Assessment Of Temporal Variations In Leachate Characteristics At An Active Landfill Site Of Delhi.

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Abstract
Extraordinary population growth joined with commercial development, industrialization and rapid urbanization have led to the significant generation of municipal solid waste (MSW). Landfilling requires the lowest invest investment but it is the least favoured step in the integrated waste management order. The current effort was accomplished to measure the temporal variation of the leachate quality from the Okhla landfill site, operational since 1996 closed in 2022 and receiving approximately 2,000 tons of MSW daily in this period. Analysing leachate samples from 2018 to 2022 reveals significant temporal variations, Chemical Oxygen Demand (COD) levels consistently exceed 3,600 mg/L in pre-monsoon samples, decreasing to approximately 3,400 mg/L post-monsoon. Total Solids (TS) also decreased, indicating a dilution effect from rainfall. Notably, heavy metals, particularly lead, remain a concern, with concentrations persistently above 0.35 mg/L, highlighting ongoing contamination risks. The leachate, which lacks adequate treatment facilities, can migrate through nearby drainage systems, ultimately polluting the Yamuna River. This poses significant ecological risks, by impacting the water quality of River Yamuna. The findings emphasize the need for improved waste management practices and leachate treatment strategies to mitigate environmental risks and protect the Yamuna River's water quality and its aquatic life.

Keywords: Solid Waste Management; Landfill, Leachate, Environment; Groundwater; Aquatic Life a

Introduction

Over the past decade, there has been a significant shift in the nature and rates of solid waste generation due to various factors such as fast industrialization, population growth, and lifestyle changes. Considering the current infrastructure, solid waste landfill management is typically a big challenge in India. The unlawful disposal of municipal solid trash on the outside of the city is seriously endangering public health and causing major environmental degradation in rivers. Solid waste management (SWM) is a worldwide problem, particularly in underdeveloped nations where there is a very small public budget for it (Khan et al., 2022; Ashraf et al., 2022).

In India, every city, town, and hamlet dispose of MSW in an unscientific manner. Typically, MSW created is dumped immediately in low-lying locations. The majority of urban local bodies (ULBs) lack sufficient engineered landfilling capabilities, and MSW is dumped along the city's outskirts. Unscientific MSW disposal increases the risk of floods, and leachate percolation is the primary cause of contamination in surface and groundwater bodies. The majority of MSW is dumped in open dumps without liners or leachate collection and treatment facilities in developing nations like India (Parihar et al., 2019).

Because it allows for the disposal of large amounts of MSW at a lower cost than other waste disposal techniques, landfilling is one of the most straightforward solutions for MSW disposal worldwide (Ahmed et al., 2020; Parihar et al., 2019). MSW landfills are important sources of many different types of pollutants that are harmful to the environment. Most MSW disposal sites remain open dumps, particularly in emerging and impoverished nations. When precipitation seeps through an open landfill or the cap of a finished site, leachate is produced (Ahmed et al., 2020).

Globally, open dump sites pose the greatest risk of contaminating water supplies. Leachate, a contaminated liquid that oozes out of dump sites and percolates through the underlying soils, contaminating groundwater supplies, varies in content and chemical properties. When landfills are not properly planned and do not adhere to the specifications of the liners used in the landfill, the leachate discharge from municipal solid waste (MSW) landfills may degrade soil and water resources (Samal et al., 2020). The type of trash disposed of, the landfill's age, the waste's composition, the site's hydrology, and the climate all affect the leachate produced by landfills (Panwar & Ahmed, 2018).

High levels of organic, inorganic, and heavy metals can be found in leachate, a highly concentrated liquid produced by these landfills (Ahmed et al., 2020). It eventually forms beneath the solid trash as a result of the organic stuff in the waste being broken down by microbes and biochemical processes (Samal et al., 2020). BOD, COD, TSS, TKN, AN, pH, and heavy metals such As, Cu, Cr, Fe, Zn, Ni, Cd, Pb, Hg, Co, and V are among the main contaminants in leachate (Angmo & Shah, 2021).

The production and treatment of landfill leachate are the main issues facing municipal solid waste management. Depending on the weather, leachate flow may increase during the rainy season or decrease during the dry/summer season. The release of landfill leachate could cause major environmental issues. Leachate may seep into the subsurface through landfills, contaminating surface and groundwater supplies.

Given the significant environmental effects of leachate, accurate characterization through routine monitoring is crucial to its effective management. Because of the organic matter's biological and chemical deterioration, the waste's composition drastically changes over the landfill's lifespan (Puvvadi et al., 2015). An effective method for understanding the patterns and behavior of contamination is temporal analysis characterization, which also provides information for deciding on environmental protection and dump closure strategies (Ashraf et al., 2022b).

In the early acidic phase, robust decomposition and leaching result in the production of leachate with high strength of all components. More stable leachate with lower concentrations and a low BOD/COD ratio is seen during the extended methanogenic phase. The likelihood of a heavy metal leak occurring decreases as the landfill site ages and stabilizes. (Saha and others, 2023) Understanding the leachate's composition facilitates the design of an efficient treatment system and suitable liners to contain the leachate, as well as the assessment of the contamination risk it poses to the nearby ecosystem (D'Souza & Somashekar, 2013; Esakku et al., 2007).

The solid waste composition varies from place to place within the landfill and also changes over time at the same locations within the landfill sites due to the daily disposal of MSW of various compositions over a wide area. Variations in the composition of the leachate are also greatly influenced by the amount of rainfall that falls over the landfill sites. Malik and Naveen (2017). Human health may be negatively impacted by the leachate produced by open dumps and uncontrolled landfill sites, which can seriously endanger groundwater and surface water (Kulikowska & Klimiuk, 2008; (D'Souza & Somashekar, 2013).

One unavoidable effect of disposing of waste in landfills is the creation of contaminated leachate.It becomes essential to understand leachate formation mechanisms and characterize leachate quality in order to ensure proper leachate management that will minimize any potential adverse effects. El-Fadel and collaborators, 2002 Surface and groundwater resources are more at risk from landfills in developing and impoverished countries, where they are usually uncontrolled open dumps and hazardous industrial waste is also disposed of alongside municipal waste. Singh and Mittal (2011). The current study was carried out in order to evaluate the temporal variations of physiochemical parameters as well as toxic trace elements and compounds in the Okhla landfill site in Delhi.

According to Guleria and Chakma (2019), landfills like Okhla, Ghazipur, and Bhalswa are open, unengineered disposal sites. Aquatic life is seriously at risk since leachate from these dumpsites can enter the Yamuna River through nearby drains because there is no bottom line system in place (Srivastava and Chakma 2020). Leachate may also contain high concentrations of hazardous elements like Cd, Cr, Cu, Pb, Ni, and Zn as a result of the disposal of industrial waste. Water contamination may result from heavy metals leaking from a landfill (Chaudhary et al., 2021). The current study is divided into six sections. There will be a brief introduction in Section 1. A review of the literature will be conducted in Section 2. The case of these will be covered in Section 3.

Literature review

Anglo et al. (2023) examined approximately twenty-five (25) parameters from the leachate samples that were collected during the pre-, monsoon, and post-monsoon seasons. COD, BOD, NH4-N, EC, and TDS were among the 25 pollutants that were found to be above the established standard limit throughout the year. High levels of other contaminants, including TKN, TSS, TCB, and Cl, were also discovered. During the post-monsoon, the concentration of arsenic (As) was found to be higher than allowed. At the Okhla landfill in South Delhi, the lead (Pb) concentration was found to be higher than the usual limit during the pre- and post-monsoon seasons.

All leachates had high levels of Pb (1.2 mg/l), Cr (1.5 mg/l), Zn (1.15 mg/l), Ni (3 mg/l), and Fe (6.74 mg/l). The iron eventually seeps into groundwater from landfills with rainwater during the monsoon season. The steel industry typically dumps its effluents in adjacent landfills with high iron concentrations (Singh & Mittal, 20191). According to numerous studies, the leachate from MSW landfills has contaminated Delhi's groundwater supplies (Panwar & Ahmed, 2018). Health risks were associated with high levels of heavy metals (Pb, Cd, Ni, Cr, Mn, Co, and Zn). According to these studies, the point source of water contaminants is landfills. Leachate organics, nitrogen, heavy metals, and toxicity were found to have very high concentrations that varied with sampling time. The variance in leachate properties suggests that the leachate from an active landfill is affected by climate, age, and the kind of waste that is disposed of. In contrast to old leachate, which has a high pH and diminished strength as a result of degradation, fresh leachate has a low pH and high organic strength.

Young landfills may have higher COD due to bacterial activity, organic matter, higher temperatures, and a lack of aeration (Ashraf et al., 2022a). A young landfill site (one to two years old) may have a chloride concentration of 200–3000 mg/L, whereas an old landfill site (five to ten years old) may have a concentration of 100–400 mg/L. Wintertime BOD5 concentrations are high because the oxidation process slows down in a confined space due to the lower temperature (Ashraf et al., 2022).

Glass, building materials, medical waste, soil plants, food waste, and beverage waste all contain fluoride, which either dissolves or degrades in leachates. Large volumes of leachate may contribute significant amounts of pollutants to the environment, so low concentrations of toxic compounds do not always make the leachate less dangerous. Numerous substances are hazardous at low concentrations, and their combined effects amplify adverse environmental effects (Ahmad et al., 2022).

A variety of physical, chemical, and biological parameters may exhibit significant fluctuations in the leachate's properties, ranging across multiple orders of magnitude. Nonetheless, a useful tool for comparing the pollution potential of landfill sites is the Leachate Pollution Index (LPI). An estimate of how the type of waste is changing year over year can be obtained from the landfill LPI trend over time. The LPI of a specific landfill depends on the amount (concentration) and type of waste (organic or inorganic). The type of waste being disposed of in these landfills determines the concentration of a particular component in the leachate. Therefore, one of the causes of these erratic trends may be differences in the waste type and leachate composition (Chaudhary et al., 2021)

To estimate the pollution potential of the Okhla landfill site, a leachate sample was taken and examined for nine important leachate pollutant variables: chromium, lead, pH, TDS, BOD5, COD and chloride (Cl^-), nitrate, and iron. All of the leachate pollutant variables under study had concentrations above allowable limits. In their analysis of the seasonal variation in LPI values, Samal et al. (2020) and Sarkar et al. (2023) found that landfill leachate has a lower potential for pollution during the post-monsoon period than it does during the pre-monsoon period.

According to the Solid Waste (Management and Handling) Rules, 2016, the acceptable LPI value for leachate disposal standards in inland surface water is 6.8. However, the LPI values recorded at the Okhla landfill site indicate significant contamination, as all measurements taken across the three seasons—pre-monsoon, monsoon, and post-monsoon—exceeded the established standards.

The LPI values for Okhla and Ghazipur landfills showed an irregular trend, but there was a significant decrease in LPI in 2017 and 2018, (Chaudhary et al., 2021)

Additionally, researchers examined leachates from Delhi landfill sites for Mn, Al, sulfate, Cd, Co, electrical conductivity (EC), and salts (Ca, Mg, Na and K) (Gupta & Arora, 2016). Groundwater will be contaminated by the Okhla, Ghazipur, and Bhalswa landfills, and cadmium poses a greater risk than other metals. Adults in Okhla (2.22×10^{-3}), Ghazipur (8.37×10^{-4}), and Bhalswa (1.39×10^{-3}) had higher cancer risk exposures to Cd from these landfills than children in Okhla (1.04×10^{-3}), Ghazipur (3.90×10^{-4}), and Bhalswa (6.49×10^{-4}). Thus, in Okhla, landfill leachate, Cd and Pb can be considered pollutants of concern (Chaudhary et al., 2021).

According to Singh and Mittal (2011), heavy metals contribute substantially more to landfill pollution at the Okhla landfill. The presence of Pb indicates that there may be a risk of cancer and that the contamination source may be the disposal of lead-acid batteries (Chaudhary et al., 2021).

The Okhla landfill site's location, specifically in the Yamuna River's floodplains, increases the likelihood that surface runoff water will contaminate the river and nearby water sources. Additionally, it raises concerns about the possible effects of Yamuna water quality on aquatic life.

The present study explores the temporal variation of leachate characteristics of the Okhla landfill from 2018 to 2022 observing various parameters such as As, CN, Cd, Ni, Pb, Zn, Cr, Cu, Fe, Phosphate, pH, Mg, Ammonical Nitrogen (AN), SO_4^{2-}, Cl, TKN, VS, COD, BOD, TS, TDS, and VS, TKN were monitored along with rainfall pattern. The result shows a decrease in the strength of leachate formation.

Case Study

Delhi city is home to about 27 million people, according to the 2011 Indian census. It is the world's third-largest urban area and the second most crowded city after Mumbai. It covers an area of 1483 km². About 60% of the 9,000 metric tons of solid waste produced daily in Delhi are dumped in landfills. Delhi's homes, businesses, hospitals, construction and demolition wastes, and retail and commercial markets are the main sources of MSW (Naveen & Malik, 2017). Delhi is home to three operational landfills: Okhla, Bhalswa, and Gazipur. All three are classified as uncontrolled solid waste disposal facilities because they are not lined. According to Singh and Mittal (2011), leachate from these landfills typically collects in low-lying areas or seeps through the soil surface, contaminating groundwater and surface water supplies.

The landfill site receives a wide range of waste, including liquid waste, hospital waste, slaughterhouse waste, food waste, oil products, debris, agricultural waste, and chemical materials. There is no landfill designated for each type of waste, nor is there waste segregation at the source. Municipal and hazardous waste are not pre-treated before being dumped. None of Delhi's waste disposal sites have established proper landfill management. Because of the site's steep slopes, the waste pile is typically not covered. High temperatures are also known to cause self-waste combustion and unpleasant odours (Singh & Mittal, 2011).

The Okhla dumpsite receives about 3000 MT of waste per year from South Delhi's homes, businesses, industries, institutions, and offices. The Okhla Compost plant on Mathura Road receives 200 tons of it. despite MCD's assertion that the Okhla Landfill site does not receive any industrial waste (Samal et al., 2020). The solid waste from South Delhi that was dumped in the Okhla landfill has a high potential for biomethanation due to its physical and chemical makeup, which includes 28.62% biodegradable waste, 32.7% inert material, 19.7% bio-resistant material, 4.45% plastic, and 0.1% metal. Additionally, it has a high moisture content and calorific values, which make it extremely promising for generating environmentally friendly energy for society (Kumar and Allapat 2003; Angmo & Shah, 2023).

Schedule 3 of the MSW Rules 2000 does not apply to the design of the dumping sites in Okhla, Ghazipur, and Bhalswa (Chaudhary et al., 2021). Only about 20% of the waste that is produced is processed; the other 80% is disposed of in landfills. According to Angmo and Shah (2023), Delhi produces the most municipal solid waste per person.

Materials and methods

Study Area

The Okhla landfill site provided the leachate used in the investigation. It takes waste of all kinds from a variety of sources. The location is close to residential areas. The risk of pollution to the aquifers and River Yamuna is increased by the fact that all three of the active landfills are located in the alluvial plains of the river (Singh & Mittal, 2011).

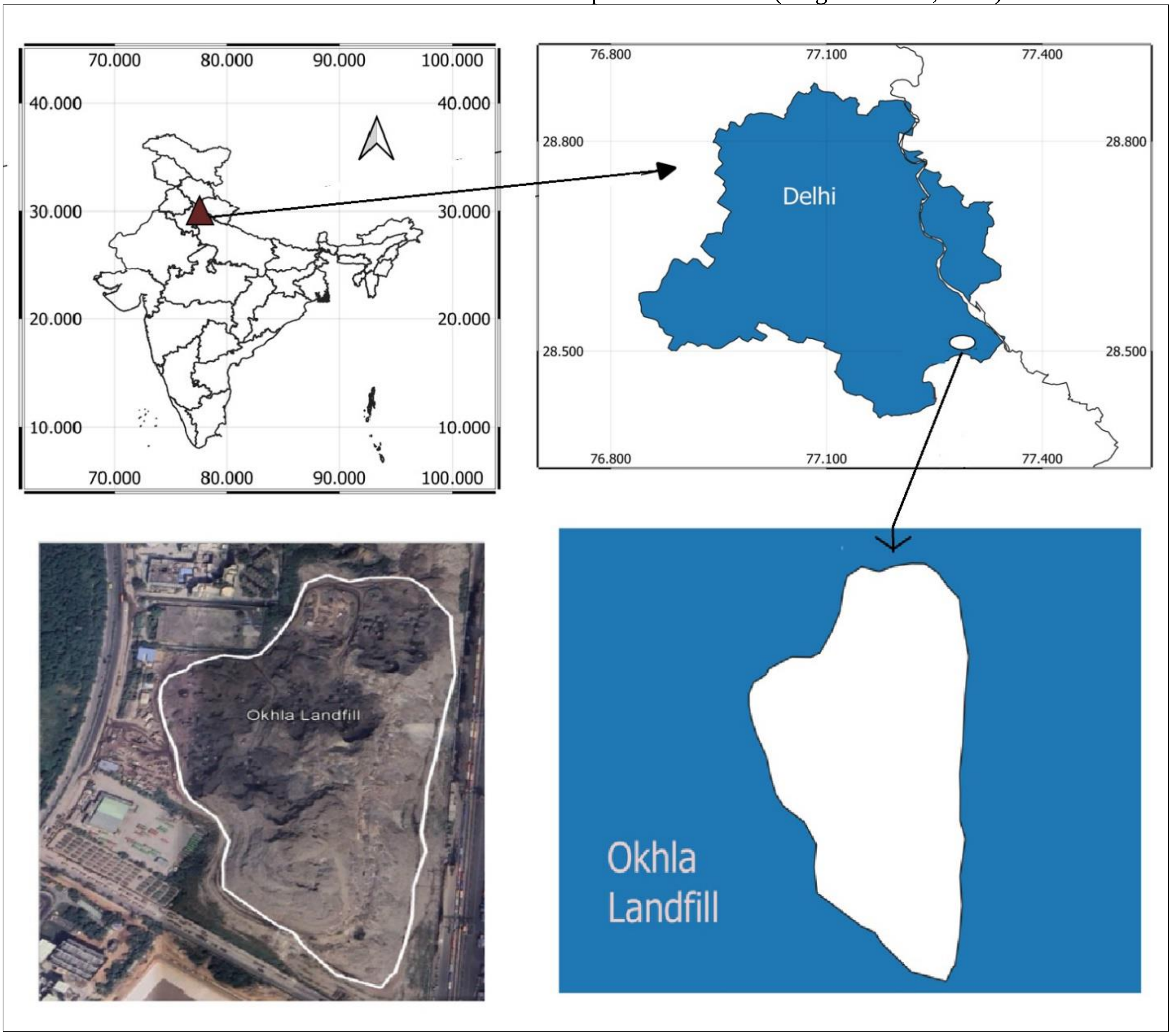

Figure 1: Study Area and Satellite Image

The Okhla landfill is situated in the Southeast Delhi district, next to the ESIC hospital Tughlagabad, at latitude and longitude 28°30'40.05''N, 77°17'4.47''E. Established in 1994, Okhla landfill is an active, uncontrolled, and non-engineered landfill that began dumping waste in 1996. It reached its capacity in 2010 and was decommissioned in 2022, but solid waste is still dumped there without any consideration for segregation (Angmo et al., 2023a). Every day, about 2000 tons of waste are disposed of, including waste from agriculture production, construction and demolition waste, and municipal solid waste (APMC). Waste from the four South Delhi zones—Central, South, West, and Najafgarh—arrives at the landfill. Of the total average waste from these zones, 51% goes straight to the Okhla landfill (Angmo et al., 2023b). The Okhla landfill site receives around 3000 MT of non-segregated Solid Waste daily. There is no arrangement for leachate collection and treatment at this site. Leachate is generated and migrates into the existing sewer through open drains and ultimately reaches River Yamuna (Samal et al., 2020).

Rainfall Pattern in Delhi During Study Period

The rainfall statistics of the study area is provided on a seasonal basis i.e., Winter (Jan-Feb), Pre-Monsoon (Mar-May), Southwest (SW) Monsoon (Jun-Sep) and Post-Monsoon (Oct-Dec). The Rainfall Normal used in the study is based on rainfall records from 1961 to 2010, while the study data was collected for the period from 2018 to 2022, as reported in the "Rainfall Data in Annual Reports of India (2018–2022)".

The annual rainfall recorded in 2018 was 687.28mm whereas SW monsoon rainfall was 559.5 mm in the year 2018 rainfall was much below the annual average i.e., 774.4 mm. In the subsequent year i.e., from 2019-2022, the rain was significantly above the norms of 1961-2020, in the year 2021 it was recorded as high as 1333.2 mm and 708 mm in the years 2021 and 2022 respectively. The year 2021 was the second highest wettest year after 1931 and the rainfall recorded was 1755.6 mm. The year 2022 also witnessed a good annual rainfall i.e., 1089.6 mm. The rainfall pattern is shown in

Figure 2. More number of rainy days and high rainfall increases the moisture content of the substrate of the landfill sites and result in the high rate of biodegradation and a large volume of leachate (Salleh & Hamid, 2013)

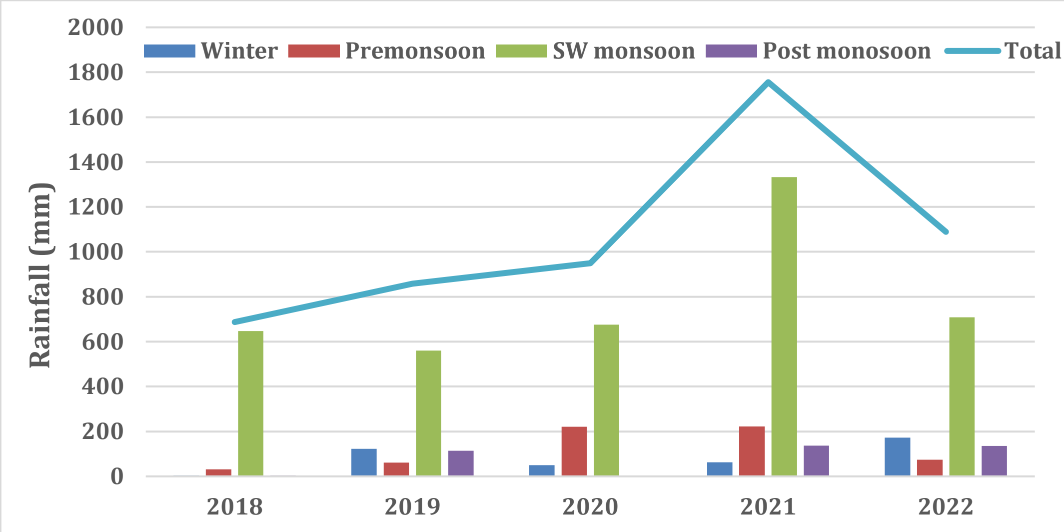

Figure 2: Rainfall pattern of Delhi during the study period

Leachate characteristics

Landfill leachate characterization is a critical factor to establish and understand its implication on nearby water bodies. However, it is often difficult to forecast leachate quality because of a variety of influencing factors such as waste composition and landfill operations. The temporal variations of several parameters was monitored

The leachate used in the study was collected from the Okhla landfill site, Delhi. Three leachate samples were collected each from five different locations of the landfill sites at intervals of one week. Hence 30 samples were collected during pre-monsoon (May 2018 & May 2022) and similarly, 30 samples were collected during post-monsoon (Oct 2018 & Oct 2022). The collected leachate was stored in the laboratory at 4°C for further analysis. The selected parameters were used to evaluate the characteristics of leachate are As, CN, Cd, Ni, Pb, Zn, Cr, Cu, Fe, Phosphate, pH, Mg, AN, SO_4^{2-}, Cl, COD, BOD, TS, TDS, and VS, TKN.

The older landfills do not have blockade systems or leachate collection systems to control the movement of leachate to the surrounding soil and groundwater. Leachate has a greater chance of contaminating groundwater when landfills are located in permeable soils with low water tables. Heavy metals pose an ecological risk because they are extremely toxic, persistent, bio-accumulative, and can contaminate nearby waterbodies and landfills (Naveen & Malik, 2019).

After the sampling, the samples were brought on the same day and stored at 4 ºC in the Environmental lab, Jamia Millia Islamia. Various leachate parameters such as pH, Total Solids, Volatile Solids, TDS, BOD, COD, Cl^-, PO_4^{3-}, SO_4^{2-} and heavy metals like Fe, Pb, Cr, Cd, Cu, Zn, Ni and As were examined. Analytical methods were carried out according to "Standard methods for the examination of water and wastewater," specified by the American Public Health Association (APHA, 2005). Elico, an electronic pH meter, was used to measure the pH. The unfiltered sample was shaken to determine TS, which was then estimated using the gravimetric method (2540B of Standard Methods). After passing the sample through Whatman filter paper-44, the TDS was calculated using gravimetric estimation (2540C Standard Methods). The difference between the sample's initial and final dissolved oxygen levels was used to estimate BOD (5210B Standard methods). Using 5220C Standard Methods, COD was measured by refluxing the sample and then titrating with FeSO4. The concentration of heavy metals was estimated using PerkinElmer's Atomic Absorption Spectroscopy.

Results and Discussion

This study focuses exclusively on the temporal leachate characteristics of the Okhla landfill site, with samples collected during pre and post-monsoon seasons in 2018 and 2022. Seasonal variations in the leachate quality were assessed during this period. Additionally, cumulative rainfall data for the sampling period were considered to evaluate the impact of rainfall on leachate composition. The findings were also compared with results from previous studies to highlight temporal and seasonal trends. Rainfall plays a critical role in the composition of landfill leachate by diluting its constituents and increasing its overall volume (Zaki et al., 2022). Higher rainfall during the post-monsoon season significantly influences the quality of leachate, primarily through dilution effects. This phenomenon results in lower concentrations of various contaminants when comparing pre-monsoon and post-monsoon periods and the data from 2018 and 2022 are shown in **Figure 3**, highlighting the temporal variations in leachate parameters.

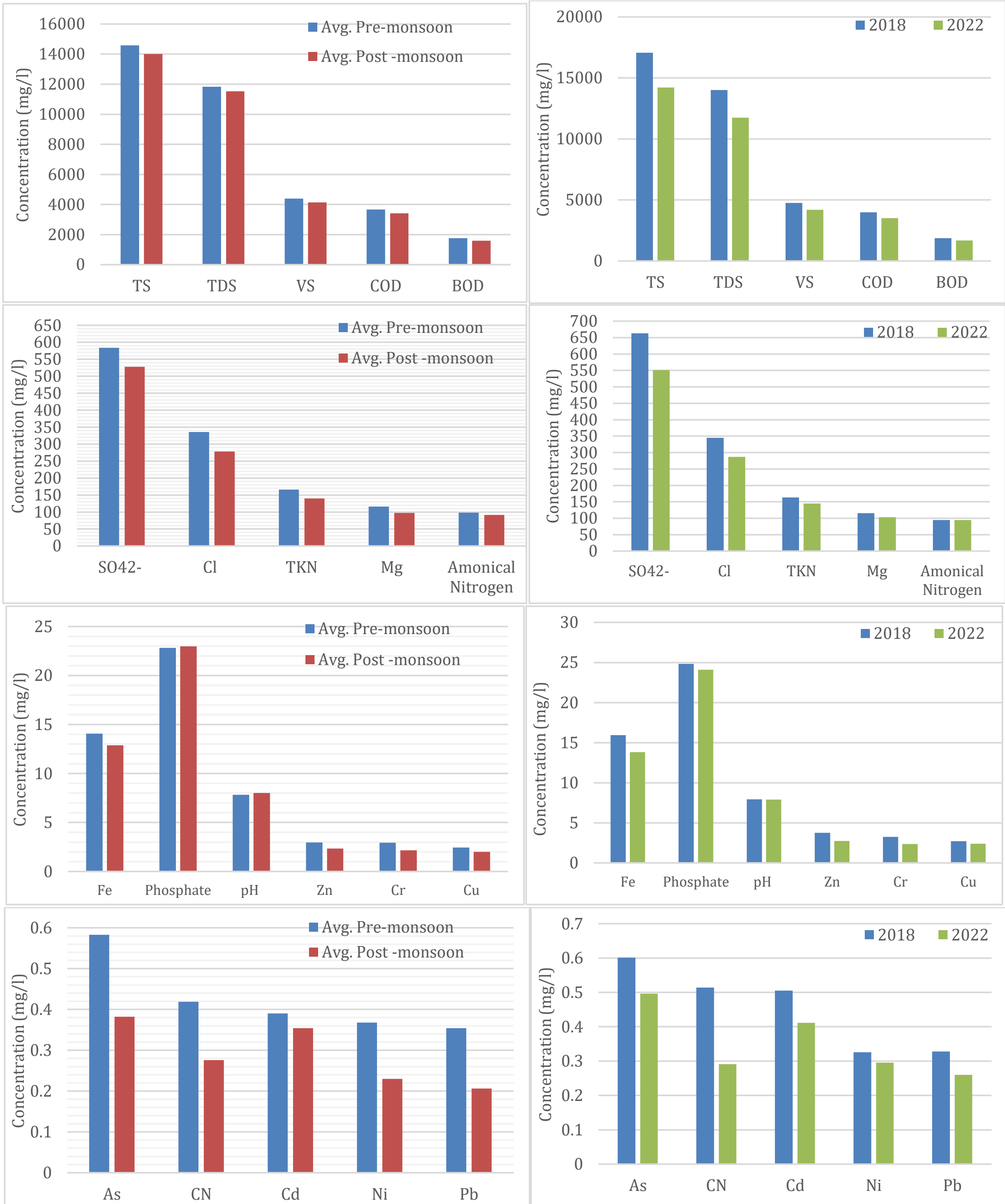

Figure 3: Concentration of various parameters in Pre -Post Monsoon over the year

Total Solids (TS), Total Dissolved Solids (TDS), VS, COD and BOD:

The average values of TS and TDS in the leachate samples collected from the landfill site during the pre-monsoon and post-monsoon seasons shown in **Figure** 3 exhibit a notable seasonal variation, which can be attributed to the dilution effect of rainfall. During the pre-monsoon phase, the average TS concentration was 14,575.704 mg/L, which decreased to 14,001.1 mg/L post-monsoon. Similarly, TDS concentrations dropped from 11,823.79 mg/L in the pre-monsoon period to 11,523.4 mg/L in the post-monsoon phase. A similar trend was observed in other parameters such as volatile solids (VS), (COD) and (BOD). The VS concentration decreased from 4,399.935 mg/L pre-monsoon to 4,133.5 mg/L post-monsoon, while COD dropped from 3,659.98028 mg/L to 3,406.22 mg/L. BOD levels showed a reduction from 1,758.62597 mg/L to 1,591.2099 mg/L, reflecting the dilution of organic and inorganic constituents in leachate due to seasonal rainfall. These seasonal variations underscore the influence of climatic conditions on leachate composition and highlight the need for adaptive leachate management strategies.

A comparison of the average values from 2018 and 2022 reveals a significant reduction in pollutant concentrations over the years, suggesting an improvement in leachate quality or enhanced management practices. In 2018, the average TS concentration was 17,059.404 mg/L, which declined to 14,222.7 mg/L in 2022. Similarly, TDS levels decreased from 14,007.99 mg/L in 2018 to 11,737.8 mg/L in 2022. Other parameters also followed this declining trend, with VS concentrations reducing from 4,749.735 mg/L to 4,206.2 mg/L, COD levels dropping from 3,985.10028 mg/L to 3,501.92 mg/L, and BOD concentrations decreasing from 1,863.62337 mg/L to 1,671.9974 mg/L. This overall reduction indicates a gradual decline in organic and inorganic pollutants, which could be attributed to changes in landfill management practices, aging of waste, or natural attenuation processes. These findings emphasize the importance of regular leachate monitoring and effective environmental management to ensure compliance with disposal standards and minimize the ecological impact of landfills.

Sulfates (SO_4^{2-}) , Chlorides (Cl^-), TKN, Mg & Ammonical Nitrogen:

The analysis of sulfate, chloride, total Kjeldahl nitrogen (TKN), magnesium, and ammonical nitrogen concentrations in landfill leachate samples revealed significant seasonal variations influenced by rainfall. During the pre-monsoon season, sulfate levels averaged 584.104 mg/L but decreased to 527.9 mg/L post-monsoon, suggesting dilution due to increased water infiltration. A similar trend was observed for chloride, which declined from 335.98 mg/L pre-monsoon to 278.3 mg/L post-monsoon. Total Kjeldahl nitrogen also exhibited a seasonal reduction, dropping from 165.986 mg/L to 140.195 mg/L, while magnesium levels decreased from 116.447 mg/L to 97.194 mg/L. Ammoniacal nitrogen concentrations followed a comparable pattern, decreasing from 97.938 mg/L pre-monsoon to 91.329 mg/L post-monsoon. These reductions demonstrate the substantial impact of rainfall on leachate composition, particularly in diluting dissolved salts and nitrogenous compounds.

A comparative evaluation of leachate data from 2018 and 2022 further revealed a temporal decline in several parameters, reflecting potential improvements in landfill management or natural attenuation of pollutants. Sulfate concentrations decreased from 663.004 mg/L in 2018 to 551.3 mg/L in 2022, while chloride levels dropped from 345.08 mg/L to 286.7 mg/L over the same period. TKN concentrations showed a modest reduction, from 163.481 mg/L in 2018 to 144.895 mg/L in 2022, indicating reduced nitrogen loads. Similarly, magnesium levels decreased from 115.741 mg/L to 102.894 mg/L, reflecting a decline in mineral content. Interestingly, ammoniacal nitrogen concentrations remained consistent at approximately 94.329 mg/L across both years, suggesting that specific nitrogenous compounds may persist in the landfill environment despite temporal changes. These observations underscore the need for continued monitoring and targeted interventions to manage persistent contaminants effectively while acknowledging seasonal and temporal dynamics in leachate composition.

5.2.3. Fe, Phosphate, Zn, Cr, Cu:

The mean concentrations of Fe, phosphate, pH, Zn, Cr, and Cu during pre-monsoon and post-monsoon periods, as well as across the years 2018 and 2022. In the pre-monsoon phase, iron levels averaged 14.077295 mg/L, decreasing to 12.882 mg/L post-monsoon, indicating a dilution effect from rainfall. Phosphate levels showed a slight increase from 22.81802 mg/L pre-monsoon to 22.988 mg/L post-monsoon, suggesting enhanced nutrient runoff. The pH remained stable, averaging 7.8288 pre-monsoon and 8.0 post-monsoon. Zinc concentrations decreased from 2.9644 mg/L to 2.342 mg/L, while chromium levels declined from 2.93486 mg/L to 2.147 mg/L. Copper concentrations also fell from 2.439 mg/L pre-monsoon to 2.013 mg/L post-monsoon, reflecting the overall trend of dilution during the rainy season.

When comparing the years 2018 and 2022, iron concentrations decreased from 15.932295 mg/L to 13.831 mg/L, indicating a downward trend over time. Phosphate levels were 24.81362 mg/L in 2018 and slightly decreased to 24.1164 mg/L in 2022. The pH values remained stable at around 7.91. Zinc levels were higher in 2018 at 3.7654 mg/L, dropping to 2.743 mg/L in 2022, while chromium concentrations decreased from 3.26186 mg/L to 2.363 mg/L. Copper levels also showed a decline from 2.696 mg/L in 2018 to 2.383 mg/L in 2022. These findings highlight the influence of seasonal changes and time on the concentrations of these parameters, underscoring the need for ongoing monitoring to inform effective environmental management strategies.

5.2.4 As, CN, Cd, Ni & Pb

This study examines the temporal variations in the levels of arsenic (As), cyanide (CN), cadmium (Cd), nickel (Ni), and lead (Pb) in landfill leachate. During the pre-monsoon period, arsenic concentrations averaged 0.583 mg/L, which decreased to 0.382 mg/L post-monsoon, indicating dilution due to rainfall. Similarly, cyanide dropped from 0.41876 mg/L to 0.276 mg/L, cadmium from 0.39 mg/L to 0.35421 mg/L, nickel from 0.368 mg/L to 0.229804 mg/L, and lead from 0.354 mg/L to 0.206 mg/L. A comparison of data from 2018 and 2022 shows a general reduction in these contaminants over time, with arsenic levels decreasing from 0.60112 mg/L to 0.49612 mg/L, cyanide from 0.51376 mg/L to 0.291 mg/L, cadmium from 0.50521 mg/L to 0.41121 mg/L, nickel from 0.325804 mg/L to 0.295804 mg/L, and lead from 0.328 mg/L to 0.26 mg/L. These trends suggest that seasonal dilution and improved waste management practices may have contributed to decreased contamination levels, highlighting the importance of ongoing monitoring to ensure environmental safety.

5.3 Comparative Analysis from Previous Studies

Previous studies have reported that the leachate quality parameters from the Nam Son & other landfills reveal significant insights into the composition and variability of landfill leachate across different regions and periods. This comparative analysis focuses on organic pollutants, inorganic pollutants, and heavy metals, drawing on data from various sources, including (Hoai et al., 2021) and recent our findings from 2018 to 2022.

Organic Pollutants: The levels of biochemical oxygen demand (BOD) and chemical oxygen demand (COD) are critical indicators of organic pollution in leachate. In the Nam Son landfill, average BOD values ranged from 1,591.21 mg/L post-monsoon in 2022 to 1,758.63 mg/L pre-monsoon in 2018. These values are consistent with global trends, where BOD values in tropical regions have been reported at 2,127.79 mg/L in Asia. COD levels in the Nam Son landfill also showed a decline from 3,659.98 mg/L pre-monsoon to 3,406.22 mg/L post-monsoon, aligning with findings from other regions, such as Africa, where COD values reached 7,985.1 mg/L (Lindamulla et al., 2022). The variability in these parameters underscores the influence of climatic conditions and waste composition on leachate quality.

Inorganic Pollutants: The concentrations of total dissolved solids (TDS) and ammonium nitrogen (NH_4^+-N) in the Nam Son landfill also reflect significant variability. TDS levels decreased from 11,823.79 mg/L pre-monsoon to 11,523.4 mg/L post-monsoon, which is comparable to TDS values reported in Polish landfills, ranging from 2,225 mg/L to 7,830 mg/L (Wdowczyk & Szymańska-Pulikowska, 2021) . Ammonium nitrogen concentrations in the Nam Son landfill averaged 97.94 mg/L pre-monsoon and 91.33 mg/L post-monsoon, which aligns with findings from China, where NH_4^+-N levels ranged from 100 to 3,100 mg/L, averaging 1,300 mg/L (Ma et al., 2022). This highlights the need for tailored treatment strategies to address the specific characteristics of leachate in different regions.

Heavy Metals: The concentrations of heavy metals such as arsenic (As), cadmium (Cd), nickel (Ni), and lead (Pb) in the Nam Son landfill show notable trends over time. For instance, arsenic levels decreased from 0.583 mg/L pre-monsoon to 0.382 mg/L post-monsoon, while cadmium concentrations dropped from 0.39 mg/L to 0.354 mg/L. These values are consistent with findings from Thailand, where heavy metals were generally below 1 mg/L, although they still pose potential ecological risks (Ma et al., 2022). In contrast, zinc concentrations in the Nam Son landfill averaged 2.9644 mg/L pre-monsoon, which is higher than the levels reported in inactive Polish landfills (0.019 mg/L) but lower than those in active landfills (up to 2,560 mg/L) (Wdowczyk & Szymańska-Pulikowska, 2021).

The comparative analysis of leachate quality parameters from the Nam Son and other landfills highlights significant variations in organic and inorganic pollutants, as well as heavy metals, over time and across different regions. These findings underscore the specific characteristics of leachate in various contexts, as well as the importance of ongoing monitoring to ensure environmental safety and compliance with regulatory standards. The data presented here not only reflect local conditions but also contribute to a broader understanding of landfill leachate dynamics globally.

5.4 T-test Analysis for Significance

The analysis of leachate characteristics before and after the monsoon season is crucial for understanding the impact of seasonal rainfall on water quality. This study, employed t-tests to compare the means of various leachate parameters, assessing whether significant differences exist between pre-monsoon and post-monsoon measurements. The parameters analyzed include heavy metals and other contaminants into different groups, which are critical for evaluating environmental health and compliance with regulatory standards (Talalaj, 2015). The t-test results provide insights into how monsoon conditions influence leachate composition, which is essential for developing effective management strategies for waste disposal and water treatment.

The results of the t-test analysis of the study as given in Table 1, reveal notable variations in leachate characteristics before and after the monsoon season, with several parameters approaching statistical significance. For instance, GR2, which includes metals such as zinc, chromium, and copper, showed a significant reduction in concentration from 3.2411 to 1.7057, with a t-statistic of 4.1085 and a p-value of 0.0544. This suggests that the monsoon may effectively dilute these contaminants, although the p-value is just above the conventional threshold of 0.05, indicating a trend that merits further investigation. Similarly, GR6, which encompasses volatile solids, COD, and BOD, also demonstrated a significant decrease from 3532.82 to 2783.67, with a t-statistic of 4.0119 and a p-value of 0.0569. This reduction highlights the potential for rainfall to mitigate organic pollution in leachate. Notably, GR7, which includes total solids (TS) and total dissolved solids (TDS), exhibited a substantial decrease from 15533.70 to 10428.30, with a remarkably high t-statistic of 11.6933 and a p-value of 0.0543, further emphasizing the impact of monsoon conditions on leachate quality.

Table 1: T-test Result

GR	Parameters	Pre-Monsoon Mean	Post Monsoon Mean	T-static	P-value (two-tailed)	Significance Level
GR1	As, CN, Cd, Ni, Pb	0.4333	0.2646	2.3283	0.08	Medium
GR2	Zn, Cr, Cu	3.2411	1.7057	4.1085	≤ 0.05	Strong
GR3	Fe, Phosphate, pH	16.2216	13.3098	1.9610	0.18	Low
GR4	Mg, AN	105.0350	96.4190	0.9340	0.52	Low
GR5	SO_4^{2-}, Cl, TKN	390.5217	286.9667	1.8019	0.21	Low
GR6	VS, COD, BOD	3532.8196	2783.6708	4.0119	≤ 0.05	Strong
GR7	TS, TDS	15533.6970	10428.3000	11.6933	≤ 0.05	Strong

Conversely, parameters such as GR3, GR4, and GR5 did not show significant changes, with p-values above 0.05, indicating that the concentrations of Fe, phosphate, magnesium, AN and SO_4^{2-} etc. were relatively stable despite seasonal variations and suggesting that these contaminants may be less influenced by seasonal rainfall or that other environmental factors play a more significant role in their concentrations. Overall, these findings underscore the importance of continuous monitoring and analysis of leachate characteristics, particularly during seasonal transitions, to inform effective environmental management practices and ensure compliance with water quality standards.

Conclusion

The analysis of landfill leachate from the Okhla landfill site in Delhi demonstrates significant temporal variations, particularly influenced by rainfall, which leads to notable reductions in contaminant concentrations. For instance, the study revealed a substantial decrease in Chemical Oxygen Demand (COD) from 3,659.98 mg/L during the pre-monsoon period to 3,406.22 mg/L post-monsoon, reflecting the dilution effects of increased precipitation. Similarly, the total solids (TS) concentration dropped significantly from 14,575.70 mg/L to 14,001.10 mg/L across the same periods. However, despite these seasonal improvements, heavy metals such as lead and cadmium remained alarmingly high, with lead concentrations exceeding the permissible limits at 0.354 mg/L pre-monsoon and dropping to 0.206 mg/L post-monsoon. This underscores the persistent environmental risks posed by leachate, necessitating continuous monitoring and effective management strategies. The findings highlight a significant t-statistic of 4.1085 for zinc, chromium, and copper, with a p-value approaching significance at 0.0544, indicating that temporal rainfall significantly dilutes these contaminants as compared to age of landfills,

Leachate from landfills is a major source of groundwater and surface water contamination. Leachate from Delhi landfill sites with no scientific collection system enters nearby drains, Najafgarh, Shahdra, VP Singh, and Pepsi-Cola drains, ultimately reaching the Yamuna, further deteriorating its water quality. This results in hardly any fish or aquatic life in the Yamuna River passing through the Delhi region.

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