



# Municipal Solid Waste Landfill Leachate Characteristics and Their Treatment Options in Tropical Countries

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Accepted: 8 May 2022 / Published online: 29 June 2022  
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## Abstract

This review assesses the leachate quality from waste disposal sites in tropical climate zone. Through this review, data from 228 leachate samples from 145 waste disposal sites from 18 countries in the tropical region were analyzed. The 12 types of sites were considered for the analysis based on the climatic conditions, age, and the operating condition of the site. Tropical rainforest, tropical monsoon, and tropical savanna climates were identified for the climatic zone classification. Age of site was classified as young and old. The operating conditions were classified as engineered landfill and open dump site. Eighteen leachate quality parameters were included in the analysis. Leachate pollution index indicated that young sites from tropical rainforest zone and tropical monsoon zone have higher pollution potential, while the pollution potential in tropical savanna zone did not demonstrate considerable difference in pollution potential in terms of age of the landfill. Considering the operating method of the sites, open dumpsites pose higher pollution potential. Positive correlation could be seen among biological oxygen demand, chemical oxygen demand, total dissolved solids, and total Kjeldahl nitrogen. pH negatively correlated with organic pollutants as well as heavy metals. Analysis of emerging contaminants present in landfill leachate is limited in tropical region; thus, it is recommended to conduct studies on emerging contaminants. Further, the leachate treatment options considered in tropical region are discussed in this review.

**Keywords** Landfill leachate · Leachate pollution index · Leachate treatment · Tropical countries

## Highlights

- Leachate quality from tropical landfills is analyzed.
- Leachate Pollution Index is used to assess the pollution potential.
- Young open dumpsites poses higher pollution potential.
- Different treatment options are considered for leachate treatment.

This article is part of Topical Collection on *Water Pollution*

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## Introduction

### Background

A landfill is an engineered method commonly used for the systematic disposal of municipal solid waste (MSW) and hazardous waste safely. In most of the developing countries, a primary stage of landfilling in the form of open dumping is used to dispose solid waste [1]. Landfill leachate, gas emissions, slope stability, and odor control are identified as concerns of designing and operating a landfill [2••].

Idris et al. [3•], Hoornweg and Bhada-Tata [4], and Rajoo, et al. [5•] classified landfilling sites as open dumps and engineered landfills. Idowu et al. [6] also used similar classification system. The sites where there is no environmental protection and control are classified as open dumps. Engineered landfills are characterized with proper location and design, compaction of waste, use of daily cover and leachate, and gas and odor control systems. The engineered

landfills are equipped with onsite leachate treatment and post-closure management plan.

MSW in landfills undergo complex degradation by means of chemical, physical, and biological processes. The percolation of rainwater through waste results in leaching of degraded matter [7•]. Landfill leachate is the main by-product of the MSW degradation process [8]. Thus, “landfill leachate is defined as the liquid effluent generated from rainwater percolation through solid waste disposed of in a landfill, as well as the moisture present in the waste and the degradation products of residues” [9••]. The leachate quantity is mainly determined by precipitation, evapotranspiration, surface runoff, groundwater infiltration, and the degree of compaction within landfill [10••].

Leachate comprise of four types of pollutants: dissolved organic matter (organic carbon, fatty acids), inorganic compounds (chlorides, ammonium, phosphates, nitrates), heavy metals (copper, zinc, lead, mercury), and xenobiotic organic compounds (XOCs) (benzene, phenols, phthalates) [11•, 12]. In recent studies, landfill leachate is identified as one of the main sources of emerging contaminants (EC). As landfills become the most common disposal practice for MSW, landfills receive EC of different origins [13••].

The leachate composition mainly depends on the age of the landfill, solid waste composition, climatic conditions, temperature, hydrological conditions, and landfill operation practices [7•, 14•, 15••, 16, 17•]. The literature reviews currently available on landfill leachate can be classified as reviews on leachate characteristics [18••], reviews on factors influencing leachate characteristics [15••], reviews on leachate treatment methods [19, 20•], and combination of these topics [21•, 22••]. These reviews take into account leachate from disposal sites all over the world. Studies on leachate have mostly considered countries like China [23•], the USA, and European countries which are located in the temperate region [22••]; thus, data from temperate region

was analyzed. Studies that focused on leachate from tropical landfills and dumpsites are limited.

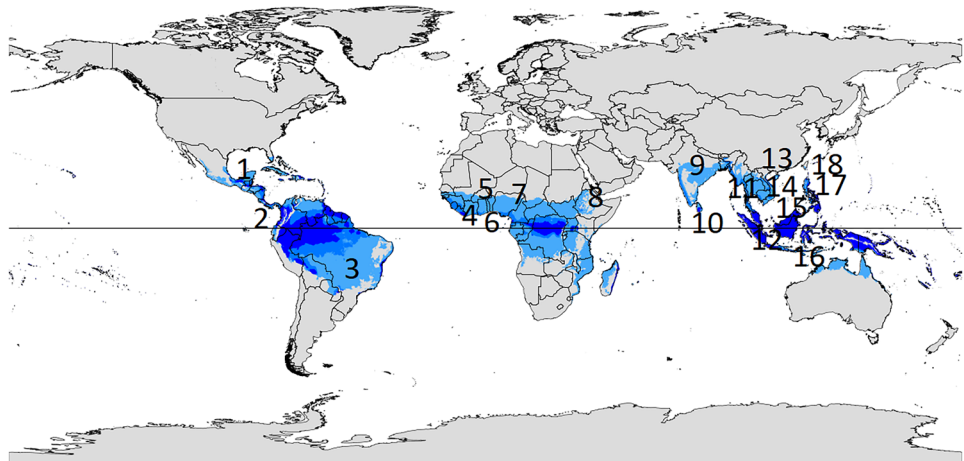
Considering the lack of reviews on tropical leachate, the objectives of this review focus on the variations of the landfill leachate characteristics with the age, climatic conditions, and landfill operating practices in tropical region. Leachate pollution index for the sites investigated was calculated using the data available in the literature, and the correlation between leachate characteristics was analyzed. Understanding the composition of leachate is essential for predicting the long-term effects of landfills. It allows for proposing alternative treatment methods for leachate from tropical landfills.

## Types of Sites

The literature search concentrated on landfills and dumpsites in tropical climates to achieve the aims of the study. Studies published in databases such as Scopus and Science Direct were used, and published data from 228 leachate samples from 145 landfills and dumpsites in the tropical region were analyzed. The locations of countries from which these samples were taken are shown in Fig. 1. The types and further details on sites are given in the “Data Collection”.

Temperature and precipitation have shown significant effect on leachate production; therefore, data were initially classified based on them. To categorize the locations into climatic zones, the Köppen-Geiger climate classification method was used, which is the most widely used method [24]. The Köppen climate classification categorizes climates into five major categories, with each category subdivided depending on seasonal precipitation and temperature trends: A (tropical), B (dry), C (temperate), D (continental), and E (polar). Tropical climatic condition is characterized by average temperature above 18 °C and considerably high annual rainfall. This tropical climatic region is further subdivided into three subcategories, tropical rainforest climate (AF),

**Fig. 1** Locations for leachate samples: (1) Belize (9 samples), (2) Colombia (2 samples), (3) Brazil (15 samples), (4) Ivory Coast (1 sample), (5) Nigeria (41 samples), (6) Ghana (11 samples), (7) Cameroon (1 sample), (8) Ethiopia (9 samples), (9) India (29 samples), (10) Sri Lanka (20 samples), (11) Thailand (2 samples), (12) Indonesia (8 samples), (13) Laos (2 samples), (14) Cambodia (2 samples), (15) Vietnam (8 samples), (16) Malaysia (60 samples), (17) Philippines (2 samples), (18) Taiwan (4 Samples)



tropical monsoon climate (AM), and tropical savanna climate (AW), based on average monthly rainfall [24–26].

### Types of Sites

The locations investigated are classified according to (i) the climatic zone in which they are located, (ii) the mode of operation of the site, and (iii) the age of the site, which were taken into account for sites analysis. Figure 2a shows the number of samples from open dumps sites (OD) and engineered landfills (LF) that are in operation in various climatic zones that were considered in this review. More LF than OD are in operation in the AF zone. This tendency has reversed in the drier AW zone, where there are more OD and fewer LFs. Figure 2b demonstrates that the majority of the sites investigated in tropical region are older than ten years, whereas the number of studies on young and intermediate sites is significantly lower.

A landfill, during its life time, passes through four phases; aerobic phase, acetogenic phase, methanogenic phase, and stabilization phase [27••]. During these periods, characteristics of leachate such as pH, BOD<sub>5</sub>, COD, NH<sub>4</sub><sup>+</sup>-N, heavy metal concentration, and biodegradability vary and considering the ranges of values of these parameters, leachate is classified into stages as young leachate (age below 5 years), intermediate leachate (age between 5 and 10 years), and old leachate (age over 10 years). Table A.1 shows the general ranges of values reported for the parameters during the different stages of leachate. The high BOD/COD ratio (more than 0.5) of leachate produced in young landfills is

an indicator of leachate biodegradability. As amino acids are released during the degradation of organic molecules, they are present in young landfill leachate. Leachate from old landfills is high in ammonia nitrogen because the nitrogenous fraction of biodegradable substrates is hydrolyzed and fermented. The change in organics and ammonia nitrogen over time could have a big impact on leachate treatment. Leachate comprises a variety of toxins that is harmful to life and affects the ecosystem, regardless of landfill age. Due to its high nutritional content, it can accelerate algal growth, reduce dissolved oxygen in the receiving water, and have a harmful effect on aquatic life [7•].

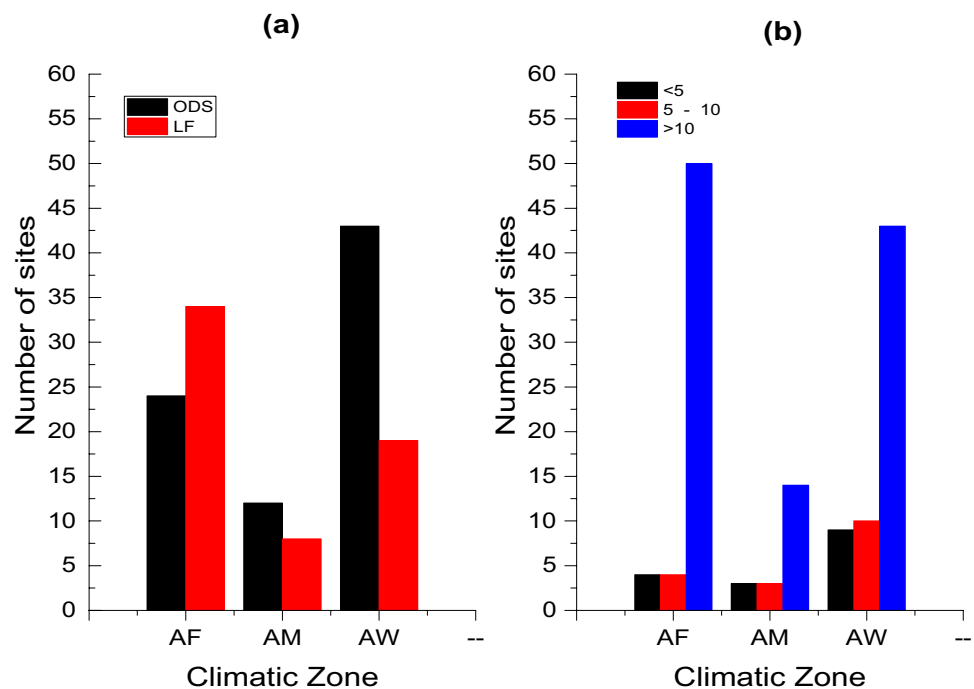
Considering the distribution of the sites, for the analysis of data, the sites are categorized based on three climatic zones, AF, AM, and AW, mode of operation as LF and OD, and the age of site as less than ten (Y) and greater than ten (O). Thus, for the purpose of analysis, the sites under consideration are categorized into 12 groups as shown in Table A.2. The number of samples from open dumpsites of young age was low as the solid waste management is moving from open dumpsites to sanitary landfills. Most of the young disposal facilities can be categorized as sanitary landfills.

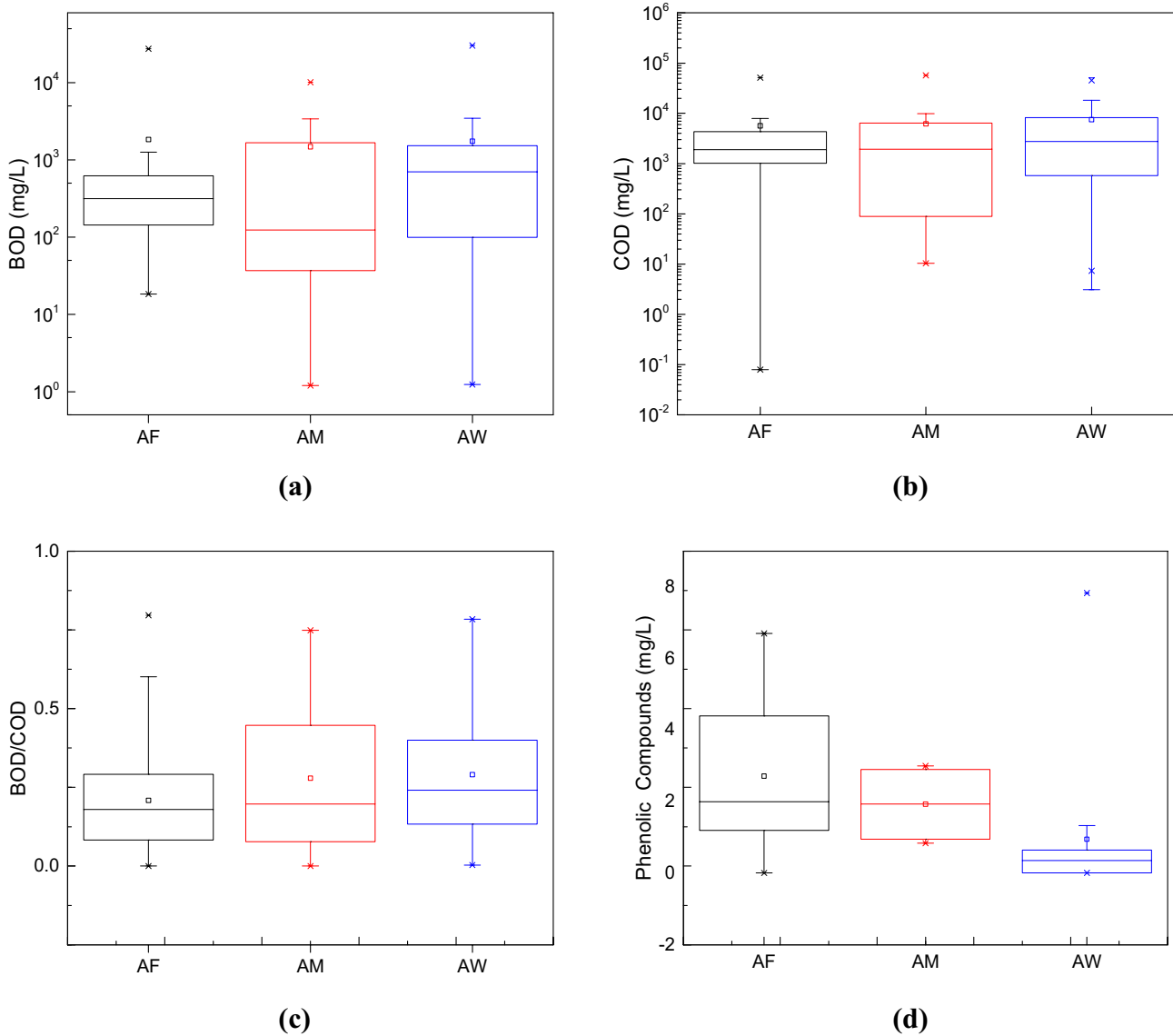
## Leachate Characteristics

### Organic Parameters

Observing the Boxplot diagrams in Fig. 3a and b, it can be seen that both the BOD<sub>5</sub> and COD values follow a similar

**Fig. 2** Number of sites considered for the analysis **a** according to mode of operation and **b** according to age of the site, with climatic zone





**Fig. 3** Variation of organic characteristics in different tropical climates (AF, tropical rainforest climate; AM, tropical monsoon climate; AW tropical savanna climate)

trend in all the climatic zones considered. Both  $BOD_5$  and COD values are distributed over a wide range in AM compared to the other two zones. The mean  $BOD_5$  values were 2435.16 mg/L, 3455.77 mg/L, and 2127.79 mg/L in AF, AM, and AW zones, respectively. The mean COD values were 7985.1 mg/L, 6185.17 mg/L, and 7504.32 mg/L, respectively. There is no particular trend in the  $BOD_5$  value or COD value across the climatic conditions analyzed. However, Table A.3 shows that the  $BOD_5$  values of old engineered landfills are relatively smaller with values of 159 mg/L in AM/LF/O and 531 mg/L in AF/LF/O. The COD values also show the same trend by giving lowest COD value in old engineered landfills with 1813 mg/L and 2712 mg/L in AM/LF/O and AF/LF/O respectively. These low  $BOD_5$

and COD values of old landfill sites attribute to the degradation of organics over the time. The  $BOD_5$  and COD values of open dumps have not reduced to an extent as those from landfills with the age owing to the fact that open dumps continues to receive waste continuously releasing new leachate.

Table A.3 shows that the BOD/COD ratios of the young leachates are higher than the old leachates in each zone. The proportions of biodegradable organics in leachate are represented by the BOD/COD ratio. Due to the quick decomposition of biodegradable waste, BOD concentrations decline in higher rate than COD with time. As a result, the BOD/COD ratio is used to determine the age of landfills. BOD/COD ratios of leachate from new waste disposal facilities (WDFs) are in range of 0.5–1.0, and those from old leachates

are less than 0.1 [27••]. Due to their complicated molecular architectures, XOCs present in landfill leachate are typically difficult to extract using traditional leachate treatment systems [28]. Even when present in low concentrations, XOCs are hazardous to the ecology and natural environment, and they are rarely regulated. Among them, phenolic compounds (Ph.Cs) are commonly found in landfill leachate [29]. However, their presence has been rarely measured in the studies conducted in the tropical region. Out of the available data from the zone, by observing Fig. 3d, it can be seen that XOCs values are ranging from 0 to 6 mg/L in AF, 1 to 3 in AM and 0.95 in AW. Under aerobic conditions, Ph.Cs degrade rapidly, whereas under anaerobic conditions, the degradation is ambiguous [30, 31•, 32••]. As a result, low Ph.Cs concentrations are attributed to aeration at WDFs. It has been discovered that aeration has a significant effect on increase of the decomposition of hazardous compounds such as phenols [5•].

### Inorganic Parameters

Young landfill leachate showed a pH of less than 6.5, whereas old landfill leachate showed a pH higher than 7.5. It was also reported that leachates with high concentration of volatile fatty acids (VFAs) have low pH [33]. The pH of stabilized leachate is ranging between 7.5 and 9 [34]. During the anaerobic degradation of the wastes, the pH of leachate becomes alkaline due to the decrease in the concentration of partially ionized free volatile fatty acids which are being used up by the methane producing bacteria [35••]. Furthermore, pH of leachate tends to increase gradually with time from slightly acidic towards alkaline values as the site gets older and more stabilized. Figure 4a shows that pH of zone AM is within larger range that of zones AF and AW. Table A.3 illustrates that the average pH of all types of sites are above 7 apart from AM/OD/O where it is 6.7. This observation is contradicting to the fact that young leachate has pH below 6.5 due to presence of higher concentrations of volatile fatty acids. The higher pH values in relatively younger WDF indicate the short acidic phase and early methanogenic phase. The higher temperature that tropical landfills and dumpsites exposed compared to the sites from cold regions causes accelerated bacterial growth and chemical reaction rates resulting in early methanogenic phase.

The majority of total nitrogen is made up of ammonium. In comparison to soluble organics, the release of soluble nitrogen from waste into leachate occurs over a longer period of time [31•]. The amount of ammonia nitrogen, a common element of landfill leachate due to biological breakdown of amino acids and other organic nitrogenous materials, is measured in  $\text{NH}_4^+\text{-N}$ . The sum of organic nitrogen and ammonia nitrogen is known as total Kjeldahl nitrogen (TKN).  $\text{NH}_4^+\text{-N}$  appears to be the element which exists the longest in leachate due to the stability in anaerobic conditions, and it is thus utilized

to estimate landfill contamination potential. Higher levels of  $\text{NH}_4^+\text{-N}$  have also been linked to eutrophication and a reduction in dissolved oxygen.

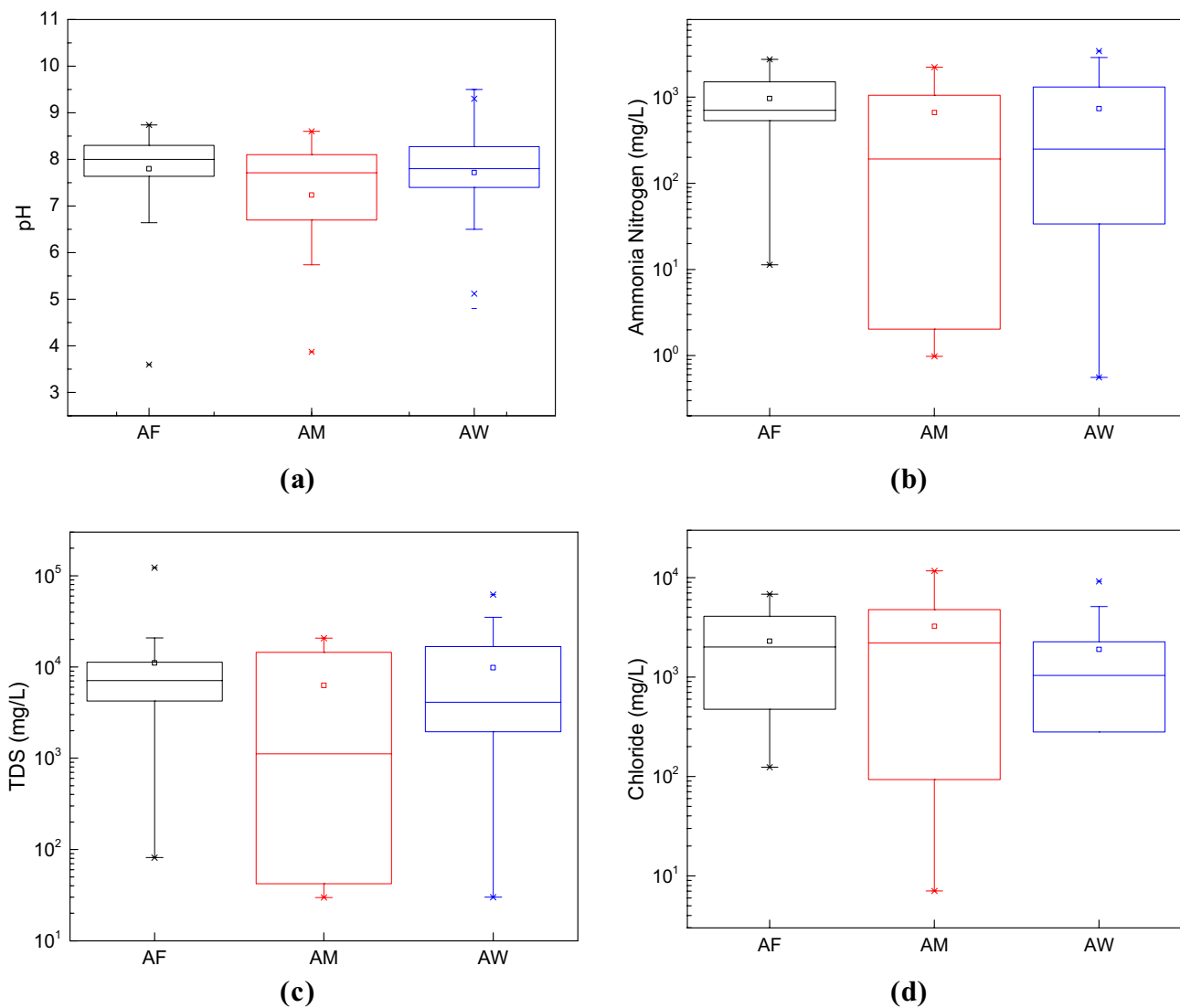
Figure 4b shows that zone AM has ammonia values over a wider range than AF and AW. Table A.3 depicts that ammonia concentrations in younger landfills are higher than those of older landfills. Data from young landfills and dumpsites from AF and AM zones showed higher average ammonia concentrations than old sites. However, in AW zone, this trend is seen only in engineered landfills, whereas old leachate from open dump sites from AW had higher ammonia concentrations (716 mg/L) than younger leachate from same zone (14 mg/L). This variation could be due to low data availability. Only four  $\text{NH}_4^+\text{-N}$  measurements were available for the old open dump sites out of 13 sites considered for the category.

Inorganic salts and dissolved organics make up the majority of TDS. The quantity of TDS represents the degree of mineralization, and a higher TDS concentration might alter the receiving water's physical and chemical properties. By altering the ionic composition of water, a rise in salinity owing to an increase in TDS concentration also increases toxicity. Similar to those of ammonia, TDS is scattered over a wide range in AM that AF and AW (Fig. 4c). Table A.3 shows that TDS values of old leachate from both landfills and open dump sites from AM have lower TDS values of 7400 mg/L and 3015 mg/L respectively. Those of young leachate from landfills and open dump sites in AM have high TDS of 14490 mg/L and 17850 mg/L respectively. TDS levels represent the degree of mineralization. As the acidity of the landfill decreases, the dissolving of ions decreases. As a result of this, TDS decreases with age [31•].

Chloride ( $\text{Cl}^-$ ) in leachate is extremely mobile, inert, and non-biodegradable under all conditions. As a result, it can be employed as a powerful indicator of pollution as well as a leachate plume tracer element [32••, 36••]. High levels of chlorides in leachate can be caused by the presence of considerable volumes of soluble salts from probable anthropogenic sources like kitchen waste from residences, restaurants, and hotels [32••]. Figure 4d shows the average  $\text{Cl}^-$  concentration in AF, AM, and AW to be 2290 mg/L, 3235 mg/L, and 2220 mg/L respectively. The highest average concentration of chloride can be observed from AM/LF/Y as 4338 mg/L (Table A.3). Lowest average of chloride concentration is reported from AF zone with values 1453 mg/L from old leachate from landfills. The high  $\text{Cl}^-$  content of leachate is most likely due to pollution sources such as domestic effluents, fertilizers, and septic tanks, as well as natural sources such as rainfall [37].

### Heavy Metals

Heavy metal concentrations in landfill leachate are on average rather modest. Heavy metal concentrations in landfills



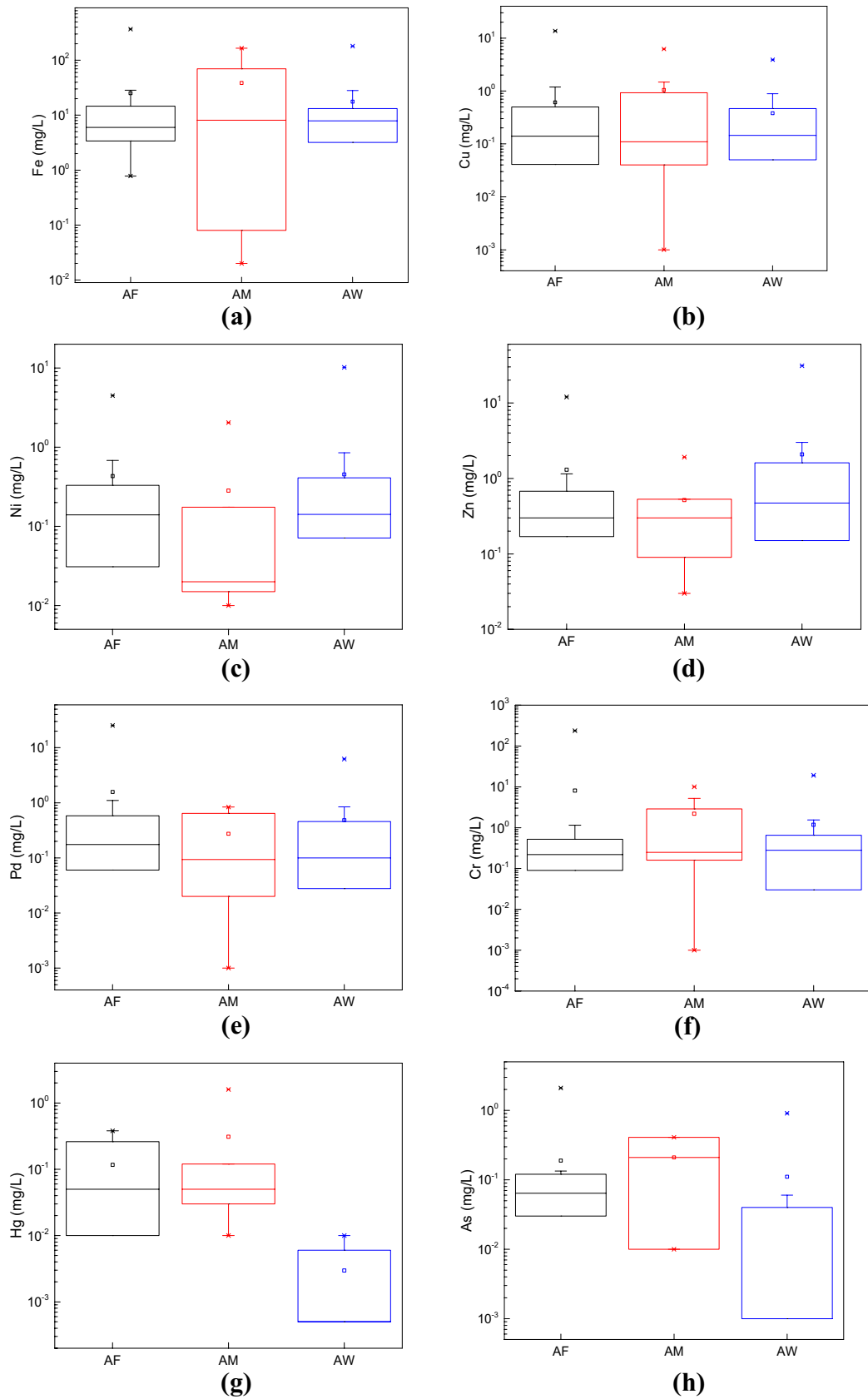
**Fig. 4** Variation of inorganic characteristics in different tropical climates: **a** pH, **b** ammonia nitrogen, **c** TDS, and **d** chloride

are usually greater in the early phases due to higher metal solubility as a result of low pH induced by organic acid generation [38]. Because of the pH rise in later stages, metal solubility decreases, causing a quick drop in heavy metal concentrations, with the exception of lead, which forms a highly heavy complex with humic acids [39].

The presence of iron (Fe) is usually due to the dumping of metal waste and tin-based waste, among other heavy metals. Figure 5a shows Fe concentrations in the different climatic regions considered. The average concentrations of Fe in AF, AM, and AW zones are 35, 39, and 18 mg/L, respectively. Considering the age and type of WDF, high concentrations of Fe are reported for AF/LF/Y (57.22 mg/L), AF/OD/O (40.15 mg/L), AM/LF/Y (33.31 mg/L), AM/OD/O (43.25 mg/L), and AW/LF/Y (20.43 mg/L). The trend in Fe concentrations for AF/LF/O (7.18 mg/L), AM/LF/O

(6.75 mg/L), and AW/LF/O (5.87 mg/L) indicate that old leachate from engineered landfills have lower Fe concentrations owing to the fact that with age, heavy metal dissolution reduce.

All the types of sites analyzed have similar trend when it comes to presence of copper (Cu) (Fig. 5b). Figure 5e shows that lead (Pb) also follows similar trend to Cu in all the three climatic regions. By observing Table A.3, it can be seen that the values also fall in a similar range for both. However, the concentration of nickel (Ni) in old leachate from both engineered landfills and open dump sites from AM zone reported were extremely of high values of 66 mg/L and 27 mg/L, respectively, whereas the Ni concentration is below 1 mg/L in all the other cases studied. The disposal of Ni containing batteries is identified as the source for Ni in landfill leachate [32••].



**Fig. 5** Variation of heavy metal characteristics in different tropical climates: **a** Fe, **b** Cu, **c** Ni, **d** Zn, **e** Pd, **f** Cr, **g** Hg, **h** As

Both Fig. 5d and the Table A.3 show that Zn concentration in leachate from AW is higher than the Zn concentration from AF and AM with highest average concentration reported from OD with values 2.86 and 2.80 mg/L from young and old leachate respectively. The Zn concentration is lowest from AF/LF/Y (0.2 mg/L). Zn might have originated from batteries and fluorescent lamps dumped in landfills. Paint solvents and preservatives for wood cause chromium (Cr) to present in landfill leachate [32••].

Data on arsenic (As) and mercury (Hg) are limited for tropical landfills and open dump sites. Figure 5g and h show that the average concentrations are below 1 mg/L. As results from the electronic waste such as computer chips, circuit boards, liquid crystal displays, and fertilizers.. Hg in landfill leachate comes from fluorescent and other lights, batteries, electrical switches and relays, barometers, and thermometers, among other things.

### Correlation Between Parameters

This section discusses the correlation between leachate quality parameters obtained using statistical analysis using Microsoft Excel by using the formula given by Eq. (1):

$$r = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 \sum(y_i - \bar{y})^2}} \quad (1)$$

where  $r$  is the correlation coefficient,  $x_i$  is the value of the  $x$  variable in a sample,  $\bar{x}$  is the mean of the values of the  $x$  variable,  $y_i$  is the value of the  $y_i$  variable in a sample, and  $\bar{y}$  is the mean of the values of the  $y$  variable.

A preliminary descriptive technique for evaluating the degree of correlation and understanding the link between the variables involved is correlation analysis. The correlation matrix for the eighteen leachate parameters is shown in Table A.4. Some of these indicators have a statistically significant correlation, indicating that they are linked.

The concentrations of BOD<sub>5</sub> and COD in the leachate showed a strong positive correlation among them with correlation coefficient of 0.81, which is typical being indicators of organic pollutants. BOD<sub>5</sub> and COD showed positive correlation with TKN as well, where the correlation coefficients are 0.76 and 0.72, respectively. The positive correlation among BOD and COD with As is another important finding by the analysis.

Phenolic compounds have positive correlation with heavy metals and TDS. The correlation coefficient between TDS and Ph.C. is 0.69, and the coefficient between Hg and Ph.C. is 0.9. High positive correlation with coefficient 0.86 was found between TC and AS as well. The positive correlation between TKN and NH<sub>4</sub><sup>+</sup>-N is obvious as NH<sub>4</sub><sup>+</sup>-N is included within TKN. Further, high positive correlation was observed

between TDS and TKN, Cl<sup>-</sup>, and Fe also with coefficient being 0.56, 0.72, and 0.52, respectively.

Another significant finding from the correlation analysis is correlation that is shown by pH with most of the other considered parameters. pH, for example, has a negative correlation with organic indicators. The correlation with parameters such as BOD (-0.43), and COD (-0.32) were negative. Similarly, numerous heavy metals, such as Cu, Ni, Zn, Cr, As, and CN, were negatively correlated with pH. This reveals a strong link between the pH of the leachate and the concentration of heavy metals. As pH levels drop, the solubility of certain metals increases. The influence of pH on heavy metals mobility in leachate is clear. According to Tafałaj et al. [27••], a rise in pH produces a drop in concentrations of Hg, Pb, and Cd. TC also shows a negative correlation with most of the other parameters considered.

### Presence of Emerging Contaminates in Landfill Leachate in Tropical Countries

Emerging contaminants (ECs) are compounds that have recently been shown to occur widely in the environment and have been identified as posing a potential environmental or public health risk, but there is insufficient data to assess their risk [13••]. Although wastewater has been extensively studied as the primary source of EC in the environment, little attention has been paid to landfill leachate as a potential source of these compounds [40]. Studies that assessed (or reported) the presence of ECs in landfill leachate are limited [13••, 23•, 41•, 42•] especially in the context of tropical countries; a study on EC in landfill leachate is rare. Yi et al. [43] presented the first information on the presence of selected ECs in raw leachate from a 16-year-old Singapore closed landfill site. Therefore, the emerging contaminants that have been studied outside the tropical zone are also used here.

Emerging contaminants found in landfill leachate can be identified under poly-fluorinated compounds (PFC), pharmaceuticals and personal care products (PPCP), aliphatic alcohols and ethers, aldehydes and ketones, aliphatic acids and esters, aromatic carboxylic acids and ethers, alkanes and cycloalkanes, benzothiazoles, benzene derivatives, drugs and metabolites, non-steroidal anti-inflammatory drugs, pesticides, phthalic acid esters, phosphoric acid derivatives, phenolic compounds, sulfur containing compounds, sulfonamides, and terpenoids [44•].

Over the last few decades, high concentrations of EC have been widely reported in various landfill leachates [23•, 44•]. For example, Clarke et al. [45] examined ten EOCs (e.g., carbamazepine, fluoxetine) in landfill leachates collected from five MSW landfills in the USA. They discovered that the concentrations were in the range of 6.9–143 g/L. In Singapore,



raw leachates from a 15-year-old closed landfill contained 15 PPCPs and EDCs at concentrations of up to 474 µg/L [43].

Due to lack of data on EC from tropical region, further analysis is not performed on EC.

### Leachate Pollution Index (LPI)

LPI combines different physical, chemical, and biological leachate parameters to get an indicative value [32••, 46]. Based on number of leachate parameters, an indicative value in range of 5 to 100 is obtained using weights ( $w_i$ ) and sub-indices ( $p_i$ ). LPI is a useful tool for assessing the contamination potential of various landfill sites at any given time [47].

LPI was utilized by Munir et al. [48] to aid WDF managers and decision-makers in identifying the level to which leachate poses an environmental danger. In addition, LPI is utilized to trace changes in landfill leachate pollution over time. LPI-identified leachate contamination patterns can help enhance treatment plant design and allow post-closure monitoring in comparable situations [46]. Abunama et al. [32••] utilized the LPI to compare the leachate polluting potentials of various landfills across the world. Other possible LPI uses include rating landfills based on their propensity for leachate pollution; facilitating resource allocation for landfill cleanup; and improving more stringent leachate standards, research and development, and public awareness [32••].

Kumar and Alappat [49••] evaluated and compared many aggregation functions focusing to obtain best formula for expressing LPI. The LPI estimation includes finding the sub-index scores ( $p_i$ ) for all of the leachate parameters based on their concentrations using the sub-index score figures [36••].

The LPI is calculated according to Eq. (2) as follows:

$$LPI = \sum_{i=1}^m w_i p_i \tag{2}$$

where  $w_i$  is the weight for the  $i^{\text{th}}$  pollutant  $p_i$  is the sub-index value of the  $i^{\text{th}}$  leachate pollutant variable, and  $m$  is the number of leachate pollutant variables used in calculating LPI.

However, if leachate parameters are unavailable, the LPI may be approximated using the known values, as shown in Eq. (3):

$$LPI = \frac{\sum_{i=1}^m w_i p_i}{\sum_{i=1}^m w_i} \tag{3}$$

There are primary eighteen leachate pollutant metrics that make up the total LPI. Each of these characteristics was given a weight ( $w_i$ ) considering the extent of importance of a pollutant. These represent the relative relevance of each pollutant parameter on the total polluting potential of the leachate. Used parameters and the respective weightages are given in Table A.5. The sub-index ( $p_i$ ) curves from [36••] were used to determine the connection between  $p_i$  values and matching

concentrations. The  $p_i$  curves for the 18 leachates were discovered in Kumar and Alappat, and they varied from 5 to 100. The LPI estimation requires estimating the  $p_i$  for all of the leachate parameters based on their concentrations using the sub-index score numbers. [36••].

Figure 6 illustrates the leachate contamination potential in terms of LPI for the categories identified in this study. Considering the overall figures, the AM/LF/Y has the highest LPI of 35.2. The lowest LPI resulted from AW/OD/Y with value of 15.76. Comparing the LPI based on the climatic zones, leachate from AM zone has higher pollution potential. The LPI of AW and AF are lower compared to the AM.

In comparison, the LPI in AF and AM, the open dump sites show higher LPI than engineered landfills. This is obvious as the engineered landfills takes better precautions to reduce the possible pollution from leachate to the environment. The findings of Vaccari et al. [18••] agree with the LPI trends in open dump sites and engineered landfills from AF and AM where they have stated that the leachate pollution potential of the open dump sites are higher than that of engineered landfills. However, this is not the case in AW zone. In the AW zone, the average LPI from engineered landfills is greater than that of open dumpsites. Abunama et al. [32••] have also come across with such trend for LPI from open dump sites and engineered landfills and state that it is due to the fact that leachate from open dumpsites get diluted which can result in reduction of the overall pollution potential. Similar to the trend observed for the type of landfill facility considered, the LPI for young leachate is higher in both the AF and AM in both open dump sites and engineered landfills. This is in agreement with the fact that the age has an effect on pollution potential of the leachate. The degradation of waste matter over the time causes lower strengths of leachate during older ages than younger age. Figure 6 shows this clearly for sites in AF and

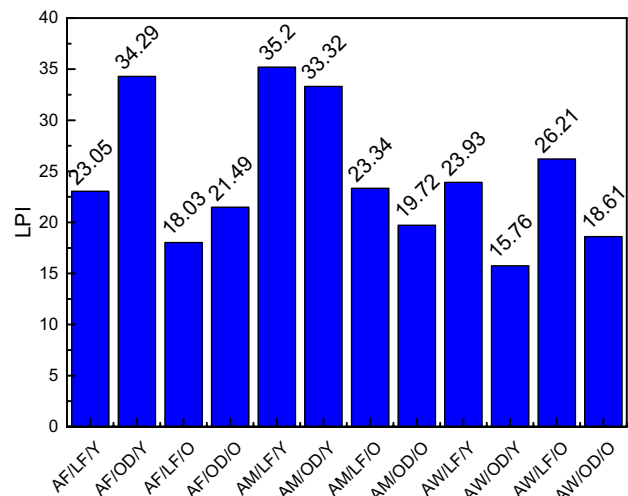


Fig. 6 Variation of average LPI of leachate across different types of sites considered

AM. However, contradicting results were observed in AW as in the case of method of operation. In AW, the older leachate has shown higher pollution potential.

## Leachate Treatment

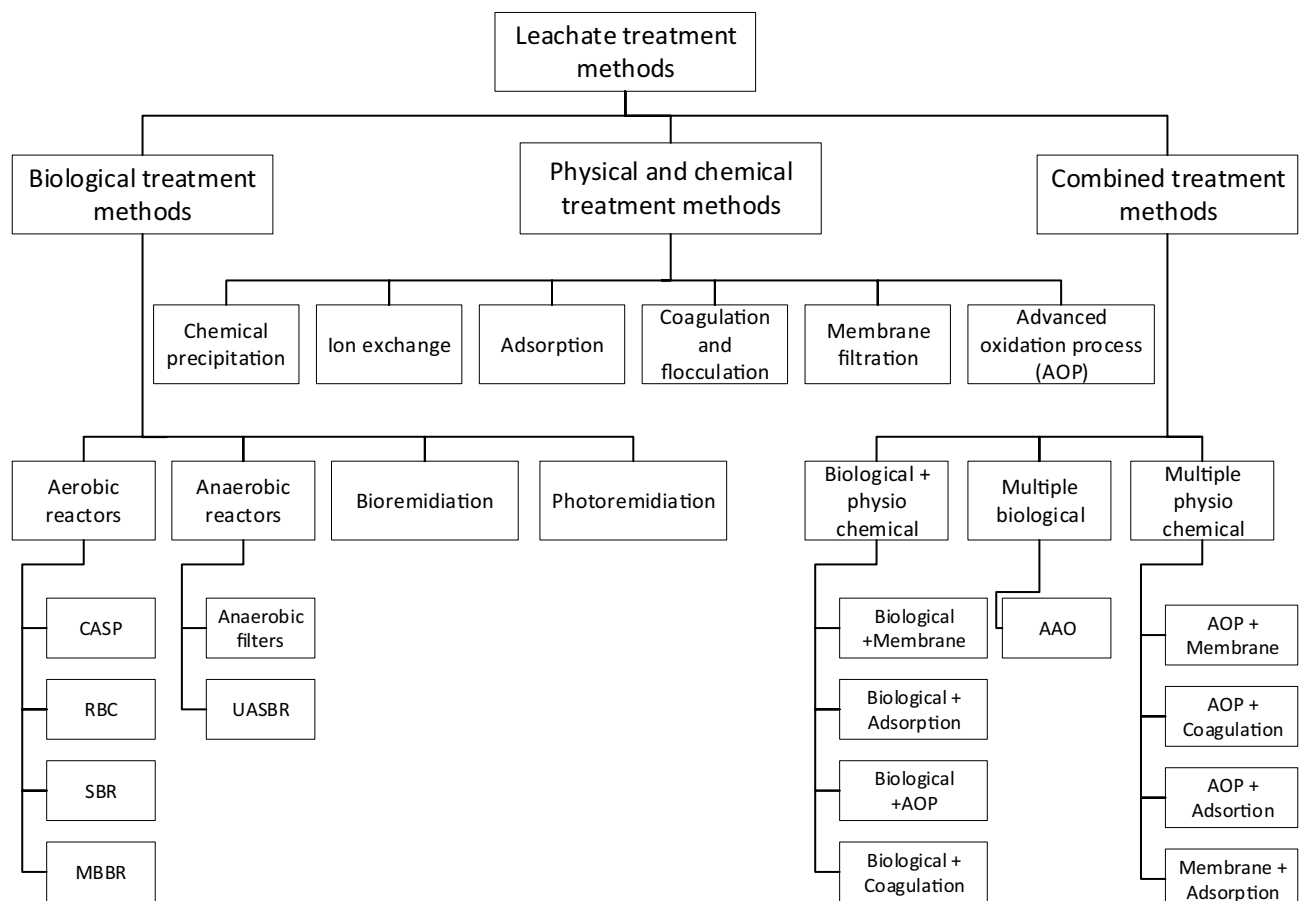
To comprehend the varying performance found in treating landfill leachate using biological, physical, or physicochemical approaches, adequate information of landfill leachate characteristics is essential. Common landfill leachate treatment methods utilized are identified in Fig. 7. Leachate treatment methods can be classified as biological treatment methods, physical and chemical treatment methods and combined treatment methods [10••, 50•, 51•]. Apart from these, leachate channeling methods which include recycling of leachate and combined treatment with domestic sewage also practiced as a method to reduce the pollutant load in landfill leachate [19, 50•].

The metabolic activities of microorganisms result in the biological breakdown of pollutants. Biological approaches

are often employed to remove nutrients (e.g., ammonia) and organic compounds due to their cost effectiveness; yet, such procedures may not be able to effectively remove heavy metals and non-biodegradable organics [21•]. Based on whether the biological processing medium requires oxygen, biological purification techniques can be classified as aerobic or anaerobic [51•]. Conventional activated sludge processes (CASP) [52•], sequencing batch reactor (SBR) [53•, 54•], rotating biological contactor (RBC) [27••], and moving bed biofilm reactor (MBBR) [55•] can be identified under aerobic biological methods that can be used to treat landfill leachate. Anaerobic filters [56], up-flow anaerobic sludge blanket reactor (UASBR) [57•], are among the widely used anaerobic methods.

Chemical precipitation [58•], advanced oxidation process (AOP) [59•], coagulation-flocculation [60•], membrane filtration [61•], ion exchange, adsorption [62•], and electrochemical treatment [63•] are among the physical–chemical methods investigated for landfill leachate treatment.

For leachates of high BOD/COD ratio, a biological treatment procedure is often preferable [64]. The limited



**Fig. 7** Common leachate treatment methods (AOP, advanced oxidation processes; CASP, conventional activated sludge process; RBC, rotating biological contactor; SBR, sequencing batch reactor; MBBR, moving bed biofilm reactor; AAO, anaerobic anoxic aerobic process)

**Table 1** Leachate treatment options used in tropical countries

Treatment technology	Conditions used	Country/ zone	Influent conditions				Removal efficiency	References
			BOD (mg/L)	COD (mg/L)	BOD/COD	NH <sub>4</sub> <sup>+</sup> -N (mg/L)		
<b>Biological treatment methods</b>								
Bioremediation	Using garbage enzyme	India	ND	ND	ND	ND		[67]
Constructed wetland	Using <i>Colocasia esculenta</i> , <i>Gynerium sagittatum</i> , and <i>Heliconia psittacorum</i>	Colombia	ND	626	ND	ND	COD 67%	[68•]
Anaerobic reactor	Anaerobic sequencing batch biofilm reactor	Brazil	ND	856	ND	ND	COD 71%	[69]
Aerobic reactor	Aerobic sequencing batch reactor (ASBR)	Malaysia	ND	3200	ND	1800	COD 43% Ammonia 96%	[70•]
			ND	ND	ND	ND		
<b>Physical/chemical treatment methods</b>								
AOP	Fenton process	Malaysia	ND	10,516	ND	ND	COD 79%	[71]
AOP	Ozone/catalyst (ZrCl <sub>4</sub> )	Malaysia	234	3125	0.07	1674	COD 88% Ammonia 79%	[72•]
AOP	Vermiculite/ozonation	Brazil	ND	ND	ND	ND	COD 17%	[73]
Adsorption	Silica nanoparticle	India	ND	19,691	ND	ND	COD 77%	[74]
Coagulation/flocculation	Tannin-based natural coagulant	Malaysia	59	893	0.07	531	COD 55% Ammonia 91%	[75]
Coagulation/flocculation	Polyaluminium chloride and <i>Dimocarpus longan</i> seeds as flocculant	Malaysia	130	3036	0.04	794	COD 62%	[76]
Coagulation/flocculation	Red earth as coagulant	Malaysia	ND	ND	ND	ND	COD 67% Ammonia 43%	[77]
<b>Combined treatment methods</b>								
AOP/adsorption (ion-exchange)	Supercritical water oxidation (ScWO)/zeolite	Brazil	134	1255	0.11	355	COD 74%	[78•]
AOP/ coagulation	Electro oxidation and coagulation	Brazil	2098	3181	0.66	963	COD 90%+ Ammonia 90%+	[79•]
Coagulation/membrane filtration	Integration of ultrafiltration membrane process with chemical coagulation	India	ND	ND	ND	ND	Turbidity 73%	[80•]
AOP/coagulation flocculation	UV-based sulfate radical oxidation process/ coagulation-flocculation	Malaysia	351	5123	0.07	2700	COD 91% Ammonia 5%	[81•]
AOP/adsorption	MAC/ozonation	Taiwan	ND	ND	ND	ND	COD 74%	[82]

biodegradability of stabilized landfills, on the other hand, suggests that physical and chemical approaches, such as membrane separation methods, are preferable to biological processes [65•]. While mature leachate can be treated

with physicochemical methods, young leachate requires biological treatments; integration of biological processes and physicochemical approaches has recently been shown to be extremely effective [10••]. Other integrated physicochemical

approaches and combined physicochemical/biological procedures are found to be less effective than combined coagulation-flocculation/nanofiltration and activated sludge/reverse osmosis, respectively [66••].

Table 1 shows the landfill leachate technologies followed in tropical conditions. The usage of chemical methods, in particular the use of AOP, can be recognized in the context of leachate treatment in tropical countries.

## Conclusions

Published data from 228 leachate samples from 145 landfills and dumpsites from 18 countries in the tropical region were analyzed. Tropical climatic zone was considered under 3 sub-regions for the analysis. More than 54% of WDFs in tropical climatic zone are ODs. Considering the sub-regions of the tropical zone, the number of engineered landfills is higher in AF, whereas the number of OD is higher in AM and AW. Considering the age of the sites considered, 75% of the sites are classified as old, whereas on 25% are young. Average BOD<sub>5</sub> values of 2435.16 mg/L, 3455.77 mg/L, and 2127.79 mg/L and average COD values 7985.1 mg/L, 6185.17 mg/L, and 7504.32 mg/L, respectively, were reported from AF, AM, and AW regions. As degradation of organic matter happens over the life time of the leachate, the BOD and COD values from old engineered landfills could be identified as the lowest. However, the BOD and COD values in the open dump sites did not demonstrate a considerable difference with age owing to the fact that open dumps sites receive waste continuously over layers and the leachate being renewed in the course. Inorganic contaminants in terms of NH<sub>4</sub><sup>+</sup>-N, TDS, and Cl<sup>-</sup> were over a wide range in AM compared to AF and AW regions. Average concentrations for these inorganic pollutants were highest in AF region and lowest in AM region. Higher inorganic pollutant concentrations have been reported for young leachates. Heavy metal concentrations have been modest values with exceptions for Ni in AM region with considerably higher concentrations. BOD and COD, as well as TKN and AN, had a high positive correlation in the correlation study. pH was found to have negative correlations with heavy metals owing to the low solubility of heavy metals at higher pH values. In comparison of the LPI from open dumps and engineered landfills, in AF and AM, the open dump sites show the higher LPI than engineered landfills. LPI for young leachate is higher in both the AF and AM in both open dump sites and engineered landfills. This is in agreement with the fact that the age has an effect on pollution potential of the leachate.

**Supplementary Information** The online version contains supplementary material available at <https://doi.org/10.1007/s40726-022-00222-x>.

**Author Contribution** L.M.L.K.B. Lindamulla performed the literature search and data analysis and prepared the first draft of the manuscript. All the authors commented on previous versions of the manuscript and approved the final manuscript.

**Funding** Open Access funding enabled and organized by CAUL and its Member Institutions.

## Compliance with Ethical Standards

**Conflict of Interest** The authors declare no competing interests.

**Human and Animal Rights and Informed Consent** This article does not contain any studies with human or animal subjects performed by any of the authors.

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