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RESEARCH

Physical and chemical characterization and pollution index applied in the assessment of the polluting potential of leachate from urban landfills

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Abstract During the operation of the landfills, leachate should be managed with caution to avoid possible negative environmental impacts. Considering this, the present study aims to evaluate the relationship between different variables in the leachate composition and elucidate the transformation processes through which this effluent passes during the landfill's period of operation. The study was conducted with eight sanitary landfills from the state of Minas Gerais, in southeastern Brazil, and used descriptive statistical analysis, principal component analysis (PCA), correlation analysis, and calculation of the leachate pollution index (LPI). The biochemical oxygen demand (BOD5)/chemical oxygen demand (COD) ratio was between 0.20 and 0.60. We also observed a significant correlation of 0.45 between Cl^- and $N\text{-}NH_4^+$, which reflects the biological degradation processes that contribute to the presence of both variables. The PCA showed that inorganic variables and organic matter dominated the first component, with coefficients above 0.65, indicating the importance of those variables in determining the general data variability. The LPI values were between 15.26 and 25.97, with BOD_5, COD, and $N\text{-}NH_4^+$ having sub-indexes above 35, being the main variables that increase the pollution potential of the leachate. On the other hand, trace metals present sub-indexes below 7 due to precipitation caused by increased pH and the characteristics of the waste discarded in landfills. The study provides essential information regarding the landfill leachate characteristics and its variation over time, which can contribute to the definition of treatment technologies for this affluent in different scenarios.

Keywords Landfill leachate · Leachate pollution index · Physical and chemical characterization · Multivariate analysis

Introduction

The constant changes that have been taking place in the processes of production and consumption have resulted in an increased production of solid waste of different characteristics, and the inadequate disposal of those wastes has become a diffuse source of soil and water pollution. Faced with this problem, solid waste management presents one of the most significant challenges for municipalities, especially in developing countries. The most common method of environmentally correct final disposal of waste is the landfill; 1.4 billion tons of solid waste were discarded in landfills or dumps, representing approximately 70% of global production (Ma et al., 2022). In 2020,

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there were 16 incineration treatment units in Brazil and 652 sanitary landfills (SNIS, 2021).

One of the main byproducts of the decomposition of solid waste is landfill leachate, which can produce negative environmental impacts if not adequately controlled (El Fadili et al., 2022). Therefore, one of the challenges for landfill projects is the leachate treatment since there are variations in its composition due to the landfill's age, the waste's nature, rain patterns, percolation, and hydrology of the area (Moradi & Ghanbari, 2014).

Leachate results from physical, chemical, and biological processes in landfills, such as rainwater infiltration, compaction, and biodegradation of the organic portion of the waste (Ma et al., 2022). Because of its characteristics, leachate must be treated before being placed back into the environment to avoid higher risks of contamination of the soil and the underground and surface waters, leading to severe consequences for public health.

Landfill leachate is a complex effluent comprising several products, such as recalcitrant organic pollutants, nitrogen, inorganic salts, and trace metals (Paiva et al., 2021). Moreover, emerging contaminants are also found in this composition, such as pharmacological products (Wu et al., 2021) and microplastics (Shen et al., 2022). Such characteristics make leachate treatment a challenge for the management of landfills. The literature describes several technologies for this type of treatment, ranging from physical-chemical treatment, such as systems of coagulation/flocculation, adsorption, and air stripping (Amor et al., 2015; De et al., 2019; Li et al., 2010); systems of filtration by membranes (Chen et al., 2020; Dong et al., 2014; Ushikoshi et al., 2002); advanced oxidative processes, such as photo-Fenton and ozonization (Singh et al., 2013, 2014); as well as biological treatments, such as activated sludge systems, stabilization ponds, membrane bioreactors, and constructed wetlands bioreactors (Azari et al., 2017; Martins et al., 2013; Wojciechowska, 2017; Xie et al., 2014). Moreover, a commonly adopted practice is the co-treatment of landfill leachate and sewage, which should be adopted with caution since adding leachate in an uncontrolled manner can reduce the efficiency of domestic sewage treatment (Paskuliakova et al., 2016).

However, the characteristics of landfill leachate may vary due to the age of the landfill, the composition of the residue in it, and geographic conditions (Hussein et al., 2019). Landfills undergo four main phases during their operations: the aerobic, the acetogenic, the methanogenic, and the stabilization phases. During these phases, characteristics such as pH, biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), ammoniacal nitrogen, trace metals, and biodegradability will show alterations (Lindamulla et al., 2022). Some studies evaluate the difference between leachate from active landfills and leachate generated in closed landfills (Anand & Palani, 2022; Hussein et al., 2019).

In this context, the present study aims to assess the qualitative characteristics of leachate from different landfills in Minas Gerais, Brazil, through statistical analysis and to calculate the leachate pollution index (LPI) for each landfill. The statistical approach for the qualitative characterization transforms the database into information essential for effluent integrated management. From them, public managers and companies can act in adopting adequate treatment technologies, planning strategies for the optimization of the separation of residues, and the operation of sanitary landfills. Additionally, the study of the leachate pollution index allows for identifying the variables that most contribute to the leachate pollution potential. Such information can support more assertive measures for pollution control by identifying the sources of the main variables.

Material and methods

Characterization of the area of study

This study was conducted based on the leachate from the municipalities of Além Paraíba, Conselheiro Lafaiete, Contagem, Juiz de Fora, Sabará, Santana do Paraíso, Uberaba, and Uberlândia (Fig. 1).

In Minas Gerais, in 2021, there were 74 sanitary landfills, 254 controlled landfills, and 122 garbage dumps. As regards the final destination of solid and urban cleaning waste, and considering that 90.4% of the total population and 98.1% of the urban population was covered by the collection of solid waste, 70.6% was sent to sanitary landfills, 20.2% to controlled landfills, and 9.2% to garbage (SNIS, 2022).

Data on the leachate from sanitary landfills were obtained from reports of technical inspections conducted by the Institute for the Management of Social

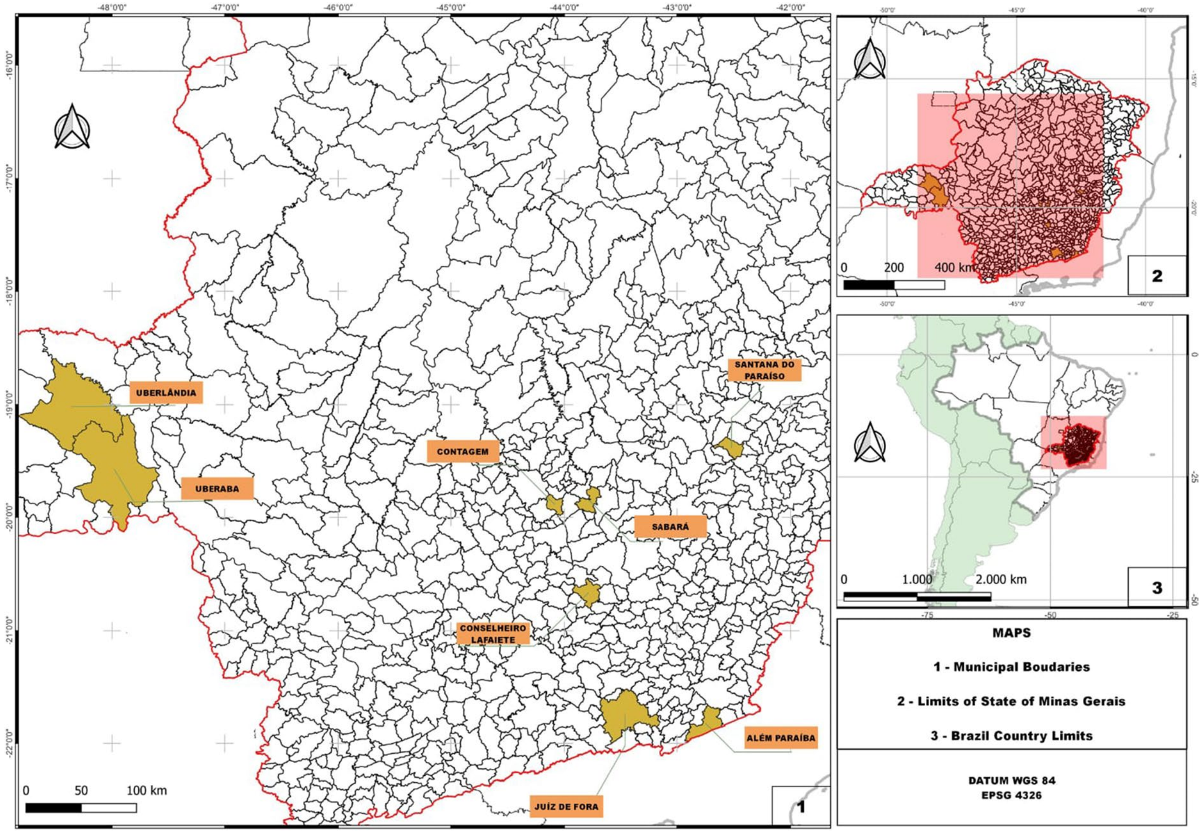

Fig. 1 Localization of the area of study.

Policies (Gesois, in Portuguese). The Gesois Institute works in partnership with the State of Minas Gerais through the State Environment Foundation (FEAM, in Portuguese) to cooperate towards developing activities that support FEAM in the execution of the public policy of management of urban solid waste (USR). Such support actions are consonant with the National and State policies for solid waste, aimed at improving the population's quality of life.

Table 1 shows the quantity of the residue received daily, the time of operation, and the systems for treating leachate in landfills used in the present study.

Composition of the leachate

The information regarding the raw leachate composition from each landfill was obtained between 2013 and 2019 based on the availability of data in the reports delivered to FEAM. The evaluated variables were electric conductivity, settleable solids, pH, biochemical oxygen demand for 5 days (BOD_5), chemical oxygen demand (COD), chlorides, cadmium, led, dissolved copper, chrome, phosphorus, nickel, nitrate, ammoniacal nitrogen ($N\text{-}NH_4^+$), surfactants, zinc, and *Escherichia coli* (*E.coli*). At each of the landfills, samples of raw leachate were collected and sent to certified laboratories, which carried out the analyses following the Standard Methods for the Examination of Water and Wastewater (APHA, 2012).

The variables were monitored with different frequencies, and electric conductivity, BOD_5, COD, *E.coli*, settleable solids, and pH were monitored with bimonthly frequency. The remaining variables were monitored quarterly landfills except for Conselheiro Lafaiete, Além Paraiba, and Juiz de Fora. Conselheiro Lafaiete landfill presented results only for BOD_5, COD, and settleable solids. In Além Paraíba, the other variables presented data

Table 1 Mass of waste received, operation time, and treatment systems for landfill leachates in the present study

Town	Beginning of landfill operation	Mass of waste received (ton/day)	Leachate treatment system
Além Paraíba	2015	43	Parshall flume, sedimentation tank, anaerobic tank, stabilization pond
Conselheiro Lafaiete	2014	160	Parshall flume, two anaerobic ponds, one optional pond
Contagem	1997	500	Non-existent. The leachate is sent to a wastewater treatment plant of the concessionary company responsible for treating domestic sewage
Santana do Paraíso	2002	700	Two impermeable tanks. The leachate is sent to a wastewater treatment plant of the concessionary company responsible for treating domestic sewage
Sabará	2007	3400	Impermeable tanks. The leachate is sent to a wastewater treatment plant of the concessionary company responsible for treating domestic sewage
Juíz de Fora	2010	700	One anaerobic pond, one primary floater with the addition of aluminum sulfate and polymer, one retention pond, one aired biological pond, one aired pond with the addition of lime, secondary flotation, and reverse osmosis
Uberaba	2005	290	Two anaerobic ponds, one optional pond, two macrophyte ponds, one maturation pond, and one storage pond
Uberlândia	2010	600	Non-existent. The leachate is sent to a wastewater treatment plant

only in 2017, and in Juiz de Fora, all the variables described were analyzed only in 2013.

Evaluation of the quality data of the leachate from the sanitary landfills

Descriptive statistical analyses were conducted to evaluate the leachate from the landfills (average and standard deviation), with the Pearson correlation analysis and multivariate analysis, specifically the principal components analysis (PCA). The Pearson correlation analysis was conducted to infer possible relationships between the characteristics of the leachate produced in the landfills in the present study. The significance of the correlations was tested considering a 95% confidence level ($p < 0.05$). The classification Anand and Palani (2022) mentioned was used, considering strong correlations < -0.7 or > 0.7 coefficients; moderate correlations between 0.5 and 0.7 and −0.5 and −0.7. Furthermore, weak correlations were considered for coefficients between 0.3 and 0.5 and −0.3 and −0.5, and neglectable correlations for coefficients between −0.3 and 0.3. The PCA transforms an original data set from a multidimensional space into an equivalent, more concise set (Couto et al., 2013). In the present study, the analysis was conducted to assess the importance of the variables in the composition of the landfill leachate and, by so doing, elucidate processes that contribute to the generation of the effluent.

The statistical analyses were conducted using the statistical R software, version 4.1.0. The Corrplot and Hmisc modules were used for the Pearson correlation, and the FactorMiner module for the PCA. Also, considering the PCA, data normalization was conducted to avoid incorrect classifications due to the unity differences and the magnitude of the values of the variables. The normalization was performed according to linear transformation as defined by Fukasawa and Mierzwa (2020). Values from 0 to 100 were adopted for the variables analyzed in this study.

Leachate pollution index (LPI)

The LPI is a mathematical formula involving the concentration of the selected variables, the weights attributed to each variable, and the value of the sub-indexes obtained from curves that relate the concentration of each isolated variable to the pollution potential (Naveen et al., 2017). The LPI was calculated based on the methodology that Kumar and Alappat (2005) proposed through Eq. 1.

$$LPI = \frac{\sum_{i=1}^{m}(WxQ)}{\sum_{i=1}^{m}(W)} \tag{1}$$

M represents the number of variables in the leachate; *w* represents the weight of the variables; and *Q* represents the value of the sub-index.

For establishing the variables and their respective weight values, the authors used the Delphi method with a group of 80 experts worldwide with experience in environmental engineering, especially in waste management (Kumar & Alappat, 2005).

To establish the pollution levels, which the authors called the sub-index points of each variable, the relationships of the pollution potential in terms of the concentration of different variables that make up the index were used. The values comprehended within the coordinate axis, which are the sub-indexes, range from 5 to 100. Meanwhile, the abscissas axis represents the concentrations of the variables up to the maximum limit reported in the literature.

It is important to emphasize that LPI calculation is a quantitative tool that allows one to provide a uniform report of the pollution data for each landfill leachate, providing a general view of the leachate's contamination potential in a comparative manner (Kumar & Alappat, 2005).

In this context, for the calculation of LPI from the sanitary landfills analyzed in this study, the following variables were used: BOD_5, COD, pH, ammoniacal nitrogen, chlorides, led, copper, chrome, nickel, and zinc, except for the sanitary landfill from the town of Além Paraíba, which did not present the variables of nickel and zinc.

Results and discussion

Descriptive statistics data (average and standard deviation) of the quality variables of the leachate

The values found for the average and standard deviation variables electric conductivity (EC), BOD_5, COD, biodegradability (BOD_5/COD ratio), pH, *E. coli*, phosphorus, nitrate, and ammoniacal nitrogen from the sanitary landfill studies are presented in Table 2. The values found for the variables settleable solids, copper, lead, cadmium, chrome, nickel,

Table 2 Average data (standard deviation in parenthesis) of the leachate variables (A)

Cities	EC (µS.cm^{-1})	BOD_5 (mg.L^{-1})	COD (mg.L^{-1})	BOD_5 /COD ratio	*E. coli* (NMP/100 mL)	pH	Phosphorus (mg.L^{-1})	Nitrate (mg.L^{-1})	Ammoniacal nitrogen (mg.L^{-1})
Além Paraíba	16506.67 (2653.32)	1770 (513.59)	4308.00 (1250.90)	0.41	1.4×10^3 (7.56×10^2)	8.90 (0.20)	18.20	6.20	1290.00
Conselheiro Lafaiete	-	4821.33 (2546.84)	12426.67 (6353.59)	0.38	-	-	-	-	-
Contagem	15366.67 (3746.82)	1693.67 (2759.92)	3554.83 (5409.28)	0.47	1.2×10^4 (8.42×10^4)	8.05 (0.26)	4.46 (2.81)	9.42 (17.40)	527.58 (587.85)
Juiz de Fora	17102.00	2062.00	3438.00	0.60	2.0×10^2	8.20	3.3	11.7	0.2
Santana do Paraíso	20679.18 (13186.41)	2117.09 (1771.95)	5008.33 (2723.43)	0.42	1.9×10^2 (2.53×10^5)	7.8 (0.59)	2205.61 (5011.09)	8.99 (12.08)	1383.94 (835.75)
Sabará	15439.44 (10369.79)	728.86 (375.67)	3511.67 (1518.61)	0.20	0.69×10^2 (1.35×10^3)	8.28 (0.46)	5.94 (4.85)	18.66 (17.33)	1232.27 (980.79)
Uberaba	4228.94 (4989.01)	792.53 (534.57)	2510.34 (1884.74)	0.31	-	8.24 (0.88)	23.23 (18.64)	157.63 (465.89)	296.21 (374.78)
Uberlândia	13632.73 (9556.92)	1908.03 (951.6)	4861.59 (2427)	0.39	6.8×10^4 (5.3210^5)	7.69 (0.62)	7.71 (4.48)	13.56 (9.94)	1094.86 (922.58)

chloride, surfactants, and zinc from the sanitary landfill studies are presented in Table 3. According to Tables 2 and 3, the characteristics of the raw leachate differ from one landfill to another. Such a variation is justified not only by the variation in the characteristics of the waste but also by climatic, environmental, and local characteristics of the site where the landfill is located. Another factor to consider is the landfill's age and the different phases of waste degradation, which will influence the leachate characteristics.

The average pH values observed in our study ranged from 7.69 to 8.90. This value bracket allows one to infer that the landfills are in an advanced maturation stage, close to the methanogenic phase (Costa et al., 2019). The pH values for landfill leachates, which tend to be alkaline, are related to the consumption of volatile organic acids by methanogenic archeas in methane production (Hussein et al., 2019). In older landfills still in operation, even with the addition of new waste over time, the value is low compared to waste discarded long ago, reflected in the pH value (Demirbilek et al., 2013). On the other hand, even in young landfills, exposure of leachate to the atmosphere can cause some removal of CO2, which increases the pH (Gómez et al., 2019).

Concerning electric conductivity, the values found for the leachates from sanitary landfills are higher when compared to values found for domestic sewage. Paiva et al. (2021), when analyzing the raw leachate from a landfill in the town of Itabira, Minas Gerais, in the Southeast of Brazil, found an electric conductivity of 13,335.0 µS/cm. Regarding the landfills contemplated in the present study, the average values ranged from 4228.94 to 20,679.18 µS/cm. Gómez et al. (2019) evaluated landfills with different operating times in Spain and observed higher electrical conductivity values in young landfills. The mean electrical conductivity in young landfills was 35.2 mS/cm, and in old landfills, it was 16.6 mS/cm. Hussein et al. (2019) evaluated active and inactive landfills in Malaysia and observed maximum values for the electric conductivity of 23,000.0 µS/cm. The authors mentioned that EC indicates the presence of organic and inorganic dissolved substances, which may limit the growth of several species in water bodies. Regarding landfill leachate treatment, high electric conductivity may represent a limitation for biological systems. Gautam and Kumar (2021)

Table 3 Average data (standard deviation in parenthesis) of the leachate variables (B)

Cities	Settleable solids (mg.L^{-1})	Cadmium (mg.L^{-1})	Lead (mg.L^{-1})	Dissolved copper (mg.L^{-1})	Chrome (mg.L^{-1})	Nickel (mg.L^{-1})	Surfactants (mg.L^{-1})	Chloride (mg.L^{-1})	Zinc (mg.L^{-1})
Além Paraíba	43.87 (39.05)	0.00	0.07	0.03	0.54	0.15	1.14	2950.00	1.30
Conselheiro Lafaiete	10.70 (16.74)	-	-	-	-	-	-	-	-
Contagem	0.15 (0.07)	0.01 (0.00)	0.01 (0.01)	0.01 (0.01)	0.17 (0.0)	0.15 (0.01)	1.16 (1.11)	3343.75 (439.31)	0.15 (0.04)
Juiz de Fora	0.40	0.03	0.3	0.004	0.2	0.1	3.4	2481.00	0.7
Santana do Paraíso	0.42 (0.25)	0.00 (0.00)	0.01 (0.00)	0.78 (3.42)	0.28 (0.07)	0.14 (0.03)	13.18 (36.66)	2827.27 (1000.52)	0.54 (1.06)
Sabará	1.01 (1.79)	0.02 (0.02)	0.34 (0.27)	0.03 (0.02)	0.13 (0.09)	0.31 (0.12)	0.80 (0.26)	2704.75 (1193.47)	0.32 (0.24)
Uberaba	0.67 (0.33)	0.08 (0.17)	0.07 (0.04)	2.13 (2.42)	0.13 (0.05)	0.18 (0.19)	1.44 (0.91)	418.50 (309.19)	0.54 (0.87)
Uberlândia	3.24 (9.40)	0.02 (0.02)	0.01 (0.01)	0.04 (0.02)	0.16 (0.18)	0.14 (0.12)	8.27 (19.97)	2196.59 (793.08)	0.38 (0.56)

mentioned adequate electrolytic processes to treat the effluent in that context.

The BOD_5 ranged from 728.9 to 4821.3 $mg.L^{-1}$, and the COD ranged from 2510.3 to 12,426.7 $mg.L^{-1}$. The BOD_5/COD ratio in the leachate may indicate the age of the landfill and the change in the presence of biodegradable organic compounds within it. The BOD_5 will reduce than the COD more quickly due to the degradation of more biodegradable compounds, which causes the BOD_5/COD to tend to be lower over time. In this context, biological treatment is more indicated for leachates with higher BOD5/COD ratios. On the other hand, for lower values of BOD_5/COD ratio, physical-chemical treatment technologies are more indicated (Abunama et al., 2021). Hence, in the acidogenic phase, the concentrations of BOD_5 and COD are higher in the landfill leachate due to the higher production of dissolved organic matter. In the methanogenic phase, dissolved organic matter is reduced, and the BOD_5/COD ratio may present values below 0.1 (Kjeldsen et al., 2002). The BOD_5/COD ratio in the present study was between 0.20 and 0.47, indicating moderate stability in the landfills (Baettker et al., 2020), except for the Juiz de Fora landfill, which presented 0.60. Baettker et al. (2020) presented similar results, with BOD_5/COD ratios higher than 0.27 for the landfill in Curitiba, Brazil. Naveen et al. (2017) stated that the 0.5–0.7 BOD_5/COD ratio indicates a large amount of biodegradable organic matter, while values below 0.1 indicate the presence of a stabilized leachate. In this case, the organic matter present in the leachate consists mainly of recalcitrant compounds, such as humic and fulvic acids (Costa et al., 2019).

The average concentration of $N\text{-}NH_4^+$ ranged from 296.2 to 1383.9 $mg.L^{-1}$. The concentrations of $N\text{-}NH_4^+$ are reported with similar values in different studies (Anand & Palani, 2022; Gautam & Kumar, 2021; Naveen et al., 2017). Ammoniacal nitrogen may be present in sanitary landfill leachate due to the degradation of proteins and amino acids and has a direct relationship with other variables, such as pH and alkalinity. In alkaline pH values, the fraction of $N\text{-}NH_3$ in the total ammoniacal nitrogen will be higher, which may affect the environment since this compound is toxic to aquatic life. Moreover, ammoniacal nitrogen may constitute a limiting nutrient in eutrophication in bodies of water. Unlike the BOD_5, the concentration of $N\text{-}NH_4^+$ does not reduce significantly in old landfills, and it may be the primary source of contamination in the stabilized leachate (Costa et al., 2019).

The age of the landfill can interfere with the composition of the leachate (Gómez et al., 2019). However, in the present study, some expected differences were not observed. For example, the Contagem landfill, in operation since 1997, could have higher pH values and a lower BOD_5/COD ratio than younger landfills, which was not observed. Despite being older, the Contagem landfill continues to operate, and the continuous deposition of organic waste means that there are still regions of the landfill in the acidogenic phase and readily biodegradable organic matter.

Correlation analysis of the physical and chemical variables of water quality

The Pearson correlation analysis was elaborated to contemplate possible relationships between the variables of the leachate produced in the landfills covered in the present study. The results are presented in Fig. 2. It is possible to note that most of the correlation coefficients were not significant at a 95% confidence level, represented by the slots marked with an "X."

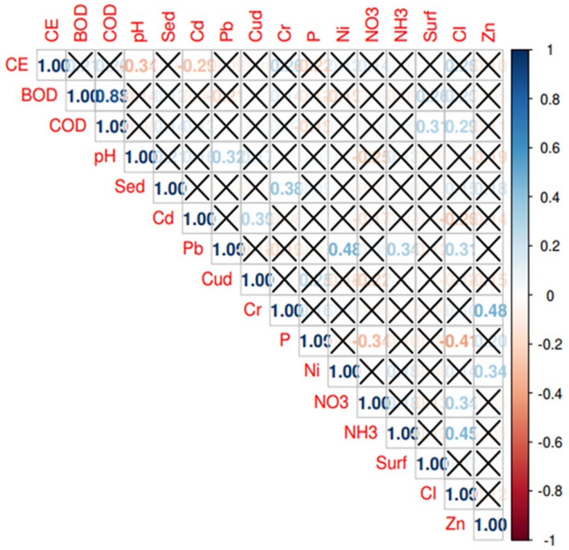

Fig. 2 Correlation analysis for the variables in the landfill leachate samples.

BOD_5 has a positive and significant correlation with COD since both express the organic matter content in the leachate. Cl^- presented a weak positive relationship with $N\text{-}NH_4^+$ (0.45) and was inversely correlated with P, also showing a weak correlation (−0.41). The kinetics of organic matter degradation may explain the relationship of Cl^- with $N\text{-}NH_4^+$ by anaerobic digestion in sanitary landfills. The degradation of organic compounds releases Cl^- ions linked to organic and inorganic compounds (Long et al., 2018) and $N\text{-}NH_4^+$ from the degradation of amino acids, increasing the concentration of both variables in the leachate, thereby justifying the positive correlation. Similar results were found in different studies in the literature. Ergene et al. (2022) obtained a positive correlation coefficient of 0.68 between $N\text{-}NH_4^+$ and Cl^- when evaluating the landfill leachate from different countries. Naveen et al. (2017), when evaluating sanitary landfill leachate from India, also obtained a significant and positive correlation between $N\text{-}NH_4^+$ and Cl^- of 0.99. As the process progresses, the organic and the carbonic acids produced in the acidogenic phase are consumed, provoking an increase in pH. This pH increase may promote the precipitation of soluble phosphorus in the form of the n PO_4^{3-} anion (Wijekoon et al., 2022), reducing its concentration in the leachate.

Furthermore, the trace metals Pb and Ni (0.48) and Cr and Zn (0.48) are directly correlated, with a weak correlation. These results suggest that metals have similar chemical behavior and sources (Abunama et al., 2021). Similar to the present study, Anand and Palani (2022) found a significant correlation between entre Ni and Pb and neglectable correlations between metals and other parameters. Ergene et al. (2022) found a moderate correlation between some metals, such as Zn with Cu, Pb, and Mn. The authors stated that the correlation between the trace metals and other parameters might vary significantly among different studies due to the characteristics of the residues dumped in each location as well as the time of operation of the landfill. As a rule, the metal concentrations tend to be higher in the initial stages of the landfill operation since their solubility is reduced with the increase in pH in the methanogenic phase.

The obtained results are essential, as they can help to identify leachate composition patterns from different sanitary landfills. In some ways, few significant correlations were expected, considering the wide variety of the characteristics of the residues and the times of operation of the landfills considered in this study, which will influence the correlations

Table 4 Results from the PCA

Variable	PC 1	PC 2	PC 3	PC 4	PC 5	PC 6
EC	**0.6546**	0.1034	−0.0489	−0.2391	−0.2142	0.0919
BOD_5	**0.7002**	−0.0058	−0.4216	0.1672	0.4227	0.0162
COD	**0.7160**	−0.1528	−0.3547	0.1587	0.5002	0.0133
pH	−0.3249	−0.4564	0.0817	**0.6760**	−0.1789	−0.1853
Settleable solids	0.1083	0.0101	0.1169	0.5489	−0.1184	0.4567
Cd	−0.3766	−0.1613	−0.2184	0.2445	**0.5222**	−0.1201
Pb	−0.0985	−0.5357	**0.6028**	0.0722	0.2928	−0.1597
Cu	−0.2880	−0.0221	−0.3136	0.3073	0.2373	0.1763
Cr	0.3588	0.3362	0.1410	0.4468	−0.1682	0.4723
P	−0.4438	0.3746	0.0602	0.2286	0.0918	0.3808
Ni	0.1077	−0.1757	**0.7329**	−0.0328	0.4256	0.0852
NO_3^-	−0.1397	0.4853	0.3702	−0.4008	0.4427	0.2909
NH_4^+	0.2929	−0.4420	0.3532	−0.0275	−0.1373	0.1926
Surfactants	0.2649	0.5387	0.1408	0.3195	−0.0273	**−0.6442**
Cl	**0.6784**	−0.3445	0.3011	0.0438	−0.1669	−0.0074
Zn	0.1830	**0.6988**	0.4699	0.3171	0.0652	−0.2800
% variation	17.4	13.5	12.4	10.3	8.8	8.2
% cumulative variation	17.4	30.9	43.3	53.6	62.4	70.6

Information in bold highlights the largest coefficients found in the principal components analysis as well as the physical, chemical, and biological mechanisms that take place inside the landfill.

Principal components analysis (PCA)

Table 4 shows the results obtained in the PCA, with the 16 initial variables being reduced to 6 principal components (PC), which, together, explained 70.6% of the data variability.

PC1 explained 17.5% of the data variation, which is related mainly to the biological degradation of the waste. BOD_5 and COD presented the highest positive loads, followed by variables Cl^- and EC. Sanitary landfill leachates are formed by the percolation of water through the waste, considering that the interaction between water and waste occurs in an anaerobic environment, concentrating inorganic and organic matter (Clarke et al., 2015). The variables related to ions are heavily linked to PC1; the organic matter may also indicate that the ions are present in the leachate, mainly due to biological processes, throughout the anaerobic digestion of organic matter. Ergene et al. (2022), when evaluating the landfill leachate quality from 46 countries, found PC1 related only to monovalent cations with no significant COD load. The authors explained that, in this case, the inorganic material in the leachate comes only from such mechanisms as dissolution and dilution. Still, according to Ergene et al. (2022), such differences can occur, mainly due to the time of operation of the landfills, with inorganic variables presenting higher concentrations in landfills in the initial or intermediate phases. The landfills considered in the present study have operation times ranging from 25 to 8 years, corroborating the data obtained since they may present different stabilization states.

PC2 explained 13.5% of the data variation, and the variable Zn represented the higher contribution, 0.6988. Moreover, the principal components, PC3 and PC5, were also related to trace metals. In PC3, which explained 12.4% of the data variation, Ni and Pb were the variables with higher contributions, 0.7329 and 0.6028, respectively. In PC5, the variable Cd presented 0.5222. The trace metals may be present in the landfill leachate due to the disposal of waste, such as batteries, light bulbs, paint leftovers, remains from cleaning products, packaging from chemical products and sprays, lubricant oils, solvents, photographic material, electronic components, cans, plastics, and medication, among others (Alloway, 2013). According to Carvajal-Flórez and Cardona-Gallo (2019), specifically with trace metals, the concentrations are highly variable and depend on the hazardous waste discarded in the landfills. Reduced concentrations of trace metals in leachate from operating landfills may indicate that their waste is primarily municipal waste, without products with metals in their composition (Wdowczyk & Szymańska-Pulikowska, 2020).

The leachate trace metal composition varies during the landfill activity, depending on the waste composition and age, the technology used in the landfill, and the water quality that percolates through the waste (Talalaj, 2015). The trace metal concentration tends to decrease as the age of the landfill increases due to the increase in pH and the consequently lower solubilization of the metals, as well as the reactions of adsorption and precipitation (Hussein et al., 2019). Such reactions may occur with organic and inorganic compounds, such as carbonates, sulfites, and other inorganic materials (Ergene et al., 2022).

According to Naveen et al. (2017), the metals are considered hazardous pollutants, capable of interrupting the normal functions of a cell due to their ability to make strong metallic connections with a series of functional macromolecules at the same time, causing the formation of agglomerates. Therefore, the concentration of trace metals may represent a limitation for biological treatment.

PC4 explained 10.3% of the data variation, and pH represented the highest contribution: 0.6760. As previously discussed, pH is an essential parameter in the follow-up of the decomposition process of solid urban waste, indicating the microbiological degradation of organic matter and the global evolution of the process of stabilization of the waste's mass. During the anaerobic digestion process, the production of organic and carbonic acids (which dissociate into hydrogen cations and bicarbonate anions) during acidogenesis tends to reduce the pH. These acids are consumed in the phases of acetogenesis and methanogenesis, making the pH rise over time. Furthermore, the leachate's pH is influenced by the partial pressure of the carbon dioxide gas in contact with the leachate (Naveen et al., 2017). Therefore, pH values below 7.0 are characteristic of newer landfills in the acidogenic phase, while alkaline pH values are expected in landfills in a more advanced maturation state in the methanogenic stage. Wdowczyk and Szymańska-Pulikowska (2020) reinforce this statement when evaluating operating sanitary landfills and landfills that do not show pH values between 7.4 and 9.1, respectively. Moreover, the pH variation provoked by the biological degradation of organic waste may influence the occurrence of physical and chemical mechanisms, such as adsorption, precipitation, and dissolution of different ions present in the leachate. High pH values also contribute to a higher percentage of NH_3, which is more toxic than the ammoniacal ion (NH_4^+) and inhibits anaerobic treatment (Baettker et al., 2020).

Finally, PC6 explained 8.2% of the data variation, which is affected negatively by the variable surfactants (−0.6442), whose presence in the leachate may be explained by the presence of soap, shampoo, detergent, cosmetics packaging, and cleaning products packaging containing leftovers, among other things (Ramakrishnan et al., 2015). Eggen et al. (2010) investigated leachate from three municipal sanitary landfills as a significant source of new and emerging pollutants and observed the presence of perfluorinated compounds (PFCs) in two of the evaluated landfills. According to the authors, these compounds have a generalized application in many products, including domestic cleaning agents, carpets, textiles, paper coatings, cosmetics, flame retardant foam, and food packaging. Therefore, it is possible to infer that such elements present in the leachate stem from the landfill disposals of packaging containing the remains of the products mentioned above.

Leachate pollution index (LPI)

The calculations of the leachate pollution index were conducted for each sanitary landfill, and the data used and the values found are shown in Table 5. The "Value" columns show the mean concentrations of each variable in each landfill. The sub-index values were obtained from the curves that relate the pollution potential of each variable with their concentrations, presented in Kumar and Alappat (2005). It should be noted that the sub-index ranges from 5 to 100. The higher it is, the greater the potential for pollution, as described in the "Leachate pollution index (LPI)" section in the Material and methods. The LPI values varied from 15.26 to 25.97. The LPI from the Uberaba landfill had the lowest value, while the Santana do Paraíso landfill presented the highest value. Although the LPI may range from 5 to 100, an LPI above 5 represents some possibility of contamination (Kumar & Alappat, 2005). Abunama et al. (2021) evaluated landfills worldwide and compared LPI results from 15 landfills in South America, finding an average value of 28.51. The landfills in this study are all fully operational and receive urban solid waste without previous segregation, which may influence the leachate characteristics and the LPI values. In general, when observing the values of the sub-index, it is possible to notice that the variables that contributed the most to raising the values of LPI were BOD_5, COD, ammoniacal nitrogen, and

Table 5 Leachate pollution index of landfills

Variable	Além Paraíba			Contagem		Santana do Paraíso		Sabará		Juiz de Fora		Uberaba		Uberlândia	
	W	Value	*Q*	Value	*Q*	Value	*Q*	Value	*Q*	Value	*Q*	Value	*Q*	Value	*Q*
BOD_5 (mg.L^{-1})	0.061	1770	35	1693.7	35	2117.1	42	728.9	23	2062	40	792.5	24	1711.4	35
COD (mg.L^{-1})	0.062	4308	63	3554.8	60	5088.3	65	3511.7	58	3438	58	2510.3	53	4163.6	62
pH	0.055	8.9	10	8.1	5	7.8	5	8.3	5	8.2	5	8.2	5	7.7	5
N-NH_4^+ (mg.L^{-1})	0.051	1290	100	527.6	58	1383.9	100	1232.3	100	0.2	5	296.2	29	1094.9	100
Chlorides (mg.L^{-1})	0.048	2950	25	3343.8	25	2827.3	22	2704.8	20	2481	19	418.5	7	2196.6	15
Lead (mg.L^{-1})	0.063	0.067	7	0.006	5	0.011	5	0.34	6.5	0.3	7	0.073	5	0.011	5
Copper (mg.L^{-1})	0.05	0.028	5	0.007	5	0.781	6.5	0.033	5	0.004	5	2.128	9	0.035	5
Chromium (mg.L^{-1})	0.064	0.54	6	0.165	6	0.282	6	0.128	5	0.2	6	0.135	6	0.156	5.5
Nickel (mg.L^{-1})	0.052	0.15	6	0.146	6	0.123	5.2	0.309	6	0.1	5	0.184	6	0.136	5
Zinc (mg.L^{-1})	0.056	1.30	5	0.154	5	0.545	5	0.323	5	0.7	5	0.416	5	0.384	5
LPI		25.90		21.04		25.97		22.96		16.17		15.26		24.07	

W weight of each variable, *Q* sub-indexes chlorides. Similar behavior was observed in other studies based on the calculation of the LPI. Anand and Palani (2022) obtained a result of 26.65 from an operating sanitary landfill in India, with higher sub-indexes for COD, chlorides, ammoniacal nitrogen, and total coliforms. Hussein et al. (2019) found LPIs of 15.28 and 13.89 in operating sanitary landfills in Malaysia, with higher sub-indexes for the variables BOD_5, COD, and some metals, such as Fe, As, and Cr. The authors compared the LPI from operating landfills and landfills that were already closed and obtained higher values in operating landfills. The results were attributed to the constant addition of waste from different sources, thus maintaining a high concentration of organic matter in the leachate. Arunbabu et al. (2017), when evaluating the landfill in Kerala, India, found a 31.99 LPI. Likewise, in the present study, the variables that contributed the most to the high LPI were BOD_5, COD, and ammoniacal nitrogen. The authors highlight the high BOD_5/COD ratio in the leachate (0.69), indicating the importance of biological treatment, and the high concentration of ammoniacal nitrogen, 2240.0 mg.L^{-1}.

It is important to highlight that the sub-indexes obtained for the trace metals ranged from 5 to 9 in each landfill, thus reducing LPI values. Kumar and Alappat (2005), when calculating the LPI for the raw leachate from the landfill in Harewood Whin, observed that the effluent is poor in metals, presenting sub-index values between 5 and 5.5. The authors calculated the LPI of the metals at 5.531 and for the general LPI, with a value of 19.66. Anand and Palani (2022) also obtained LPI values only for metals that were 2.15, while the LPI for organic and inorganic parameters was 54.86 and 44.72, respectively. The result is justified to pH above 8 for operating landfills, which reduces the solubility of the metals and, consequently, their concentration in the leachate. The authors also noted that the metal concentration in the leachate might be related to the characteristics of the waste in the landfill. Considering this, it is essential to highlight the importance of previous segregation in increasing the landfill lifespan and decreasing the leachate contamination potential. Gautam and Kumar (2021) evaluated the concentrations of different variables from a sanitary landfill in India over time. The authors did not observe any specific pattern of variation for metals such as chrome, lead, and zinc, which indicates that possible variations are not due to external factors such as precipitation and temperature.

In the present investigation, the pH values ranged from 7.69 to 8.9, which may also justify the concentrations of metals observed and the sub-index values. This result corroborates Costa et al. (2019), who state that the concentrations of metals in the leachate of a sanitary landfill in Brazil are low due to the alkaline pH. Nonetheless, it is essential to highlight that the presence and the concentrations of trace metals in the leachate must be monitored since they may interfere in the biological treatment systems and cause negative environmental impacts when discarded into the environment if in low concentrations.

Conclusions

Through the BOD_5/COD ratio, it was possible to observe that the leachate from the sanitary landfills studied herein has moderate biodegradability characteristics. The PCA indicated that the first six components explained 70.7% of the data variability. PC1 explained 17.45% of the data variation and involved COD, BOD_5, chlorides, and electric conductivity as those with the highest contribution and the BOD_5 and COD variables with the highest values. The variability of organic matter and, consequently, of the biodegradability of the landfills directly influenced the data variation.

LPI values between 15.26 and 25.90 indicate that the leachate generated from landfills is not totally stabilized and may constitute a severe source of contamination for the soil and water resources. In this context, the highest values for the sub-indexes were for BOD_5, COD, and ammoniacal nitrogen. By contrast, the trace metals presented a lower contribution for the LPI values due to the time of operation of the landfills or because they reflected the characteristics of the predominantly domestic waste in the landfill. The LPI results highlight the importance of separating waste before sending it to landfill. This separation allows the use of materials that can still be used and the control of the shipment of products that contain dangerous substances, such as metals. The importance of organic content in the data variability and the LPI highlights biological systems' applicability in landfill leachate treatment. Many of these systems have widely known operating parameters for sanitary sewage. With this, it is essential to carry out future studies to optimize the operational parameters of different biological systems, aiming at applying landfill leachate to guarantee the effectiveness of the technologies.

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Authors' contribution Fabiana de Ávila Modesto: Investigation, Data curation, Writing – Original Draft. Roberto Cezar Almeida Monte-Mor: Conceptualization, Supervision, Writing – Review & Editing. Eduardo Couto: Conceptualization, Methodology, Writing – Review & Editing, Supervision.

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

Declarations

Competing interests The authors declare no competing interests.

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