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Assessment of the Toxic Characteristics and Pollution Potential of Leachate generated from a Municipal Solid Waste (MSW) landfill site in Guwahati, Assam, India

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Abstract

The disposal of Municipal Solid Waste (MSW) in unregulated landfills can have serious consequences for both the environment and human health. Landfills produce leachate, a major pollutant of soil and water. This liquid waste contains dissolved organic materials, heavy metals, hazardous substances, inorganic pollutants and suspended particles. This investigation focused on the characterisation of the leachate and its potential impact on the existing environment near the open dumping site located in West Boragaon, Guwahati, Assam, India. In total, 15 composite samples from varying distances were analysed for physico-chemical parameters and heavy metals, including Fe, Cu, Ni, Pb, Mn, Co, Cr, Zn, As, and Cd. The Results reveals that the TDS (0.7–1.648 × 10^3 mg/L), TSS (1.1–1.8 × 10^3 mg/L), COD (1.693–2.526 × 10^3 mg/L), BOD (4.16–16.67 mg/L), TA (1.25–2.0 × 10^3 mg/L) and ions su ch as SO_4^{2-} (0.09-0.28 × 10^2 mg/L), Cl^- (0.916–3.007 10^2 mg/L), Ca^{2+} (1.002–2.104 × 10^2 mg/L), Mg^{2+} (0.22– 0.548 × 10^2 mg/L), NO_3^- (0.43–0.83 mg/L), PO_4^{3-} (1.4–1.6 mg/L) which undergo significant variations. The average concentrations of heavy metals were in the order of: Fe > Mn > Zn > As > Cu > Ni > Cd > Co > Pb > Cr. Moreover, the study investigated the environmental and ecological impacts of leachate, as well as the potential health hazards associated with it. The leachate pollution index (LPI) was 7.96 (~8) indicated moderate level of heavy metal pollution in the entire site. The I_{geo} values for most of the heavy metals indicated moderate to high levels of pollution.

Keywords: Solid waste, Leachate, Heavy metals, Leachate pollution index (LPI), Geo-accumu lation index (I_{geo})

Highlights

- The amount and composition of leachate produced in a landfill are greatly influenced by climatic conditions.
- A strong correlation exists between leachate parameters.
- The degree of metal contamination is high for specific metals.

Introduction

In recent decades, the rise in population, along with urbanization and industrialization, has led to the generation of huge amounts of solid waste (both municipal and industrial), with a significant portion unfortunately being dispos ed of in landfills [Gholami et al.,2020; Torkashvand et al., 2022]. The production of municipal solid waste is largely influenced by the progression of human activities.When industrial waste, which is highly hazardous in nature, is dumped in landfills, it undergoes physical and chemical changes, leading to the formation of leachate.

Landfilling is the earliest method of solid waste disposal, poses potential risks to both the environment and human health. Because of its simplicity and affordability, landfilling is the most commonly used method for municipal solid waste disposal across the world [Wang et al., 2022; Najafi Saleh et al., 2020]. Solid waste is disposed of in landfills undergoes biological, physical, and chemical changes. As a result of these reactions, landfills generate gas and leac hate [Hoss eini Beinabaj et al., 2023].

Waste degradation in landfill sites can be categorized into five distinct phases based on the variation in parameters over time. These phases include: the initial aerobic phase, the anaerobic acid phase**,** the early methanogenic phase**,** the stable methanogenic phase**,** and the humic or final decomposition phase [Kulikowska and Klimiuk,2008; Mukherjee et al., 2015]. During the initial aerobic phase, microorganisms utilize the oxygen present in the freshly buried waste to break it down, generating carbon dioxide and releasing heat as a result of their exothermic biological activity, the temperature of the waste increases [Kjeldsen et al., 2002; Bhalla et al., 2012, Mihelcic et al., 2014].

During the second phase, acetogenic, hydrolytic, and fermentative bacteria play a major role by transforming long-chain volatile fatty acids into acetic acid and breaking down complex polymers into simpler monomeric compounds [Wijekoon et al., 2022].The low pH of leachate enhances the solubility of various compounds, including

heavy metals. As a result, the concentration of volatile acids rises, promoting the effective breakdown of organic matter and leading to an increase in heavy metal content during this phase [Hosseini Beinabaj et al., 2023] . During this phase, the BOD:COD ratio reaches its highest levels.

During the initial methanogenic phase, the acids gathered during the acid phase are transformed into methane and carbon dioxide by methanogenic bacteria, causing an increase in generation of methane. The pH of leachate rises as the acids produced in the preceding phase are broken down and as a result of the breakdown of organic matter BOD :COD ratio decreases [Wijekoon et al., 2022].

The fourth phase, known as the stabilized methanogenic phase, it involves the hydrolysis of polymeric substances, which controls methane generation [Joshi and Pant, 2017]. As the landfill ages, the leachate pH increases due to the breakdown of previously generated acids. Meanwhile, the BOD:COD ratio decreases sharply as the organic content in the leachate decreases [Kjeldsen et al., 2002; Chen, 1996].

The humic phase, which is the last stage of decomposition, takes place in the absence of oxygen, where organic materials like proteins, lipids, and carbohydrates are gradually converted into humic and fulvic substances [Wijekoon et al., 2022].

Despite the applied protective measures, leachate generation remains an unavoidable outcome of landfill operations. It forms when excess rainwater penetrates and percolates through the waste layers [Gupta et al., 2014]. The amount and composition of leachate produced in a landfill are greatly influenced by climatic conditions; for example, duri ng the rainy season, leachate becomes more diluted,resulting in lower concentration of the dissolved substances [Wij ekoon et al., 2022]. The quality of leachate is directly affected by chemical processes like oxidation, synthesis, decomposition, and replacement reactions [Renou et al., 2008].

The properties of leachate differ based on the composition of municipal solid waste, the geographical location, and the landfill's stage of decomposition [Contrera et al., 2014]. It carries a significant risk of contaminating the surrounding soil and groundwater. Leachate can deplete oxygen levels in surface water, and prolonged exposure to its compounds may lead to their absorption by aquatic organisms, resulting in bioaccumulation throughout the food chain [Wdowczyk and Szymańska-Pulikowska, 2022]. Based on the temporal changes in leachate characteristics during the waste degradation process, landfill leachate can be broadly categorized into two types: acetogenic and methanogenic [Wijekoon et al., 2022]. It has been shown that acetogenic leachate shows the highest values of COD, BOD, and the BOD:COD ratio, primarily due to the presence of high concentrations of organic pollutants [Ro binson , 20 07] . Acetogenic leachate contains high levels of heavy metal contaminants, largely because its acidic conditions enhance the solubility of metals. The quantity and characteristics of landfill leachate depend on factors like composition of waste, climate, and site-specific surface conditions, making it difficult to achieve efficient treatment [Bhalla et al., 2012].

Dissolved organic matter (DOM) plays a significant role in landfill leachate, as it engages in interactions with numerous inorganic and organic pollutants, including heavy metals [Oloibiri et al., 2017]. Landfill leachate generally contains high levels of inorganic macro compounds like Sodium (Na^{+}), Potassium (K^{+}), Calcium (Ca^{2+}), Magnesium (Mg^{2+}), NH_4^{+}, NO_3^{-}, NO_2^{-}, SO_4^{2-}, PO_4^{3-}, Cl^{-}, Iron (Fe^{2+}), etc; with the concentrations of some components varying according to the landfill's age [Robinson, 2007].

Landfill leachate is generally treated using physical, chemical, and biological methods. Physical methods involve processes such as precipitation, flocculation, and adsorption [Oloibiri et al., 2017]. Biological treatment methods include the aerobic stabilization pond [Hu et al., 2018], activated sludge process [Wang et al., 2018] and rotating biological contactors [Cortez et al., 2011]. Chemical treatment methods generally include processes such as advanced oxidation, precipitation and reduction [Zhang et al., 2015; Poblete et al., 2019; Wang et al., 2021].

Studies on leachate composition have identified over 400 contaminants, with many more likely remaining undiscovered [Öman and Junestedt, 2008]. Hence, additional research is necessary to explore the connection

between the evolving physicochemical properties of leachate and its toxicity, along with its effects on various environmental components [Zloch et al., 2018].

Environmental hazards of leachate and their consequences

Landfill leachate is a highly complex and concentrated form of wastewater that contains both suspended and dissolved substances, including heavy metals, inorganic salts, nutrients, microbial contaminants, and a variety of organic compounds released during the decomposition of waste within the landfill [Arunbabu et al., 2017; Wdowczyk et al., 2022]. The migration of landfill leachate into groundwater, surface water bodies, and surrounding soils undeniably poses significant environmental hazards [Ashraf et al., 2019].

Impact of municipal solid waste landfill leachate on groundwater and surface water resources

Municipal solid waste landfills are major sources of groundwater pollution due to leachate, which contains high COD, ammonium, heavy metals, and persistent toxins [Li et al., 2014; Teta and Hikwa, 2017]. Studies show that key landfill pollutants in groundwater include chloride, sodium, ammonium, total hardness, total dissolved solids, organic matter (like COD), heavy metals, and phosphate [Azizi et al., 2015; Cheng et al., 2013; Milosevic et al., 2012; Singh et al., 2023].

Leachate from municipal solid waste landfills can pollute water resources via groundwater movement, surface runoff, migration into the soil, and precipitation [Mor et al., 2006]. Once contaminants enter the groundwater, leachate pollutants can merge with the hydrogeological systems [Gunarathne et al., 2024]. Leachate contains numerous toxic byproducts, with heavy metals being major contributors to water pollution [Ebadi Torkayesh et al., 2019]. Research indicates that assessing the behavior of heavy metals in groundwater contaminated by leachate is difficult, as these metals are tightly bound to microscopic colloids and organic compounds [Matura et al., 2011].

Changes in soil physical, chemical, and biological properties due to landfill leachate exposure

As leachate migrates through the soil layers, it not only pollutes it but also modifies the physical, chemical, and biological properties of the affected layers [Ingle, 2022]. Research indicates that soil near landfills becomes directly contaminated by leachate if it is not adequately treated [Gu et al., 2022]. The influence of microplastics introduced into soil systems through leachate remains insufficiently investigated [Manikanda Bharath et al., 2023]. The main sources of microplastics in landfill leachate are solid waste materials and residuals generated from wastewater treatment processes [Golwala et al., 2021].

As microplastics age in landfill leachate, their properties change, making them important carriers of both microplastics and antibiotic resistant genes [Anand et al., 2021]. The bacterial community on microplastics shows greater ability to form biofilms and a higher potential for causing disease compared to that in the leachate [Gunarathne et al., 2024].

Potential impacts of microplastics

In 2018, around 42% of the global plastic waste—originating from both industrial and household sources—was disposed of in landfills and open dump sites, making them major recipients of plastic waste [Hahladakis et al., 2018]. Microplastic concentrations in leachate can differ, and the variety of microplastic types is typically related to the types of plastic waste deposited in the specific landfills [Shen et al., 2022]. Due to their hydrophobic nature, microplastics can serve as carriers for long-lasting toxic chemicals. When microplastics are not effectively managed or treated within landfills or their leachate, they can escape containment and disperse into the surrounding environment. This can lead to widespread contamination of nearby soil, water bodies, and ecosystems, posing potential risks to environmental and public health [Hartmann et al., 2017]. In soil, they may change soil structure, reduce microbial activity, and influence plant growth, microplastics can be eaten by aquatic organisms, causing physical harm and affecting their growth and reproduction.

Materials and methods

Objectives of the Present Study

The detailed objectives of the present study includes: (i) to determine the physical and chemical characteristics of leachate, (ii) to determine the toxic heavy metal contents in the leachate (iii**)** to evaluate the inter relationships among leachate parameters, (iv) to access the level of contaminati on using Leachate Pollution Index (LPI) and Geo-accumulation Index (I_{geo}).

Study Area

The study area (Fig.1) comprises the Municipal Solid Waste (MSW) dumping site located adjacent to the Ramsar site Deepor Beel at Boragaon in Guwahati, Assam, India (26°06.9150′ N latitude and 91°40.6690′ E longitude) Guwahati covers a total geographical area of 328 km² and has a population density of approximately 4,400 persons per km², ranking it among the largest metropolitan cities in Northeast India [Gujre et al., 2021]. Deepor Beel, a southern channel of the Brahmaputra River, is the wetland which formerly covered an enormous 40 km^2, has drastically shrunk to a pitiful 4.1 km^2 stretch of water and land due to fast urbanization, urban sprawl, and an ineffective watershed management system by the rival authorities. No appropriate safeguards have been implemented, even though it is a Ramsar site under the Convention on Wetlands of International Importance for the Protection of the Global Biological Diversity. The eastern portion of the wetland is the main area of concern for Deepor Beel pollution, as the MSW landfill site's proximity to the wetland has resulted in major problems.

Guwahati receives an annual rainfall of approximately 180 cm, primarily during the monsoon months (June–September), with peak rainfall typically recorded in July. The average annual temperature is approximately 24–26 °C, with summer temperatures reaching up to 38 °C and winter temperatures dropping to around 10 °C.

Sample Collection

The study was conducted in the post-monsoon season (October- December) for a period of three years (2023 – 2025). 60 samples were collected from 15 different locations in four directions, four samples at each location, and agglomerated to make 15 composite samples for every 15 different locations surrounding the dumping site. All leachate samples were collected in pre-cleaned, tightly sealed 1-L polyethene bottles. To ensure accurate tracking and traceability, the samples were labeled with unique identification codes representing their descriptions. The sampling map is shown in Fig.1.

Physico-chemical and heavy metal analysis of landfill leachate

The physicochemical properties of leachate are mainly influenced by the composition of waste and its water content. Metal analysis was performed by treating 50 mL of the sample with concentrated nitric acid, which helped to extract metals associated with organic matter, particulates, or those adsorbed onto solid particles [Ogundiran and Afol abi, 2008].

The physico-chemical parameters were examined in the laboratory in accordance with the standard methods for the examination of water and wastewater i.e. APHA and IS.

Heavy metal analysis of the leachate samples was carried out using the standard APHA (2024) method for acid digestion, in which 50 mL of leachate sample was digested with 5 mL of concentrated HNO_3. The selected heavy metals (Fe, Cu, Ni, As, Cr, Zn, Pb, Mn, Co and Cd) in the digested samples were analysed using an atomic absorption spectrometer (Agilent SpectraAA 220, Agilent Technologies, Australia).

Leachate Pollution Index (LPI)

The Leachate Pollution Index (LPI) is a mathematical equation that combines various physicochemical and biological parameters of leachate into a single numerical value to indicate its overall contamination [Kumar and Alappat, 2005]. Kumar and Alappat (2005) defined the theoretical range of the LPI as 5–100, with increasing values representing greater pollution potential. In the present study, 12 leachate pollutants were selected. The LPI is determined through four basic steps—selecting parameters, assigning weights (w_i), formulating sub-index (p_i) curves, and applying an aggregation formula—to represent the overall pollution potential of landfill leachate [Abunama et al., 2021]. LPI can be calculated using Eq. (1).

$$\text{LPI} = \sum_{i=1}^{n} wipi \qquad (1)$$

where w_i represents the weight of the ith pollutant variable, p_i represents the sub-index value and n is the total number of leachate pollutant variables included in LPI calculation. For w_i standard table developed by Kumar and Alappat was used, sub-index score for each parameter was derived from the LPI sub index curves [Kumar and Alappat, 2005].

Geo Accumulation Index (I_{geo})

The geo-accumulation index (I_{geo}), first introduced by Müller in 1969, is used to determine present heavy metal contamination by comparing measured concentrations with natural background levels in sediments [Müller, 1969]. It is calculated using Eq. (2).

$$I_{geo} = \log_2 (C_n / 1.5\ C_{ri}) \qquad (2)$$

Here, C_n represents the concentration of the analysed metal i in the sediment, while C_{ri} denotes its geochemical background concentration. Factor 1.5 is used to account for natural fluctuations in background levels of metals and also anthropogenic contributions [Ahmed et al., 2019]. The reference values used were As: 13, Cd: 0.3, Co: 20, Cr: 100, Pb: 20, and Cu: 50 µg/g [Al-Haidarey et al., 2010]. Cd was chosen as the reference metal for calculating I_{geo} because its distribution is generally not associated with other metals and is often found in moderately high amounts in groundwater [Ahmed et al., 2019]. I_{geo} categories are: unpolluted ($I_{geo} = 0$), unpolluted to moderately poll uted ($I_{geo} = 0$-1), moderately polluted ($I_{geo} = 1$-2), moderately to heavily polluted ($I_{geo} = 2$-3), heavily polluted ($I_{geo} = 3$-4), heavily to extremely polluted ($I_{geo} = 4$-5), extremely polluted ($I_{geo} \geq 5$)[Müller, 1969].

Statistical Analysis

After collecting the data, the relationships between the physical and chemical properties were systematically analyzed. Statistical analysis (mean, median, maximum, minimum, SD, Std.error) was performed using XLSTAT (version 2024.3) integrated with Microsoft Excel 2016. For geospatial data processing and mapping ArcGIS10.8, Google Earth Pro were used. Data analysis and graphical representations were performed using Origin 61 and OriginPro 2024 (OriginLab Corporation, Northampton, MA, USA). The Pearson correlation approach was applied to evaluate the interrelationships among heavy metals and several physicochemical parameters. It is calculated using Eq. (3) [Ahmed et al., 2019].

$$r = \frac{\sum(x-X)(y-Y)}{\sqrt{\sum(y-Y)^2 \sum(x-X)^2}} \qquad (3)$$

where r is Pearson correlation coefficient, the correlation coefficient is calculated for the variables x and y, where X and Y represent the mean values of x and y, respectively. Its value is always between –1 and 1 [Ahmed et al., 2019]. Values greater than 0.75 are categorized as strong, values ranging from 0.75 to 0.5 as moderate, and those between 0.5 and 0.3 as weak correlation.

Results and discussion

Quality of Leachate in terms of Physico-Chemical Characterization

pH and Electrical Conductance (EC): The pH value helps to determine the reactive nature of leachate and indicates whether aerobic or anaerobic processes dominate within the waste material [Sarkar et al., 2024]. pH values ranging from 6.5 to 8.7 with an average of 7.3 indicated that leachate was either slightly acidic, close to neutral, or slightly alkaline (Table 1). The highest pH value 8.7 in L_{15}, lowest in L_1, L_4 and L_6. EC serves as a useful indicator of the concentration of dissolved substances in water, increased EC levels indicate high concentrations of dissolved materials. EC observed in the study area was relatively high, ranging from 490 to 1250 µS/cm with an average of 818.7 µS/cm (Table 1). The high conductivity was primarily due to major ions such as calcium, magnesium, sodium, and potassium in the leachate [Sarkar et al., 2024].

Total Dissolved Solid (TDS) and Total Suspended Solids (TSS): TDS provides an indication of the overall quality or salinity of the leachate TDS and when its concentration is high, it can effect both the physical and chemical properties of the leachate [Lindamulla et al., 2022]. The TDS levels range between 700 mg/L and 1648 mg/L (Table 1). TDS value was found to be highest in L_{10}. TS values were calculated by combining the amounts of TDS and TSS [Omer, 2019]. Highest TS value was found in L_{14} and lowest in L_4 and L_5.

Chemical Oxygen Demand(COD) and Biological Oxygen Demand(BOD): COD represents the oxygen required to oxidize the organic compounds and indicates the level of oxidizable and toxic contaminants [Karagozoglu and Asar, 2023]. BOD and COD concentrations varied from 4.2 to 16.7 mg/L and 612.2 to 1878.3 mg/L respectively (Table 1). Highest and lowest COD values were found in L_{14} and L_4 respectively.The landfill leachates exhibited a low biodegradability, as the BOD/COD ratio ranging from 0.003 to 0.02.

Oil and Grease and Chloride: Oil and Grease was in the range of 540-820 mg/L with an average of 708.7 mg/L (Table 1). The primary source of oil and grease in the leachate are oily materials used in food preparation and later disposed of with food waste [Ashraf et al., 2022].

Total Hardness: Elements like sodium, potassium, calcium, and magnesium are regarded as the primary cations found in leachate [Liu et al., 2011]. Ca hardness were in the range of 100.2-210.4 mg/L. The Mg hardness in the leachate was lower than that of calcium and ranged from 22.0 -54.8 mg/L (Table 1). Total hardness is the sum of concentration of Ca^{2+} and Mg^{2+} ions in leachate. Monitoring calcium and magnesium concentrations in leachate is crucial, as elevated levels of these elements can impede their efficient removal [Aziz et al., 2007].

Total Alkalinity (TA): Total alkalinity is primarily influenced by the concentratios of bicarbo nate,carbonate,and hydroxyl ions present in leachate [Naveen et al., 2017]. In this study TA was found in the range of 1250 - 2000 mg/L (Table 1). Organic waste decomposition releases dis solved CO_2, leading to higher leachate alkalinity [Naveen et al., 2017].

Sulphate and Chloride: Sulphate contents of leachate were in the range 6.5-28.0 mg/L, this may be due to the presence of different inorganic constituents in the waste. Highest sulphate content in L_4 and lowest in L_{15}. Chloride contents in the leachates vary between 91.6-300.7 mg/L (Table 1).

Phosphate and Nitrate: Phosphate concentration in the leachate ranged from 1.4-1.6 mg/L. Phosphate conta ining leachate is harmful and can affect aquatic ecosystems by increasing nutrient levels resulting in eutrophication and excessive growth of algae [Asibor et al., 2016]. Concentration of Nitrate ranged from 0.43-0.83 mg/L (Table 1). Nit rates are considered as conservative contaminants because they are resistant to biochemical degradation and natura l remediation processes[Asibor et al., 2016].

Presence of Heavy Metals in Leachates

The concentration of heavy metals in leachate varied between landfills, primarily depending on the characteristics of the deposited solid waste and the stabilisation process of the landfills [Slack et al., 2005]. Heavy metals in municipal solid waste (MSW) leachate are primarily released from sources such as batteries, vehicle components, electrical wiring,metal alloys, paints, lamp filaments, and ceramics [Trabelsi et al., 2009]. The concentrations of the tested metals in landfill leachates were highly influenced by weather conditions.

Table 1 provides the data on heavy metal concentrations in leachate collected from MSW dumping site. Among the ten heavy metals examined (namely Cr, Mn, Fe, Co, Ni, Cu, Zn, Cd, Pb and As) concentration of Fe was highest which ranged from 2.1 mg/L to 5.2 mg/L. L_2 exhibited the highest concentration of Fe (5.2 mg/L). Mn concentration was highest in L_4 (2.27 mg/L). The concentration of copper in the leachate from the analyzed landfill was relatively low (<1mg/L). The average concentrations of Cd, Pb and Ni were also found to be low across all the leachate samples analyzed, with values <1 mg/L. This could be attributed to the alkaline nature of the leachate, which likely caused metal immobilization by decreasing their solubility [34]. Mn concentration in leachate samples was average (>2 mg/L). In the majority of the investigated landfills, Zn concentrations were below 1 mg/L. The Cu concentration in leachate from the examined landfill was below 1 mg/L. Throughout the research, the levels of zinc, lead, nickel, and cadmium remained within the permissible limits (5.0 mg/L for Zn, 0.1 mg/L for Pb, 3.0 mg/L for Ni and 2.0 mg/L for the Cd) (Table 1). **The comparison and variation of heavy metals in all samples is shown in Fig 2.**

According to the findings, the average concentrations of heavy metals were in the order of: Fe (3.089 mg/L) > Mn (2.319 mg/L) > Zn (1.628 mg/L) > As (1.134 mg/L) > Cu (0.981 mg/L) > Ni (0.629 mg/L) > Cd (0.50 mg/L) > Co (0.488 mg/L) > Pb (0.081 mg/L) > Cr (0.053 mg/L) (Table 1).

Comparison of the results

The chemical compositions of leachate from the MSW dumping site of the present study were compared with the leachate from other countries such as Oman, Malaysia, Nigeria, Ireland, Sweden and Iran, and the data are summarized in Table 2. Leachate from the present study had a high concentration of TSS, Ca, Cu, Ni, Mn, Co, and Zn as compared to other countries. In this study, the value of TDS was much lower than those of the other countries, because rainwater dilutes the leachate and lowers its concentration since our collection time was in the post-rainy season. It is important to note that the present study reveals that As concentration in the range (0.28-2.7) mg/L suggest a risk of migration of arsenic into surrounding soil and groundwater.

Correlation study of parameters

Table 3(a) and 3(b) displays the results of Pearson's correlation analysis among various selected physical and chemical parameters of landfill leachate. It can be seen that a positive correlation exists among the parameters. The correlation coefficients (r) ranged from 3E-8 to 0.81.

A strong co-relation (r = 0.81) was seen between TSS (total suspended solids) and TS (total solids) indicating that they likely originate from a common source. Also a strong co-relation (r = 0.61) was seen between BOD and pH, indicates that the organic degradation and microbial processes are closely related and also mature leachate formation. EC and BOD (r = 0.53), EC and Oil & Grease (r = 0.57), it suggests that both organic and inorganic pollutants originate from similar sources. pH and Oil & Grease (r = 0.6) and BOD and Oil & Grease(r = 0.51) i.e. leachate contains oily and organic wastes, which make it slightly alkaline (Table 3a).

For heavy metals, significant correlation was seen between Fe and Pb (r = 0.51) (Table 3b). However, the absence of significant correlations among the majority of heavy metals indicates that these metals are independent of one another. The observed correlations between NO_3^- and As, NO_3^- and Pb as well as between NO_3^- and Cr, (Table 3b) suggest manmade pollution sources, such as industrial activities, use of fertilizer, electronic waste, and agricultural solid waste disposed of in open dumps [Weju and Getaneh, 2024]. So, the close relationships among these parameters are mainly caused by human activities instead of natural processes.

Leachate Pollution Index(LPI)

LPI was determined from the concentrations of 12 analyzed physicochemical parameters, with their weights and sub-index values shown in the Table 4. For determination of overall LPI (Table 4, first three sub LPIs i.e. organic (LPI_{or}), inorganic (LPI_{in}) and heavy metals (LPI_{hm}) were calculated and then aggregate the values using Eq. (4) [Kumar and Alappat, 2005] .

$$LPI = 0.232\ LPI_{or} + 0.257\ LPI_{in} + 0.511\ LPI_{hm} \quad (4)$$

The overall LPI was 7.96, with values of LPI_{or}, LPI_{in} and LPI_{hm} were 16.27, 3.76 and 6.28, respectively. The relatively high value of LPI_{or} indicates that organic pollutants had the major contribution to the overall pollution potential of the leachate. The contributions from inorganic pollutants and heavy metals also indicates the complex chemical nature of the leachate.

Inadequate information on leachate characteristics has been identified as a major factor contributing to the absence of waste disposal regulations in many countries. Therefore, LPI provides useful information for evaluating leachate pollution and developing appropriate waste management and disposal strategies [Gunarathne et al., 2024]. Various researchers have proposed improved approaches to enhance the accuracy of leachate pollution assessment. Advanced laboratory techniques and modelling tools such as machine learning and AI have been proposed by Abunama et al. (2021) to improve the accuracy and reliability of the LPI.

Geo-accumulation Index (I_{geo})

I_{geo} is a quantitative indicator used to assess the degree of soil contamination [Gujre et al. 2021]. Analysis reveal that in terms of I_{geo} values, the heavy metals Fe (I_{geo} = 3.53), and Mn (I_{geo} = 3.08) fall into highly polluted, Cu, Zn and As fall into moderately to highly polluted category with I_{geo} values ranging from 2.44 to 2.58, whereas Cd (I_{geo} = 1.83) and Ni (I_{geo} = 1.33) indicated moderate pollution. In contrast, Cr(I_{geo} = 0.45)and Pb(I_{geo} = -0.6) showed negative I_{geo} values i.e. unpolluted in nature. Overall I_{geo} values indicate the selective enrichment of heavy metals, particularly Fe, Mn, Cu, Zn and As, representing the main contributors to soil contamination.

Conclusions

In cities, solid waste management is a major problem. Leachate, which is produced when garbage is dumped in dumpsites, contaminates the surrounding water and soil resources.

Overall, this study demonstrates that leachate generated from the open dumping site at MSW dumping Site at West Boragaon, Guwahati, represents a significant source of environmental contamination. The observed pollution characteristics indicated a potential risk of leachate migration into surrounding soil and water quality, increasing environmental risks to Deepor Beel, an ecologically significant Ramsar site.

The higher concentrations and considerable spatial variations in TDS, TSS, COD, alkalinity, chloride, sulphate, and other dissolved ions indicate the heterogeneous and complex nature of the leachate. The average concentration of heavy metals in leachate samples was found to be in the order of Mn > Fe > As > Co > Cu > Zn > Pb > Ni > Cd. The leachate analysis showed high concentrations of Zn, Cu, and Ni. A significant correlation was seen between Cd and Mn. However, for other metals, no such correlation was found, indicating that these metals are independent of one another. A strong correlation was seen between TSS and TS, and also between BOD and pH. The I_{geo} results revealed the degree of metal contamination in the leachate from the MSW dumping ground, particularly for Fe, Cu, Ni, Mn, Co, Zn, As, and Cd, indicating moderate to high levels of pollution across most of the study area. With an LPI of 7.96 (~8), the elevated Leachate Pollution Index indicates a critical threat to the surrounding groundwater and surface water quality.

The surrounding regions might be viable for agricultural use if the dumping site is properly managed, including trash segregation by source. These results offer a comprehensive understanding of how landfilling affects the environment and can aid in better landfill management. In the end, the best way to reduce the overall environmental impact of urban waste on the Brahmaputra valley ecosystem is to switch from open dumping to a sustainable, engineered landfill design.

In order to support well-informed decision-making regarding waste management infrastructure, future research should focus on the creation of a localized planning index that integrates site-specific data, such as population density and leachate pollution measurements.

Table 1 : **Statistical analysis of the physico-chemical characteristics and heavy metals of leachate and comparison with Indian standards for treated leachate**

Parameter	Mean±SD	Median	Maximum	Minimum	Standard Error	Indian Permissible limit[#]
pH	7.29±0.65	7.3	8.7	6.5	0.17	5.5-9.0
EC (µS/cm)	818.67±257.04	730	1250	490	66.37	NR*
TS (mg/L)	2566.53±498.58	2550	3348	1800	128.74	NR*
TDS (mg/L)	1189.87±265.14	1200	1648	700	68.46	NR*
TSS (mg/L)	1376.67±255.56	1300	1800	1000	65.98	100
Oil & Grease (mg/L)	708.67±83.57	700	820	540	21.58	NR*
COD (mg/L)	1203.87±605.27	955.6	2526.8	645.6	156.28	250
BOD (mg/L)	12.14±3.05	12.92	16.67	4.16	0.79	30
TA (mg/L)	1640±219.74	1650	2000	1250	56.74	NR*
Sulphate (mg/L)	13.33±6.11	12.5	28	6.5	1.58	NR*
Phosphate (mg/L)	1.54±0.07	1.6	1.6	1.4	0.02	NR*
Nitrate (mg/L)	0.68±0.12	0.7	0.83	0.43	0.03	NR*
Ca (mg/L)	128.65±29.61	114.2	210.4	100.2	7.65	NR*
Mg (mg/L)	36.91±11.11	37.8	54.8	22	2.87	NR*
Chloride (mg/L)	183.07±60.54	188.8	300.7	91.6	15.63	1000
Fe(mg/L)	3.089±0.95	2.76	5.2	2.1	0.25	NR*
Cu(mg/L)	0.981±0.743	0.4	2.45	0.35	0.19	3.0
Ni(mg/L)	0.629±0.445	1.01	1.13	0.01	0.11	3.0
Pb(mg/L)	0.081±0.079	0.07	0.3	0.01	0.02	0.1
Mn(mg/L)	2.319±0.711	2	3.8	1.6	0.18	NR*
Co(mg/L)	0.488±0.017	0.49	0.52	0.45	0.004	NR*
Cr(mg/L)	0.053±0.104	0.02	0.33	0.003	0.03	2.0
Zn(mg/L)	1.628±0.524	1.3	2.63	1.23	0.14	5.0
As(mg/L)	1.134±0.678	0.99	2.7	0.28	0.18	0.2
Cd(mg/L)	0.5±0.562	0.2	1.6	0.01	0.17	2.0

**NR= Not specified in the standard*

 # Central Pollution Control Board, Environmental Standards,The Environment Protection Rules,1986, Schedule VI, General Standards for Discharge of Environmental Pollutants-Part A: Effluents, CPCB, New Delhi, India.

Table 2 : **Comparison of West Boragaon leachate characteristics with those reported from other countries**

Parameters (All Parameters are in mg/L except pH, EC (mS/cm), COD (mgO_2/L), BOD (mgO_2/L)							
	Oman*	Malaysia*	Nigeria*	Ireland*	Sweden*	Iran*	This study
pH	8.54±0.2	8.18-8.76	5.78±0.54	7.6-8.5	8-9	4.57-8.95	6.5-8.7
EC	54.1±0.7	2951-12270	4.194±0.0686	3.089-28.430	0.5-14	0.014-0.133	0.49-1.25
TDS	24,210	2197-6142	2330±40.4	-	-	7140-67,000	700-1648
TSS	1270	144-291	-	-	-	-	1000-1800
COD	33,600±300*	1516-2954	103.11±11.6	411-7160	500-4000	2000-90,000	612.2-1878.3
BOD	13,200±600*	54.38-240.75	35.3±8.4	36-984	10-800	350-22,000	4.16-16.67
Alkalinity	-	-	-	998 - 9682	-	-	1250 - 2000
Sulphate	129.8±0.3	-	110.43±16.8	7.2-1950	-	-	6.5-28
Nitrate	-	-	38.11±6.2	-	-	-	0.43-0.83
Phosphate	39.8±0.2	-	63.26±6.4	-	-	-	1.4-1.6
Chloride	7636.8±17.5			160-2620	1000-6000		91.6-264
Ca	109.32±0.1	-	-	-	-	-	100.2-210.4
Mg	157.88±0.9	-	-	-	-	-	22-54.8
Fe	26.47±0.7	5.88-14.31	10.217±4.2	-	3.5-13.0	-	2.1-5.2
Cu	1.83±0.4	-	-	0.003-2.423	0.007-0.027	0.25-0.716	0.35-2.45
Ni	BDL	-	0.215±0.08	0.01-0.661	0.02-0.03	0.25-0.676	0.01-1.13
Pb	BDL	0.036-0.147	0.843±0.11	0.0006-1.047	0.002-0.019	0.24-0.251	0.01-0.3
Mn	1.16±0.3	-	0.144±0.06	-	0.5-1.9	-	1.6-3.8
Co	-	-	-	-	0.004-0.008	-	0.45-0.52
Cr	10.42±0.2	-	3.873±1.02	0.033-1.436	0.01-0.03	0.25-0.782	0.003-0.33
Zn	BDL	-	-	0.01-7.639	0.08-0.44	-	1.23-2.63
As	BDL	-	0.043±0.02	0.011-0.412	0.001-0.380	0.25-0.523	0.28-2.7
Cd	-	-	504±40	0.1-7.4	0.05-0.41	245-256	0.01-1.05

*Oman [Siddiqi et al., 2022],
*Malaysia [Mohd-Salleh et al., 2020],
*Nigeria [Godwin and Oghenekohwiroro, 2016],
*Ireland [Brennan et al., 2016],

*Sweden [Morling, 2007],
*Iran [Saghi et al., 2024]

Table 3 (a) : **Pearson's correlation analysis of leachate samples**

	pH	EC	TS	TSS	TDS	O&G	COD	BOD	TA	SO_4^{2-}	NO_3^-	PO_4^{3-}
pH	1											
EC	0.43	1										
TS	0.008	0.005	1									
TSS	0.0002	0.0002	0.81	1								
TDS	0.03	0.03	0.24	0.003	1							
O&G	0.6	0.57	0.001	0.003	0.0002	1						
COD	0.17	0.13	0.08	0.13	0.1	0.17	1					
BOD	0.61	0.53	0.18	0.3	0.33	0.51	0.32	1				
TA	0.009	0.006	0.05	0.01	0.09	0.007	0.05	0.01	1			
SO_4^{2-}	0.35	0.3	0.17	0.13	0.04	0.42	0.3	0.15	0.03	1		
NO_3^-	0.003	0.11	0.01	0.05	0.51	0.005	0.06	0.06	0.13	3E-8	1	
PO_4^{3-}	0.43	0.41	0.02	0.04	0.01	0.25	0.12	0.13	0.13	0.31	0.02	1

Table 3(b) : **Pearson's correlation analysis of leachate samples**

	Fe	*Cu*	*Ni*	*Pb*	*Mn*	*Co*	*Cr*	*Zn*	*As*	*Cd*	PO_4^+	NO_3^-
Fe	1											
Cu	0.03	1										
Ni	0.01	0.06	1									
Pb	0.51	0.03	0.003	1								
Mn	0.002	0.08	0.15	0.001	1							
Co	0.005	0.03	0.06	0.009	0.13	1						
Cr	0.05	0.04	0.07	0.001	0.04	0.07	1					
Zn	0.06	0.04	0.002	0.13	0.05	0.09	0.08	1				
As	0.22	0.001	0.02	0.02	0.04	0.05	0.04	0.007	1			
Cd	0.11	0.006	0.002	0.003	0.05	0.05	0.04	0.11	0.1	1		
PO_4^+	0.15	0.001	0.01	0.04	0.03	0.22	0.29	0.05	0.13	0.29	1	

NO_3^-	0.06	0.22	0.09	0.11	0.07	8E-5	0.05	0.11	0.07	0.05	0.06	1

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399 **Table 4** : **LPI classifications and overall LPI value**

Index	Parameters (mg/L) , pH	w_i	p_i	$w_i p_i$	Concentration	LPI
$LPI_{inorganic}$	pH	0.214	5	1.07	8.7	LPI_{in} = 3.76
	TDS	0.195	8	1.56	1648	
	Chloride	0.187	6	1.13	135	
$LPI_{organic}$	COD	0.267	55	14.69	1878.3	LPI_{or} = 16.27
	BOD	0.263	6	1.58	14.67	
$LPI_{heavy\ metals}$	Cu	0.098	18	1.76	2.45	LPI_{hm} = 6.28
	Fe	0.088	5	0.44	5.2	
	Ni	0.102	7	0.71	1.13	
	Pb	0.123	6	0.74	0.3	
	Cr	0.125	5	0.63	0.33	
	Zn	0.110	5	0.57	2.63	
	As	0.119	12	1.43	2.7	
Overall LPI = 0.232 LPI_{or} + 0.257 LPI_{in} + 0.511 LPI_{hm}						7.96

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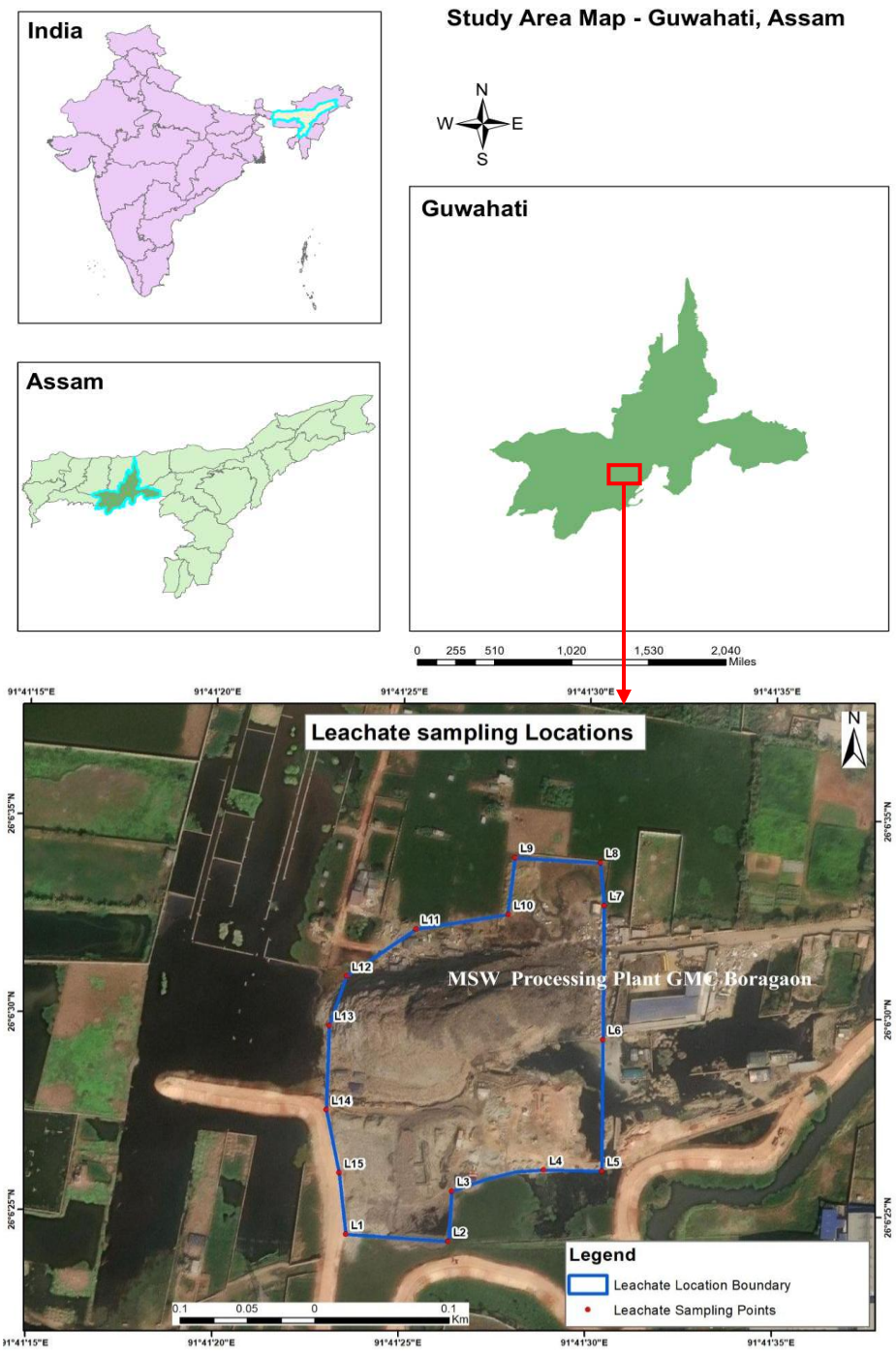


Fig 1: Map showing the sampling locations near MSW dumping site

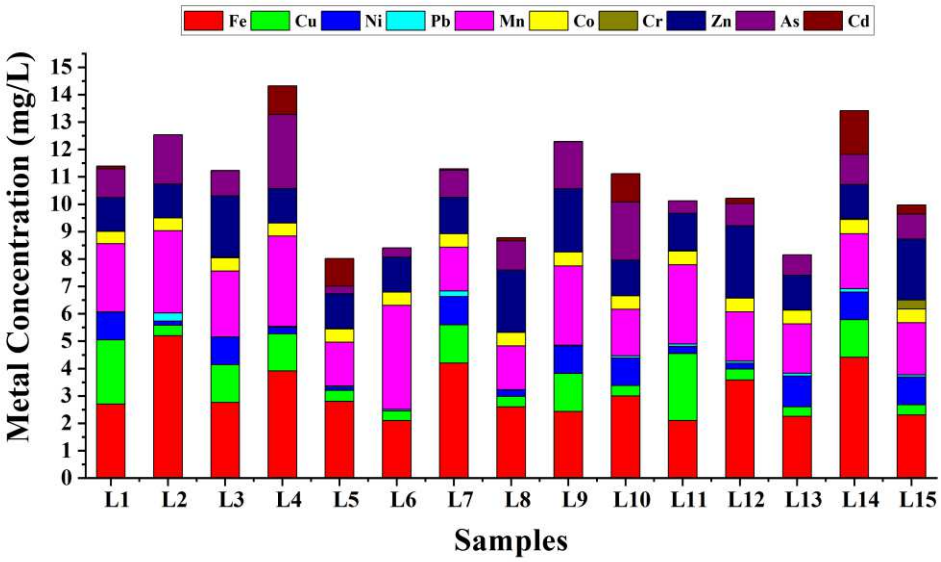


Fig 2: Comparision and variation of heavy metals in all samples

Funding Declaration : Not Applicable

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