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DISCUSSIONS ON ALTERNATIVE TREATMENTS FOR LANDFILL LEACHATE IN BRAZIL IN THE FACE OF THE CHALLENGE OF EMERGING CONTAMINANTS

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ABSTRACT

Landfill is a final waste disposal technique that complies with Brazilian legal requirements. However, the processes that occur in landfill cells produce an effluent with a complex composition called leachate, which requires adequate treatment. Various advanced leachate treatment processes are currently used in Brazil. In addition, a common strategy is to send the leachate to wastewater treatment plants (WWTPs) so that the two effluents are treated together. However, both the processes adopted in leachate treatment plants and those used in WWTPs aim to remove organic matter and nutrients without considering the so-called emerging contaminants. Therefore, this study aims to discuss the main forms of landfill leachate treatment, with an emphasis on removing these contaminants. Many of the techniques studied have been adopted to treat leachate in Brazilian landfills, which may indicate the eventual removal of these compounds. The inclusion of these techniques as leachate pre-treatment and post-treatment steps in the WWTPs that receive it could promote the reduction of emerging contaminants in the final effluent.

KEYWORDS: Solid waste, Leachate, Emerging pollutants, Wastewater.

DISCUSSÕES SOBRE AS ALTERNATIVAS DE TRATAMENTO DE LIXIVIADO DE ATERRO SANITÁRIO NO BRASIL DIANTE DO DESAFIO DOS CONTAMINANTES EMERGENTES

RESUMO

Os aterros sanitários são uma técnica de disposição final de resíduos que vai ao encontro das exigências legais brasileiras. No entanto, os processos que ocorrem nas células dos aterros originam um efluente de complexa composição denominado lixiviado, o qual requer tratamento adequado. Diferentes processos de tratamento de lixiviado considerados avançados já têm sido empregados no Brasil. Além disso, uma estratégia muito comum é o envio do lixiviado para as estações de tratamento de esgoto (ETE), para que os dois efluentes sejam tratados de forma conjunta. Porém, tanto os processos adotados nas estações de tratamento de lixiviado quanto os que se utilizam nas ETE, têm por objetivo a remoção de matéria orgânica e nutrientes, não contemplando os chamados contaminantes emergentes. Diante disso, este trabalho se propõe a discutir as principais formas de tratamento do lixiviado de aterro sanitário, com ênfase na remoção desses contaminantes. Muitas das técnicas de tratamento estudadas já são adotadas para tratar lixiviados em aterros brasileiros, o que pode significar eventual remoção desses compostos. A inclusão destas técnicas, como etapa de pré-tratamento do lixiviado e pós-tratamento nas ETE que o recebem, poderia promover a redução de contaminantes emergentes no efluente final.

PALAVRAS-CHAVE: Resíduos sólidos, Chorume, Poluentes emergentes, Esgoto.

1 INTRODUCTION

Urban solid waste has a highly diversified composition, consisting of food residues, paper, plastics, metallic materials, glass, and even components considered hazardous because of their potential harm to the environment and public health (Castilhos Junior, 2003). They reflect the economic scenario of a country as well as the consumption patterns of its population, and it is essential to have effective waste management in accordance with local specificities.

Sanitary landfills constitute an engineering technique for the disposal of urban solid waste designed and operated to minimize the impact on public health and the environment (Kreith & Tchobanoglous, 2002). In this method, solid waste is confined to the smallest possible area and covered with layers of soil (ABNT, 1984). However, certain factors hinder the widespread adoption of this technique. One important issue is the proper treatment of one of the byproducts generated in this process, leachate. In Brazil, especially in small municipalities, leachate treatment is often performed through biological processes owing to their relative simplicity and economic viability. More advanced treatment techniques, such as membrane processes, are commonly employed (Costa et al., 2019). In some cities, leachate is directed to wastewater treatment plants (WWTPs) for combined treatment with sanitary wastewater, utilizing the existing processes at the WWTP (Gomes, 2009).

A wide range of techniques are currently available for the treatment of landfill leachate. In general, these techniques are based on the same parameters adopted for the treatment of sanitary wastewater, that is, the removal of organic compounds, nitrogen compounds, phosphorus, and suspended solids. However, none of these processes have been specifically designed for the removal of pharmaceutical or personal care products, the so-called emerging contaminants (Bellver-Domingo, Fuentes & Hernández-Sancho, 2017).

In this context, this study aims to discuss issues related to leachate treatment in Brazil from the perspective of removing emerging contaminants, based on literature and documentary research. This article addresses aspects related to urban solid waste management, with a focus on sanitary landfills and the problems associated with landfill leachate. It also presents the main technologies used for leachate treatment in Brazil and their potential for removing emerging contaminants.

2 DEVELOPMENT

2.1 Management of Urban Solid Waste

The improper disposal of urban solid waste can have several negative impacts. These effects extend beyond water, air, and soil pollution and ecological imbalance, to social aspects such as property devaluation, potential public health impacts, and the proliferation of vectors (Kjeldsen et al., 2002).

In most developing and recently developed countries, sanitary landfills are likely to remain the primary means of final solid waste disposal for a long time (Yu, 2013). According to the latest Diagnosis of Urban Solid Waste Management in 2021, which annually publishes data from the National Sanitation Information System (SNIS), there are 1,572 open dumps, 595 controlled landfills, and 669 sanitary landfills in the Brazilian territory (Brazil, 2022b).

Compared to open dumps, controlled landfills pose a lower risk to public health, primarily because of the coverage of waste (Bocchiglieri, 2010). It is crucial to note that of these three disposal practices, only sanitary landfills meet Brazilian environmental requirements, in addition to presenting technical and economic advantages from the country's perspective (Gomes, 2009). A common factor among the three disposal methods is the generation of gases and a liquid effluent known as leachate. In sanitary landfills, both leachate and gas are collected for subsequent treatment. This is done by sealing the soil to prevent leachate from entering the groundwater, and by installing buried pipes in landfill cells to collect gas. Although gases captured in landfills can be burned and/or utilized for energy generation, leachate is an effluent that must be properly managed and treated. Therefore, leachate is a byproduct of sanitary landfills that deserves greater attention for its reintroduction into the environment in a carefully controlled manner to avoid harmful effects on groundwater and surface water (Great Britain, 2003).

It is worth noting that, even after the closure of a sanitary landfill, leachate generation continues for decades. According to the SNIS, 244 sanitary landfills were inactive in Brazil in 2021, but there is no information on their monitoring. In Brazil, NBR 13896/97 requires the maintenance of leachate treatment systems as long as this effluent is generated (ABNT, 1997). Some authors argue that monitoring should extend up to 30 years after closure, focusing on geotechnical stability, gas generation, and leachate treatment (Barlaz et al., 2002). This timeframe is recommended in many environmental regulations, although some authors advocate a period of approximately 50 years (Lee & Jomes-Lee, 1996). It is clear, therefore, that proper leachate treatment is a challenge that will persist beyond the operational life of a landfill, even after the disposal of solid waste, and in this case, the generation of revenue, has ceased.

2.2 Landfill Leachate

Landfill leachate is the most appropriate term to describe the liquids that result from the solubilization of solid compounds within a sanitary landfill (Souto, 2009). Leachate consists of a potentially polluting, dark-colored liquid. Contributors to leachate generation include surface drainage, liquid generated from the decomposition of the waste itself, and most importantly, the amount of precipitation in the landfill (Kreith & Tchobanoglous, 2002; Shroff, 1999). The composition of leachate is highly variable and is influenced by various factors, such as the time and type of landfill operation and the type of waste disposed. Leachate can contain various pollutants, including biodegradable and refractory dissolved organic materials, inorganic macro components, toxic metals, dissolved gases, and xenobiotic organic compounds (Kjeldsen et al., 2002; Pesenti et al., 2023).

Despite being an effluent with such a complex composition, the disposal standards required for leachate in Brazil are the same as those recommended for effluents from any polluting source, according to National Environmental Council (CONAMA) Resolution 430/2011 (Brazil, 2011). From this perspective, the specific characteristics of leachate have not been adequately considered in Brazilian legislation. An example illustrating one of these inadequacies is the adoption of the Biochemical Oxygen Demand (BOD) parameter to assess organic matter in leachate. The presence of toxic compounds in this effluent can inhibit the microorganisms used as inoculum in the BOD analysis, resulting in underestimated values for organic matter (Campos, 2014).

The toxic potential of sanitary landfill leachate for human health has already been demonstrated in cell-level studies. Baderna et al. (2011) used in vitro assays on HepG2 hepatoma cells to evaluate the toxic effects of raw leachate at different volumetric concentrations (1.25, 2.5, 5, 10, 20, and 30%). Inhibition of cell proliferation was observed even at low concentrations of leachate (2.5 to 5%), and cytotoxic effects were observed at higher concentrations (from 10%) after 48 hours of exposure. Toufexi et al. (2013) assessed the exposure of human lymphocyte cultures to leachate concentrations of 0.1%, 0.2%, and 1%, v v^{-1}. The results showed an increase in the frequency of micronucleus formation and a decrease in cell proliferation, indicating the genotoxic and cytotoxic effects of the leachate as well as its potential aneugenic activity in human lymphocytes.

Studies have often addressed the health-damaging effects of numerous contaminants present in landfill leachates. However, many of these contaminants have not been properly identified, and their risks to humans and environmental receptors have not been clearly defined (Toufexi et al., 2013). This issue represents a significant gap in proposing appropriate leachate treatments, as the full range of potentially polluting compounds that must be removed during the treatment stages is not fully known.

2.3 Types of Treatment for Landfill Leachate

According to NBR 15849/2010, landfill leachate treatment involves facilities and structures aimed at mitigating leachate characteristics to comply with relevant effluent disposal legislation (ABNT, 2010). The extremely variable composition of landfill leachate poses challenges for its treatment. Consequently, various treatment methods, often requiring a combination of multiple techniques, have been employed to achieve satisfactory efficiency (Moura et al., 2023).

Biological treatments are commonly used to treat highly biodegradable leachates. These techniques are relatively simple and inexpensive compared to other treatment types (Miao et al., 2019). However, biological treatments alone are insufficient to meet the disposal standards (Oller, Malato & Sánchez-Pérez, 2011). The most commonly used biological processes for leachate treatment are lagoons, activated sludge, membrane biological reactors (MBRs), moving bed biofilm reactors (MBBRs), percolating biological filters, and constructed wetlands.

Compared with other biological processes, lagoon systems require larger built areas. This is because a specific concentration of suspended biomass is used in this process, which remains in contact with the leachate for extended periods. The most commonly used variants are anaerobic and aerobic lagoons; however, facultative lagoons can also be used for leachate treatment (Carrilho & Carvalho, 2016). Lagoons have low operational costs and are easy to maintain;

however, climatic factors can strongly affect their performance. Notably, lagoons alone may not satisfactorily meet the stringent regulations (Maynard, Ouki & Williams, 1999; Renou et al., 2008).

During the activated sludge process, microorganisms (biomass) undergo biochemical reactions using the substrate present in the effluent to be treated. This process occurs in a tank where aerobic metabolic activity is promoted and the sludge is mixed with the effluent. After the reaction time, biomass (solid) and treated effluent (liquid) were separated using a settler. Part of the solid is discarded, whereas another portion is recirculated into the reactor, resulting in high removal efficiencies (Von Sperling, 2002). Because of this recirculation, the area occupied by the process is smaller than that required for lagoons. Over more than 100 years, many variants of the activated sludge process have been developed, such as extended aeration, sequential batch operation, MBR, and MBBR (Jordão & Pessôa, 2014).

The MBR process combines two types of treatment: a biological reactor in which microorganisms degrade organic material, similar to the conventional activated sludge process, and a membrane module replacing the settler (Sutherland, 2010). In the MBBR process, support materials are added and kept in motion in an aeration tank, where the biomass grows and develops in the form of an attached biofilm (Mannina & Viviani, 2009).

Percolating biological filters use a fixed support material to which biofilms are formed and remain attached. This support material is denser than that used in MBBR, which often utilizes gravel. The effluent to be treated was distributed over the filters using rotating distributors on the support material surfaces, allowing interaction with the biofilm. The effluents percolate through the support material in a downward flow, carrying the oxygen required to promote the reactions occurring in the biofilm (Daigger & Boltz, 2011).

Constructed wetlands are designed to simulate natural wetland areas by incorporating specific plant species adapted to these conditions. These systems commonly utilize not only microorganisms for effluent treatment but also plants and soil. These conditions promote the removal of contaminants from effluents (Kivaisi, 2001; Bakhshoodeh et al., 2020). An important aspect of these systems is the contact time between the effluent and the plant root zone, which often requires a larger built area, similar to that of lagoon systems.

Physical and chemical processes have been successful in removing suspended solids, colloids, and colors present in landfill leachates. They can also be employed as a pretreatment step to remove ammonia nitrogen or as a post-treatment step to remove recalcitrant compounds (Renou et al., 2008). The most prominent processes in leachate treatment are coagulation-flocculation, advanced oxidative processes, membranes, and the use of activated carbon.

Coagulation-flocculation is a relatively simple physicochemical process for removing non-settleable solids such as surfactants, toxic metals, fatty acids, and humic substances (Torretta et al., 2017). It is important to note that this process generates an undesirable byproduct, that is chemical sludge. The disposal of sludge is a challenge in this technique, as it tends to have high concentrations of aluminum and/or iron depending on the coagulant agent used.

Advanced oxidative processes require the generation of hydroxyl radicals (●OH), responsible for degrading recalcitrant compounds (Cho, Hong & Hong, 2002; Pera-Titus et al., 2004). Thus, strong oxidants, such as ozone, hydrogen peroxide, ferrous ions, UV radiation, and titanium dioxide, are used as promoters of these radicals. However, some of these processes, which have limitations on a real scale, can be ineffective in turbid effluents, and in some cases, the generation of iron-containing sludge may occur, as in the Fenton and photo-Fenton processes (Brienza & Katsoyiannis, 2017). Another limitation of these techniques is the non-specific action of hydroxyl radicals, which can generate other compounds through the condensation of intermediate degradation products.

The use of membranes for leachate treatment has expanded, particularly in large cities. Membranes are thin interfaces that control the permeation of chemical species that are in contact with them. Membranes can exhibit homogeneous or heterogeneous structures with layers of different compositions. Microfiltration, ultrafiltration, nanofiltration, and reverse osmosis are examples of membrane processes that can be applied for leachate treatment (Baker, 2004; Metcalf & Eddy, 2016). The issues with this technique include the effluent discharged from the process (concentrate), which typically has high contaminant concentrations, and the disposal of the used membranes.

Techniques utilizing adsorption have also been applied to leachate treatment, and activated carbon has been successfully used as an adsorbent for contaminant removal. However, the frequent need for regeneration is a disadvantage when using carbon (Renou et al., 2008). Regeneration involves a set of processes aimed at partially recovering the adsorption capacity of spent carbon, which results in increased operating costs (Metcalf & Eddy, 2016).

Therefore, different processes can be used for landfill leachate treatment, each of which has intrinsic advantages and disadvantages that must be understood before implementation. Table 1 lists some processes adopted to treat landfill leachates in Brazilian landfills.

Table 1: Types of leachate treatment used in Brazilian landfills

Landfill	Location	Type of Treatment	References
Central de Tratamento de Resíduos Seropédica	Seropédica/RJ	Physical, chemical and biological processes, including reverse osmosis	(Ciclus, 2020)
Central de Tratamento de Resíduos Alcantara	São Gonçalo/RJ	Pre-treatment (filtration) and reverse osmosis in 3 steps	(AST, 2020)
Conselheiro Josino	Campos dos Goytacazes/RJ	Pre-treatment (filtration) and reverse osmosis in 3 steps	(AST, 2020)
Nova Friburgo	Nova Friburgo/RJ	Pre-treatment (filtration) and reverse osmosis in 2 steps adapted for the concentrate	(AST, 2020)
Osasco	Osasco/SP	MBR (Membrane Biological Reactor)	(Sprovieri & Contrera, 2017)
Rio Claro	Rio Claro/SP	MBR (Membrane Biological Reactor)	(Sprovieri & Contrera, 2017)
Rincão das Flores	Caxias do Sul/RS	Coagulation/flocculation, biological filter and activated sludge	(Pertile, 2013)

Lajeado	Lajeado/RS	Coagulation/flocculation, sand filter and reverse osmosis	(Roehrs et al., 2019)
Aterro sanitário de Foz do Iguaçu	Foz do Iguaçu/PR	Pre-treatment (filtration) and reverse osmosis	(CATVE, 2019)
Maceió	Maceió/AL	Anaerobic and aerated lagoons, coagulation/flocculation, filtration (activated carbon and zeolite) and nanofiltration	(Araújo, 2019)

Although many Brazilian landfills employ advanced technologies for leachate treatment, it is essential to clarify that only 30% of all installed landfills have on-site leachate treatment, which is conducted within landfill premises (Brazil, 2019). In this scenario, a common strategy is to transport the leachate to wastewater treatment plants for what is known as combined treatment. This technique involves the simultaneous treatment of leachate and wastewater at a wastewater treatment plant, ensuring that the treated effluent meets the legislative requirements (Gomes, 2009). The positive aspects of adopting this alternative focus on economic considerations are low operating costs, without the need for the addition of nitrogen, phosphorus, and elements present in higher concentrations in the leachate and wastewater (Renou et al., 2008). The drawbacks are related to compounds with potential toxic effects on biomass or low biodegradability present in leachate, which may reduce treatment efficiency (Çeçen & Aktaş, 2004).

Legally, with the enactment of Law 11.445 in 2007, new national guidelines were established emphasizing the planning of basic services as a fundamental tool to achieve universal sanitation in Brazil. The document advocates the Municipal Basic Sanitation Plan to be developed by the municipalities of all the country's cities so that, after approval by the Federal Government, funds can be allocated for sanitation projects (Brazil, 2007). It is also clear that these plans should cover the four areas: water services, wastewater, solid waste, and urban stormwater drainage (Trata Brasil, 2017). According to SNIS reports, in 2021, at least 95.4% of municipalities will have water supply systems, and 50% will have public wastewater systems. Furthermore, 65.6% of the municipalities reported serving their entire urban population with direct and indirect collection of household waste, and 68.2% of the municipalities had some form of drainage system (Brazil, 2022a, 2022b, 2022c).

Both wastewater and solid waste services are under the jurisdiction of municipal authorities, creating a conducive environment for the combined treatment of leachate and wastewater. Table 2 lists examples of Brazilian landfills currently sending leachate to treatment plants.

Table 2: Brazilian landfills that use combined treatment

Landfill	Location	Status	WWTP[1]	Type of Treatment	References
Bandeirantes	São Paulo/SP	Deactivated	Barueri	Conventional activated sludge	(Bocchiglieri, 2010; Silva, 2011; ECOURBIS, 2020; Rosa et al., 2017; Figueiredo,
São João		Deactivated			
Santo Amaro		Deactivated			
Vila Albertina		Deactivated			

Essencis		In operation			2011; CONSEMA, 2018; Brasil, 2017)
CDR Pedreira		In operation			
Extrema	Porto Alegre/RS	Deactivated	Lami	Stabilization lagoons	(Bocchiglieri, 2010; Kreling, 2006; Gomes, 2009)
Santa Tecla	Gravataí/RS	Deactivated	Canoas	Activated sludge in batches	(Sousa, 2011)
Salvaterra	Juiz de Fora/MG	Deactivated	Barbosa Lage	Activated sludge with prolonged aeration	(Magalhães, 2012; Brasil, 2017)
CTR BR-040	Belo Horizonte/ MG	Deactivated	Ribeirão Arrudas	Conventional activated sludge	(Moravia, 2010; Brasil, 2017)
Dois Arcos	São Pedro da Aldeia/RJ	In operation	São Pedro (ProLagos)	Activated sludge with biological nutrient removal	(Nascentes, 2013)

[1]WWTP – Wastewater Treatment Plant that receives the leachate.

Many of these landfills have already been deactivated, emphasizing the importance of this treatment method beyond the lifespan of sanitary landfills. Because combined treatment is already a reality in Brazil, efforts are needed to establish the criteria for the use of this technique, which should be appropriately defined for the Brazilian scenario, especially concerning the leachate/wastewater relationship (Gomes, 2009).

Some authors have claimed that the volumetric ratio between leachate and sanitary wastewater that can be applied is 2%. For leachates with chemical oxygen demand (COD) values of up to 10,000 mg L^{-1}, it is possible to adopt up to 5% (Mcbean, Rovers & Farquhar, 1995). Other studies have focused on the volumetric percentage of leachate during the operation of landfills. Leachate from a landfill of intermediate age (between 5 and 10 years) can be applied at a volumetric ratio of up to 4% (corresponding to 50% of the total ammonia-nitrogen load at the station). For leachate from a recently operational landfill (less than 5 years), a percentage below 2% by volume is recommended (Brennan et al., 2017).

It is worth noting that the usual concern is to assess the percentages of leachate that may compromise the efficiency of treatment processes. In this regard, only the parameters required by Brazilian regulations are typically considered, which do not include emerging contaminants. Leachate is a potential source of these substances and could represent a significant contribution of these compounds depending on the applied volumetric percentage.

2.4 Emerging Contaminants

Emerging contaminants can be understood as any synthetic or naturally occurring chemical that may cause harm to humans and/or wildlife but is not yet regulated; therefore, their monitoring has no legal effect. This classification includes medications (both prescription and nonprescription drugs), personal care and hygiene products (such as soaps and disinfectants), and chemical additives (USGS, 2017).

Unlike the "conventional" pollutants present in wastewater, such as organic matter and nutrients, there is still little information on the dynamics of emerging contaminants in aquatic systems and their effects on health (Ma et al., 2018). Hence, there is a need for continuous improvement in analytical techniques to identify and quantify a variety of compounds that may be found, usually at very low concentrations. As these substances are not regulated, there are currently no concentration limit values for the safe discharge of these contaminants into the environment, and only international guidelines are available (EU Directives 2013/39/EU and 2015/495/EU) (Barbosa et al., 2016). However, the literature emphasizes that the discharge of these contaminants poses a risk to water quality and can affect aquatic organisms (Luo et al., 2014). Within this universe of compounds, some deserve special attention, such as hormones because of their potential for endocrine disruption, psychotropic drugs for their action on the central nervous system, and antibiotics for their association with an increase in antibiotic-resistant bacteria (Montagner, Vidal & Acayaba, 2017).

Although matrices such as sanitary wastewater, drinking water, and soil already have extensive knowledge of emerging contaminants, studies on their occurrence and removal from landfill leachate are still limited (Qi et al., 2018). Waste disposed in landfills (medications and personal care items) is a potential source of these compounds, which are likely to be present in the generated leachate.

Eggen, Moeder, and Arukwe (2010) detected different emerging contaminants in leachate, highlighting flame retardants with carcinogenic potential, plasticizers with neurotoxic effects, and insect repellents. Lu et al. (2016) reported the presence of various pharmaceuticals in raw leachate samples, including analgesics, anti-inflammatories, lipid regulators, cholesterol-reducing statins, psychiatric drugs, macrolide antibiotics, stimulant drugs, beta-lactams, proton pump inhibitors, dissociative anesthetics, and sympathomimetic compounds. The occurrence of different emerging contaminants in landfill leachate is possible at levels similar to those found in sanitary wastewater (between $\mu g\ L^{-1}$ and $ng\ L^{-1}$). The challenge lies in determining which processes leachate can undergo to remove not only "conventional" and recalcitrant contaminants but also emerging ones.

2.5 Removal of Emerging Contaminants by Different Treatment Processes

Over the past 15 years, several studies have assessed the potential removal of various emerging contaminants from landfill leachate using existing treatment processes. Most of these studies have evaluated different isolated or combined processes for the removal of specific groups of emerging micropollutants, such as chemical additives used in plastic materials (bisphenol A and phthalic acids), endocrine disruptors (estrogenic hormones), and pharmaceuticals and personal care products (PPCPs).

He et al. (2009) investigated the removal of phthalic acid esters and bisphenol A from leachates of both young and old landfills. Using the Fenton process, over 40% removal of phthalic acid esters and 62% removal of bisphenol A were achieved from the old leachate. However, the removal efficiencies of the young leachate were only 20% and 37%, respectively. The authors also added the target compounds to the raw leachate, after which the removal efficiency exceeded 88%. Thus, the initial concentrations of contaminants were related to their removal efficiencies, indicating that low concentrations of the investigated compounds in the leachate may hinder the performance of the Fenton process. Silva et al. (2013) used a combination of different processes to treat landfill leachate (activated sludge + photo-Fenton process + activated sludge). In the first biological stage, high contaminant removal efficiencies (> 80 %), including for BPA, were achieved.

Zhang and Wang (2009) observed the removal of phthalate esters via coagulation and flocculation. Higher efficiencies were obtained using poly-aluminum chloride than using ferric chloride and aluminum sulfate, which are commonly used coagulants in this type of process.

Joseph et al. (2013) assessed the removal of bisphenol A and 17α-ethinylestradiol (EE2) in various matrices through the combination of coagulation and adsorption processes (carbon nanotubes and powdered activated carbon). The authors used synthetic solutions with leachate from young and old landfill sites. Removal efficiencies of over 99% were observed for both bisphenol A and EE2 with a combination of coagulation and activated carbon adsorption. Maximum contaminant removal was achieved with a carbon dose of 80 mg L^{-1}; however, for the old landfill leachate, a slightly higher concentration was required. The use of coagulants did not significantly increase the removal of contaminants, and activated carbon performed better than the carbon nanomaterials.

Sui et al. (2017) studied the removal of PPCPs from landfill leachates using MBR. The MBR system comprised an anoxic tank, two aerobic tanks, and an ultrafiltration module. Of the eighteen PPCPs investigated in the study, fourteen were detectable in raw leachate samples with concentrations ranging from 0.39 to 349 µg L^{-1}. With MBR treatment, removal efficiencies of over 90% and 86% were achieved for metoprolol (antihypertensive) and gemfibrozil (a lipid regulator), respectively.

Yi et al. (2017) evaluated the removal of PPCPs using a hybrid system comprising equalization tanks, aerobic lagoons, constructed wetlands, and maturation lagoons. The highest efficiency obtained was greater than 77%.

When evaluating raw and treated leachate samples using biological and/or reverse osmosis processes, Nika et al. (2020) observed that the reverse osmosis process was necessary to remove over 98% of the main pollutants and emerging contaminants among the 50+ considered in the study.

The only study on combined treatments was conducted by Pereira et al. (2018). The authors achieved a reduction in estrogenic activity during the combined treatment using a continuous-flow activated sludge process in batch mode. The results also indicate that an increase in the concentration of leachate added to wastewater may be detrimental to the removal of estrogenic compounds.

In the case of combined treatment, a strategy to promote the removal of contaminants could be the inclusion of a post-treatment stage in WWTPs using techniques already applied to leachate treatment, such as advanced oxidative processes and membrane use. However, these techniques have high operating costs when applied to raw leachate treatment and require frequent membrane replacements. However, if adopted as a post-treatment for effluents from a combined system (wastewater with leachate), the effluent to be treated would already be more tolerable, with low concentrations of organic matter, solids, and occasionally, nutrients. The addition of a coagulation-flocculation pre-treatment only to leachate can also minimize membrane damage (Alfaia et al., 2019), making the treatment system more efficient and less costly.

In the state of Rio de Janeiro, Law 9.055, sanctioned on October 8, 2020, states in Article 13 that the treatment of raw leachate in WWTPs is prohibited unless there is pre- or post-treatment to ensure compliance with the discharge standards of CONAMA Resolution 430/2011 (Rio de Janeiro, 2020). This determination may, even if unintentional, result in a higher removal of emerging contaminants.

3 FINAL CONSIDERATIONS

In Brazil, the final disposal of solid waste occurs predominantly in open dumps, controlled landfills, and sanitary landfills. As the National Solid Waste Policy mandated the eradication of open dumps in 2010, thus encouraging the expansion of final disposal in sanitary landfills, the debate on leachate treatment has continued for a long time.

However, various treatment techniques are still primarily designed for the removal of organic matter and nutrients, whereas other issues, such as the removal of emerging contaminants, are limited to the few academic studies available. Nevertheless, these studies demonstrate the potential for removing some of these contaminants through the treatment processes already employed in Brazil. Thus, it is possible that their removal occurred during the treatment of Brazilian leachates.

The combined treatment of landfill leachate and wastewater in wastewater treatment plants is a convenient treatment approach from a management perspective. The possibility of sending leachate from closed landfills to wastewater treatment plants provides a solution to the problem that all landfills eventually face.

However, the addition of leachate to wastewater treatment plants may introduce emerging contaminants, for which the plants are not prepared. In this regard, the inclusion of pre- and post-treatment steps could be a successful strategy for removing these contaminants. In addition to this operational concern, there is a need for proposals to improve the regulations for the safe disposal of these effluents, which are grounded in studies that integrate efficiency, economic viability, and health assurance.

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