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The Influence of biodegradation on the development of settlements in urban solid waste covered with an intermediate landfill cover

Influência da biodegradação no desenvolvimento de recalques em resíduos sólidos urbanos cobertos com uma cobertura intermediária de aterros sanitários

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Abstract: This study aimed to verify the behavior of USW and OSW settlements due to biodegradation. Since biodegradation is responsible for a large part of the settlements in USW landfills, monitoring the biodegradation phases in which the mass of waste is located is essential. In this perspective, three lysimeters were built, 1 containing MSW and 2 containing OSW, all covered by an intermediate cover soil layer disposed of in landfills in Ceará State. The lysimeters were designed under surface drainage conditions (with and without slurry recirculation). The settlements were higher in the lysimeters containing only OSW than in the lysimeters containing USW. In the lysimeter without recirculation, there were decreases in COD, about the lysimeter with recirculated slurry. The slurry recirculation contributed to higher settlements and made the leachate more concentrated, with salts such as chlorides that directly influenced the increased electrical conductivity. The compaction of the intermediate cover layer of the landfill proved to be adequate since the degree of compaction was 95% of the Normal Proctor, with dry specific weight values of 18.2 kN/m³ in the field and 19.1 kN/m³ obtained in the laboratory.

Keywords: Biodegradation; Settlements; Urban Solid Waste.

Resumo: Este trabalho teve como objetivo verificar o comportamento dos recalques de RSU e RSO, em função da biodegradação. Tendo em vista que a biodegradação é responsável por grande parte dos recalques que ocorrem em aterros de RSU, é imprescindível fazer um monitoramento das fases de biodegradação, em que se encontra a massa de resíduos. Nesta perpectiva, foram construídos 3 lisímetros, sendo 1 contendo RSU e 2 contendo RSO, todos cobertos por uma camada de solo de cobertura intermediária disposta em aterros sanitários do estado do Ceará. Os lisímetros foram projetados em condições de drenagem na superfície (com e sem recirculação de chorume). Nos lisímetros contendo apenas RSO, os recalques foram maiores que no lisímetro contendo RSU. No lisímetro sem recirculação, observou-se decréscimos na Dqo, em realação ao lisímetro com chorume recirculado. A recirculação de chorume contribuiu para maiores recalques e para tornar o lixiviado mais concentrado, com sais como cloretos que influenciaram diretamente no aumento da condutividade elétrica. A compactação da camada de cobertura intermediária do aterro demonstrou-se adequada, já que o grau de compactação foi de 95% do Proctor Normal, com valores de peso específico seco de 18,2 kN/m³, em campo, e de 19,1 kN/m³ obtido em laboratório.

Palavras-chave: Biodegradação; Recalques; Resíduos sólidos urbanos.

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1. Introduction

The degradation of the organic matter on organic solid waste (OSW) occurs in different phases, aerobic and anaerobic. Each of these phases involves interdependent chemical, physical, and biological interactions. The physicochemical processes include changes in the following parameters: hydrogen potential (pH), chemical oxygen demand (COD), and nitrification reactions, among others. The change in these factors contributes to changes in the structure of the USW, impacting volume changes. As a result of these volume changes, physical phenomena called settlements occur over time in the waste.

Regarding the magnitude of settlements, they are more prominent when there is a higher percentage of organic solid waste (OSW) since removing organic matter will occur in a higher volume. Seok and Soon (2022) explain that a large part of the settlements in USW is due to the fraction of biodegradation of organic matter. And this is precisely what makes USW settlements in landfills much higher than in soils. The behavior of settlements happens in stages: in the first stage, they depend on mechanical requests (overlapping of materials), and in the second stage, they depend on the physicochemical changes that happen in the mass of waste due to microbiological activity, over time (BOSCOV, 2008; SEOK; SOO, 2022).

The biodegradation of these organic materials, caused by microorganisms, transforms solid matter into liquid and gaseous matter. The liquid from biodegradation, called slurry, is formed in the transition from the aerobic phase to the anaerobic phase of decomposition of the USW in a landfill and can reach high COD values of up to 100,000 mg/L (BOSCOV, 2008; LINS, 2003; SOUTO; POLIVINELLI, 2007).

In the aerobic to anaerobic transition phase, there is a lot of organic matter to be removed, and the physicochemical analyses of the slurry generated are essential methods of evaluating the degree of biodegradation of the organic matter in the landfill. When the matter is biodegradated, voids are generated in the waste mass. The non-degraded USW has a high void ratio, being susceptible to intense compressibility, as many particles are deformable to the point of undergoing consolidation, which occurs due to the loads imposed on the landfill (compacting machines, the self-weight of the upper layers, workers, garbage trucks traffic, etc.). The settlements occur due to this compression imposed by the applied loads, combined with the degradation processes of organic matter, which generates voids and leaves the USW structure more fragile and susceptible to new vertical deformations (CATAPRETA, 2008; CARVALHO, 1999; DA SILVA, 2013).

Therefore, the action of microbial groups in digestion, predominantly anaerobic, generates the slurry that is important in investigations of settlements in USW landfills. From this perspective, the results of the physicochemical analyses of the slurry allow us to know in which phase of biodegradation the landfill is located. Degradation is influenced by internal factors such as the action of microbial agents, temperature, waste composition, and external agents such as precipitation, evaporation, and slurry recirculation, if any (CARVALHO, 2005; OLIVEIRA *et al.,* 2016).

In the aerobic phase of digestion, settlements in landfills occur due to particle rearrangements and the conversion of carbonaceous matter into carbon dioxide and water, as shown in General Equation 1. According to Sperling (1996), this equation is generic and represents the oxidation of carbonaceous organic matter. At this stage, the leachate generated comes from the moisture of the waste and infiltrated water, the latter resulting from precipitation.

$$C_xH_y\,O_z + \frac{1}{4}(4x+y-2z)O_2 \rightarrow CO_2 + \frac{Y}{2}H_2\,O \quad \text{(Eq.1)}$$

In the anaerobic phase, oxygen is absent, as shown in General Equation 2. At this stage, settlements occur when carbonaceous matter is converted into carbon dioxide and methane.

$$C_x\,H_y\,O_z + \frac{4x-y-2z}{4}\,H_2O \rightarrow \frac{4x-y+2z}{8}CO_2 + \frac{4x+y-2z}{8}CH_4 \quad \text{(Eq.2)}$$

Anaerobic conversion happens in two phases: acidogenic and methanogenic. In the acidogenic phase, the pH values of the slurry are lower than 5.0 (WORREL; VESILIND, 2012; O'LEARY; TCHOBANOGLOUS, 2002). At this time, the activity of fermentative bacteria that produce enzymes responsible for the hydrolysis of complex materials into carbohydrates, proteins, and lipids occurs. In the methanogenic phase, organic compounds are transformed into methane and carbon dioxide, with a pH of at least 7.5 and 9.0 (BOSCOV, 2008; SOUTO; POLIVINELLI, 2007).

The physicochemical properties of the slurry over time, in the settlement monitoring phase, allow us to investigate the dynamics of the deformations that happen in USW landfills. Therefore, the use of lysimeters in the field will enable us to examine the evolution of settlements due to the action of degradation of organic matter. In this perspective, the present article aims to monitor the evolution of settlements in lysimeters filled with USW and correlate these settlements with physicochemical parameters such as pH, COD, electrical conductivity, and dissolved salts, such as chlorides. The study sought to reproduce the occurrence of settlements during the construction phase, using soil cover from the intermediate layer of a landfill.

2. Methodology

2.1 Delimitation of the research area

The experimental lysimeters were installed inside the Federal University of Ceará (UFC) campus in Fortaleza, as seen in Figure 1. The waste used to fill the lysimeters was collected at the transshipment station of the Jangurussu neighborhood, also located in Fortaleza. The soil was collected in the intermediate cover layer of the West Metropolitan Sanitary Landfill of Caucaia – CE (ASMOC), located approximately 18 kilometers from Fortaleza.

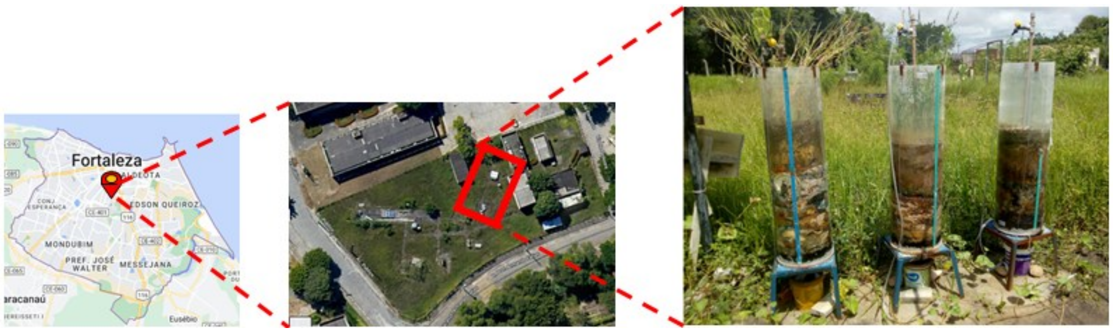

Figure 1 – Installation of lysimeters.
Source: Authors (2023).

2.2 Constructive aspects of lysimeters

Three lysimeters were constructed in acrylic material, as shown in Figure 2, with a length of 100 cm, thickness of 0.5 cm, internal diameter of 29 cm, and external diameter of 30 cm. A 3cm waterproofing layer was placed on the base and made of a butyl mat. A PVC (Polyvinyl Chloride) lid was attached inside the base with silicone. A vertical PVC drain was installed in the center of the lysimeters to measure gases from biodegradation. In the center of the cover installed at the base of the lysimeter, a hole was made to install a PVC drain for the periodic slurry collection. On the external surface of the lysimeters, three measuring tapes were fixed to allow manual measurement of the settlements. A plastic watering bottle was used to recirculate the slurry in one of the lysimeters. Recirculation was performed weekly at the time of leachate collection.

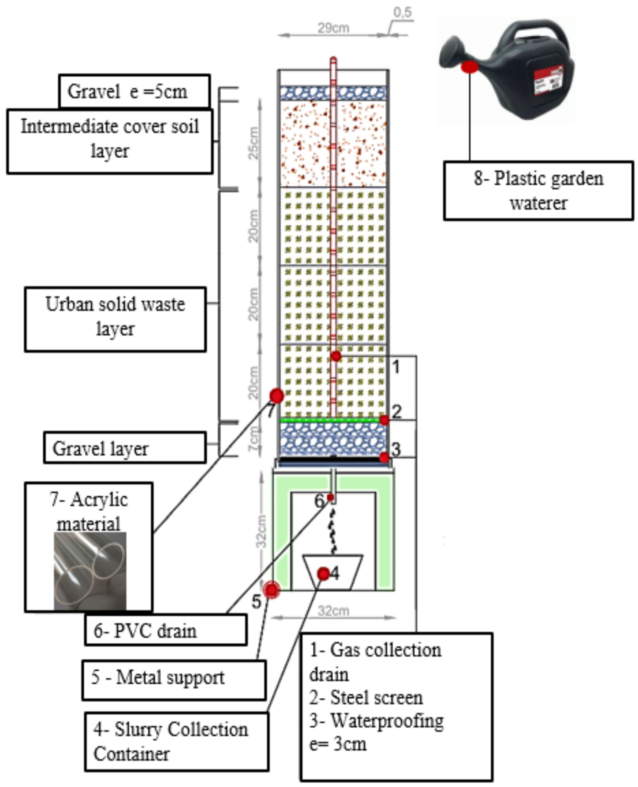

Figure 2 – Experimental lysimeter design.
Source: Authors (2023).

It is important to note that the gas catchment drain was designed for another research stage. The volume of gases measured, including methane (CH_4), was low, indicating that the residues had not reached the methanogenic phase.

2.3 Gravimetric composition of lysimeters

The gravimetric composition of the lysimeter (L1) was USW, typical of the city of Fortaleza, while the compositions of the lysimeters L(2) and L(3) were OSW. The slurry was recirculated only in L(2) to verify the influence of recirculation on the biodegradation process.

The collected material was divided into seven categories of waste: organic, waste, plastics, paper, textiles, glass, and metals. The residues belonging to each group were weighed correctly to obtain the percentage for each fraction of the material type, as shown in Figure 3. The organic materials were remnants of household foods (fruit peels, meats, plant remains). In the other groups, plastics, glass bottles, some metals (aluminum, electronics fragments), papers, and cardboard were found. Materials such as diapers, toilet paper, sanitary pads, and Styrofoam were observed in the tailings category.

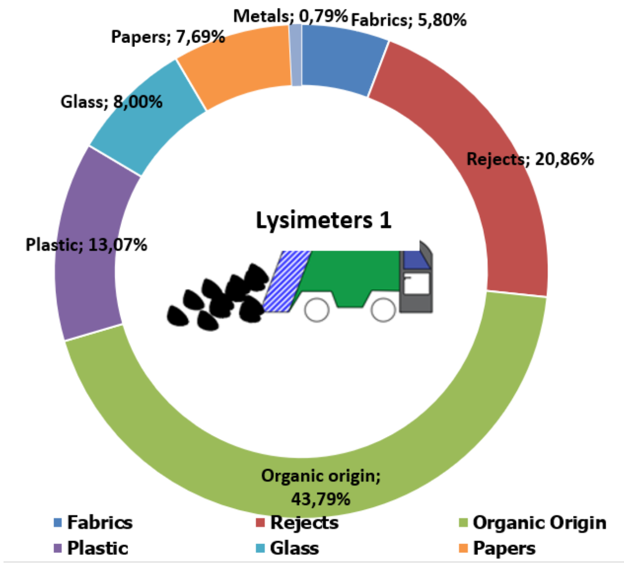

Figure 3 – Gravimetric Composition - lysimeter 1.
Source: Authors (2023).

Urban solid waste was separated in the yard of the transshipment station in the Jangurussu neighborhood. The residues were segregated and classified according to the illustrations in Figure 4.

Figure 4 – Separation of USW; a)USW b)OSW c) Plastics d) Cardboards, papers e) Fabrics f) Glasses g) Metals h) Scale.
Source: Authors (2023).

2.4 Preparation of samples and filling of lysimeters

Geotechnical tests were performed with the soil samples in Figure 5 according to the standards listed in Table 1.

Figura 1 – Ensaios geotécnicos; a)Granulometria b) Cilindro de cravação c) Limite de liquidez d) Limite de plasticidade e)Permeabilidade f)Compactação.
Fonte: Authors (2023).

Table 1 – Geotechnical tests.

Denominations	References
Preparation of samples	NBR 6457 (ABNT, 2016)
Granulometric analysis	NBR 7181 (ABNT, 2016)
Liquidity limit	NBR 6459 (ABNT, 2017)
Plastic Limit	NBR 7180 (ABNT, 2016)
Permeability	NBR 13292 (ABNT, 2021)
Compaction Test	NBR 7182 (ABNT, 2016)
Specific mass, with the crimping cylinder.	NBR 9813 (ABNT, 2016)

Source: Authors (2023).

After the geotechnical tests, the lysimeters were filled. Before compaction of the residues, a 7 cm layer of gravel 0 was placed at the base of each lysimeter, as seen in Figure 6a. A stainless steel screen was placed above the gravel layer to serve as a filter and prevent the passage of fine materials through the drain. Subsequently, the lysimeter samples were compacted into three layers of 20 cm. At this stage, it was necessary to manually centralize the gas capture drain while compaction occurred through a concrete compactor, shown in Figure 5b, 9 cm in diameter, 10 cm in height, and 9.8 kg in mass. In the intermediate cover layer soil compaction step, a sample with a thickness of 25 cm was compacted, as seen in Figure 5c. Above the soil layer, a 5cm layer of gravel was deposited to mitigate the effect of erosion due to the rainy season.

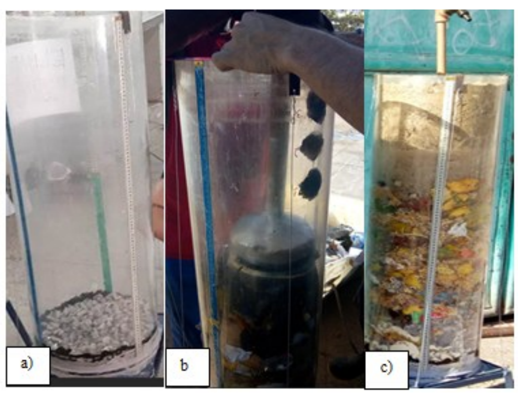

Figure 6 – Filling of lysimeters; a) Gravel b) USW compaction c)Soil compaction.
Source: Authors (2023).

The quantities of USW and soil compacted in each lysimeter are presented in Table 2. The specific mass of the residues was calculated using the data obtained from the mass of USW and OSW, compacted to a volume of cylindrical geometric shape (internal radius of the base of 14.5 cm and thickness of 60 cm). Usually, in research with USW of landfills, it is important to calculate the specific weight, considering that this parameter is influenced by the thickness of the final and intermediate cover layers, as both are overload applications.

It is important to note that the specific weight values of L2 and L3 differed since the samples contained organic materials of different masses and shapes.

Table 2 – Configuration of the three lysimeters.

Lysimeter volume = 39,631.19 cm³			
Composition	**USW**	**OSW**	
	Lysimeter[1]	**Lysimeter[2]**	**Lysimeter[3]**
Waste mass (kg)	39.00	29.84	30.00
Soil mass (kg)	34.00	34.00	34.00
Specific mass of waste (g/cm³)	0.98	0.75	0.76
Total unit weight (kN/m³)	9.65	7.38	7.42

Source: Authors (2023).
1- USW lysimeter with the gravimetric composition shown in Figure 3;
2- Lysimeter with 100% OSW and leachate recirculation;
3- Lysimeter with 100% OSW

The soil mass of the three lysimeters was obtained by calculating the specific mass with the data obtained in the field, through the driving cylinder test, and with the lysimeter volume data (internal radius of the base of 14.5 cm and thickness of 25 cm), as shown in Table 3. The compaction tests allowed a comparison between the values obtained in the field and the laboratory. The Proctor test was carried out using standard energy, considering that the intermediate and modified energies could impact the intense approximation of the grains, which could hinder the soil permeability of the landfill cover layer.

Table 3 – Geotechnical properties of the soil.

Lysimeter volume = 16,512.99 cm³			
Data obtained in the laboratory		**Data obtained in the field**	
Specific Gravity, Gs	2.63	Specific Mass (g / cm³)	2.06
Permeability (cm/s)	1.4x10-3	Total unit weight - kN/m³	20.2
Dry unit weight - kN/m³	19.1	Dry unit weight – kN/m³	18.2
Optimum water content (%)	11.3	Water content (%)	10.5

Source: Authors (2023).

As soil with an intermediate cover layer, the soil presented a well-graded particle size distribution curve, classified as NBR 7181 sand (ABNT, 2016), as shown in the graph in Figure 7.

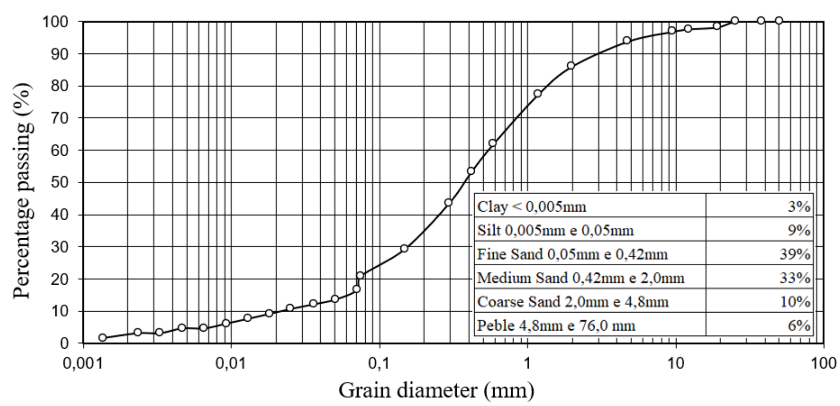

Figure 7 – Particle Size Distribution Curve.
Source: Authors (2023).

After the filling step, the lysimeters were installed in the field and exposed to local weather conditions.

2.5 Monitored Data

2.5.1 Leachate volume

Leachate collection was carried out every two weeks, according to the schedule in Table 4, between September 2022 and February 2023, for 180 days of monitoring. Rainfall data were obtained through the UFC weather station, about 500 meters from the lysimeters' installation site.

Table 4 – Collection Schedule.

Period	Number of collections
09/05 to 09/15/22	3
09/15 to 09/30/22	2
10/03 to 10/18/22	1
10/18 to 10/31/22	1
10/31 to 11/15/22	1
11/15 to 11/30/22	1
11/30 to 12/15/22	1
12/15 to 12/31/22	1
12/31 to 01/13/23	4
01/13 to 01/27/23	5
01/27 to 02/10/23	4
02/10 to 02/25/23	5

Source: Authors (2023).

2.5.2 Physicochemical analysis of leachate

The physicochemical analyses were performed every two weeks at the UFC Environmental Sanitation laboratory. Table 5 describes the physicochemical parameters analyzed and the methods used.

Table 5 – Physical-chemical parameters.

Analysis	Method	References
pH	4500-H+ B	APHA (2012)
COD (mg/L)	5220 D: Colorimetric method with closed reflux digestion.	APHA (2012)
Electrical conductivity uS/cm	Potentiometer method	APHA (1998)
Chlorides	4110 B: Ion Chromatography	APHA (2012)

Source: Authors (2023).

2.5.3 Measurement of settlements

The settlements were verified every two weeks through the differences in heights observed with measuring tapes fixed to the surface of the lysimeters, as shown in Figure 8.

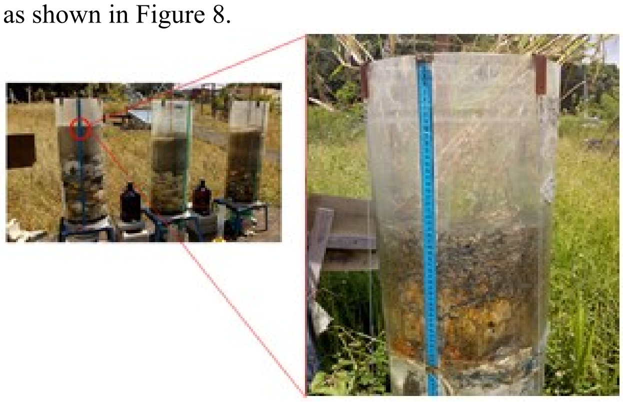

Figure 8 – Manual measurement of settlements.
Source: Authors (2023).

3. Results and discussion

3.1 Leachate volumes

According to the graph in Figure 9, leachate generation in the lysimeter (L1) happened only after 90 days. The composition of L1 had several types of non-organic materials, which interfered with the generation of a low volume of slurry in this period, such as papers, tailings, glass, plastics, etc. Guedes *et al.* (2021) explain that plastic materials serve as an obstacle to the passage of leachate; in addition, materials such as cardboard and textiles absorb moisture inside the lysimeter, contributing even more to the low generation of leachate when comparing lysimeters containing only OSW.

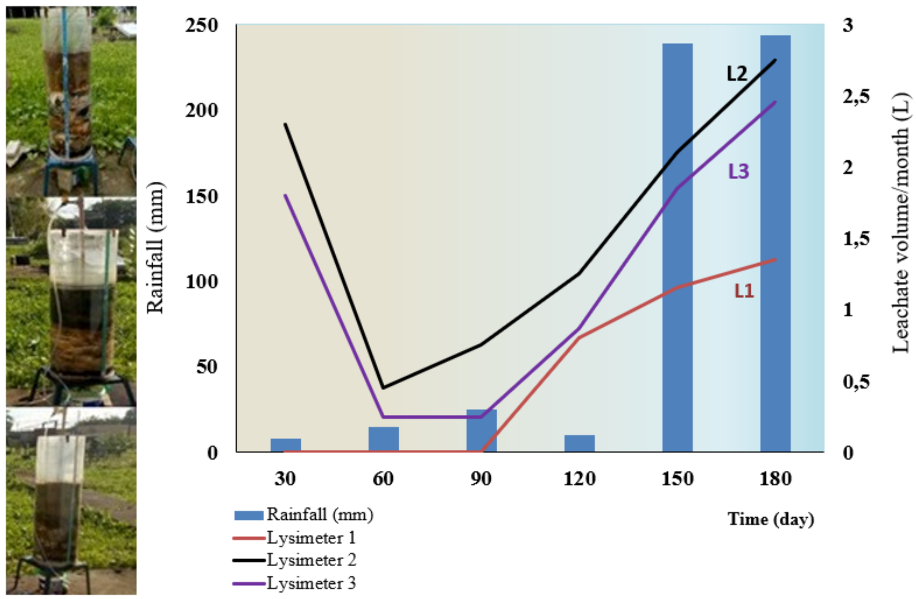

Figure 9 – Leachate volume and Rainfall x time.
Source: Authors (2023).

Little leachate volume was observed between 30 and 120 days of the installation for all three lysimeters, precisely in the lower precipitation period, as seen in the graph in Figure 9. The generation of leachate increased between 90 and 180 days, especially between 150 and 180 days, due to the increase in rainfall in the final months of monitoring. In other studies carried out with lysimeters, such as that of Alcântara (2007), Da Silva (2013), Bareither *et al*. (2012), Guedes *et al*. (2017), Santos and Matos (2017), the authors also observed that the occurrence of higher rainfall impacts on higher volumes of leachate.

3.2 Physicochemical parameters

3.2.1 COD and pH

COD is an important parameter for evaluating the presence of organic material to be degraded in a sample. From the tests, it is possible to find how much digestion reagent was used for a given sample. In other words, the higher the COD values in a sample, the greater the oxygen demand to degrade it. As shown in Figure 10, the lysimeters L2 and L3 presented different behaviors regarding the COD results over the months, even though the two have equal organic matter contents.

Leachate recirculation in L2 may have influenced the increase in COD values compared to the values of this same parameter for L3. For L2, the COD increased between September/22 and January/23, while from January/23, it suffered a slight decrease. According to Pinto (2000), COD increases when enough acids dissolve in the leachate. The recirculation in L2 may have contributed to an overload of nutrients resulting from hydrolysis, which is characteristic of the beginning of the anaerobic phase. For L3, which did not have leachate recirculation, the COD values had successive increases and decreases between September/22 and December/22, while from December/22, there was a decrease in this parameter, suggesting that it was migrating from the transition phase to the acid phase, between January/23 and February/23, there is a tendency to decrease the pH for the last two months of monitoring.

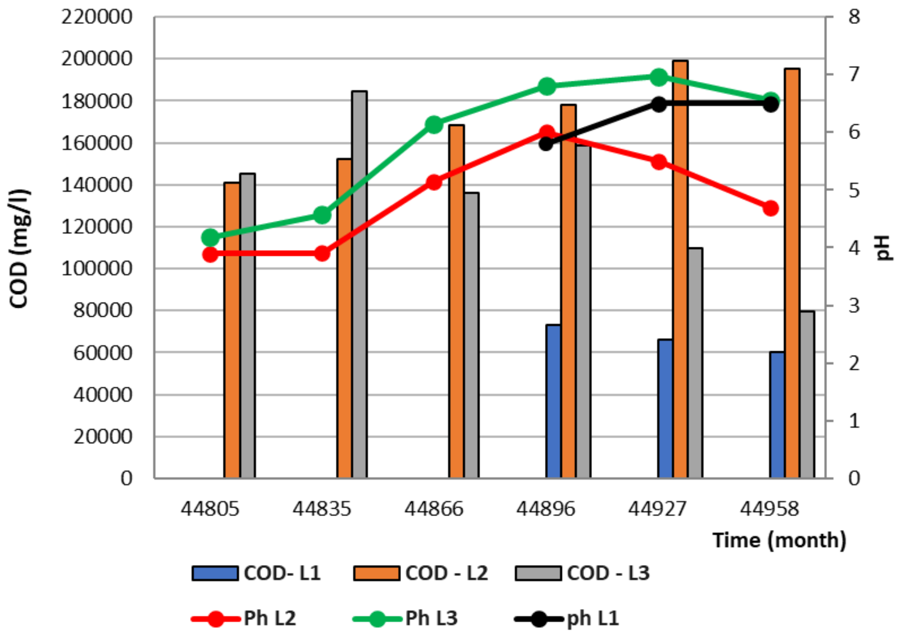

Figure 10 – COD and pH Lysimeter L1, L2, and L3.
Source: Authors (2023).

The COD values in L1 were lower than the L2 and L3 values, which was expected, considering that the percentage of organic matter was lower in L1 than in L2 and L3.

In L1, the pH values could only be verified after 90 days due to the delay in leachate generation. For this same lysimeter, the pH increased from 5.8 to 6.5 between December 22 and February 23, suggesting that it is still in phase I of initial adjustments, in which aerobic microorganisms consume free oxygen. According to Zanetti (2008) and Pinto (2000), the pH can reach close to 7 in the initial phase.

Between September/22 and December/22, there is a trend of increasing pH values in the L2 and L3 lysimeters. Between December/22 and February/23, in L2, there is a decrease in pH values from 6 to 4.5, indicating that this lysimeter may enter the acid phase. According to Pinto (2000), there is a drop in pH to values below 6.0, and at this stage, the hydrolysis of complex compounds into compounds easily metabolized by bacteria occurs. In L3, pH was slightly decreased between January/23 and February/23, approximately from 7 to 6.5, suggesting that it is still in the aerobic-to- anaerobic transition phase. According to Worrel and Vesilind (2012), the pH of the aerobic-to-anaerobic transition phase is about 6.7.

In the transition phase, verified in the L2 lysimeter, oxygen practically does not exist, and the organic matter is converted into volatile acids. This is possible due to the oxy-reduction conditions. At this stage, there is still no total removal of organic matter; there is only its transformation of carbonaceous matter into acids, so the pH of the leachate samples tends to reduce (LINS, 2003; SPERLING, 1996).

3.2.2 Ions and electrical conductivity

The analyses performed on the collected slurry indicated the presence of chloride salts ($^{Cl^-}$), which was measured during the monitoring period, as can be seen in Figure 11. It is observed that chloride concentrations were higher in L2, which had recirculation. According to Alcântara (2003), the salt ions in the leachate conduct electricity, so there is a hypothesis that the electrical conductivity was higher in L2 due to recirculation when compared to L3 without recirculation, as seen in Figure 12. As the physicochemical parameters of leachate are interconnected, it is observed that the high chloride values in the L2 samples influenced the high electrical conductivity values.

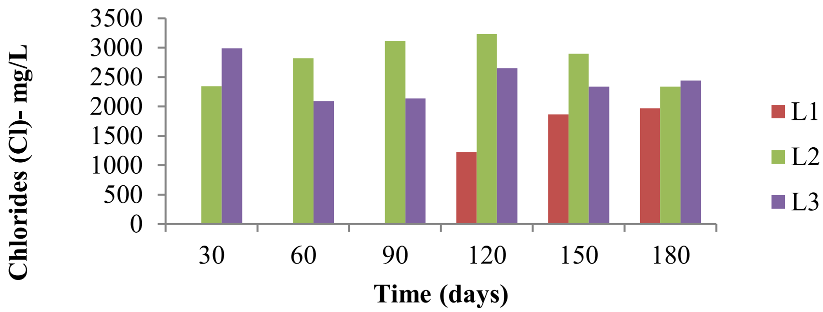

Figure 11 – Chlorides.
Source: Authors (2023).

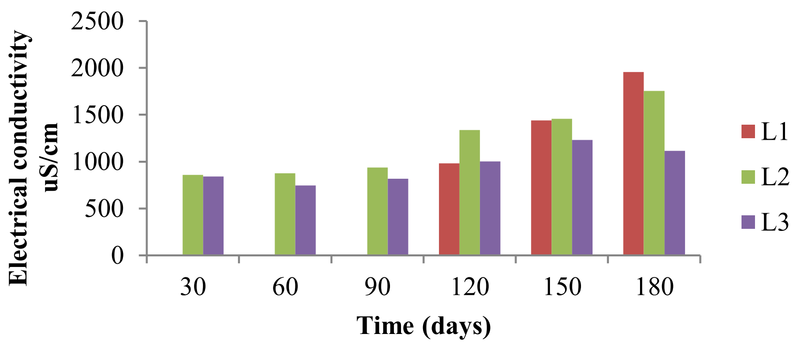

Figure 12 – Electrical conductivity uS/cm.
Source: Authors (2023).

For Catapreta (2008), high values of chlorides indicate the presence of mineral salts in the residues, and the concentration of dissolved salts in the leachate may contribute to the inhibition of some microorganisms that act in the biodegradation of carbonaceous matter (DA SILVA, 2013). As microorganisms are important in reducing COD values, the increase in dissolved salts in L2 (recirculated) did not contribute to the reduction of COD during the monitoring period compared to the COD behavior for L3.

For L2 (recirculated), the high nutrient load in the leachate samples, due to the high COD values, when compared to non-recirculated L3, revealed that recirculation contributed to making the leachate more concentrated. According to Cintra (2003), the recirculation of raw slurry should be carried out with caution, as it may cause a partial inhibition effect on the methanogenesis processes, a phase not reached by the lysimeters of this research. The author also mentions that it would be important to pre-treat the leachate before recirculating it.

3.3 Evolution of settlements

In the graph in Figure 13, it was observed that for the three lysimeters, the speed of the settlements was more considerable at the beginning of the experiment, being higher in the lysimeters L2 and L3, which had higher organic matter contents. According to Sowers (1973) and Seok and Soo (2022), primary settlements occur before biodegradation processes and last a few days, which explains the sharp slope of the curves of the three lysimeters for the first 30 days of waste accommodation, which depend on the overload of the waste layers.

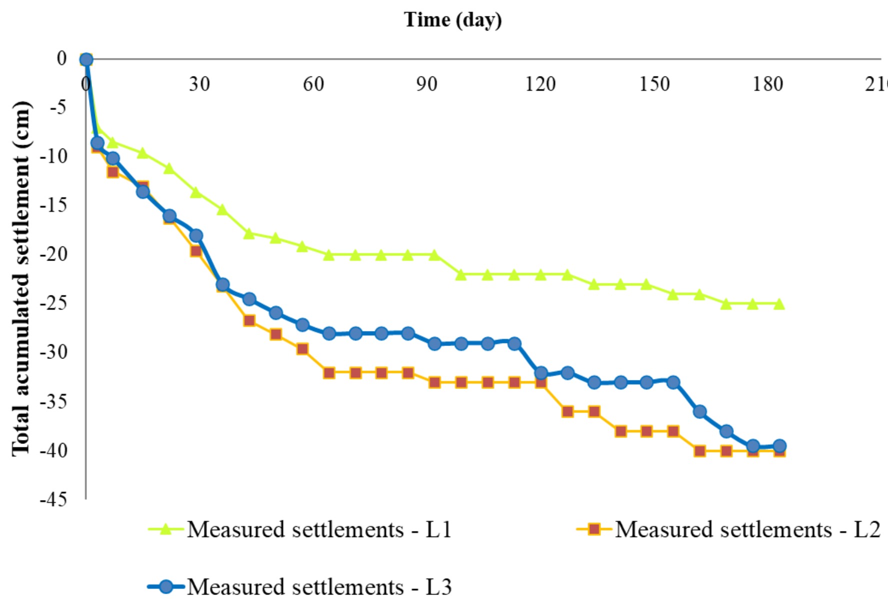

Figure 13 – Volution of settlements.
Source: Authors (2023).

In the L2 lysimeter (recirculated), the accumulated settlements were higher on most days, between 30 and 120 days, and between 120 and just before 180 days. At some points, the accumulated settlements of L2 and L3 were very similar in the first month of monitoring and on some days, as at the end of the 4th month and the 6th month. The recirculation of the L2 lysimeter may have influenced the acceleration of biodegradation, contributing to higher vertical deformations; consequently, the measurements of the settlements were higher in most of the monitored months. According to Boscov (2008) and Carvalho (1999), it is a fact that the most considerable portion of settlements in landfills is influenced by biodegradation. Still, according to Melo *et al.* (2016), high organic matter levels do not always provide settlements of the same magnitude, as not all OSW are biodegradable. Factors such as the type of OSW (presence or absence of recalcitrant materials) may impact the magnitude of settlements, considering that not all types of putrescible material will degrade in the same time interval. The OSW composition may have different components, enabling different degrees of degradation.

In experiments with USW carried out by Grisolia *et al*. (1992), the authors found that there are phases of waste settlement over the years, as seen in the graph in Figure 14. The authors explain that phase I corresponds to the initial settlements caused by the reduction of voids at the time of the first accommodation of the material. In phase II, settlements occur due to mechanical compression. In phase III, settlements are caused by organic matter decomposition; in phases IV and V, residual settlements arise. In this research, the monitoring took place for 180 days, indicating that the lysimeters L1, L2, and L3 reached phase III of the settlement behavior.

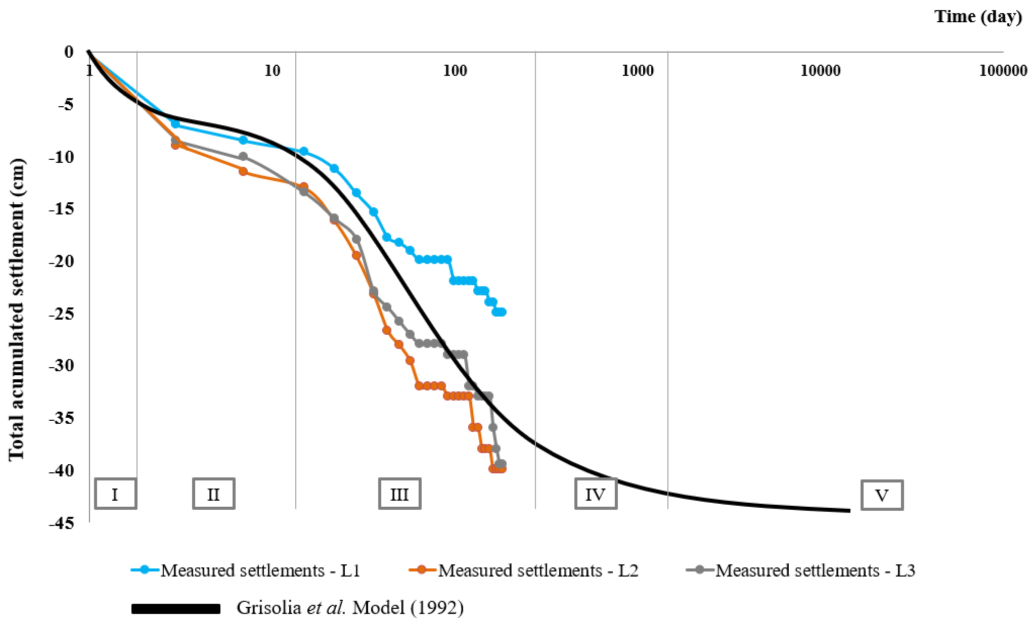

Figure 14 – Phases of settlements.
Source: Adapted from Grisolia et al. (1992).

According to the graph in Figure 14, there is an indication that for the 183 days of monitoring, the research reached phase III of settlement behavior influenced by biodegradation processes. The organic material content in the lysimeters L2 (recirculated) and L3 influenced an asymptote settlement curve, indicating more pronounced values in short intervals. According to Melo (2003), this organic material content, at the time of hydrolysis, is transformed into compounds of lower molecular weight, which are leached at the time of drainage in the landfill, contributing to volume reductions.

Because the L2 and L3 lysimeters have a higher percentage of organics, this mass reduction behavior may have happened at a higher intensity. For immediate and initial settlements, there is a portion in which the development of pore water pressure may or may not occur. After the immediate and initial settlements in the first months, the compressions of the massif are intensifying due to the decomposition of the organic portion (SOWERS, 1973).

Phase III of the settlements, shown in Figure 14, corresponds to the biodegradation phase, in which the solid mass begins to be converted into liquid products. At this stage, while settlements occur, leachates may be generated only from the residue of the lysimeter or may contain a portion of the local rainwater. The degradation of the matter existing in the three lysimeters is greatly influenced by physicochemical processes, which take place in the USW mass. That is why studying the physicochemical parameters of the generated percolate is so important, considering that the results indicate acceleration or inhibition of organic matter removal.

The results of the physicochemical parameters of the leachate were important to correlate with the behavior of the settlements over time, considering that the mass of waste did not remain stable due to the re-accommodation of the USW particles and, consequently, of the intermediate cover soil. This re-accommodation is a consequence of the chemical and biological interactions of the components that exist in the leachate, the concentration and dilution of contaminants, the influence of water infiltration by precipitation, the leachate percolation itself inside the lysimeters, the formation of gases that move between the particles; as occurs in landfills (OLIVIER; GOURC, 2007; GRISOLIA; NAPOLEONI, 1996; ALCÂNTARA, 2007).

4. Final considerations

The settlements of OSW-filled lysimeters were higher than those of USW-filled lysimeters. In some periods, the L2 lysimeter (recirculated) presented higher settlement values than the L3, indicating that the recirculation contributed to maintaining a humid environment and was favorable to degradation by microorganisms. Recirculation in L2 also contributed to a high nutrient load in the leachate samples; this was observed in the high COD values in most of the months monitored.

The cover soil used to fill the lysimeters, as it was collected from an intermediate layer, represented a situation of the construction phase of a landfill. In addition, the high permeability of the soil layer, around $^{10-3}$ cm/s, which was on the residues, conferred a more significant dissolution of the salts in an aqueous medium. The chloride salts (Cl-1) results showed accumulations in the L2 lysimeter, which had leachate recirculation. The pH values of the lysimeter L2 (recirculated) are lower than those of the lysimeters L1 and L3, showing that the recirculation also caused an acidification of the medium.

The lysimeters L1 and L3, both of different compositions, the first of USW and the second of OSW, showed decreases in COD values. In contrast, the COD values were always high for the lysimeter L2 (recirculated). This research indicates that recirculation did not contribute to the decrease in COD but made the environment more concentrated with chloride salts that directly influenced the increase in the electrical conductivity of the leachate in the L2 lysimeter (recirculated).

The intermediate cover soil layer showed a degree of compaction equivalent to 95% of the Normal Proctor, with a dry unit weight of 18.2 kN/m³ obtained in the field and 19.1 kN/m³ obtained in the laboratory. This indicates that the intermediate cover layer had efficient compaction in the field, even though it is a factor that is not adequately controlled in the routine of many landfills.

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