the exposure of workers and ecosystems to latent and severe hazards (OIT, 2014).

To mitigate these risks at the national level, the Industrial Solid Waste Inventory, established by CONAMA Resolution No. 313/2002, is a fundamental management tool. This tool aims to systematize essential information about the generation, characteristics, and final destination of these materials, allowing for more efficient planning, regulatory control, and the prevention of environmental impacts (CONAMA, 2002).

Brazilian standards ABNT NBR 10.004-1:2024 and 10.004-2:2024 establish the fundamental classification of waste into Hazardous (Class 1) or Non-Hazardous (Class 2) (ABNT, 2024). Hazardous waste is defined by characteristics such as flammability, corrosiveness, or toxicity. The list of hazardous industrial waste is extensive, including contaminated soil, lead slag, and various sludges, and its improper management leads to environmental damage and significant risks to human health (Minelgaité et al., 2019).

The generator of hazardous waste has full legal responsibility for the entire life cycle of these materials, from generation to final disposal, and must ensure that all stages comply with current legislation (Barros, 2014). For the environmentally sound management of these materials, Class 1 landfills are essential. Its operation requires rigorous technical care, including constant monitoring of soil and groundwater quality (Barros, 2012), as well as compliance with regulatory obligations.

Brazilian national legislation, specifically the National Solid Waste Policy (PNRS, in Portuguese acronym), Federal Law No. 12.305/2010 (Brasil, 2010), requires operators of Class 1 Landfills to register with the National Registry of Hazardous Waste Operators (CNORP, in Portuguese acronym), informing IBAMA of the waste received and submitting the Hazardous Waste Management Plan (PGRP, in Portuguese acronym).

This article aims to evaluate the environmental compliance of a Class 1 Hazardous Waste Landfill with the current legislation and to analyze the potential for implementing



Landfill Mining as a strategy to promote sustainability in the management of this waste. Using the Caieiras Landfill in São Paulo as a case study, this article aims to contribute to the development of more efficient solutions that align with the principles of the circular economy.

2. THEORETICAL FOUNDATION

The management of hazardous industrial waste is a multi-stage process that, due to its complexity and legal requirements, is mostly outsourced. Most industries hire licensed companies for the treatment and final disposal stages (Barros, 2013). Packaging, whether in containers, drums, or in bulk, is strictly regulated by NBR 12.235/1992 (ABNT, 1992), requiring storage areas with waterproofed floors and containment systems (Barros, 2012).

Collection and transportation are highly regulated activities that require specific permits from environmental agencies and compliance with safety requirements (Barros, 2013). In the state of São Paulo, the transport requires a Certificate of Movement of Environmentally Relevant Waste (CADRI, in Portuguese acronym), issued by CETESB, which ensures the prior consent of the recipient (Barros, 2012). Additionally, the Waste Transportation Manifest (MTR, in Portuguese acronym), generated by SINIR, ensures the traceability of waste from origin to destination. Upon completion of the process, the recipient issues the Certificate of Final Destination (CDF, in Portuguese acronym) (Barros, 2014).

The National Solid Waste Policy (PNRS), established by Federal Law No. 12.305/2010 (Brasil, 2010), sets guidelines and imposes full legal responsibility on the generator throughout the entire life cycle of hazardous waste (Barros, 2014). Chapter IV of the PNRS details obligations such as registration in the National Registry of Solid Waste Operators (CNORP) and the submission of an updated Hazardous Waste Management Plan (PGRP, in Portuguese acronym) to the National Environmental System (SISNAMA, in Portuguese acronym) (Brasil, 2010). Although the National Solid Waste Plan (Planares, in Portuguese acronym), approved in 2022, improved overall management, it did not introduce new specific guidelines for hazardous waste (Brasil, 2022).

The technical criteria for the design, construction, and operation of Class 1 Landfills are governed by NBR 10.157/1987 (ABNT, 1987) and depend on state environmental licenses. In São Paulo, CETESB regulates this management, requiring installation and operation licenses, registration in the State Online Solid Waste Management System (SIGOR in Portuguese

acronym), and the submission of monitoring reports. This continuous monitoring is essential to ensure compliance and environmental protection (Barros, 2014).

In Brazil, the final disposal of hazardous industrial waste prioritizes thermal solutions, notably incineration (a waste treatment process that consists of the controlled and complete burning of materials at high temperatures) and co-processing, an energy recovery practice in cement kilns that contributes to mitigating greenhouse gas emissions (Barros, 2013). Class 1 Landfills are reserved strictly for the safe disposal of waste with low calorific value or those that do not have technical viability for thermal treatment (Barros, 2012).

Historically, landfill disposal was the primary solution; however, the scenario has evolved: materials such as electric arc furnace dust and metal composites, previously discarded, now have recycling potential and market value (Barros, 2013). Given this, landfill management, once seen as a definitive solution, shifted to a more dynamic model, where the landfill is a temporary containment measure rather than a final disposal method (Barros, 2012).

This shift is fueling interest in Landfill Mining, a practice that involves the extraction and recovery of previously discarded solid materials. Landfill Mining represents a secondary source of inputs (Krook et al. 2013; Fricke 2009; Cossu et al. 2015), aligning waste management with the circular economy.

To systematize the national regulatory framework relevant to the management of hazardous waste, the following details are presented:

- ✓ NBR 10.005:2004 – Procedure for obtaining percolate extract from solid waste (ABNT, 2004a).
- ✓ NBR 10.006:2004 – Procedure for obtaining a soluble extract from solid waste (ABNT, 2004b).
- ✓ NBR 10.007:2024 – Sampling of solid waste (ABNT, 2024).
- ✓ NBR 10.157:1987 – Hazardous waste landfills: Criteria for design, construction, and operation (ABNT, 1987).
- ✓ NBR 12.235:1992 – Storage of hazardous solid waste: Procedure (ABNT, 1992).
- ✓ NBR 12.988:1993 – Free liquids: Verification in residue samples (ABNT, 1993).
- ✓ Federal Law No. 12.305/2010 – Establishes the National Solid Waste Policy (PNRS) (Brasil, 2010).

- ✓ Federal Decree No. 10.936/2022 – Regulates the National Solid Waste Policy (PNRS) and establishes the National Information System on Solid Waste Management (SINIR) (Brasil, 2022a).
- ✓ Federal Decree No. 11.043/2022 – Establishes the National Solid Waste Plan (Planares) (Brasil, 2022b).
- ✓ Federal Decree No. 9.177/2017 – Regulates Article 33 of the PNRS (Reverse Logistics) (Brasil, 2017).
- ✓ Federal Law No. 9.974/2000 – Deals with pesticides and their related components (Brasil, 2000).
- ✓ CONAMA Resolution No. 313/2002 – Provides for the National Inventory of Industrial Solid Waste (CONAMA, 2002).

According to data from the Brazilian Association of Waste and Effluent Treatment Companies (ABRETE), in 2006, Brazil had 21 Class 1 Landfills in operation. Three of these projects were in the state of São Paulo, in the municipalities of Caieiras, Jardinópolis, and Tremembé (ABRETE, 2006).

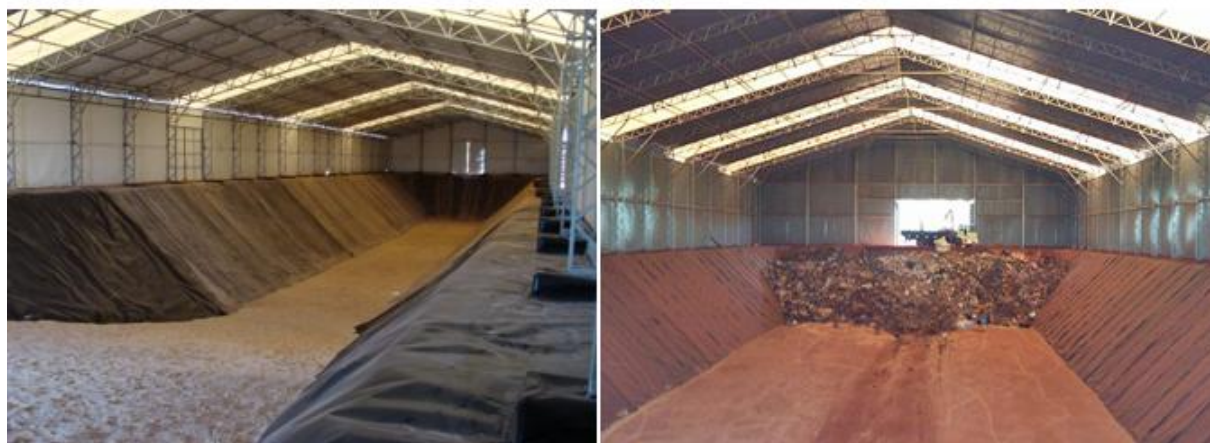
Class 1 Landfills (Figure 1) are structures designed for the safe reception and containment of hazardous waste in the soil, following strict sanitary and environmental engineering principles. The project typically involves excavating the disposal cells below ground level and operating them with a movable cover to minimize water infiltration, primarily by preventing waste compaction (Barros, 2014).

The implementation of these landfills requires a rigorous analysis of the site's characteristics, which must include: the topography, geology, and geotechnics of the land, the identification of geological risks, the properties of the soil and subsoil, the depth of the water table, and the location of surface and groundwater resources. This detailed assessment is essential to select an area that minimizes environmental impacts and the risks of contamination (Rosenfeld and Feng, 2011; Zanon, 2016).

Figure 1

Operational cells of an industrial landfill.

A – Titara’s industrial landfill. **B** – The company’s industrial landfill.



A

B

Source: **A** - <https://www.cgatitara.com.br/institucional/o-que-fazemos/aterro-industrial-classe-i/>. **B** - <http://www.estre.com.br/solucoes-para-empresas/aterro-classe-i/>

The basic infrastructure of a Class 1 Landfill is complex and layered, designed to isolate the waste completely from the environment. The main systems include (Cepollina, 2016):

Base Drainage System: (i) **Subsurface Drain:** Positioned at the base of the embankment, and (ii) **Witness Vertical Drain:** Installed between the HDPE (High-Density Polyethylene) geomembranes, 1.5 to 2.0 mm thick. Its primary function is to detect and collect potential leaks (percolations) through the waterproofing layer.

Percolate Collection System: Composed of vertical and horizontal drains, installed inside the waste mass, to capture the percolate generated.

Rainwater Harvesting system: Involves surface drainage and retention basins lined with HDPE geomembrane. The collected water is mainly used to moisten the access roads to the landfill after analysis and quality control.

Waste Cover System: During operation, asphalt sheets are used to protect the active cells from rainwater. The final top layer consists of multiple layers: compacted clay, a geomembrane, a soil layer, and, finally, grass planting. This structure aims to minimize rainwater infiltration and, consequently, reduce percolate generation.

Wheel Washing System: Mandatory for use upon exiting the control area to sanitize the tires of all trucks, preventing the dispersion of contaminants.

3. MATERIALS AND METHODS

The methodology employed in this study combined a three-pronged approach: Bibliographic Research, Analysis of Normative and Regulatory Documents, and a Case Study at the Caieiras Landfill (Class 1 Industrial Landfill).

A literature review was conducted to establish the State-of-the-Art and international best practices in the management of hazardous solid waste and the application of the Landfill Mining technique. The research utilized the platforms Scielo, CAPES/Portal de Periódicos, and Google Scholar. The search was guided by keywords: Hazardous Waste (*Resíduos Perigosos*), Class 1 Landfill (*Aterro Classe 1*), and Landfill Mining (*Mineração de Aterro*).

This stage focused on the legal and technical compliance of hazardous waste management in Brazil and at the study site. The analysis included the Brazilian regulatory framework (ABNT standards and federal legislation), engineering projects, operational manuals for the unit, and specific Environmental Impact Assessments (EIA) for the Caieiras Landfill. The main objective was to compare the landfill's operational practices with current environmental and safety guidelines and standards.

The Caieiras Landfill (Class 1 Industrial Landfill), located in the state of São Paulo, was selected as a case study. Technical field visits and in-situ data collection were conducted from 2016 to 2020. The purpose of data collection was to validate the compliance of landfill management and engineering practices, specifically in relation to Brazilian technical and legal guidelines, providing an empirical basis for the feasibility analysis of Landfill Mining.

4. RESULTS AND DISCUSSION

The Class 1 Landfill subject of this study is located within the private Sustainable Valorization Unit (UVS) complex – Caieiras Landfill in the northwestern region of the São Paulo Metropolitan Region. The company specializes in the final disposal of hazardous waste for industries in the São Paulo Metropolitan Region, the state, and other Brazilian states. During the analysis period, this Class 1 Landfill received an average of 1,500 tons of hazardous waste per month. In addition to sharing UVS's general infrastructure, the area has sectors for temporary waste storage and a laboratory dedicated to quality control and monitoring of receipts.

The construction of the embankment base (Figures 2A and 2B) was conducted in accordance with NBR 10.157/1987, to create a double hydraulic barrier system: geological (soils) and geosynthetic (geomembranes):

Compacted Base: Construction began with leveling the ground and compacting a 3.0-meter-thick layer of soil positioned above the water table. On top of this, a 0.60 m thick layer of local clay was applied, divided into 0.20 m sublayers to optimize compaction. The degree of compaction achieved resulted in a permeability coefficient of 5×10^{-5} cm/s, lower than the regulatory requirement (Cepollina, 2016).

Geosynthetic System: Above the compacted soil layer, a waterproofing system was installed with a Geosynthetic Clay Liner, a 2.0 mm textured HDPE (High-Density Polyethylene) geomembrane, and another 1.5 mm geomembrane. A geogrid was inserted between the geomembranes to drain any percolate to the witness drain and detect possible failures in the waterproofing system (Cepollina, 2016).

A 600 g/m^2 non-woven geotextile sheet with high tensile strength (31 kN/m) was installed (Figure 2C) to protect the last geomembrane. Above, a 40 cm layer of crushed stone (No. 4), with drainage function, was laid to collect any percolate. Finally, another lighter geotextile (150 g/m^2) with a tensile strength of 7 kN/m was added to prevent the migration of fine aggregate particles to the upper layers (Figure 2E).

Figure 2E also shows that protection for the geomembrane was implemented on the slope using tires, filled with soil, installed over the 600 g/m^2 geotextile. This is an interesting use for unusable tires, which are employed to provide mechanical protection and cushioning against potential physical impacts on slopes. Waterproofing was conducted on the base and slopes of the landfill cells, the geosynthetics were welded using thermofusion, and the geomembranes were anchored in perimeter trenches along the edges of the landfill cells, according to the detailed design (Cepollina, 2016).

The witness drain (Figure 2D) is composed of the following systems: Geotextile, HDPE Geomembrane, Geogrid, and Geosynthetic Clay Liner. The geogrid has a thickness of 5 mm, transmissivity of $1.80 \times 10^{-3} \text{ m}^2/\text{s}$ (hydraulic gradient 1 and head 200 kPa), and is applied only to the upper part of the drain. The function of the witness drain is to drain, by gravity, any flow that may leak from the landfill, conducting it through a layer of crushed stone (No. 1) and a perforated HDPE pipe, 160 mm in diameter, to the pumping system. This system consists of HDPE piping with a 355 mm diameter, installed parallel to the slope, for leak detection. The

witness drain is installed below the landfill percolate pumping system, allowing it to receive and accumulate liquids leaking, as well as facilitate their detection and collection (Cepollina, 2016).

The percolate collection system (Figure 2E) was installed above the 1.5 mm HDPE geomembrane. The elements of this system in descending order are:

- (i) Non-woven geotextile of 150 g/m², installed above the gravel layer with the function of filtering the leachate before it reaches the drainage layer,
- (ii) A drainage layer of crushed stone (No. 4), 0.40 m thick, distributed throughout the base of the embankment, to collect percolated liquids and direct them to the percolate collection piping and the pumping well (Figure 2D),
- (iii) Vertical drain constructed with perforated reinforced concrete piping, from the base and surrounded with rubble contained using welded mesh, with the function of increasing the efficiency of percolate collection (Figure D),
- (iv) A pumping well installed at the lowest elevation point, for pumping the percolate using a submersible pump, constructed of perforated reinforced concrete pipe with a diameter of 1.0 m, supported on a slab for mechanical protection of the geomembrane (Cepollina, 2016).

An intermediate cover layer, with a thickness of 0.50 m of compacted local clay soil, was applied after completion of each cell (phase) of landfill operation. The intermediate layer of cover serves to minimize rainwater infiltration and percolate generation. The work fronts inside the trench are also covered to prevent rainwater infiltration into the landfill (waste deposited in the landfill cells), using waterproof tarpaulins measuring approximately 20 m by 20 m or larger, with a Velcro system on the sides and anchored with sandbags.

The final roofing system (Figure 2F) is composed of the following elements in descending order:

- (i) Local protective clay soil, 0.40 m thick, serving to protect the drainage geocomposite and geomembrane, and preparing the area for grass planting,
- (ii) A drainage geocomposite, consisting of a geogrid (5.0 mm) and non-woven geotextile (300 g/m²), with the function of capturing and draining rainwater infiltrated through the topsoil, and the geotextile with the function of protecting the HDPE geomembrane from physical damage and preventing clogging of the geogrid,
- (iii) A 1.5 mm thick HDPE geomembrane, textured on both sides, designed to prevent water infiltration into the waste mass, is installed over the Geosynthetic Clay Liner (GCL),



(iv) Geosynthetic Clay Liner (GCL), composed of a layer of sodium bentonite between two non-woven (upper) and woven (lower) geotextiles, with the function of a secondary hydraulic barrier, and

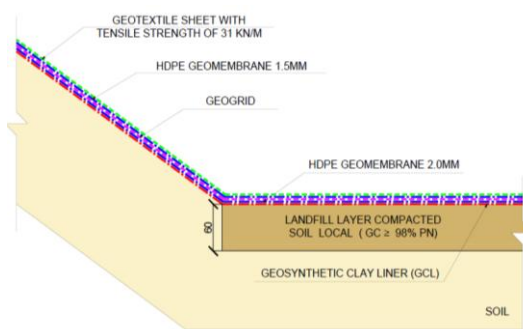
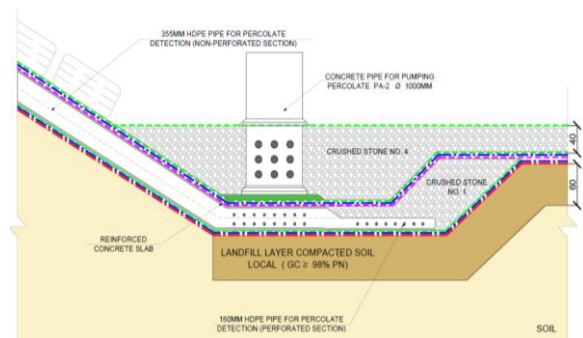
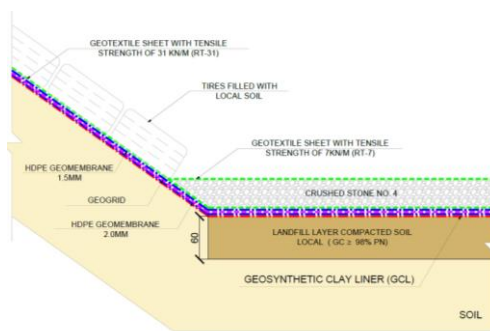
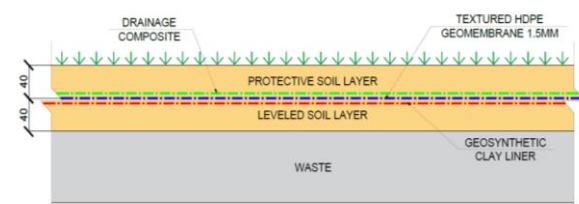
(v) Leveling soil, a compacted layer with an average thickness of 0.40 m, applied over the final surface of the residue layer (Cepollina, 2016).

The rainwater drainage elements of the Class 1 Landfill consist of triangular and trapezoidal channels installed on the waste berms at the foot of the embankment slopes to collect the flows from the cell slopes and direct them to the hydraulic downpipes in a Reno Mattress. Additionally, triangular channels lined with grass are installed on the upper platforms of the embankment, being constructed in the topsoil seal with a width of 2.50 m and a depth of 0.50 m (Cepollina, 2016).

Figure 2

Construction elements of the Class 1 Landfill, UVS-Caieiras (Essencis).

A – Landfill's base waterproofing system. **B** – Landfill cover shed. **C** – Waterproofing of the base and slope at the landfill. **D** – Installation of the witness drain at the landfill. **E** – Installation of tires on the landfill slope. **F** – Final landfill cover system.

**A****B****C****D****E****F**

Source: **A** and **B** - Essencis (2016). **C**, **D**, **E**, and **F** - Cepollina (2016).

The protocol sequence for receiving and disposing of hazardous waste at a Class 1 Landfill is presented below:



- (i) Pre-acceptance of waste involves obtaining detailed information on its nature and composition, in accordance with the requirements of technical standards NBR 10.004:1 and NBR 10.004:2/2024, to ensure its correct characterization and final disposal,
- (ii) The receiving process begins with identifying and authorizing access for the trucks, followed by two weightings (entrance and exit). The required documentation, including the CADRI and MTR, is checked and recorded. After weighing, a ticket is issued (serving as proof and a permanent record of the transaction). Additionally, inspections are conducted of the vehicles' sanitary conditions and the operators' personal protective equipment. Finally, the cargo is directed to the sampling station (laboratory) for analysis,
- (iii) After weighing, a sample of the residue is collected and sent to the laboratory for rapid/expedited analysis. The purpose of this analysis is to confirm the information declared in the CADRI and MTR. The release of the cargo for disposal at the landfill is conditional upon the analysis results conforming to the declared information. In the event of non-compliance, the cargo is retained, and the waste generator and the competent environmental agency are immediately notified,
- (iv) Waste sampling is conducted in accordance with NBR 10007/2004. The expedited analysis covers parameters such as pH, free liquids, and reactivity; and the complete analysis evaluates a wide range of physicochemical parameters and elements (Metals: arsenic, cadmium, selenium, barium, chromium (total and hexavalent), beryllium, nickel, antimony, lead, mercury. Volatile organic compounds (VOCs): benzene, carbon tetrachloride, tetrachloroethene, trichloroethene. Cyanide: cyanide. Physicochemical parameters: gross mass, pH, physical appearance, odor, free liquids, moisture content, total solids, and fixed and volatile solids).

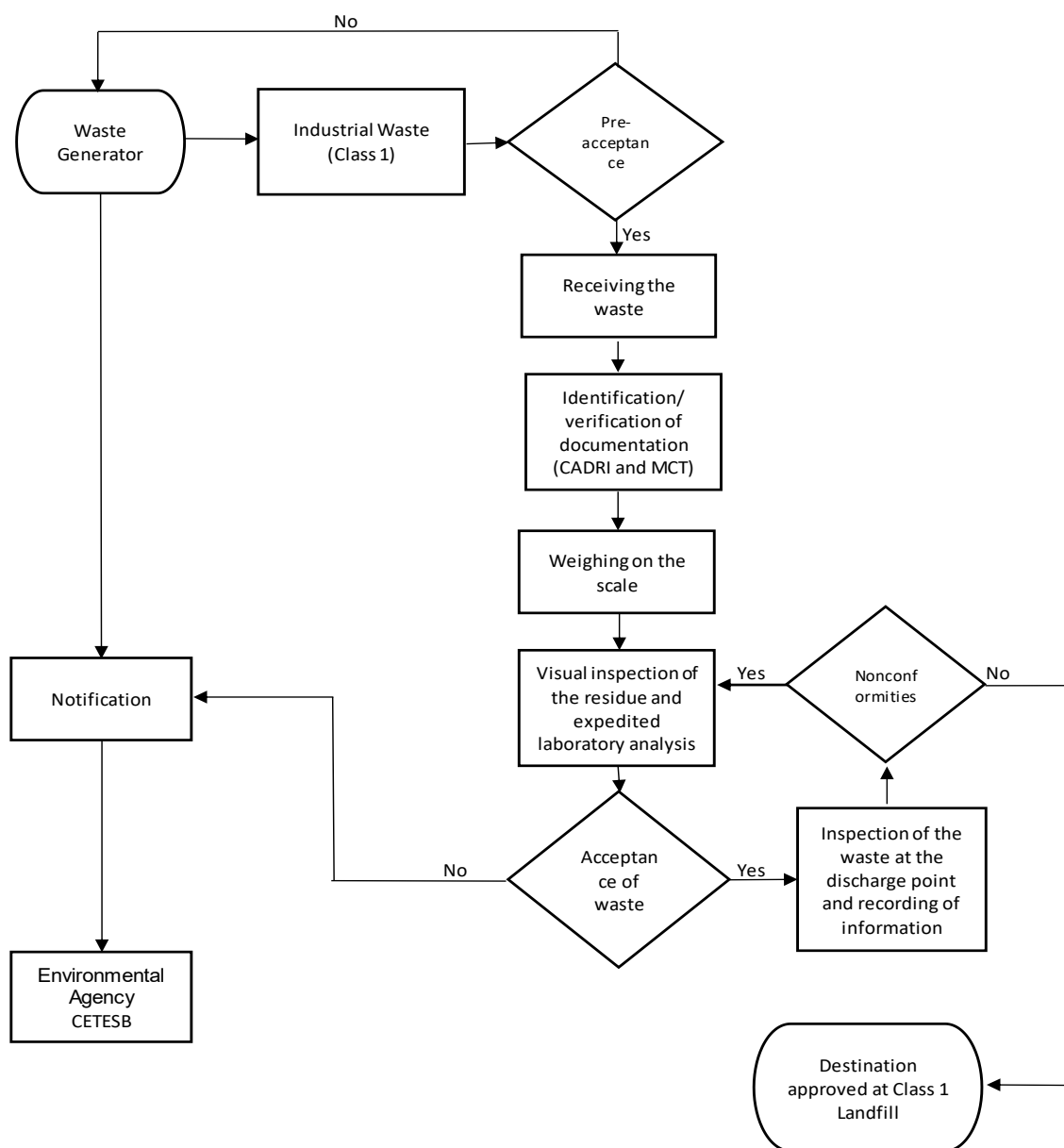
For each shipment, an expedited analysis is performed, and complete analyses are conducted periodically or when half of the contracted quantity is reached. The samples are stored for 12 months. In the event of non-compliance, the generator and the environmental agency are notified, and the cargo is rejected if it lacks valid documentation or presents characteristics incompatible with its intended destination.

During the waste disposal process, loads authorized by the laboratory are sent to the landfill's unloading area, where the operational supervisor inspects the unloaded waste. This



landfill site is identified and recorded using GPS, which measures its geolocation and elevation and registers it in a spreadsheet along with the following supplementary data: date of landfilling, quantity of waste landfilled, and landfill discharge cell module. All this information is part of the waste traceability process at the landfill. Figure 3 shows the flowchart for the process of receiving and handling hazardous waste at Class 1 Landfill.

Figure 3
Waste reception flowchart at the Class 1 Landfill - UVS-Caieiras (Essencis)

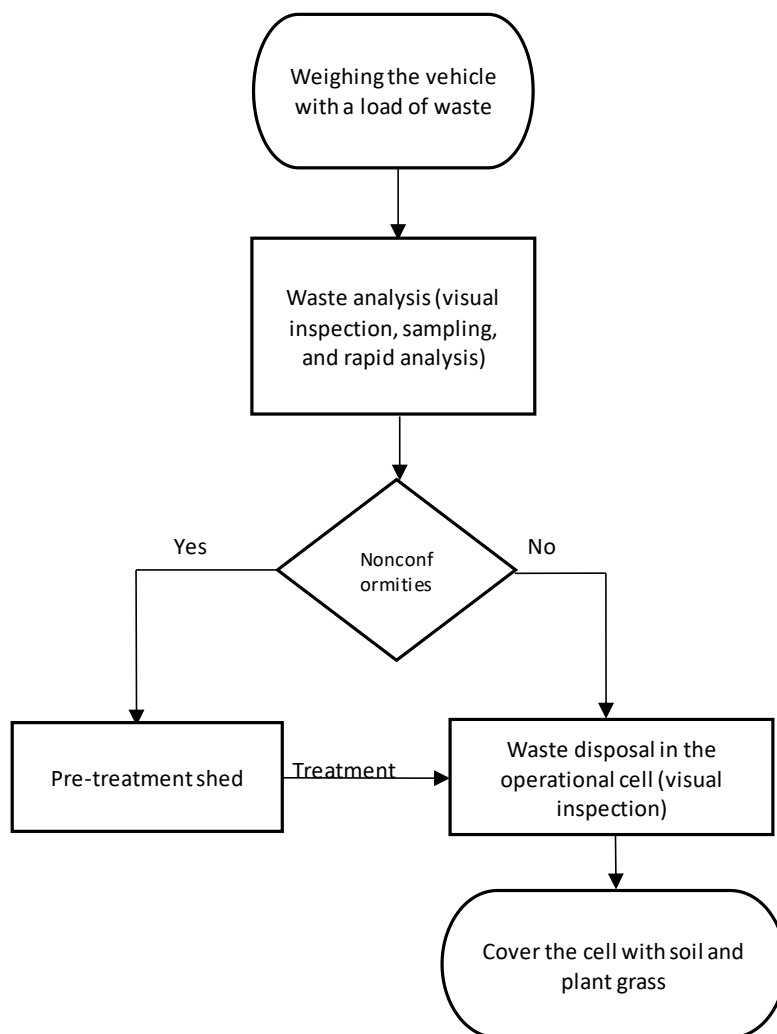


Source: Cepollina (2016).

Figure 4 shows the basic operational flow of hazardous waste management at the landfill. Initially, the vehicle is weighed with its cargo, followed by a visual inspection and collection of samples for analysis. At this stage, possible nonconformities are checked. When irregularities are identified, the cargo goes to the pre-treatment warehouse. After this stage, the waste is sent for disposal in the operational cell, where it is subsequently covered with soil and planted with grass as a final closing step. If the waste is accepted after analysis, it is sent directly to the disposal cells.

Figure 4.

Basic operational flowchart at the Class 1 Landfill - UVS-Caieiras (Essencis)



Source: Cepollina (2016).

4.1. Potential and Challenges of Landfill Mining

Landfill Mining is emerging as a promising alternative for waste management, aiming at resource recovery and mitigating environmental impact. This practice enables the recovery of valuable materials and the generation of energy from historically disposed waste, contributing significantly to the rehabilitation of degraded areas and the elimination of environmental liabilities (Laner et al., 2019).

Despite its potential, significant challenges surround the development of Landfill Mining. According to Krook et al. (2012), the main obstacles involve the need for technological innovation, cost reduction for project implementation, and standardization of structures for performance evaluation.

Frändegård et al. (2013) identify four crucial uncertainties that challenge the design of viable projects:

- (i) Heterogeneity of the waste: The diverse and unpredictable composition of the excavated material.
- (ii) Efficiency of processing technologies: The ability to separate and treat recovered waste effectively.
- (iii) Market instability: Price fluctuations for recovered materials.
- (iv) Environmental and health risks: Hazards associated with the excavation and handling of old waste, as evidenced by Einhaupl et al. (2021) and Goli and Singh (2023).

The uniqueness of each landfill is a determining factor, with age, waste type, and location directly influencing its recovery potential and economic and environmental viability. A detailed assessment of each case is essential for defining appropriate mining strategies (Bockreis and Knapp, 2011; Winterstetter et al., 2015). Case studies illustrate this potential:

- (i) Energy Recovery (Remo Landfill, Belgium): The analysis of the Remo Landfill indicated energy recovery as the most suitable route, given the high contamination of the material with plastics, paper/cardboard, textiles, and wood, which makes direct recycling unfeasible. The energy potential of these residues was estimated to be between 18 and 23 MJ/kg. Additionally, the study identified high concentrations

of heavy metals (Cu, Cr, Ni, and Zn) in fine industrial waste, opening prospects for their recovery and commercialization (Quaghebeur et al., 2013).

- (ii) Recovery of Valuable Metals (Europe): Analyses conducted in four European landfills revealed a significant presence of high-value metals, such as palladium, neodymium, copper, and aluminum, at depths of up to 30 meters, with an estimated aggregate economic potential of 360 million euros (Greedy, 2016).

4.2. Economic Viability of Landfill Mining

The economic viability of Landfill Mining remains a critical and highly restrictive factor. European studies indicate a wide variation in costs, which can reach from 127 to 139 euros per ton of excavated waste. This disparity reflects low profitability, with only 20% of the projects demonstrating a positive financial return (Esguerra et al., 2021). Given this scenario, the implementation of projects in Class 1 Landfills requires a thorough risk analysis to optimize benefits and reduce technical, economic, and environmental risks (Esguerra et al., 2021).

The potential for generating revenue for Landfill Mining projects involving hazardous waste is limited by high operational costs and inherent process uncertainties, directly impacting the project's financial stability (Laner et al., 2019). The main cost and risk factors include:

- (i) Initial Studies and Characterization (high upfront investment): The need to conduct in-depth studies (geotechnical, chemical, and market-related) before the start of operations represents a substantial initial investment. It is essential to obtain an accurate characterization of the contaminants and their behavior in the landfill matrix to design treatment processes and mitigate risks (Frändegård et al., 2013),
- (ii) Pre-treatment and extraction costs (operational complexity): The material in Class 1 Landfills is notoriously heterogeneous and potentially reactive. This fact makes the costs of extraction, separation (due to compaction), and pre-treatment, such as decontamination or stabilization, significantly higher than those observed in municipal solid waste landfills (Jain et al., 2023),
- (iii) Volatile Market and Waste Costs (financial risk): Profitability depends directly on the market price of recoverable materials (metals, aggregates). However, the uncertainty is compounded by the fact that the final disposal cost of the tailings (the excavated material that is not recoverable) can easily exceed the total value of the

marketable materials. This volatility necessitates the development of a more robust and complex risk management strategy (Esguerra et al., 2021).

4.3. Environmental and Occupational Risks of Landfill Mining

Excavation in Class 1 Landfills exposes critical environmental and safety risks that must be addressed and mitigated through rigorous planning. Landfill Mining operations destabilize the tailings dam, requiring specific control measures:

- (i) Contaminant Monitoring and Control: The removal of the material may lead to the sudden release of toxic gases, such as Volatile Organic Compounds (VOCs). Furthermore, there is a risk of mobilization of soluble contaminants (e.g., heavy metals) due to increased infiltration of rainwater into the excavated area (Bockreis and Knapp, 2011). Therefore, constant monitoring of soil and groundwater quality is essential (Barros, 2012),
- (ii) Percolate Control: The mining process drastically alters the landfill's water balance. This can increase the volume and pollutant load of the percolate generated, potentially overloading the existing treatment system, which already operates under stringent standards (Cepollina, 2016),
- (iii) Operational and Geotechnical Safety: Geotechnical monitoring of slope stability becomes more critical during excavation. Worker safety requires the use of appropriate PPE (Personal Protective Equipment) when exposed to hazardous agents, and strict adherence to safety guidelines for handling chemicals is essential (OIT, 2014).

Regarding the positive aspects of Landfill Mining, Johansson, Krook, and Eklund (2017) conducted a comprehensive analysis and identified several advantages:

- (i) Material Recovery: This practice provides large quantities of minerals in high concentration, enabling the recycling and reuse of materials,

- (ii) Mitigation of Primary Extraction: Resource recovery reduces the need for new extractions of virgin raw materials, contributing to environmental remediation and sustainability,
- (iii) Land Recovery: Excavation and waste treatment allow for the recovery of landfill areas, generating new spaces for other purposes (Johansson, Krook, and Eklund, 2017).

4.4. Future Research in Landfill Mining

To promote the application of Landfill Mining in Class 1 Landfills, further research aligned with global trends in sustainable waste management is recommended (Krook et al., 2012):

- (i) Development of a Specific Feasibility Model: It is essential to design a Risk and Economic Assessment Model specifically for Class 1 Landfills. This model must necessarily integrate the high costs of treating hazardous waste (incineration, co-processing, or stabilization) with the potential revenue from recoverable materials. The quantification of resources and reserves must follow robust and standardized principles (Winterstetter et al., 2015),
- (ii) Pilot-Scale Characterization Studies: Promoting pilot-scale chemical and physical characterization studies is fundamental. Such studies should employ advanced screening technologies (such as ballistic separation or optical sensors) that are adapted to handle the complex and potentially corrosive matrix of a Class 1 Landfill,
- (iii) Environmental Liability Reduction Analysis: It is necessary to quantify the reduction of environmental liability resulting from a Landfill Mining project through modeling. The quantification should encompass the area of land recovered, the volume of percolate generated that was avoided, and the reduction in gaseous emissions,
- (iv) Investigation of Regulatory and Institutional Analysis: Future investigations should focus on institutional capacity and regulatory barriers to the adoption of hazardous waste Landfill Mining within the context of the PNRS (Brasil, 2010). The goal is to



ensure that resource recovery does not compromise the generator's legal responsibility for the final waste resulting from the process.

5. FINAL CONSIDERATIONS

This article evaluated the implementation, operation, control, and monitoring procedures of the Class 1 Landfill at UVS-Caieiras Landfill, demonstrating compliance with regulatory requirements, notably NBR 10.157/1987. This adherence ensures operational safety and environmental protection, pillars of improved management that, aligned with the PNRS, contribute to decarbonization and the mitigation of climate change impacts through the optimization of the disposal and capture of greenhouse gases.

Landfill Mining emerges as an innovative approach that complements the waste management hierarchy (reduction, reuse, and recycling). By transforming landfills into strategic secondary resource reserves, this technique offers an opportunity to manage already disposed waste, reducing pressure on landfills and helping achieve the SDGs.

Analysis of the entry records at the Caieiras Landfill indicates the presence of significant quantities of valuable metallic waste (such as aluminum and copper). The recovery of these materials has high potential for economic and environmental valorization, contributing to reducing energy and water consumption and decreasing pressure on natural resources.

Despite the potential, implementing Landfill Mining projects, especially in Class 1 Landfills (as in this case study), requires caution. It is essential to conduct detailed technical and economic feasibility studies to assess the initiative's profitability and sustainability, given the complexity of treating the remaining hazardous waste. For this practice to be implemented, the following are essential: the development of specific technologies to address the heterogeneity and hazardousness of materials, and the creation of an appropriate regulatory framework that ensures environmental safety and public health without compromising the legal responsibility of the generator.

In this case study, it is essential to conduct a rigorous sizing and physical-chemical characterization of the waste disposed of in the landfill. This precision is critical to determining the resource recovery potential and, consequently, ensuring the technical, economic, and environmental viability of a potential Landfill Mining application.

The potential for recovering valuable materials from Hazardous Landfills (Class 1) makes Landfill Mining a promising alternative for obtaining strategic resources. The adoption

of public policies that encourage this practice (through tax and financial benefits) is essential to promote the circular economy in Brazil. By leveraging existing infrastructure, Landfill Mining generates socioeconomic benefits (such as job creation) and reinforces the landfills' role in environmental sustainability and the exploitation of secondary resources.

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