



# Biogas production from the landfilled easily degradable fraction of municipal solid waste: mining strategy for energy recovery

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Received: 14 May 2022 / Revised: 11 August 2022 / Accepted: 26 August 2022  
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## Abstract

The growing demand for space and financial resources to manage current and new municipal solid waste (MSW) landfills has become a massive challenge for several countries. Additionally, landfills contribute to adverse environmental impacts such as pollution and CO<sub>2</sub> (carbon dioxide) and CH<sub>4</sub> (methane) emissions. This paper has analyzed the possibility of producing biogas from landfilled MSW. An easily degradable fraction of landfilled MSW with 8 years of landfilling was mined and subjected to chemical characterization and elemental composition analysis. The abbreviation for the study sample was called ED8 – Mined. The low values of lignin (24.5%) and nitrogen content (0.7%) and high values of holocellulose (75.9%) and C/N (46.1%) on dry basis were obtained resulting in materials with the potential to be used for biogas generation. Recalcitrant materials were found in greater amounts than easily biodegradable fresh MSW fractions. The reuse of energy from landfilled MSW can contribute positively to the country's environment and economy, reducing environmental liabilities and generating energy in a controlled way. In Delta A Sanitary Landfill, Southeastern Brazil, the recovery of the ED8 – Mined would reflect a significant recovery of about 100,000 tonnes of landfilled materials for annual MSW cells of about 450,000 tonnes, allowing recovery of materials and space expansion for rejects.

**Keywords** Anaerobic digestion · Landfill mining · Municipal solid waste · Recovery · Energy

**Statement of Novelty** Biogas production potential by anaerobic digestion from easily degradable fractions of MSW is the research object in some energy recovery studies; however, these research use fresh waste. Therefore, since sanitary landfills are current global liabilities, it is necessary for a strategy for energy recovery by biogas production from the landfilled MSW, given its different composition. So, the characterization of landfilled MSW can richly contribute to landfill mining activities, seeking recovery energy, and still, allow expansion of useful space for rejects in the sanitary landfills. However, limited literature in South America shows that the landfilled MSWs are generally not valorized. Moreover, the paper also evaluates environmental benefits and policy implications on biogas production from the easily degradable fraction of landfilled MSW.

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## 1 Introduction

Energy is essential to life and development; however, energy production conventional methods and energy use generally imply negative environmental impacts, so the studies that seek conservation and optimization of energy sources, such as biogas production from municipal solid waste (MSW), directly influence sustainable development and economic improvement [1].

Additionally, the scarcity of adequate areas for installing and operating new sanitary landfills in large urban centers and the unavailability of modern technologies for MSW treatment make waste management a vast and current

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challenge for Brazil [2]. Each year, more than 900,000 tonnes of MSW are disposed of in Brazilian sanitary landfills since they are the main form of adequate waste disposal in the country [3]. The annual increase of MSW disposal in sanitary landfills requires areas and financial resources to manage, contributing to the rapid reduction of their useful life and carbon dioxide (CO<sub>2</sub>) and methane (CH<sub>4</sub>) emission [1].

The Delta A Sanitary Landfill, located at Campinas city (22°54'50"S; 47°08'41"W), southeastern Brazil, was designed to receive domestic waste, pruning and weeding services, and solid waste from health services (after microwave treatment). It operated from 1993 to 2013 and is currently a transshipment area. In 2013, the per capita MSW disposal in Campinas was 1.11 kg/inhabitant/day, with 1,114,862 inhabitants [4], thus totaling about 1237.69 t/day of MSW disposed of in the Delta A Sanitary Landfill [5].

According to the MSW State Inventory of 2013, when Delta A Sanitary Landfill closed MSW disposal in site, it was classified as an adequate condition until the end of its activities, ending with a Waste Quality Index score of 9.6, which ranges from 7.1 to 10.0 for acceptable conditions [5]. The Waste Quality Index is based on the technical, environmental, sanitary, structural, and operational requirements of the treatment and final destination of MSW in the municipalities of São Paulo State, Brazil [5]. The current generated Campinas MSW is disposed of in a private sanitary landfill in an adjacent municipality, causing high costs for Campinas city hall in addition to those of maintenance of Delta A Sanitary Landfill. This fact reveals the urgency of studying the feasibility of mining this sanitary landfill to reuse the area for new rejects disposal.

The primary and secondary recyclings are quite inaccessible for most fractions obtained from mined MSW due to their highly heterogeneous compositions and presence of possible contaminants, so the transformation of mined materials into energy becomes more viable, being adapted to the characteristics of the material obtained [6]. The MSWs deposited in sanitary landfills, which are often closed due to reaching their maximum capacity, have a high fuel content and calorific value, allowing their mining and recovery to generate sustainability actions and increase the useful life of these sites [7]. The plastic, paper, cardboard, textiles, and wood mined fractions were considered usable energy fractions found in mined MSW samples with 11 years old in a Finland sanitary landfill [8]. MSW mined in Belgium sanitary landfill, from about 40 years of landfill, presented relatively high calorific values of 15,328 J/g for paper and 17,096 J/g for wood [6].

Although the easily degradable fractions of MSW comprises a material consisting mostly of residential paper, cardboard, organic matter, pruning, and wood, it can contain various contaminants adhered to its compounds, given

landfilled time, such as small fragments of plastic, pathogens, and even metals that, when in high concentrations, are harmful to health and the environment. Study of the potential of mined MSW for energy recovery showed that several processes and technologies for converting mined MSW into energy. Each technologies of them being better or worse depending on specific variables of each waste, such as land-filling age, way of managing the sanitary landfill, ranges of calorific value, moisture content of waste, granulometry of its components, high or low presence of contaminating materials, such as organic matter or heavy metals, presence of volatile organic compounds, and among others. This way, after sorting and separating the mined waste into categories, materials with high calorific value can be treated by waste-to-energy technologies, such as incineration, gasification, pyrolysis, and anaerobic digestion [9]. Energy recovery from mined waste can occur in the form of electricity or heat [10].

The MSW biodegradable fraction is heterogeneous, consisting of several subfractions. The cellulose, lignin, sugars, lipids, and proteins comprise the main degradable chemical compositions of MSW biodegradable fractions, which consist not only of food waste but also of paper, cardboard, textile, leather, and wood [11]. Therefore, the waste biodegradable fraction can also be considered a heterogeneous energy source, depending on its composition [12]. The proper management of MSW biodegradable fraction can be done by anaerobic digestion of microorganisms, called methanization [2]. This digestion generates biogas, with high energy power [13], which contains about 60% of methane [14] and can reduce or mitigate adverse environmental impacts and become a source of energy [15].

The anaerobic digestion can increase the sanitary landfill's useful life by municipal waste mass and volume reduction, and it represents a potential electricity generation. However, before MSW recovery, energy planning is essential to realize a complete diagnosis, including quantification and detailed characterization [13]. Thus, the biogas generating possibility from the landfilled MSW biodegradable fraction, by landfill mining technique, can be discussed, recovering them and reducing the spent of natural resources, contamination by CH<sub>4</sub> emissions and leachate, increasing sanitary landfill useful life and area [16]. Consequently, knowing the mined MSW used and its specific characteristics is essential. Thus, for the first discussion of FD—Mined, in its potential for energy recovery, we worked with the hypothesis that this material is capable of generating energy through anaerobic digestion by biogas production since this is already a technology that occurs naturally in landfills, including in Delta A Sanitary Landfill [1].

The easily degradable fractions of MSW anaerobic digestion process to obtain biogas are the object of research in many global energy recovery projects; however, these research use fresh waste, recently discarded, and not even

landfilled waste. Therefore, it is necessary to characterize the easily degradable fractions of landfilled MSW, mined from sanitary landfill cells, given its different physical and chemical composition for biogas production plants. So, the characterization of landfilled MSW can richly contribute to landfill mining activities, seeking recovery energy and still allow materials recovery and expansion of useful space for rejects in the sanitary landfills, which are reaching maximum capacity. Therefore, this research aims to obtain and analyze the chemical and elemental composition of the easily degradable fraction of landfilled municipal solid waste within 8 years of disposal in a sanitary landfill in Southeastern Brazil. The abbreviation for the study sample was ED8 – Mined, suggesting the sample was composed of an easily degradable fraction of a mined MSW with 8 years of landfilling. Furthermore, was evaluated the ED8 – Mined for energy generation through biogas production from the anaerobic process. Although specific energy recovery tests were not carried out in FD—Mined, its physical–chemical characterization performed in this study was essential to obtain previous results that can help in decision-making for Campinas and all of Brazil, which is also relevant when considering works with mined waste.

## 2 Materials and methods

The research followed six steps (Fig. 1): (i) material collection by landfill mining technique; (ii) mixing and quartering, in situ, for representative MSW sample obtaining; (iii) gravimetric characterization in 25 categories; (iv) sample preparation by drying, crush and mixed in representative

percentages based on the dry gravimetric characterization of ED8 – Mined; (v) laboratory analysis of chemical characterization and the elemental composition; and (vi) data analysis.

### 2.1 Sample preparation: easily degradable fraction of landfilled

The ED8 – Mined studied was composed of organic matter, paper, cardboard, wood, and pruning, obtained from the mining of municipal waste cells with 8 years of landfilling in Delta A Sanitary Landfill (Campinas City — Brazil). The focus of research in the five categories was given by the high disposition of easily degradable fractions in Brazilian landfills, corresponding to 61.1% of fresh MSW in Campinas [17] and 55.7% of fresh MSW in Brazil [18], in wet basis. These values were reduced after 8 years of landfilling but yet they corresponded significantly to 23.164% of Campinas’ landfilled MSW [19]. Furthermore, the easily degradable fraction of landfilled municipal solid waste shows the energy potential described in the scientific literature [1, 2, 13, 14, 15, 20]. The easily degradable fraction corresponds to categories with an average degradation time of up to 50 years in a sanitary landfill.

The MSW collection was realized on December 16, 2019, using a backhoe to open a trench in an MSW cell of the Delta A Sanitary Landfill, aged approximately 8 years. The trench had 2.5 m (width), 6.0 m (length), and 2.8 m (depth), being removed 1.0 m of the cover layer. The representative sample collected (about 250 kg) was tactile-visual separated into 25 categories: organic matter, paper, cardboard, wood, pruning, hard plastic, soft plastic, plastic bags, rubber, glass, styrofoam, construction and demolition waste (CDW), compound

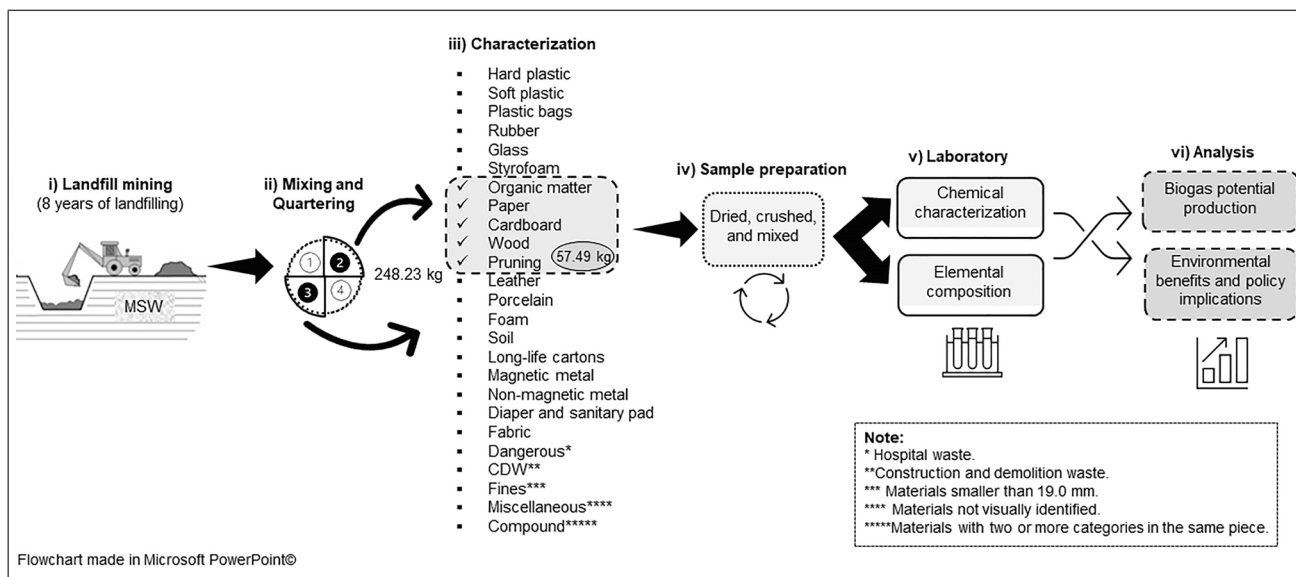


Fig. 1 Research steps flowchart

(materials with two or more categories in the same piece), leather, porcelain, foam, soil, fines (smaller than 19.0 mm), long-life cartons, magnetic metal, non-magnetic metal, diaper and sanitary pad, fabric, dangerous (hospital waste), and miscellaneous (materials that are not visually identified) (Fig. 2). After separation, a 500 g sample of each category was subjected to the drying in an oven at 60 °C to obtain the moisture contents on a dry and wet basis and dry basis gravimetric composition. More details of waste collection, separation, gravimetric characterization, and moisture content determination methodologies were presented in [19].

The categories of organic matter, paper, cardboard, wood, and pruning were dried in a laboratory oven at 60 °C (recommended value to avoid loss of solids by volatilization) [21]. After this, they were separately crushed using a granulator mill to obtain a sample equal to or less than 3.0 mm in diameter (Fig. 3). Therefore, they were adequately mixed in representative percentages based on the dry gravimetric characterization of ED8 – Mined, which was composed of 27.7% of organic matter, 34.9% of paper, 6.8% of cardboard, 16.6% of wood, and 14.0% of pruning, on a dry basis (Fig. 3).

## 2.2 Chemical characterization

The ED8 – Mined were homogenized, quartered, and separated into three portions (samples I, II, and III) and carried

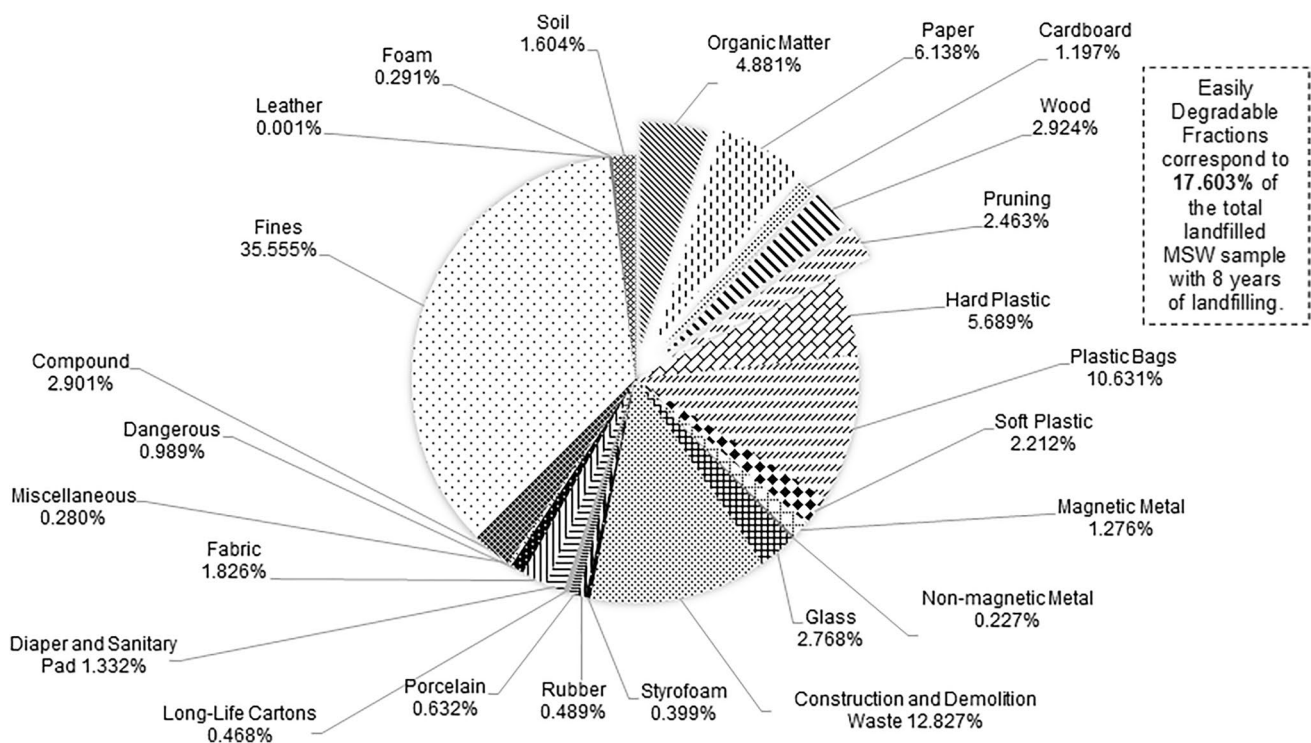
out in triplicate (A, B, and C) for lipid, lignin, and holocellulose contents determination since MSW materials are very heterogeneous. Lignin, cellulose, and hemicellulose are essential components of lignocellulosic biomass [22], beyond lipids. The holocellulose (cellulose plus hemicellulose) is the total carbohydrate fraction of biomass after lignin removal [23].

### 2.2.1 Lipid content


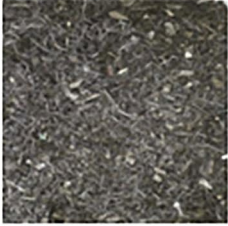


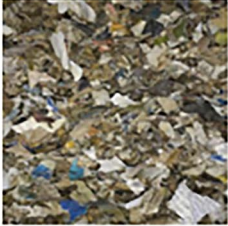


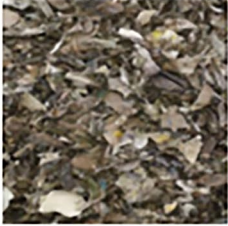







The lipid content determination was carried out in the Soxhlet apparatus system using cyclohexane p.a. (C<sub>6</sub>H<sub>12</sub>) as a solvent extraction for 3 h according to the procedures of NREL/TP – 510 – 42,619 [24], adapted to methodologies of sugarcane bagasse and straw chemical characterization [25], and lignocellulosic analysis procedures [26], adjusting the procedures for MSW samples.

### 2.2.2 Lignin content

The soluble and insoluble lignin contents were determined by procedures of NREL/TP methodology – 510 – 42,618 [27]. First, the solid sample, extractives free, was diluted in sulfuric acid 72% (m/m) in an incubator at 185 rpm agitation and 30 °C for homogenization. Then, the ultrapure water was added, and the samples were placed in a vertical autoclave for an hour (121 °C). After cooling, the sample



**Fig. 2** Gravimetric characterization of representative MSW sample in dry basis (highlights of ED8 – Mined) (source: adapted from [19])

Category	a) Field material (dry) (Sanitary landfill cell)	b) Crushed material (3.0 cm sieve)	c) Crushed material (3.0 mm sieve)	Gravimetric percentage (dry basis)	Percentage in ED8 – Mined
Organic Matter				4.881%	27.7%
Paper				6.138%	34.9%
Cardboard				1.197%	6.8%
Wood				2.924%	16.6%
Pruning				2.463%	14.0%

**Fig. 3** The categories’ physical aspect of ED8 – Mined: **a** in the sanitary landfill cell, **b** crushed with 3.0 cm, and **c** crushed with 3.0 mm of diameter

was filtered, and the liquid fraction obtained was analyzed in a spectrophotometer for soluble lignin determination. The solid fraction remaining from filtration was dry in a laboratory oven (105 °C) and a muffle (575 °C) for insoluble lignin content determination. All samples were carried out in triplicate.

### 2.2.3 Holocellulose content

For holocellulose content determination, the solid sample, extractives free, was placed in an Erlenmeyer with deionized water, sodium chlorite, and acetic acid in a thermostatic bath (75 °C). After the bath, the sample was filtered. The solid

fraction remaining from filtration was dried in a laboratory oven (105 °C) for holocellulose content determination, calculated by the difference between the initial dry mass and the procedure final dry mass. The holocellulose content was determined according to [23].

### 2.3 Elemental composition

The ED8 – Mined were homogenized, quartered, separated, and analyzed in three distinct portions (samples I, II and III). The elemental composition analyses were performed to determine carbon (C), hydrogen (H), and nitrogen (N) content in ED8 – Mined.

### 2.4 Biogas potential production from ED8 – Mined

The ED8 – Mined for energy potential through biogas production from the anaerobic process was evaluated by laboratory analysis of chemical characterization and elemental composition. The results were discussed by comparing chemical characterization and elemental composition for Brazilian and Campinas fresh and landfilled MSW. In addition, carbon to nitrogen ratio (C/N), holocellulose (cellulose plus hemicellulose), lipid, and lignin concentrations of ED8 – Mined were used to discuss the materials' biodegradability, determine the degree of stabilization of MSW and evaluating the methane potential.

### 2.5 Environmental benefits and policy implications

The Brazilian environmental benefits and policy implications of landfill mining activities were briefly discussed but in essential points, based on chemical characterization and elemental composition results of ED8 – Mined, since Campinas is a social and economic important city in Brazil, responsible for significant greenhouse gas emissions and has a closed sanitary landfill for reaching maximum capacity. Campinas, such as Brazil, have current environmental, social, and economic problems with sanitary landfills and no relevant activities with mined waste.

## 3 Results and discussion

The research evaluated the easily degradable fraction of landfilled municipal solid waste with 8 years of disposal in a sanitary landfill in Southeastern Brazil for energy generation through biogas production from the anaerobic process. For this, the chemical characterization and the elemental composition were obtained for dry and crushed (3.0 mm sieve) material, mixed in representative percentages based on the dry gravimetric characterization of ED8 – Mined.

### 3.1 Biogas potential production from ED8 – Mined

ED8 – Mined chemical characterization and elemental composition are presented in Table 1.

The ED8 – Mined presented high values of holocellulose content and lower lignin and lipids contents in comparison, being related to its gravimetric composition, with a higher content of paper and cardboard (41.7%), followed by organic matter (27.7%), wood (16.6%), and at last pruning (14.0%). The lipid, lignin, and holocellulose content sum were higher than 100%, in dry basis (Table 1). This situation can probably be due to “impurities” in ED8 – Mined samples such as plastics, rubber, and other small waste fragments or sample heterogeneity such as different types of paper, wood, cardboard, organic matter, and pruning. Chemical characterization (Table 1) showed positive for the initial analysis for the potential use of these categories in the biogas generation, demonstrating that these materials are not yet fully biodegraded, even after 8 years of landfill. The holocellulose (cellulose plus hemicellulose) and lignin concentrations of landfilled MSW have been used to characterize the materials' biodegradability, in addition to determining the degree of stabilization of MSW, and evaluating the potential for methane [28]. The ED8 – Mined presented a holocellulose to lignin ratio average of 3.1. The fresh MSW and the mined MSW with up to 2 years of landfilling showed an average holocellulose to lignin ratio of about 3.0 and 1.0, respectively [11, 29]. In this way, the ED8 – Mined is still in the rapid degradation stage, even after 8 years of landfilling, demonstrating a considerable presence of non-recalcitrant organic fraction, susceptible to anaerobic biodegradation.

The holocellulose to lignin ratio is expected to decrease during methane production in anaerobic conditions [30]. The holocellulose to lignin ratio of ED8 – Mined was similar to Brazil's fresh organic fraction value (food waste, paper, cardboard, textile, leather, and wood) of 3.27 [11], which is positive over biogas generation aims.

On the other hand, the biodegradable fraction (food waste and pruning) of Campinas MSW landfilled for 3 years [31] had a smaller holocellulose to lignin ratio average (1.64) than 8 years of landfilling, and this can be explained by a large amount of pruning, rich in lignin. Therefore, the landfilled MSW biodegradable fraction can be used in energy generation to convert highly functionalized molecules into methane and carbon dioxide [32]. However, lignin content can be a limiting compound present in landfilled MSW for biogas production aims.

In the comparison of holocellulose, lignin, and lipids contents in the fresh organic fraction (food waste, paper, cardboard, textile, leather, and wood) of MSW in Brazil, in on a wet basis (18.94%, 5.80%, and 0.64%) [11], the biodegradable fraction (food waste and pruning) of Campinas MSW landfilled with 3 years (28.63%, 20.78%, and 2.79%),

**Table 1** The lipid, lignin, holocellulose, nitrogen, carbon, hydrogen contents, and C/N in ED8 – Mined, in dry basis

ED8 – Mined	Lipid (%)	Soluble lignin (%)	Insoluble lignin (%)	Total lignin (%)	Holocellulose (%)	N (%)	C (%)	H (%)	C/N	Total (%)
Sample I—A	4.82	1.34	23.78	25.12	72.45	0.74	32.06	4.79	43.32	37.91
Sample I—B	4.86	1.38	24.97	26.34	74.69					
Sample I—C	4.94	1.36	24.85	26.22	77.32					
Average	4.87 ± 0.06	1.36 ± 0.02	24.53 ± 0.66	25.89 ± 0.67	74.82 ± 2.44					
Sample II—A	5.04	1.32	24.27	25.59	77.98	0.76	36.72	5.73	48.32	43.47
Sample II—B	5.14	1.37	23.38	24.75	76.59					
Sample II—C	5.8	1.37	22.42	23.79	75.98					
Average	5.33 ± 0.41	1.35 ± 0.03	23.36 ± 0.93	24.71 ± 0.90	76.85 ± 1.03					
Sample III—A	4.43	1.35	17.55	18.9	74.45	0.77	35.84	5.65	46.55	42.5
Sample III—B	4.86	1.4	24.42	25.82	75.89					
Sample III—C	4.32	1.54	22.49	24.03	78.23					
Average	4.54 ± 0.29	1.43 ± 0.10	21.49 ± 3.54	22.92 ± 3.59	76.19 ± 1.91					
Average (3 samples)	4.91 ± 0.40	1.38 ± 0.04	23.13 ± 1.54	24.51 ± 1.50	75.95 ± 1.04	0.76 ± 0.01	34.87 ± 2.53	5.39 ± 0.52	46.06 ± 2.53	41.29 ± 2.97

in dry basis [31], and the ED8 – Mined (75.95%, 24.51%, and 4.91%), in dry basis, the contents of the materials increased with landfilled time, affirming their more complex degradation by anaerobic digestion over time. The cellulose, hemicellulose, and lignin comprise essential plant compounds, while lignin is more complex, being a highly branched and recalcitrant polymer to chemical and enzymatic degradation. In addition, lignin is insoluble in water and is present mainly in the stems and seeds of vegetables, fruits, and cereals [33]. In the anaerobic biodegradation process, lipids are organic compounds not easily decomposed, including vegetables and animal materials [34]. The lignin and holocellulose structures are hardly biodegradable by the anaerobic microorganisms, resulting in very long retention times and a low digestion output [15]. Feedstock with higher lignocellulosic content comprises less biodegradable feedstock, presenting the lowest volatile solids removal but better anaerobic digestate stability [35, 36]. Therefore, ED8 – Mined presents material for biogas production but with a more significant amount of recalcitrant materials for anaerobic microorganisms than fresh wastes. But comparing lignin content in the organic fraction of Brazilian fresh MSW (food waste, paper, cardboard, textile, leather, and wood) obtained by [11] (5.80%), on a wet basis, and in the total fresh MSW in Northeastern Brazil obtained by [37] (8.90%), in dry basis, the organic fraction presented lower values of this recalcitrant compound. Therefore, segregation of landfilled MSW in categories of the easily degradable fraction could be positive for biogas generation compared to whole MSW samples, which contain fragments of plastics, metals, rubber, and others. However, it should be emphasized that there will be labor costs of segregation in this activity. The view that landfill mining corresponds to a probable environmental mitigation activity should be accounted. The segregation operation would be part of a proper management operation.

Another point to discuss is the ED8 – Mined dimension in Delta A Sanitary Landfill, which may influence the efficiency and time of the anaerobic degradation process to obtain biogas. The large biodegradable particles are considered impurities of the organic fraction of MSW [20], and they need a size reduction beneficiation before the biogas production process [38]. The organic matter category (organic fragments and seeds) corresponded to smaller materials in the sample, with 73.37% of them in 2.0 mm to 6.0 cm dimension range; paper (fragments of bond paper, newspaper, others) and pruning (branches, foliage, and tree leaf), which consisted of 70.02% and 78.77% of materials in 2.0 mm to 20.0 cm dimension range, respectively; cardboard (cardboard fragments and paper cup holders), consisting of 60% of materials in 6.0 to 20 cm dimension range; and, corresponding with the largest dimension materials in the sample, the wood categories (wooden floor fragments, wooden sheets, others) with 60% of materials in

20 to 50 cm dimension range (Fig. 4). The waste materials are non-symmetric objects. The dimension considered and noted was the most significant extension of the material. The large biodegradable particles impurities observed in the ED8 – Mined were whole newspapers and fruit seeds, tree leaves, branches, and low-quality wooden fragments.

One more important fact for large biodegradable particles present in ED8 – Mined is that most MSW is stored in plastic bags (garbage bags) for collection and disposal, wrapping biodegradable fractions in plastic material. These allow few and slower biodegradable fraction degradations in a sanitary landfill. Thus, the ED8 – Mined milling before entering biogas generation reactors should be discussed due to the material fragmentation of smaller pieces which can increase the substrate availability and biodegradability. In this way, by particle sizes from Campinas ED8 – Mined processing by a mill is essential to reduce the particle sizes to improve the biogas generation process.

ED8 – Mined chemical characterization and elemental composition (Table 1) indicated that its carbon possibly comes mostly from cellulose compounds than from lignin and lipid, given the higher increase by holocellulose content with landfilling time. Lower carbon content from lignin is better for biogas generation potential since lignin is a significant recalcitrant component of anaerobic digestion [39].

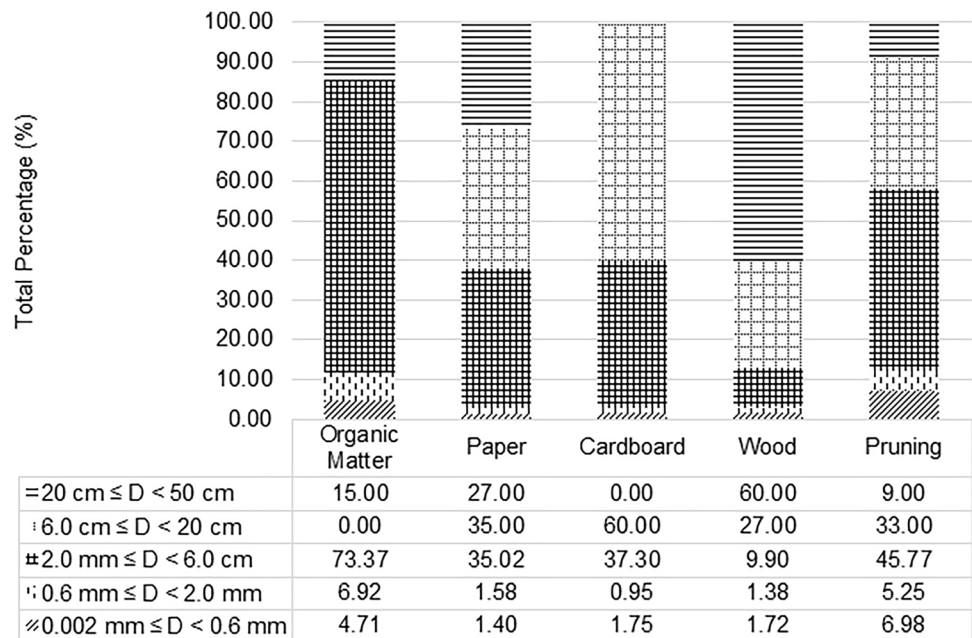
Although the carbon to nitrogen ratio (C/N) ED8 – Mined showed well at the first moment, given lower nitrogen content than carbon content, the C/N was higher than the ideal C/N for the biogas generation process. In biogas production from MSW anaerobic digestion, the optimal C/N should be 20 [40] or between 20 and 30 [41]. A higher C/N average (46/1) was presented in ED8 – Mined (Table 1) in

comparison to the C/N average of biodegradable fraction (food waste and pruning) of Campinas MSW landfilled with 3 years (12/1) [31]. This higher C/N is probably related to the age of landfilled MSW and your feedstock condition since it has been biodegradable for 8 years in a sanitary landfill. An anaerobic medium where the C/N ratio is higher than 25 represents that the methanogens microorganisms are consuming nitrogen rapidly, resulting in lower biogas yields [42, 43]. However, for biogas production by anaerobic digestion of ED8 – Mined, the C/N ratio can be maintained at the required or acceptable range by mixing low C/N ratio biodegradable material, such as fresh food waste, as required by the biogas plant project [43].

The removal of half waste paper and cardboard in the organic fraction of MSW in anaerobic digestion for methane production can be sustained by a larger waste biodegradability, but removing all waste paper and cardboard has reduced methane production by about 15% [36]. For this, it is essential to know the compounds of the material. Therefore, ED8 – Mined has the potential to generate biogas. However, it contains more recalcitrant materials than fresh MSW.

Assuming ED8 – Mined represented 23.16% of the total mass of mined sample gravimetric composition, on a wet basis, contributing with 57.49 kg of a total of 248.23 kg [19]. Landfill mining activity for biogas production was reflected in a significant recovery of about 100,000 tonnes of ED8 – Mined when this value was extrapolated to whole landfilled MSW in annual cells of about 450,000 tonnes, with similar composition, in Delta A Sanitary Landfill, Southeastern Brazil. In this way, the landfill mining activity can allow ED8 – Mined recovery and expansion of useful space for rejects in the Delta A Sanitary Landfill, which is

**Fig. 4** The categories' physical dimension range of ED8 – Mined. Note: D is dimension





closed because reaching maximum capacity. Studies with Brazilian organic raw material have already demonstrated a potential for energy recovery and biogas generation by anaerobic digestion from by-products and waste. For brewer's spent grains (BSGs) were obtained, a methane yield of  $39.51 \text{ L CH}_4 \text{ kg}^{-1}$  of total volatile solids and the combustion of biogas in a combination of heat and engine power could locally generate electrical energy ( $0.101 \text{ MWh ton}^{-1}$  BSG) and thermal ( $455.21 \text{ MJ ton}^{-1}$  BSG) [44]. Theoretical biogas and methane production analysis from anaerobic digestion of vinasse and stillage estimated a biogas volume of  $6.8 \times 10^6 \text{ m}^3 \text{ year}^{-1}$  and methane production yield of  $3.8 \times 10^6 \text{ m}^3 \text{ year}^{-1}$  [45]. The methane concentration in the pilot-scale biodigester biogas with food waste and bovine manure varied between 58 and 60% [46]. Moreover, the Campinas MSW has the technical potential to be used for biogas generation since it can generate 8.3 MW of electricity per day, reducing the  $\text{CO}_2$  and  $\text{CH}_4$  emissions to the atmosphere [1]. Based on these previous and recent studies, anaerobic digestion of waste could be an approach for producing methane-rich biogas as an alternative for energy recovery in a circular economy concept in MSW management.

### 3.2 Environmental benefits and policy implications

The anaerobic digestion is a promising alternative for the MSW easily degradable fraction treatment to incorporate the circular economy principles into solid waste management [47]. Moreover, the MSW biogas generation plants can contribute to the global goals of "The 2030 Agenda for Sustainable Development Goals" of the United Nations. These plants contribute to goal 12 (responsible consumption and production), on efficient use of natural resources context and waste generation substantially reduction through prevention, recycling, and reuse and with goal 13 (climate action), through urgent measures to combat climate change and its impacts, given the greenhouse gases emissions reduction [48].

Data from an analysis of a Brazilian report on greenhouse gas emissions and their implications for Brazil's climate goals [49] showed that Brazilian greenhouse gas emissions in 2020 grew by 9.5%, while worldwide, they reduced by almost 7% due to the pandemic scenario of COVID-19. This fact leaves Brazil at a disadvantage in the Paris Agreement (a legally binding international treaty on climate change) of the United Nations Convention on Climate Change [50]. Of the five sectors of the economy that account for greenhouse gas emissions in Brazil (agricultural, waste, land and forest use, energy sector, and industrial processes), waste, land and forest uses, and agricultural sectors increased from 2019 to 2020. This increase reflected in a setback in Brazilian environmental policy, since the high greenhouse gas emissions were related to deforestation in Amazon and Cerrado

(Brazilian Biomes), which account for almost 90% of the land, and to high emission mainly from the disposal of MSW in sanitary landfills and dumps (estimated a rise of about 10% in MSW generation) [49, 51].

However, no direct measures related to landfill mining and landfilling MSW are proposed in the Solid Waste National Policy (PNRS), provided by no. 12,305 Law [52], regulated by 10,936 Decree [53], coordinated and prepared by the Brazilian Environment Ministry. Nevertheless, goals for reducing MSW disposal in sanitary landfills are mentioned, appointing for the country's current environmental, social, and economic problems with sanitary landfills.

Therefore, the incentive for solid waste reuse, including energy recovery, is recommended in no. 12,305 Law [52], one of the national goals' items. However, in the 10,936 Decree [53], a specific paragraph highlights that energy use with solid waste does not apply to gases generated in the biodigestion and decomposition of organic matter from sanitary landfills, which makes landfilled MSW even more disregarded by Brazilian competencies. In this way, the energy recovery is quite negligible in the country. However, energy generation is a possible and viable reality [13]. Moreover, the biodegradable fraction valorization needs to achieve a circular economy in the sanitary landfilled waste area, no longer treating the biodegradable fraction as waste or liability but as a resource or asset [54]. When working with MSW today, including mined MSW, one must consider the cost-benefit of its minimization and recovery in addition to the net economic profit, given that there is no longer any sanitary space to deposit MSW in the world. It is no longer sanitary feasible to allow thousands of tons of waste disposal to be landfilled daily across the planet. The current consumer culture must instantaneous value and reuse its packaging, products, and energy from waste.

Thus, chemical characterization and the elemental composition of landfilled ED8 – Mined to evaluate its potential for energy generation through the anaerobic process are essential, viable, and promising to contribute to the mined MSW reuse for power generation, admitting their differences with the biodegradable fraction of fresh composition.

## 4 Conclusion

The easily degradable fraction of MSW with 8 years of landfilling (ED8 – Mined), mined in Delta A Sanitary Landfill in Campinas city, Southeastern Brazil, showed up with the potential for biogas production. The ED8 – Mined presented low lignin and nitrogen contents and high holocellulose content and C/N values, different from the biodegradable fraction of fresh MSW. Thus, studies to enable the application of landfill mining should consider the chemical characterization and elemental composition difference between fresh

and mined MSW. In this research, the ED8 – Mined reuse for biogas generation can contribute to a recovery of about 100 thousand tonnes of ED8 – Mined in annual landfill mining cells of about 450,000 tons of whole MSW landfilled with similar composition. Nonetheless, ED8 – Mined presented more recalcitrant materials than fresh biodegradable fractions, being necessary beneficiation processes specific in biogas plants for energy recovery from mined MSW.

**Author contribution** Mariane Alves de Godoy Leme: conceptualization, data curation, writing — original draft, review and editing, and revision. Paulo César Torres-Mayanga, Daniel Lachos-Perez, and Tânia Forster-Carneiro: review and editing — original draft, review and editing — revision. Miriam Gonçalves Miguel: writing — original draft, review and editing, and revision.

**Funding** This research was supported by FAPESP (São Paulo Research Foundation) for research assistance (Process 2018/14938–4 and 2019/01559–8), CNPq (National Council for Scientific and Technological Development (Process 305508/2018–0 and Innovative Extension Grant 302451/2021–8) and the Coordination for the Improvement of Higher Education Personnel—Brazil (CAPES)—Financing Code 001 for the Doctorate scholarship.

**Data availability** All data generated or analyzed during this study are included in this article.

## Declarations

**Ethics approval** All the authors unanimously confirm:

- (i) This paper is original.
- (ii) It has not been published before, and is not under consideration for publication anywhere else.
- (iii) All authors have given their respective inputs in this manuscript, examined it as a whole, and thence mutually agree that it be submitted in the Waste and Biomass Valorization.
- (iv) The authors declare that they have no competing interests.
- (v) The manuscript has been verified during its writing in the Turnitin software, and there is no plagiarism in this work.
- (vi) All points taken from other authors are well cited in the text.
- (vii) We assure the integrity and quality of our research work.
- (viii) This research did not involve Human Participants and/or Animals.

**Competing interests** The authors declare no competing interests.

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