UFSM

CIÊNCIA e NATURA

ISSN 2179-460X
OPEN ACCESS

Ci. e Nat., Santa Maria, 47, spe. 2, e91546, 2025 • https://doi.org/10.5902/2179460X91546
Submitted: 04/11/2024 • Approved: 04/11/2024 • Published: 05/21/2025

Inovações e Soluções Sustentáveis em Engenharia Ambiental

Chemical characterization of Landfill-Mined-Soil-Like-Fractions (LFMSF) for application as fertilizer or soil conditioner

Caracterização química das frações tipo solo mineradas de aterro sanitário (FTSMA) visando a aplicação como fertilizante ou condicionador de solo

Lucas Antonio de Oliveira[I], Jerusa Schneider[II], Diego Costa Romeiro[I], Miriam Gonçalves Miguel[I]

[I] Universidade Estadual de Campinas, SP, Brazil
[II] Universidade Estadual de Santa Cruz, BA, Brazil

ABSTRACT

Brazil is actively working to improve municipal solid waste (MSW) management and extract value from it. Landfill mining, the process of recovering materials from landfills, is a potential solution. One valuable component is landfill-mined-soil-like-fractions (LFMSF). These fractions, composed of a mixture of organic materials, soils, debris, and small fragments of metals, plastics, and glass, offer potential benefits for agriculture. A chemical analysis of LFMSF (D < 19mm) after eight years of landfilling (LFMSF-8) from the Delta A sanitary landfill in Campinas, Southeastern Brazil, revealed its nutrient content. The results showed that LFMSF-8 contains essential elements for plant growth. Notably, it meets iron (Fe) concentration requirements for remineralizers. Moreover, LFMSF-8 exhibits higher levels of calcium (Ca), iron (Fe), manganese (Mn), boron (B), and cation exchange capacity (CEC) compared to traditional organic fertilizers. Importantly, it presents low levels of potentially toxic elements (PTE). These findings suggest that LFMSF can be a valuable secondary nutrient source for agriculture. Its responsible use can contribute to a more sustainable and circular economy.

Keywords: Landfill mining; Municipal solid waste; Agriculture reuse

RESUMO

O Brasil está ativamente trabalhando para melhorar o manejo de resíduos sólidos urbanos (RSU) e extrair valor deles. A mineração de aterros sanitários, o processo de recuperação de materiais de aterros, é uma solução potencial. Um componente valioso são as frações tipo solo mineradas em aterro sanitário (FTSMA). Essas frações, compostas por uma mistura de materiais orgânicos, solos, detritos e pequenos fragmentos de metais, plásticos e vidro, oferecem potenciais benefícios para a agricultura. Uma análise química de FTSMA (D < 19mm) após 8 anos de aterramento (FTSMA-8) do aterro sanitário Delta A em Campinas, Sudeste do Brasil, revelou seu conteúdo de nutrientes. Os resultados mostraram que FTSMA-8 contém elementos essenciais para o crescimento das plantas. Notavelmente, atende aos requisitos de concentração de ferro (Fe) para remineralizadores. Além disso, FTSMA-8 apresenta níveis mais elevados de cálcio (Ca), ferro (Fe), manganês (Mn), boro (B) e capacidade de troca catiônica (CTC) em comparação com fertilizantes orgânicos tradicionais. É importante destacar que contém baixos níveis de elementos potencialmente tóxicos (EPT). Essas descobertas sugerem que a FTSMA pode ser uma valiosa fonte secundária de nutrientes para a agricultura. Seu uso responsável pode contribuir para uma economia mais sustentável e circular.

Palavras-chave: Mineração de aterros sanitários; Resíduos sólidos urbanos; Reuso agrícola

1 INTRODUCTION

Municipal solid waste (MSW) generation has grown significantly over the last decade across the globe. From 2010 to 2019, MSW generation in Brazil rose from 67 million to 79 million tons annually. Simultaneously, per capita production grew from 348 kg to 379 kg per year, leading to a 19% upsurge in MSW generation in Brazil (ABRELPE, 2020). In 2022, an average of 1.043 kg of waste per capita/day was estimated (ABRELPE, 2022). Considering its relative low operational cost, landfill disposal stands out as one option for dealing with such waste (Rong et al., 2017). According to the Brazilian National Solid Waste Policy (PNRS), this method is considered an environmentally appropriate alternative. Sanitary landfills operate following specific rules and regulations to prevent damage to public health, ensure safety, and minimize adverse environmental impacts (Brasil, 2010).

However, landfills can lead to significant negative impacts, such as uncontrolled release of gases, accidental fires, and slope failures. Gases generated in landfills are one of the main sources of greenhouse gas emissions, especially methane gas, which is often not collected or adequately treated (Chandana et al., 2021; Poulsen, 2014). Furthermore, generation of large volumes of leachate is another concerning aspect of landfills (Sousa et al., 2023; Wijekoon et al., 2022). Managing leachate is a major challenge in Environmental

Engineering due to the diverse materials present in MSW and the potential pollutant load of these wastes (Prechthal et al., 2008; López et al., 2018).

Sanitary landfills create a financial burden for municipalities because they require large areas for daily coverage and need appropriate areas for waste disposal. Furthermore, it is important to ensure adequate living conditions for the local community (Abdel-Shafy and Mansour, 2018). Despite the environmental liabilities mentioned, most countries still dispose of MSW in landfills and dumps. Alongside the problem of current landfills, many are approaching their maximum capacity, and finding new sites for landfills has become a major challenge due to the scarcity of suitable areas and increased government regulations. Given these issues, landfill mining has emerged as a viable alternative for addressing soil, air, and water pollution by enabling the recovery of secondary raw materials (Krook et al., 2012).

Landfill mining is aligned with PNRS guidelines, which promote integrated and effective management of solid waste. This prioritizes non-generation, reduction, reuse, recycling, and environmentally appropriate final disposal (Brasil, 2010; Brasil, 2022a). In simple terms, landfill mining involves digging up, processing, treating, or recycling materials that have been dumped in an active or closed landfill (Krook et al., 2012). In the context of landfill mining, waste is classified into several categories, which allows for specific reuse strategies. In Brazil, the proposal for classifying landfilled waste by Leme et al. (2021) identified 25 categories, highlighting the landfill-mined-soil-like-fractions (LFMSF; d < 19 mm) as the most significant category. This category can account for 40% to 80% of the wet mass of the total excavated waste (Parrodi et al., 2018).

The scientific literature presents different denominations to refer to LFMSF, namely: fine fraction, inert fraction, soil-like fraction, inorganic soils, unidentified materials, and others (Burlakovs et. al., 2016; Chandana et. al., 2021; Hogland et al., 2004). To standardize the terminology of these fractions, Chandana et al. (2021) carried out a systematic review and proposed the term Landfill-Mined-Soil-Like-Fractions

(LFMSF). This terminology has been adopted in subsequent studies (Goli and Singh 2023; Goli et al., 2022a; Goli et al., 2022b).

LFMSF constitute a composition of organics materials, soil, debris, and small fragments of metals, plastics, and glass that are separated during landfill mining (Chandana et al., 2021). Research suggests that these fractions have structural similarities to soils and may contain higher levels of nutrients and total organic carbon (TOC) compared to agricultural soils (Mönkäre et al., 2016; Singh et al., 2020). These similarities are especially evident due to the presence of particles similar in size to those in soil, such as silt and clay, which compose the LFMSF (Martinez et al., 2022). The fine grain size of the particles allows them to retain water and nutrients due to their high specific surface area, which can significantly contribute to cropping (Ronquim, 2020).

The increasing demand for food, feed, and biofuels has led to a need for products that can enhance soil fertility. The use of LFMSF as a fertilizer is relevant in this regard. Brazil represents 8% of global fertilizer consumption, ranking fourth in the world, following China, India, and the United States. However, over 80% of the fertilizers used in Brazil are imported, indicating a high reliance on foreign suppliers in a market dominated by few companies. Such reliance makes the Brazilian economy highly dependent on agribusiness and vulnerable to fluctuations in the international fertilizer market. Excessive dependence on imported inputs can represent a significant challenge to food security and the sustainability of agricultural production in Brazil. Therefore, it is crucial to invest in research, development, and national production of fertilizers to reduce this vulnerability and strengthen the country's economic foundation (Brasil, 2022b).

Agriculture is one of the sectors that consumes natural resources the most, depleting nutrients from the soil due to crop removal during harvesting. This can only be corrected by replacing nutrients by mineral or organic fertilization. Additionally, Brazil has large tracts of land with low natural fertility related to high acidity and aluminum (Al) toxicity, as well as low phosphorus (P) fixation capacity, which are characteristic of its tropical location (Novais et al., 2007). Therefore, LFMSF use from landfilled MSW emerges as an environmentally appropriate alternative to reduce the impacts resulting from the extraction of natural resources, in addition to promoting the maintenance of organic matter in the soil. This is especially important in highly weathered soils such as those found in Brazil.

The assessment of the levels of elements considered essential from the point of view of soil fertility and plant nutrition, is crucial to verify whether the LFMSF adequately meets the majority of agricultural nutrient needs which are divided into primary macronutrients (nitrogen (N), phosphorus (P), potassium (K)), secondary nutrients (calcium (Ca), magnesium (Mg) and sulfur (S)), and micronutrients (iron (Fe), boron (B), chlorine (Cl) copper (Cu), manganese (Mn), molybdenum (Mo) and zinc (Zn)). Although essential for agriculture, nutrients can become pollutants when transferred to other ecosystems (Guelfi et al., 2021). Therefore, both elements considered essential and those that have not proven their essentiality can cause adverse effects on both plants and animals when in excess (Silva et al., 2021). For instance, inappropriate use of P and N can harm the quality of drinking water and lead to aquatic systems eutrophication, impacting the sustainability of agricultural and urban areas (Guelfi et al., 2021). Furthermore, it is common to attribute productivity gains solely to the application of fertilizers containing primary macronutrients (N, P and K). Although these nutrients are widely used and increase yields, the supply of other nutrients must be considered. However, due to the origin of LFMSF, in addition to the elements considered essential, they may contain elements categorized as toxic, i.e., their participation in biological processes is not proven and they are classified as priority pollutants, being called potentially toxic elements (PTE), such as arsenic (As), lead (Pb), cadmium (Cd), mercury (Hg), chromium (Cr), antimony (Sb) and tin (Sn). These PTE present high toxicity even at low concentrations, being of great environmental interest (ATSDR, 2022).

Given the above, this research aimed to characterize the LFMSF mined from an MSW cell (eight years of landfilling) at the Delta A sanitary landfill (LFMSF-8) in Campinas city, Southeastern Brazil, and analyze the results of this characterization with the values established in current legislation for organic fertilizers, soil conditioners, and remineralizers and in resolutions that provide for criteria and guiding values for soil quality regarding the presence of chemical substances. The goal is to identify the most appropriate application of LFMSF-8 in agriculture and to provide guidance for future research.

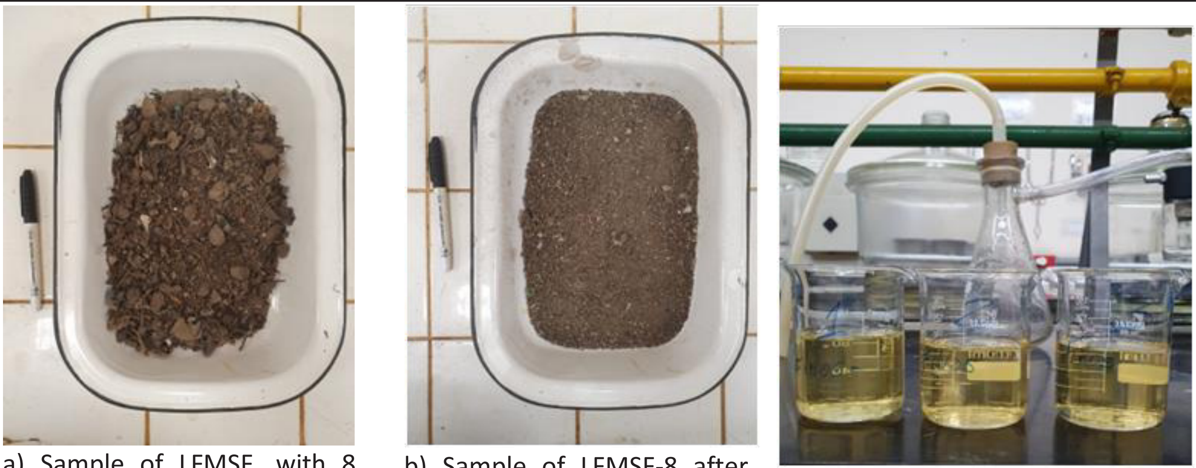
2 MATERIALS AND METHODS

The municipal solid waste (MSW) studied was collected from Delta A sanitary landfill, located in the city of Campinas, Southeastern Brazil. The waste was collected following the Brazilian standard NBR 10007 (ABNT, 2004a). The representative sample of MSW was removed from the landfill in December 2019, coming from a cell that had been landfilled for eight years, totaling around 300 kg in wet mass. This landfill receives waste categorized as Class II-A (non-hazardous and non-inert) and Class II-B (inert) in accordance with NBR 10004 standard (ABNT, 2004b).

The MSW sample was sent to the laboratory and underwent moisture content tests following the Brazilian standard NBR 6457 (ABNT, 2024). The sample was gravimetrically characterized into 25 categories, one of which is LFMSF-8, consisting of particles smaller than 19mm. LFMSF-8 represented 35.56% and 35.65% in relation to the total mass of the sample on a dry and wet basis and moisture content of 49.02% and 32.90%, on a dry and wet basis, respectively. Details of sampling procedures, determination of moisture content, and gravimetric composition can be seen in Leme et al. (2021). Afterwards, the LFMSF-8 category was placed in a freezer at a temperature between −12℃ and −18℃, aiming to stop its degradation process, still in December 2019.

Months later, a portion of the sample was removed from the freezer and thawed (Figure 1a). It was then oven-dried at 60°C until the mass remained constant. Then, the mass was measured using a precision analytical scale accurate to two decimal places with a 4,200 g capacity. Subsequently, the solid sample was crushed in a high-speed granular mill, resulting in material with a diameter of less than 3 mm (Figure 1b). Using 250 g of the crushed sample, the solubilized extract was prepared following the Brazilian standard NBR 10006 (ABNT, 2004c).

Figure 1 – Evolution of landfill material properties through processing



a) Sample of LFMSF, with 8 years of landfilling, before crushing

b) Sample of LFMSF-8 after crushing, with a diameter < 3 mm

c) Solubilized extract of LFMSF-8 after filtration

Source: authors' private collection (2023)

The solubilized extract was obtained by placing 250 g of LFMSF-8 in contact with 1 L of ultrapure water for one week, using a volumetric flask. Then, the solubilized extract underwent three filtration steps. The first step used a 1 mm pore size aquarium net to remove settleable solids. The second and third filtrations were carried out using a vacuum pump system with a compressor. For the second filtration, a fiberglass pre-filter with a 2 µm pore and a 47 mm diameter was used; while the third filtration used a cellulose acetate membrane with a 0.45 µm pore and a 47 mm diameter (Figure 1c).

A liquid sample of approximately 600 mL of the solubilized extract was subjected to chemical characterization tests to determine the potentially toxic elements (PTE) concentration. Nickel (Ni), zinc (Zn), chromium (Cr), and lead (Pb) levels were determined using an optical emission spectrometer with coupled inductive plasma (ICP-OES), specifically the Perkin Elmer – Optima 8300 equipment. Arsenic (As), cadmium (Cd), and mercury (Hg) concentrations were obtained by graphite furnace atomic absorption spectrometry (GF-AAS) using the Perkin Elmer – AA 600 equipment.

To characterize the agronomic potential of solid samples, 200 g of raw LFMSF-8 (uncrushed) were used to determine the primary macronutrients: N, P, K; secondary macronutrients: Ca, Mg, S; micronutrients: B, Cu, Fe, Mn, Zn; potential of hydrogen (pH); total organic carbon (TOC); cation exchange capacity (CEC); organic matter; ash; and carbon-to-nitrogen ratio (C/N) ratio. Such analyses, considering the waste as organic fertilizer, followed the Manual of Official Analytical Methods for Fertilizers and Correctives by the Ministry of Agriculture, Livestock and Food Supply (MAPA) (Brasil, 2017).

The concentrations of PTE, macronutrients, and micronutrients were evaluated in accordance with the values established by Brazilian legislation for organic fertilizers, conditioners, and soil remineralizers. MAPA Normative Instruction No. 61/2020 (Brasil, 2020) was used to evaluate the use of LFMSF-8 as organic fertilizers and biofertilizers, and MAPA Normative Instruction No. 05/2016 (Brasil, 2016a), for remineralizers and plant substrates. Furthermore, MAPA Normative Instruction No. 7/2016 (Brasil, 2016b), which defines maximum limits of contaminants admitted in substrates, organic fertilizers, and soil conditioners, and Brazilian CONAMA Resolution 420/2009 (Brasil, 2009) which establishes concentration limits of chemical substances and quality guidelines for soil, were also considered.

3 RESULTS AND DISCUSSION

3.1 Potential nutrient input for agricultural production purposes

The values of macro and micronutrients, TOC, Organic Matter, Ash, CEC, and pH of LFMSF-8 are presented in Table 1, as well as the values of the same parameters recommended by MAPA's Normative Instructions. It was observed that the LFMSF-8 showed levels below the minimum required for P, Zn, Cu, Mn, and B compared to the standards for remineralizers (BRASIL, 2016a). However, the Fe contents of the LFMSF-8 are within the established limits. When contrasting the values of the LFMSF-8 with the prescribed minimums for solid or fluid organomineral fertilizers for soil application or fertigation, as well as for simple, mixed, compound, and solid or fluid organomineral fertilizers for foliar application and hydroponics (Brasil, 2020), it was found that the LFMSF-8 exceeds the minimum values for Ca, Fe, Mn, B, and CEC, but are below for N, P, K, Mg, S, Zn, Cu, and TOC. These analyses indicate that LFMSF-8 could possibly supply both secondary macronutrients and micronutrients, in addition to presenting a high CEC value.

The C/N ratio of LFMSF-8 is 10, which meets the established (≤ 20) for solid or fluid organomineral fertilizers for soil application or fertigation (Brasil, 2020). C/N ratios are crucial to explain the behavior of organic solid wastes in the soil and their impact on soil fertility. Generally, the C/N ratio of a matured compound ranges from 12 to 20 (Abreu Jr et al., 2005; Brust, 2019). The use of non-stabilized organic fertilizers in agricultural crops can result in nitrogen deficiency for plants. When the organic compound is rich in carbon and poor in nitrogen (non-stabilized condition), soil decomposer bacteria use the nitrogen available in the soil to meet their needs during the decomposition process. This results in a lack of nitrogen available to plants, a situation like what happens when using an unstabilized substrate (Manu et al., 2021).

The moisture content, on a dry basis, of LFMSF-8 exceeded the maximum requirement of 20% for solid organomineral fertilizers intended for soil application or fertigation (Brasil, 2020). The CEC value of 130 mmol kg^{-1} obtained by LFMSF-8 (Table 1) meets the established minimum value of 80 mmol kg^{-1} for solid or fluid organomineral fertilizers applied to the soil or by fertigation (Brasil, 2020). The high CEC is attributed to the nature of the material, highlighting the positive impact of organic matter in improving the soil CEC. This condition improves porosity, aeration, water retention capacity, and microbiological activity when applied to the soil. The Total Organic Carbon (TOC) content of 5.64% obtained by LFMSF-8 (Table 1) meets the 3% requirement for fluid organomineral fertilizers applied to the soil or via fertigation. However, it does not meet the same specification (Brasil, 2020) when the fertilizer is in solid form.

The TOC content of LFMSF-8 is within the range observed by Kaartinen et al. (2013) and Mönkäre et al. (2016), who also studied LFMSF with particle sizes less than 20 mm. However, when examining the organic matter content, differences arise concerning these studies. Note that the MSW collected by Kaartinen et al. (2013) and Mönkäre et al. (2016) was obtained with drilling, while the MSW collected in this research was obtained via trench opening (Leme et al., 2021). The drilling technique used can result in different properties than samples obtained by excavation, as drilling tends to fragment coarser particles. Also, each landfill has specific characteristics, hence, the results of chemical tests can vary considerably according to the site. This variability highlights the need to conduct studies on an individual basis, considering the particularities of each landfill, to evaluate the environmental safety of applying LFMSF to the soil.

Considering that LFMSF-8 did not meet all the requirements stipulated by the Brazilian Normative Instructions consulted regarding nutritional supply, the direct use of these extracted materials may not be appropriate, requiring prior treatment. In this study, the characteristics of a specific LFMSF were outlined. However, factors such as year of disposal, location, type of waste, volume, variations in urban solid waste management, changes in consumption patterns, lifestyle, income, climate, local culture, and the type of urban area (e.g., tourist city or not) can influence LFMSF characteristics. Therefore, depending on the composition of the LFMSF, it may be necessary to supplement fertilization with other sources. The decision on whether mineral fertilization is necessary, in addition to the application of compost, will depend on the nutritional requirements and expected productivity of the crop, soil properties, and the type and quality of the material used, among other factors (Cantarella et al., 2022).

The productivity achieved using only LFMSF will hardly be comparable to that obtained in the conventional cultivation system, in which fertilization and liming recommendations are based on soil analysis. This is due to the imbalance of nutrients in these wastes. To achieve yield compatible with the conventional system, it is essential to manage macronutrients and micronutrients in the soil, by determining the waste application rate based on the characteristics of the soil, the waste, and the crop needs. A viable alternative to complement LFMSF nutrition is composting waste as this is a common practice, whether with urban waste (Silva et al., 2020) or agro-industrial waste (Ferreira et al., 2022) to use as organic fertilizers, soil conditioners, and remineralizers.

Table 1 – Concentration of macronutrients and micronutrients and other levels of agricultural interest in LFMSF-8 compared to remineralizers, simple, mixed, compound and organomineral fertilizers

Parameter	LFMSF-8	MAPA NI no. 05/2016[a]	MAPA NI no. 61/2020[b]	MAPA NI no. 61/2020[c]
Copper (%)	0.01	0.05	0.02	0.02
Boron (%)	0.01	0.03	0.01	0.01
Manganese (%)	0.02	0.1	0.02	0.02
Zinc (%)	0.02	0.1	0.1	0.1
Magnesium (%)	0.23	n.a.	1	0.5
Potassium (K_2O) (%)	0.25	n.a.	1	1
Sulfur (%)	0.47	n.a.	1	0.5
Total phosphorus (P_2O_5) (%)	0.50	1	1	1
Nitrogen (%)	0.53	n.a.	1	1
Iron (%)	1.70	0.1	0.02	0.02
Calcium (%)	2.00	n.a.	1	0.5
TOC (%)	5.64	n.a.	≥ 8* and ≥3**	6
Organic matter (%)	17.6	n.a.	n.a.	n.a.
Ash (%)	82.4	n.a.	n.a.	n.a.
pH	7.4	n.a.	n.a.	n.a.
C/N ratio	10	n.a.	≤ 20	n.a.
CEC (mmol kg^{-1})	130	n.a.	≥ 80	n.a.
CEC/TOC	23	n.a.	n.a.	n.a.

Source: authorship (2024)

Note: n.a) Not analyzed; a) Minimum levels of the macronutrient phosphorus and micronutrients that can be declared in remineralizers (Brasil, 2016a); b) Solid or fluid organomineral fertilizers for application to the soil or fertigation (Brasil, 2020); c) Simple, mixed, compound, and solid or fluid organomineral organic fertilizers for application via foliar and hydroponics (Brasil, 2020), *) For solid product, and **) for fluid product

3.2 Assessment of the concentration of potentially toxic elements (PTE)

After analyzing the concentration of nutrients of interest in LFMSF-8 for agriculture, it is crucial to evaluate the concentration of PTE to ensure safety and effectiveness in LFMSF-8 application.

When comparing the PTE levels in the solubilized extract with the maximum limits recommended for substrates and soil conditioners in Brazil (Brasil, 2016b), the results demonstrate that all concentrations are below the established reference values (Table 2). Therefore, these levels do not represent an impediment to the use of LFMSF-8 in agriculture, suggesting that its use is safe regarding toxic elements.

Furthermore, when considering CONAMA Resolution 420/2009, which regulates soil quality in Brazil (Brasil, 2009), especially for investigating agricultural soils, it seems that LFMSF-8 exhibits low concentrations of PTE. This is particularly important for the application of these fertilizers in agricultural environments, in which soil quality and safety are crucial to achieve successful harvests and avoid negative environmental impacts.

Table 2 – Concentration of potentially toxic elements (PTE) in LFMSF-8 compared to established limits

PTE	Unit	LFMSF-8	MAPA NI no. 7 (2016)[a]	MAPA NI no. 7 (2016)[b]	CONAMA 420 (2009)[c]
Arsenic		<0.0360	20	20	35
Cadmium		<0.0180	8	3	3
Lead		0.0576 ± 0.0072	300	150	180
Chrome	mg kg^{-1}	<0.0324	500	2	150
Mercury		0.0504 ± 0.0036	3	1	12
Nickel		0.1152 ± 0.0036	175	70	70
Selenium		0.2160 ± 0.0360	80	80	-

Source: Authorship (2024)

Note: a) Maximum limits of contaminants allowed in plant substrate (Brasil, 2016b); b) Maximum limits of contaminants allowed in organic fertilizers and soil conditioners (Brasil, 2016b); c) (Brasil, 2009)

Neutral pH (7.4) of LFMSF-8 (Table 1) plays a crucial role in supporting the analysis of the bioavailability potential of cationic elements and oxyanions that are normally present in low concentrations in the environment, usually less than 1 $g.kg^{-1}$, as in the case of the PTE evaluated in this study (Table 2). This occurs because pH directly influences the solubility of elements in the liquid medium, thus affecting their bioavailability and mobility in the soil.

Studies have shown that there is a large movement of PTE in soils with natural conditions, even those with low permeability. Due to anaerobic conditions within landfills, there is the formation of organic acids leading to a decrease in pH. This decrease in pH further increases PTE mobility (Pohland and Harper, 1985). Possibly, due to this high mobility and the age of the waste analyzed (8 years), a large part of the PTE presented in Table 2, if previously present, has already been incorporated into the landfill leachate and is no longer present in significant quantities in LFMSF samples of this age.

Gurusamy and Thangam (2023) carried out an investigation at the Ariyamangalam dump, analyzing LFMSF with a particle size < 18 mm. They were unable to determine the precise landfill age due to the sample extraction process. However, the average concentration of PTE in LFMSF was within the limits established by the World Health Organization (WHO, 2022). The results indicated that the LFMSF presented, in descending order, the following concentrations: Pb (67.1 mg kg^{-1}), Cr (44.7 mg kg^{-1}), Cd (1.41 mg kg^{-1}), Hg (0.14 mg kg^{-1}), and As (0.07 mg kg^{-1}). Despite presenting different ages of landfilling and coming from a “landfill,” these values highlights that the Pb concentration of the LFMSF studied by Gurusamy and Thangam (2023) was more than 1,000 times the Pb concentration of the LFMSF-8 evaluated in our study.

Even though LFMSF have low levels of PTE, the presence of these elements can be attributed to several sources of contamination. Firstly, LFMSF contamination may be due to their own characteristics, as these materials are composed of different waste, such as batteries, paper, paints, bottle caps, pharmaceutical products, cosmetic waste, insecticides, among others (P et al., 2023). Additionally, contamination may result from contact with construction and demolition waste (CDW) deposited in the Delta A sanitary landfill. Mikami et al., (2020) documented the leaching of Cr and Cd from CDW, indicating a potential source of contamination for nearby materials, such as LFMSF-8.

It is important to conduct a detailed analysis of the LFMSF-8 application site, that includes assessing soil fertility for both macro and micronutrients, and paint special attention to ensure the appropriate use of this fraction. It is essential to consider that soils with higher clay content are more susceptible to salinization, while sandy soils have greater leaching potential, leading to the rapid movement of liquids to deeper layers. Additionally, the assessment of the electrical conductivity of the soil solution plays an important role, enabling agile monitoring of possible salinization effects that may arise.

3.3 Implications and Future Directions

The integrated methodology adopted in this study enabled a comprehensive analysis of the potential of landfill mining, considering not only environmental but also economic and social aspects. By integrating diverse perspectives, synergies between material recovery from landfills and sustainable development were identified. Developing technologies to remove PTE from LFMSF and assessing their environmental impacts represent promising avenues for future research.

A significant research direction involves exploring stabilization and solidification processes, as well as bioremediation using microorganisms and plants, to immobilize PTE and make LFMSF-8 safer for soil application. Cutting-edge technologies such as nanotechnology and electrochemistry can offer innovative solutions for efficient and selective removal of these elements (Wijekoon et al., 2022). Concurrently, it is crucial to deepen studies on the behavior of PTE in various soil types, considering factors such as pH, organic matter, and interactions between elements. Assessing impacts on water and air quality, including groundwater contamination and toxic gas emissions, is essential to understand the risks associated with LFMSF-8 use (Poulsen, 2014; Wijekoon et al., 2022). Furthermore, analyzing PTE bioaccumulation in the food chain and conducting ecotoxicity studies are vital to evaluate human and ecological health risks (Burlakovs et al., 2016; Rong et al., 2017). A holistic approach, incorporating life cycle analysis and the development of management tools such as geographic information systems and predictive models, can contribute to more informed and sustainable decision-making regarding LFMSF-8 management.

Nonetheless, it is important to highlight certain considerations of this study, regarding methodological procedures and field application. MSW excavated from sanitary landfills presents great heterogeneity, since in addition to presenting several categories of materials, these categories are not similar in composition and quantity because they reflect the social and economic conditions of society at the time of disposal, and are found in different stages of degradation, depending on the time of landfilling. Thus, the chemical results obtained refer to MSW with a landfilling time of eight years and may be totally or partially different in samples with shorter and/or longer times. Another issue is the representativeness of the LFMSF samples when subjected to chemical tests, depending on their size, since they need to be limited to 1g.

LFMSF-8 must be cautiously applied to the soil due to the presence of PTE. The mobilization of these elements can contaminate groundwater and enter the food chain, posing risks to human health (Gurusamy and Thangam, 2023). It is essential that the use of LFMSF-8 complies with current environmental regulations, considering the maximum permissible limits for PTE. Beyond agriculture, LFMSF-8 may find applications in construction and energy production, provided that appropriate analyses and treatments are conducted to ensure environmental safety (Burlakovs et al., 2016; Chandana et al., 2021).

Despite these limitations, this research outcomes offer valuable insights into the sustainable use of. The research highlighted LFMSF-8 potential as a resource to improve soil fertility, reduce dependence on synthetic fertilizers, and promote a more sustainable agricultural system. Furthermore, the application of LFMSF-8 in degraded areas can contribute to environmental conservation and climate change mitigation. From an urban planning perspective, the results of the study can guide the development of public policies that encourage landfill mining projects in suitable locations (Parrodi et al., 2018; P et al., 2023).

While caution is advised due to the study's limitations, the findings present a promising path for sustainable waste management and agricultural practices. These insights can inform public policies that support landfill mining projects, promoting a more sustainable and resilient urban planning framework. Future research should focus on developing more efficient and cost-effective technologies for treating LFMSF-8 and exploring new applications for this valuable resource. Despite the need for caution, the promising avenues identified in this study pave the way for innovative solutions in waste management and agriculture.

4 CONCLUSIONS

Comparative analyses of LFMSF-8 with standards established for different types of fertilizers reveal a higher Fe content in relation to remineralizers. On the other hand, compared to the requirements for solid or fluid organomineral fertilizers and organic fertilizers for foliar application, LFMSF-8 exhibited higher levels of Ca, Fe, Mn, B, and CEC. Additionally, the analysis of the solubilized product from LFMSF-8 demonstrated PTE concentrations below the maximum limits allowed for organic fertilizers, substrates, and soil conditioners in Brazil.

Regardless of the individual nutrient analysis, when evaluating the nutrient supply potential of LFMSF-8, it is essential to consider the bioavailability of these nutrients to plants, as well as the stability of the organic matter present in this material. Factors such as the solubility of nutrients and the ability of LFMSF to release them gradually can influence the effectiveness of these materials as a source of nutrients for crops. In addition, phytotoxicity tests must be conducted with LFMSF-8 to confirm that the fraction would not harm plant development.

ACKNOWLEDGMENTS

The authors thank the Consórcio Renova and the City Hall of Campinas for supporting the research. Furthermore, special thanks are extended to São Paulo Research Foundation (FAPESP) for the financial support granted during the development of this study (Process 2019/01559-8). We also mention the support from National Council for Scientific and Technological Development (CNPq), which contributed through process 306892/2021-9. Finally, Coordination for the Improvement of Higher Education Personnel, Brazil (CAPES) played a fundamental role in providing master's scholarships (Financing Code 001), thus making this research possible.

REFERENCES

Abdel-Shafy, H. I. & Mansour, M. S. M. (2018). Solid waste issue: Sources, composition, disposal, recycling, and valorization. *Egyptian Journal of Petroleum*, 27 (4), 1275–1290. https://doi.org/10.1016/j.ejpe.2018.07.003

ABNT - Associação Brasileira de Normas Técnicas. (2004a). *NBR 10007*: Amostragem de resíduos sólidos. Rio de Janeiro, RJ.

ABNT - Associação Brasileira de Normas Técnicas. (2004b). *NBR 10004*: Resíduos Sólidos - Classificação. Rio de Janeiro, RJ.

ABNT - Associação Brasileira de Normas Técnicas. (2004c). *NBR 10006*: Procedimento para Obtenção de Extrato Solubilizado de Resíduos Sólidos. Rio de Janeiro, RJ.

ABNT – Associação Brasileira de Normas Técnicas. (2024). *NBR 6457*: Solos - Preparação de amostras para ensaios de compactação, caracterização e determinação do teor de umidade. Rio de Janeiro, RJ.

ABRELPE – Associação Brasileira de Empresas de Limpeza Pública e Resíduos Especiais. (2020). *Panorama dos resíduos sólidos no Brasil 2020*. São Paulo, SP, 51 p. Available at: https://abrelpe.org.br/panorama/. Accessed on: 12 jan. 2024.

ABRELPE – Associação Brasileira de Empresas de Limpeza Pública e Resíduos Especiais. (2022). *Panorama de Resíduos Sólidos Urbanos 2022.* São Paulo, SP, 59 p. Available at: https://abrelpe.org.br/panorama/. Accessed on: 11 de jan. de 2024.

Abreu Jr. C. H., Boaretto, A. E., Muraoka, T. & Kiehl, J. C. (2005). Uso de resíduos orgânicos no pomar. In: Mattos Junior, D. et al. (Eds.). Citros. Campinas: Instituto Agronômico de Campinas/Fundag, p. 871-96.

ATSDR - Agency for Toxic Substances and Disease Registry. (2022). *Substance priority list ATSDR*. Available at: https://www.atsdr.cdc.gov/index.html. Accessed on: 31 de mar. de 2024.

BRASIL. Conselho Nacional do Meio Ambiente – CONAMA. (2009). Resolução CONAMA nº 420, de 28 de dezembro de 2009. Dispõe sobre critérios e valores orientadores de qualidade do solo quanto à presença de substâncias químicas e estabelece diretrizes para o gerenciamento ambiental de áreas contaminadas por essas substâncias em decorrência de atividades antrópicas. Brasília, DF. Available at: https://cetesb.sp.gov.br/areas-contaminadas/wp-content/uploads/sites/17/2017/09/resolucao-conama-420-2009-gerenciamento-de-acs.pdf Accessed on: 13 mar. de 2024

BRASIL. Lei nº 12305. (2010). Institui a Política Nacional de Resíduos Sólidos, altera a Lei. Nº 9605, de 12 de fevereiro de 1998; e dá outras providências. Brasília, DF. Available at: https://www.planalto.gov.br/ccivil_03/_ato2007-2010/2010/lei/L12305.htm. Accessed on: 13 mar. de 2024.

BRASIL. Ministério da Agricultura, Pecuária e Abastecimento. (2016a). Gabinete da Ministra. Instrução normativa nº 5, de 10 de março de 2016. Brasília, DF, 14 mar. 2016. Available at: https://www.gov.br/agricultura/pt-br/assuntos/insumos-agropecuarios/insumos/agricolas/fertilizantes/legislacao/in-5-de-10-3-16-emineralizadores-e-substratos-para-plantas.pdf/view. Accessed on: 02 mar. 2024.

BRASIL. Ministério da Agricultura, Pecuária e Abastecimento. (2016b).Secretaria de Defesa Agropecuária. Instrução normativa nº 7, de 12 de abril de 2016. Brasília, DF. Available at: https://www.in.gov.br/materia/-/asset_publisher/Kujrw0TZC2Mb/content/id/21513067/do1-2016-05-02-instrucao-normativa-n-7-de-12-de-abril-de-2016--21512974. Accessed on: 03 mar. de 2024.

BRASIL. Ministério da Agricultura, Pecuária e Abastecimento. (2017). *Manual de métodos analíticos oficiais para fertilizantes e corretivos*. Brasília: Biblioteca Nacional de Agricultura. 240 p. Available at: https://www.gov.br/agricultura/pt-br/assuntos/insumos-agropecuarios/insumos-agricolas/fertilizantes/legislacao/manual-de-metodos_2017_isbn-978-85-7991-109-5.pdf>. Accessed on: 14 jan. de 2024.

BRASIL. Ministério da Agricultura, Pecuária e Abastecimento (2020). Secretaria de Defesa Agropecuária. Instrução normativa nº 61, de 8 de julho de 2020. Estabelece as regras sobre definições, exigências, especificações, garantias, tolerâncias, registro, embalagem e rotulagem dos fertilizantes orgânicos e dos biofertilizantes, destinados à agricultura. Brasília, DF. Available at: https://www.gov.br/agricultura/pt-br/assuntos/insumos-agropecuarios/insumos-agricolas/fertilizantes/legislacao/in-61-de-8-7-2020-organicos-e-biofertilizantes-dou-15-7-20.pdf. Accessed on: 02 fev. de 2024.

BRASIL. Decreto nº 10.936. (2022a). Regulamenta a Lei no 12.305, de 2 de agosto de 2010, que institui a Política Nacional de Resíduos Sólidos. Diário Oficial da União, Brasília, DF, seção 1, p. 20, 12 jan. 2022a.

BRASIL. Ministério da Agricultura, Pecuária e Abastecimento. 2022b. Plano Nacional de Fertilizantes. Brasília, DF. Available at: https://www.gov.br/agricultura/pt-br/assuntos/insumos-agropecuarios/insumos-agricolas/fertilizantes/plano-nacional-de-fertilizantes/o-plano-nacional-de-fertilizantes. Accessed on: 10 mar. de 2024.

Brust, G. E. (2019). Management Strategies for Organic Vegetable Fertility. In: Biswas, D.; Micallef, S. A. *Safety and Practice for Organic Food*. Massachusetts: Academic Press, p. 193-212.

Burlakovs, J., Kaczala, F., Vincevica-Gaile, Z., Rudovica, V., Orupõld, K., Stapkevica, M., Bhatnagar, A., Kriipsalu, M., Hogland, M., Klavins, M. & Hogland, W. (2016). Mobility of metals and valorization of sorted fine fraction of waste after landfill excavation. *Waste and Biomass Valorization*, 7 (3), 593–602. https://doi.org/10.1007/s12649-016-9478-4

Cantarella, H., Quaggio, J. A., Mattos Jr., D., Boaretto, R. M. & Raij, B. V. (2022). Recomendações de adubação e calagem para o Estado de São Paulo (Boletim Técnico, 100). Instituto Agronômico de Campinas - IAC. Campinas, SP, 1ed, p. 500.

Chandana, N., Goli, V. S. N. S., Mohammad, A. & Singh, D. N. (2021). Characterization and utilization of landfill-mined-soil-like-fractions (LFMSF) for sustainable development: a critical appraisal. *Waste and Biomass Valorization*, 12 (2), 641–662. https://doi.org/10.1007/s12649-020-01052-y

Ferreira, T. S., Pêgo, R. G., Antunes, L. F. S., Correia, M. F., Martins, R. C. F. & Carmo, M. G. F. (2022). Quality of seedlings of different pepper genotypes grown in millicompost: an organic substrate generated by millipedes' activity. *International Journal of Recycling Organic Waste in Agriculture*, 11 (3), 291-300. DOI: 10.30486/IJROWA.2021.1908263.1126

Gurusamy, S. & Thangam, R. S. P. (2023). Potential health risk assessment of contaminants in soil-like material recovered from landfill mining. *Environmental Monitoring and Assessment,* 195 (2), 330. https://doi.org/10.1007/s10661-022-10850-x

Goli, V. S. N. S. & Singh, D. N. (2023). Extraction and characterization of microplastics in Landfill-Mined-Soil-like-Fractions: A novel methodology. *Chemical Engineering Journal*, 452, 139217. https://doi.org/10.1016/j.cej.2022.139217

Goli, V. S. N. S., Singh, P., Singh, D. N., Singh, D. N. & Tak, L. K. (2022a). Investigations on characteristics of landfill-mined-soil-like-fractions and their dependency on organic matter. *Process Safety and Environmental Protection*, 162, 795–812. https://doi.org/10.1016/j.psep.2022.04.052

Goli, V. S. N. S., Singh, P. & Singh, D. N. (2022b). A comprehensive methodology for determining buffering capacity of landfill-mined-soil-like-fractions. *Science of The Total Environment*, 833, 155188. https://doi.org/10.1016/j.scitotenv.2022.155188

Guelfi, D., Silva, R. C., Otto, R. & Cantarella, H. (2021). Avanços nas pesquisas e tecnologias para fertilizantes nitrogenados, fosfatados e potássicos. *Tópicos em Ciência do Solo*, 11, 100-159.

Hogland, W., Marques, M. & Nimmermark, S. (2004). Landfill mining and waste characterization: a strategy for remediation of contaminated areas. J*ournal of Material Cycles and Waste Management*, 6, 119-124. https://doi.org/10.1007/s10163-003-0110-x

Kaartinen, T., Sormunen, K. & Rintala, J. (2013). Case study on sampling, processing and characterization of landfilled municipal solid waste in the view of landfill mining. *Journal of Cleaner Production*, 55, 56–66. https://doi.org/10.1016/j.jclepro.2013.02.036

Krook, J., Svensson, N. & Eklund, M. (2012). Landfill mining: A critical review of two decades of research. *Waste Management*, 32 (3), 513–520. https://doi.org/10.1016/j.wasman.2011.10.015

Leme, M.A.G., Takeda, C.M., Silva, K.G., silva, J.C.V., Miguel, M.G. 2021. Gravimetric Characterization of Brazilian Municipal Solid Waste Mined from Landfill for Assessment of Reuse Potential. In: 18th International Symposium on Waste Management and Sustainable Landfilling. Sardinia2021, Cagliari/Itália: CISA Publisher, 2021

López, C. G., Küppers, B., Clausen, A. & Pretz, T. (2018). Landfill mining: a case study regarding sampling, processing and characterization of excavated waste from an Austrian landfill. *Detritus*, 2, 29-45. https://doi.org/10.31025/2611-4135/2018.13664

Manu, M. K., Li, D., Liwen, L., Jun, Z., Varjani, S. & Wong, J. W. C. (2021). A review on nitrogen dynamics and mitigation strategies of food waste digestate composting. *Bioresource Technology*, 334, 125032. https://doi.org/10.1016/j.biortech.2021.125032

Martinez, S., Gabriel, J. L., Allende-Montalbán, R., San-Juan-Heras, R. & Delgado, M.D.M. (2022). The application of a bio-stabilized municipal solid waste-based fertilizer for buckwheat production. Agriculture, 12 (6), 776. https://doi.org/10.3390/agriculture12060776

Mikami, R.J., Kummer, A.C.B. & Döll, M.M.R. (2020). Leaching of pervious concrete produced using mixed recycled aggregates. *Brazilian Archives of Biology and Technology*, 63, e20180408. https://doi.org/10.1590/1678-4324-2020180408

Mönkäre, T. J., Palmroth, M. R. T. & Rintala, J. A. (2016). Characterization of fine fraction mined from two finnish landfills. *Waste Management*, 47, 34-39. https://doi.org/10.1016/j.wasman.2015.02.034

Novais, R. F., Alvarez, V. V. H., Barros, N. F., Fontes, R. L. F., Cantarutti, R. B. & Neves, J. C. L. (Ed.). (2007). *Fertilidade do Solo*. Viçosa: SBCS, 1017 p.

P, D., Rathod, D. & Muthukkumaran, K. (2023). Characterization of soil-like material restored from landfill mining activities in Indian cities. *Australian Journal of Civil Engineering*, p. 1–18. https://doi.org/10.1080/14488353.2023.2192022.

Parrodi, J. C. H., Höllen, D. & Pomberger, R. (2018). Characterization of fine fractions from landfill mining: A review of previous investigations. *Detritus,* 2 (1), 46. https://doi.org/10.31025/2611-4135/2018.13663

Pohland, F. G. & Harper, S. R. (1985). Critical review and summary of leachate and gas productions from landfills. Available at: https://nepis.epa.gov/Exe/ZyPDF.cgi/20007KHC.PDF?Dockey=20007KHC.PDF. Accessed on: 17 fev. 2024.

Poulsen, T. G. (2014). Landfilling, past, present and future. *Waste Management & Research*, 32 (3), 177–178. https://doi.org/10.1177/0734242X14524132

Prechthai, T., Parkpian, P. & Visvanathan, C. (2008). Assessment of heavy metal contamination and its mobilization from municipal solid waste open dumping site. *Journal of Hazardous Materials*, 156 (1), 86–94. https://doi.org/10.1016/j.jhazmat.2007.11.119

Rong, L., Zhang, C., Jin, D. & Dai, J. (2017). Assessment of the potential utilization of municipal solid waste from a closed irregular landfill. *Journal of Cleaner Production*, 142, 413–419. https://doi.org/10.1016/j.jclepro.2015.10.050

Ronquim, C. C. (2020). Conceitos de fertilidade do solo e manejo adequado para as regiões tropicais - Embrapa Territorial, Campinas 2. ed. p. 36.

Silva, M. T., Martinazzo, R., Silva, S. D. A., Bamberg, A. L., Stumpf, L., Fermino, M. H., Kohler, T. W., Matoso, E. S. & Valgas, R. A. (2020). Innovative substrates for sugarcane seedling production: sewage sludges and rice husk ash in a waste-to-product strategy. *Industrial Crops and Products*, 157, 112812. https://doi.org/10.1016/j.indcrop.2020.112812

Silva, R. C., Otto, R., Cantarella, H. & Guelfi, D. (2021). Fertilizantes contendo macronutrientes secundários, micronutrientes e elementos benéficos: Inovações e perspectivas. *Tópicos em Ciência do Solo*, 11, 160-193.

Singh, A. & Chandel, M. K. (2020). Effect of ageing on waste characteristics excavated from an Indian dumpsite and its potential valorisation. *Process Safety and Environmental Protection,* 134, 24–35. https://doi.org/10.1016/j.psep.2019.11.025

Sousa, T. A. T. D., Dantas, E. R. B., Lopes, W. D. S., Leite, V. D., Souza, J. T. D. & Lopes, W. S. (2023). Toxicity assessment of sanitary landfill leachate before and after Fenton treatment process. *Science of The Total Environment*, 893, 164870. https://doi.org/10.1016/j.scitotenv.2023.164870

WHO – WORLD HEALTH ORGANIZATION. (2022). Guidelines for drinking-water quality: Fourth edition incorporating the first and second addenda, 614 p. Available at: https://www.who.int/publications/i/item/9789240045064. Accessed on: 20 mar. de 2024.

Wijekoon, P., Koliyabandara, P. A., Cooray, A. T., Lam. S. S., Athapattu, B. C. L., Vithanage. M. (2022). Progress and prospects in mitigation of landfill leachate pollution: Risk, pollution potential, treatment and challenges. *Journal of Hazardous Materials*, 421, 126627. https://doi.org/10.1016/j.jhazmat.2021.126627

Authorship contributions

1 – Lucas Antonio de Oliveira

Civil Engineer, Master’s student in Civil Engineering
https://orcid.org/0009-0005-9393-1502 • lucasoliveiramb@hotmail.com
Contribution: Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft

2 – Jerusa Schneider

Agronomist, PhD in Soil Science
http://orcid.org/0000-0003-1176-8309 • jschneider@uesc.br
Contribution: Conceptualization, Formal analysis, Investigation, Methodology, Supervision, Validation, Writing – review & editing

3 – Diego Costa Romeiro

Environmental Engineer, M.Sc. in Civil Engineering
https://orcid.org/0000-0002-5204-5070 • diegocostaromeiro@hotmail.com
Contribution: Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft

4 – Miriam Gonçalves Miguel: (Corresponding Author)

Associate Professor
https://orcid.org/0000-0002-3363-9703 • mgmiguel@fec.unicamp.br
Contribution: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Validation, Writing – review & editing

How to quote this article

Oliveira, L. A. de, Schneider, J., Romeiro, D. C., & Miguel, M. G. (2025). Chemical characterization of Landfill-Mined-Soil-Like-Fractions (LMSLF) for application as fertilizer or soil conditioner. *Ciência e Natura*, Santa Maria, 47, spe. 2, e91546. DOI: https://doi.org/10.5902/2179460X91546