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# Geochemical Assessment Of Soils Affected By The Jawahar Nagar Dumpyard

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***Abstract***
*The proliferation of unregulated municipal solid waste (MSW) landfills in the Global South poses escalating threats to soil and environmental health. This study presents a comprehensive geochemical investigation of soils surrounding the Jawahar Nagar dumpsite in Telangana, India, one of South India's largest and most environmentally burdened landfill zones. Soil samples were collected from three spatially distinct locations (adjacent to the landfill, leachate-affected basin, and downstream runoff path) during both pre- and post-monsoon periods of 2021 and 2022. A suite of physicochemical parameters, including pH, organic content, ionic species, and salinity indicators alongside trace heavy metal concentrations, was analyzed using standard protocols and ICP-OES. Results revealed seasonal amplification of contamination, with soils near the landfill exhibiting severe ionic enrichment (sulphates up to 6100 mg/kg; potassium up to 1550 mg/kg) and elevated heavy metal concentrations, particularly post-monsoon, when lead, chromium, and zinc peaked at 15.0 mg/kg, 9.1 mg/kg, and 13.6 mg/kg, respectively. Cobalt, tin, cadmium, arsenic, and methyl mercury were also consistently detected, signifying chronic leachate infiltration and pollutant transport. Correlation analysis highlighted strong dependencies among pH, salinity, and organic matter, underscoring the landfill's role in restructuring soil geochemistry. The findings offer a spatially resolved, seasonally sensitive framework for identifying contamination hotspots, guiding remediation priorities, and informing policy decisions on buffer zoning and ecological restoration. This study serves as a critical diagnostic reference for future research and sustainable management of landfill-impacted landscapes across developing urban regions.*
***Keywords***: *Landfill Leachate Contamination, Soil Geochemistry, Heavy Metals in Soil, Municipal Solid Waste, Seasonal Variation Analysis*

## 1. INTRODUCTION

The rate of urbanization and population growth in developing countries has raised the level and complexity of municipal solid waste (MSW) management. This issue is particularly acute in India, where urbanization is taking place without an increase in waste management infrastructure. The open dumping that has been going on over decades has taken the form of the accumulative impacts of the altered soil chemistry, groundwater contamination, air pollution, and the pattern of ecological imbalance that aligns with the global assessments of metal contamination and environmental degradation in the waste-impacted regions (Kumar et al., 2019).

The long-term geochemical change of the soils around the landfill by percolation of leachate and physical disturbance of the subsurface is one of the most significant problems associated with landfills. The resulting liquid effluent, which is produced due to the degradation of waste, is termed as leachate and is typically characterized by a high level of dissolved organic matter, heavy metals, and toxic chemicals. When this leachate gets into the soil, it alters the natural geochemistry and significantly diminishes the physical, chemical, and biological soil quality (Mishra et al., 2018). Moreover, landfills are even more sources of local and global environmental degradation because they emit methane and other greenhouse gases due to the decomposition of organic matter (Mor et al., 2024).

This is even worsened by the fact that the MSW infrastructure and informal waste management systems in the Indian cities are fragmented. Most of the landfills in urban areas lack much engineering control and lack proper leachate containment, separation of wastes, and post-closure treatment strategies. The absence of scientifically developed and introduced MSW systems, as Soni et al. (2023) emphasize, results in huge environmental leakage of the environment and soil pollution. This is especially alarming in areas where landfills are close to farmlands and residential areas. The misplaced dumpsites also add to the issue, as Umar and Naibbi (2021) point out that placing landfill in hydrologically sensitive or highly populated areas promotes the rate of public health and ecological hazards.

Jawahar Nagar dumpsite in Telangana is a crucial example to study such problems. The site was originally a peripheral open dumping ground, but it has since become a combination of both legacy waste areas and partially engineered landfill cells. It covers an area of more than 339 acres and has been receiving more than 12 million tonnes of mixed municipal waste over the last 20 years. Choudhury et al. (2021) state that although some of the parts have been capped, and leachate ponds and gas extraction systems have been implemented, a considerable part of the dumpyard is not capped and is extremely prone to leachate leakage. These unengineered sections lead to long-term soil and water pollution and act as permanent pollutant stores, as shown in Figure 1, which provides a visual representation of the Jawahar Nagar Dumpyard and the leachate ponds that surround it.

**Figure 1: Partial View of the Jawahar Nagar Dumpyard and Adjacent Leachate Accumulation Zone**

Explorations of the water systems around have indicated chemical changes and the movement of pollutants. According to Reddy et al. (2021), there were considerable abnormalities in water chemistry, including high levels of nitrates, sulphates, and heavy metals in the borewells located in the impact area of the landfill. This pollution has been directly linked to the uncontrolled leachate pathways that are being released from the dumpsite. Besides this, Rao et al. (2022) found health abnormalities such as skin infection, gastrointestinal diseases, and respiratory complications among the individuals living close to the site, particularly in the villages of Malkaram, Chiryala, and Dammaiguda. These findings confirm the need for a more site-specific soil-oriented geochemical analysis, which examines seasonal and site-specific patterns of pollutant accumulation.

The primary recipient of the landfills' discharge is soil that serves as a buffer and a route for the pollutants. Its properties, like pH, the content of organic matter, and the composition of ions, are highly susceptible to alteration in landfill-affected regions. Alsbou and Al-Khashman (2018) state that the soils along the roadsides and around landfills have a high level of heavy metals due to the vehicle emissions, atmospheric deposition, and surface runoff. Similarly, Singh et al. (2022) also pointed out the long-term threat of bioaccumulation, whereby polluted soils lead to elevated concentrations of metals in crops and vegetables, which eventually enter human health through the food chain.

The pressures of the open dumpsites are not restricted to India. Koliyabandara et al. (2024) provided a global image of landfill impacts, among which the wrong waste disposal procedure leads to the long-term overload of the soil structure, microbial diversity, and groundwater recharge. These effects are normally worsened by seasonal rainfall that enhances the mobility of leachate. This is especially important in the Indian context, where the monsoon intensity enhances the rate of percolation of the contaminants, and dry seasons cause salinization and metal concentration. The combination of landfill leachate and topographical drainage patterns is the immediate factor that defines the intensity and scope of soil and groundwater contamination, as it was observed in Tamil Nadu by Manoj Kumar and Sudha (2017).

Despite the numerous studies on the degradation of groundwater, the specific influence of landfills on the geochemistry of soils has not been studied much. Soil is the first line of defence against the containment of pollutants and is normally the first to exhibit signs of environmental distress. According to Peada (2015), geotechnical changes were observed in the MSW-affected areas of Hyderabad, where compaction was lost and porosity was enhanced, and the migration of metals was possible in the soils around the waste sites. Such geotechnical weaknesses, when coupled with anthropogenic ones like unauthorized dumping and inefficient landfill engineering, cause irreversible alterations in soil functionality.

Engineered solutions like leachate recirculation systems, gas extraction wells, and geomembrane liners have been incorporated in the modern landfill design to counter these effects. Shadi et al. (2020) have conducted a review of electroflotation and other advanced treatment techniques of leachate management and have mentioned that these techniques have potential in minimizing the chemical loads. But these systems are hardly done in totality in Indian dumpsites. In addition, the ecological restoration methods like bioremediation and phytoremediation are in their early stages. Maiti and Pandey (2021) emphasized the potential of naturally growing plants in contaminated sites to remediate metals, and Khan et al. (2023) recommended the use of native soil-dwelling microbes in the natural attenuation of heavy metal toxicity. Such methods are also very theoretical without any baseline soil quality measurements.

Recent ecological studies also emphasize the importance of understanding the interaction between soil contaminants and local environmental variables. Gupta et al. (2019) noted that long-term exposure to metal-contaminated water and soil leads to substantial changes in soil microbial structure, organic matter turnover, and plant uptake dynamics. These transformations pose challenges not only for land rehabilitation but also for sustainable agriculture in regions impacted by landfill sprawl.

Hence, it becomes imperative to examine soil characteristics in and around the Jawahar Nagar dumpsite to understand the extent of chemical alteration, contamination pathways, and pollutant mobility. Despite increasing awareness and scattered interventions, a holistic, seasonally-structured, and site-stratified soil analysis from the region is still lacking.

## 2. MATERIALS AND METHODS

### 2.1 Study Area

The present study was conducted in areas surrounding the Jawahar Nagar Dumpyard, located in Kapra Mandal, Medchal-Malkajgiri District, Telangana, India. The landfill spans approximately 339 acres, making it one of the largest operational municipal waste dumps in South India. Established in 2001, the site comprises both legacy and engineered landfill zones. It is positioned at an elevation of 620 feet above mean sea level, roughly 120 feet above nearby residential clusters, thereby influencing the direction of surface runoff and leachate transport.

Engineered sections of the landfill incorporate a capping system consisting of a 300 mm cohesive soil base, a geosynthetic clay liner (GCL), a 1.5 mm HDPE geomembrane, and a 450 mm vegetative layer, bordered by stormwater diversion bunds. Supporting infrastructure includes leachate storage ponds, a compost yard, recycling facilities, and a waste-to-energy (WtE) plant. Despite these improvements, large legacy zones remain uncapped, facilitating direct leachate infiltration into surrounding soils.

To assess contamination dispersion, three sampling locations were selected based on their proximity to the landfill, drainage characteristics, and risk exposure, as presented in Table 1. The spatial distribution of sampling points is illustrated in Figure 2, while Figure 3 depicts the landfill's transformation from 2012 to 2022 following partial capping.

**Table 1: Sampling site details and coordinates.**

| S.No | Sample Type | Latitude | Longitude | Sampling Station |
|---|---|---|---|---|
| 1 | Soil I | 17.52708 | 78.58735 | Jawahar Nagar Dumping Yard Road |
| 2 | Soil II | 17.527515 | 78.588178 | Malkaram (Leachate Affected Zone) |
| 3 | Soil III | 17.516311 | 78.624185 | Chiryala (Downstream Drainage Path) |

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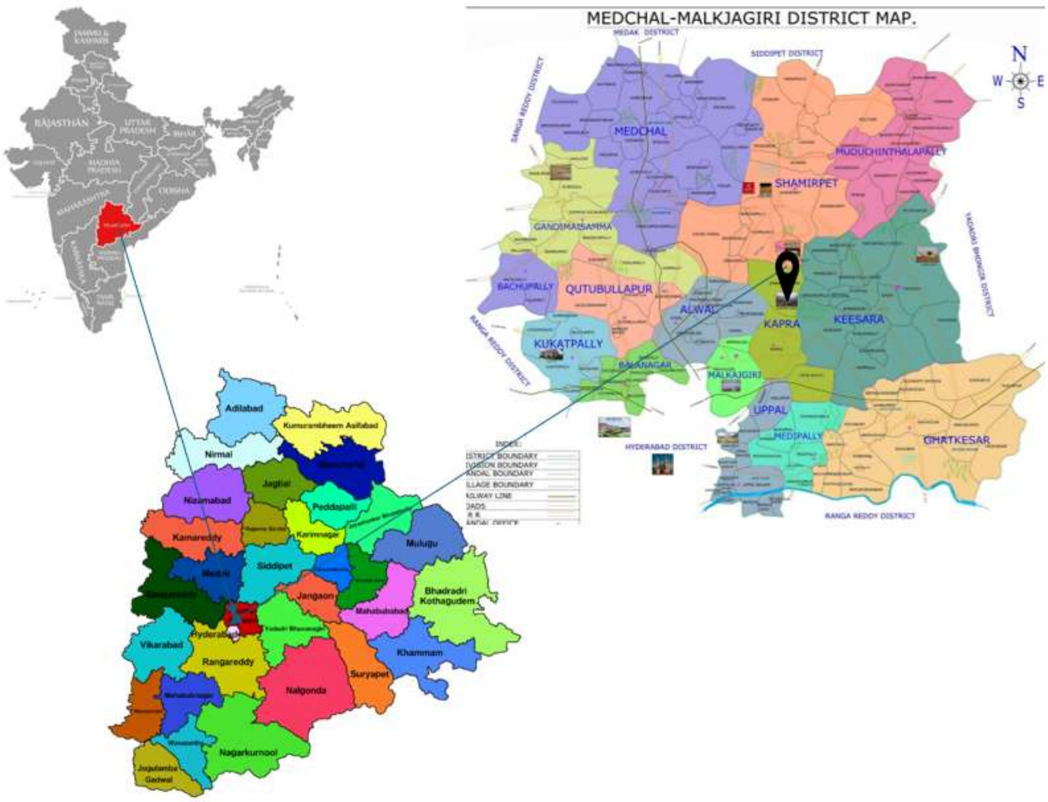


**Figure 2: Geographical Location of the Jawahar Nagar Dumpyard within Kapra Mandal, Medchal-Malkajgiri District, Telangana, India.**

Figure 2 shows the study area in Kapra Mandal, Medchal-Malkajgiri District, Telangana, India. The figure illustrates the regional position of the Jawahar Nagar dumpyard within the state and its administrative boundaries at district and mandal levels, aiding the geographic and environmental context of the sampling zones.

**Figure 3: Comparative View of the Jawahar Nagar Dumpyard Before (2012) and After (2022) Implementation of Engineered Capping.**

### 3.2 Sampling Strategy

Soil samples were collected from the three selected locations during two key seasons across 2021 and 2022, pre-monsoon (March–May) and post-monsoon (September–November). Each sample was extracted from a depth of 15–30 cm using a stainless-steel auger, following the removal of surface debris. For each site-season combination, three sub-samples within a 5-meter radius were homogenized to yield a composite sample.

Field protocols were implemented to minimize contamination risk: samples were stored in HDPE containers, pre-rinsed with 10% nitric acid and double-distilled water, and preserved at 4°C using portable iceboxes. All equipment used was non-metallic, and personnel adhered to safety standards, including the use of gloves. Figure 4 illustrates the sampling process using trowels and HDPE bags near the landfill site, while Figure 5 presents the labeled composite soil samples (Soil I, II, III) prepared for subsequent laboratory analysis.

**Figure 4: Field sampling near the landfill using a trowel and labelled HDPE bags.**

Figure 4 illustrates manual collection of soil samples using stainless-steel trowels and labeled HDPE bags during pre-monsoon sampling. Safety protocols and contamination-prevention measures are visibly maintained.


**Figure 5: Labeled Soil Samples (Soil I, II, III) Prepared for Laboratory Analysis.**

### 3.3 Analytical Procedures

#### 3.3.1 Physicochemical Characterization

All physicochemical analyses were performed in accordance with standard methods prescribed in APHA (2017). The parameters measured and the methods employed are summarized in Table 2. These analyses aimed to evaluate nutrient levels, salinity, and pollutant mobility in soils exposed to municipal waste.

**Table 2: Methods used for Analysis of Physicochemical Parameters of Samples**

| Parameter | Unit | Method |
|---|---|---|
| **pH** | — | Digital pH meter (1:2.5 soil-water ratio) |

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|---|---|---|
| **Total Organic Carbon (TOC)** | % | Walkley-Black wet oxidation |
| **Total Organic Matter (TOM)** | % | Calculated: TOM = TOC × 1.724 |
| **Nitrate ($NO_3^-$)** | mg/kg | UV-Visible spectrophotometry |
| **Phosphate ($PO_4^{3-}$)** | mg/kg | Ascorbic acid method |
| **Chlorides ($Cl^-$)** | mg/kg | Argentometric titration |
| **Sulphates ($SO_4^{2-}$)** | mg/kg | Turbidimetric method |
| **Sodium ($Na^+$)** | mg/kg | Flame photometry |
| **Potassium ($K^+$)** | mg/kg | Flame photometry |

The Total Organic Matter (TOM) was derived from TOC values using the relationship:

$$\mathrm{TOM}(\%) = \mathrm{TOC}(\%) \times 1.724$$

**3.3.2 Heavy Metal Analysis**

Heavy metal concentrations were quantified using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES). The selected metals were chosen due to their prevalence in municipal landfill leachate and their potential to impact soil fertility, microbial communities, and human health. A list of analyzed metals and their environmental relevance is provided in Table 3.

**Table 3: Heavy metals analyzed and their environmental significance.**

| **S. No** | **Heavy Metal** | **Symbol** | **Environmental Significance** |
|---|---|---|---|
| 1 | **Lead** | Pb | Neurotoxic; common landfill contaminant |
| 2 | **Cadmium** | Cd | Toxic; affects kidney function and microbes |
| 3 | **Chromium** | Cr | Carcinogenic; industrial origin |
| 4 | **Nickel** | Ni | Soil allergen and plant toxin |
| 5 | **Zinc** | Zn | Nutrient at low levels; toxic in excess |
| 6 | **Copper** | Cu | Influences microbial activity |
| 7 | **Mercury** | Hg | Toxic even in trace concentrations |
| 8 | **Arsenic** | As | Carcinogenic and groundwater-soluble |
| 9 | **Tin** | Sn | Affects the enzymatic activity in soils |
| 10 | **Methyl Mercury** | $CH_3Hg^+$ | Organic mercury; highly bioavailable |
| 11 | **Cobalt** | Co | May bioaccumulate; moderately toxic |

All procedures were performed using validated internal protocols under accredited laboratory conditions. Instrumental calibration and routine analytical checks were part of the standardized workflow.

## 4. RESULTS AND DISCUSSION

### 4.1 Seasonal Variation in Physicochemical Properties

Seasonal fluctuations and proximity to landfill operations significantly influence the geochemical characteristics of soil. To assess these effects, composite samples from three locations, Soil I (adjacent to the landfill), Soil II (Malkaram, leachate-affected), and Soil III (Chiryala, drainage pathway), were analyzed across pre- and post-monsoon seasons of 2021 and 2022 (Table 4).

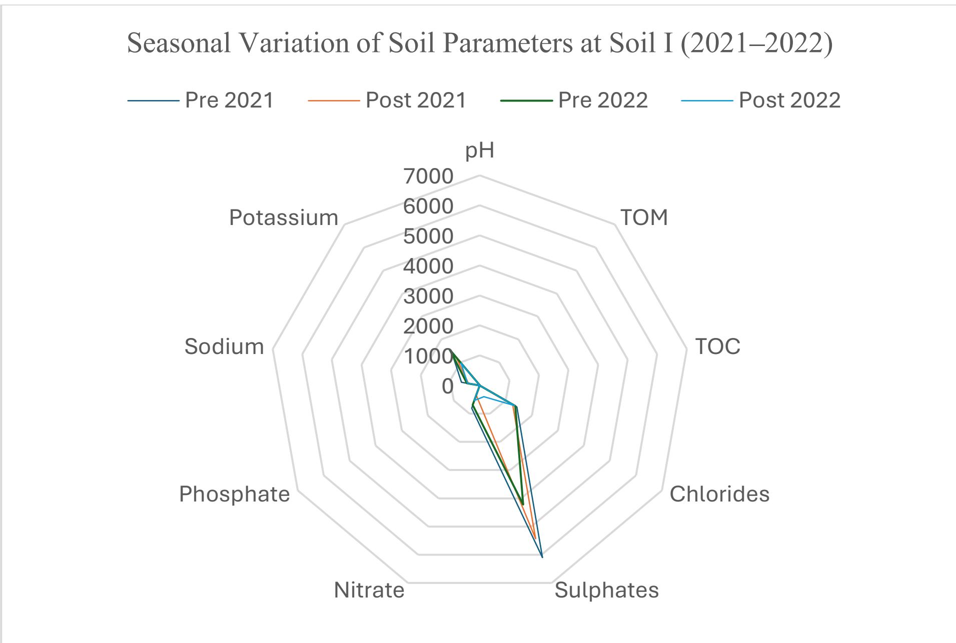
**Table 4: Seasonal Variation in Physicochemical Properties of Soil Samples (2021–2022)**

| Season | Location | pH | TOM | TOC | Chlorides | Sulphates | Nitrate | Phosphate | Sodium | Potassium |
|---|---|---|---|---|---|---|---|---|---|---|
| Pre 2021 | Soil I | 8.2 | 2.50 | 1.18 | 1420 | 6100 | 800 | 0.0300 | 615.00 | 1460.97 |
| Post 2021 | Soil I | 7.5 | 2.00 | 2.10 | 1270 | 5432 | 336 | 0.0500 | 378.00 | 1216.00 |
| Pre 2021 | Soil II | 7.93 | 4.10 | 2.70 | 1263 | 70 | 762 | 0.0030 | 323.00 | 304.44 |
| Post 2021 | Soil II | 7.1 | 2.10 | 1.60 | 2325 | 352 | 462 | 0.0014 | 423.00 | 210.00 |
| Pre 2021 | Soil III | 8.3 | 3.73 | 2.10 | 2379 | 9000 | 716 | 0.0200 | 272.71 | 1350.52 |
| Post 2021 | Soil III | 8.7 | 2.90 | 1.90 | 1650 | 6154 | 564 | 0.0500 | 457.00 | 1230.00 |
| Pre 2022 | Soil I | 8.6 | 3.15 | 1.30 | 1360 | 4220 | 691 | 0.1000 | 436.00 | 1550.00 |
| Post 2022 | Soil I | 8.5 | 2.96 | 1.76 | 1342 | 400 | 530 | 1.0000 | 412.00 | 969.00 |
| Pre 2022 | Soil II | 6.9 | 4.32 | 2.40 | 983 | 87 | 568 | 1.2000 | 523.00 | 117.50 |
| Post 2022 | Soil II | 7.4 | 2.35 | 2.30 | 2159 | 248 | 567 | 0.5000 | 641.00 | 516.00 |
| Pre 2022 | Soil III | 7.8 | 2.60 | 1.69 | 2430 | 7996 | 837 | 0.5000 | 256.00 | 960.00 |
| Post 2022 | Soil III | 8.0 | 3.10 | 1.30 | 1436 | 275 | 697 | 0.0300 | 256.00 | 1024.00 |

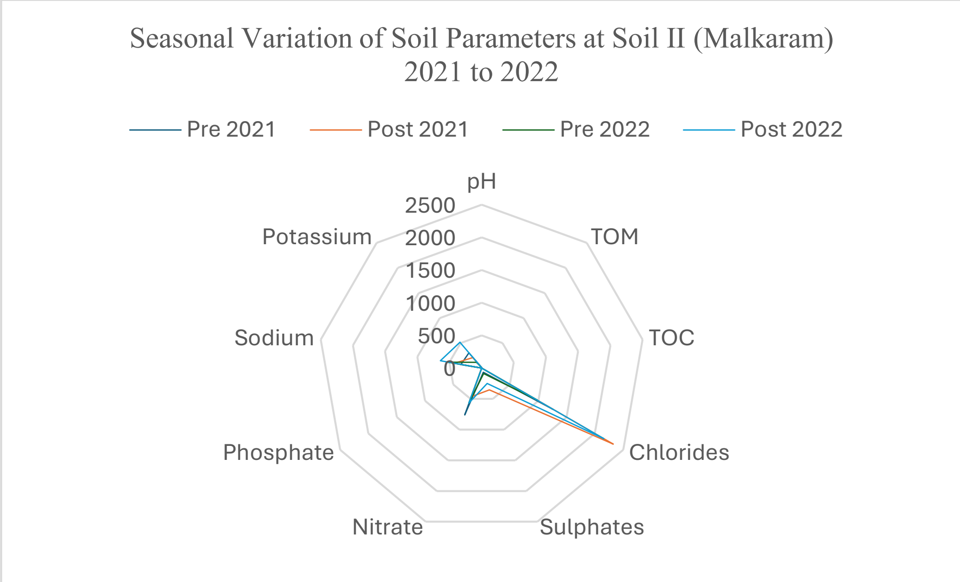
pH values across all sites ranged from slightly acidic (6.9 in Soil II, Pre-2022) to moderately alkaline (8.7 in Soil III, Post-2021). The soils maintained a generally alkaline character, particularly during post-monsoon seasons, likely influenced by the accumulation of basic ions from leachate percolation. The TOM and TOC levels were higher during the pre-monsoon seasons, especially in Soil II, where TOM reached 4.32% in Pre-2022. This could be attributed to reduced microbial activity during drier periods, allowing organic residues to persist.

Salinity-related parameters such as chlorides, sulphates, sodium, and potassium exhibited pronounced seasonal dependence, with higher concentrations generally observed during the pre-monsoon periods, especially in Soil I. Notably, sulphate levels in Soil I reached 6100 mg/kg in Pre-2021, while potassium peaked at 1550 mg/kg in Pre-2022.

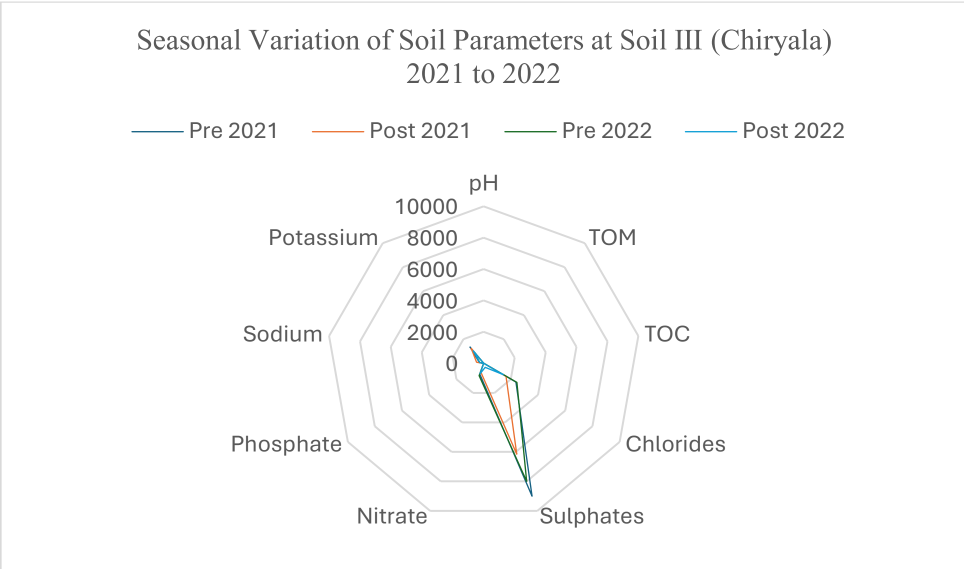
The site-wise seasonal profiles are illustrated in Figure 6(a–c). Soil I [Figure 6a], located adjacent to the landfill, consistently exhibited elevated levels of salts and nutrients, indicating direct influence from dump-derived leachate intrusion. Soil II (Malkaram) [Figure 6b], situated in a low-lying basin, showed dominance in organic matter content (TOM and TOC), likely due to stagnant conditions and limited drainage. In contrast, Soil III (Chiryala) [Figure 6c], positioned along the natural drainage route, presented a hybrid profile characterized by high nitrate and potassium levels, reflecting pollutant migration through seasonal runoff. Collectively, these patterns point to seasonally accentuated geochemical stress, shaped by landfill proximity, hydrological dynamics, and topographic gradients.




6 (a)




6 (b)




6 (c)

**Figure 6: Seasonal Radar Plots of Physicochemical Parameters in Soil Samples (2021–2022): (a) Soil I – Adjacent to Landfill, (b) Soil II – Malkaram (Leachate-Affected Zone), and (c) Soil III – Chiryala (Downstream Drainage Path)**

The observed seasonal variation in the physicochemical parameters of soils reflects the dynamic influence of landfill leachate, climatic conditions, and hydrological connectivity. The marked alkaline nature of the soils, particularly in post-monsoon periods, aligns with earlier studies (Alsbou & Al-Khashman, 2018; Sreelesh et al., 2025) that attribute elevated pH to persistent leachate intrusion rich in basic cations. The increase in TOM and TOC during pre-monsoon seasons, especially in Soil II, suggests reduced microbial degradation under drier conditions, leading to organic matter persistence, an observation consistent with Koliyabandara et al. (2024) and Gupta et al. (2019). The very high sulphate and potassium levels in Soil I (Pre-2021 and Pre-2022, respectively) are evidence of the landfill proximity and point-source contamination, which is also observed in Azeez et al. (2023). In the meantime, the abundance of nitrate and potassium in Soil III indicates that the pollutants were transported by seasonal runoff, which was also confirmed by Ashraf et al. (2013) in their research that underlines the importance of terrain and drainage in the dispersal of contaminants. These spatiotemporal trends highlight the importance of topographic gradients and seasonally varying leachate mobility in the formation of local geochemical stress.

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### 4.2 Correlation Among Physicochemical Parameters

The interaction of various soil parameters in the presence of anthropogenic pressures is important to evaluate the long-term effects of the environment and forecast the behavior of contaminants. The mobility, retention, and transformation of pollutants in landfill-affected soils are frequently controlled by the interaction of organic matter, pH, nutrient ions, and salinity-inducing compounds. Determining these interdependencies can provide a view of the geochemical processes triggered by the leachate infiltration and seasonal processes.

To evaluate such relationships in the study area, a Pearson correlation matrix was developed based on pooled data from all sites and seasons. The interrelationships among these parameters are visualized using a Pearson correlation heatmap (Figure 7), which highlights key patterns in the pooled data across all sites and seasons.

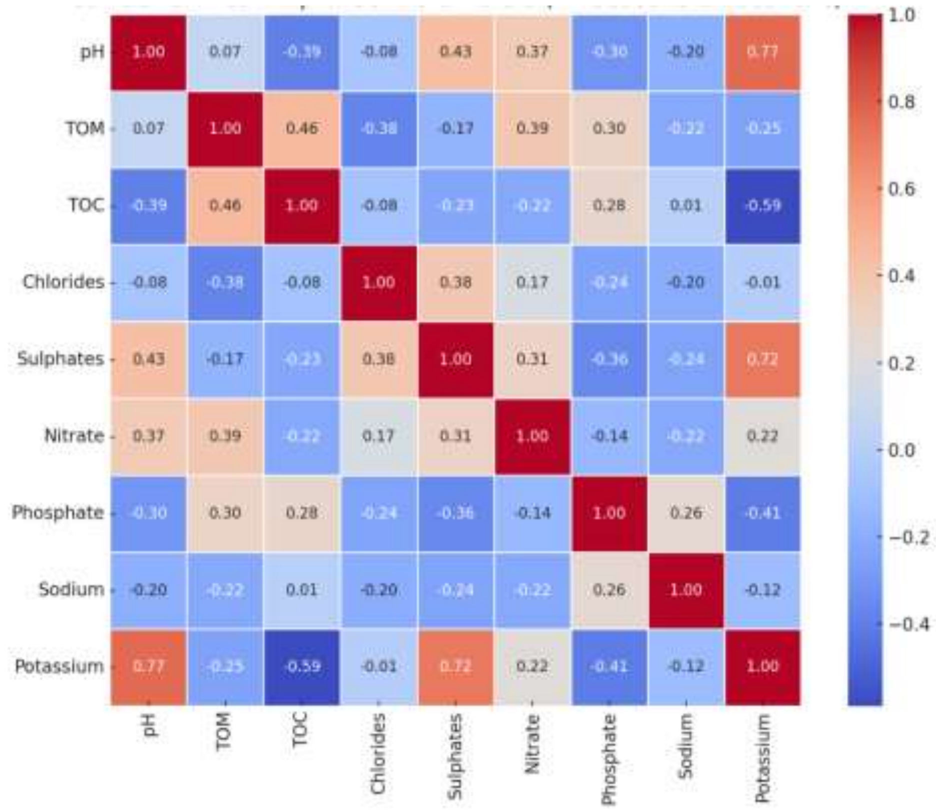


**Figure 7: Correlation Heatmap of Physicochemical Parameters**

Strong positive correlations were observed between:

- **pH and Potassium** (r = 0.77)
- **Sulphates and Potassium** (r = 0.72)
- **TOM and TOC** (r = 0.46)

These suggest that cationic enrichment and salinity are linked with elevated alkalinity, likely due to the dissolution of mineral components from persistent leachate exposure. The association of organic matter with TOC aligns with prior observations of organic-rich leachate residues accumulating in landfill-peripheral soils.

Negative correlations were recorded between TOC and both pH (r = -0.39) and Potassium (r = -0.59), indicating that alkaline, ion-rich environments may inhibit carbon stabilization via oxidative breakdown or microbial activity suppression.

These interrelationships imply that chemical gradients imposed by the landfill significantly reshape the natural geochemical equilibrium, affecting soil fertility, contaminant retention, and potentially the viability of vegetation and microbial communities in the long term.

The correlation analysis reveals key geochemical interdependencies shaped by landfill activity and seasonal influences. The strong positive correlation between pH and potassium (r = 0.77) and sulphates and potassium (r = 0.72) indicates that ionic enrichment from leachate contributes directly to elevated alkalinity, consistent with Naveen et al. (2017), who observed similar chemical relationships near waste-affected zones. The significant association between TOM and TOC (r = 0.46) supports the view that organic matter accumulations are closely linked to carbon content, especially in low-oxygen, leachate-rich environments, as noted by Gupta et al. (2019). Conversely, negative correlations between TOC and both pH (r = −0.39) and potassium (r = −0.59) suggest that elevated ion concentrations and alkalinity may suppress microbial activity and carbon stabilization, resonating with the microbial stress responses documented by Chen (2017). These findings collectively emphasize that landfill-derived chemical gradients not only reshape soil fertility but also impact biogeochemical cycling, potentially affecting plant growth, microbial colonization, and long-term ecosystem functionality.

### 4.3 Heavy Metal Distribution and Trends

The concentration of heavy metals in soil samples collected from study sites over 2021 and 2022 displayed clear spatial and seasonal variation, particularly in zones closest to active waste deposition. Table 5 presents the quantitative summary of heavy metal concentrations observed across all sites and seasons. Lead (Pb), zinc (Zn), and nickel (Ni) were consistently detected at elevated levels near the dump site (Soil I), especially during the post-monsoon season of 2022, where Pb reached 15.00 mg/kg and Zn peaked at 13.60 mg/kg. Additionally, cobalt (Co) and tin (Sn) reached 2.5 mg/kg and 2.6 mg/kg, respectively, in the same season, indicating their mobilization through seasonal leachate pulses. These values exceed typical background concentrations for unpolluted soils and suggest persistent leachate intrusion.

**Table 5: Seasonal Variation in Heavy Metal Concentrations in Soil Samples (2021–2022)**

| Season | Location | Zinc | Cobalt | Lead | Arsenic | Nickel | Mercury | Chromium | Cadmium | Copper | Tin | Methyl Mercury |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Pre 2021 | Soil I | 9.67 | BLQ | 3.95 | 0.60 | 4.33 | 2.0 | 4.09 | 0.50 | 1.30 | 1.04 | 1 |
| Post 2021 | Soil I | 8.56 | 1.2 | 2.95 | 1.60 | 3.12 | 5.0 | 3.06 | 0.71 | 1.10 | 1.56 | 2.0 |
| Pre 2021 | Soil II | 6.43 | BLQ | 3.60 | 0.03 | 1.77 | 1.2 | 1.49 | 0.02 | 0.95 | 2.0 | 1.3 |
| Post 2021 | Soil II | 4.40 | 0.02 | 2.22 | 0.60 | 0.56 | 3.2 | 1.58 | 0.51 | 0.60 | 1 | 2.6 |
| Pre 2021 | Soil III | 5.83 | BLQ | 4.14 | 0.50 | 2.60 | 0.3 | 3.34 | 0.05 | 1.24 | 5.64 | 0.5 |
| Post 2021 | Soil III | 3.30 | 0.2 | 3.15 | 0.80 | 3.60 | 0.9 | 2.20 | 2.4 | 1.00 | 4.8 | 1.3 |
| Pre 2022 | Soil I | 8.10 | 1.81 | 4.13 | 1.60 | 2.79 | 1.3 | 11.00 | 0.01 | 4.80 | 3.1 | 0.7 |
| Post 2022 | Soil I | 13.60 | 2.5 | 15.00 | 1.20 | 3.30 | 1.5 | 9.10 | 0.06 | 0.50 | 2.6 | 0.06 |
| Pre 2022 | Soil II | 7.30 | 2.18 | 2.30 | 0.72 | 1.38 | 0.12 | 1.10 | 0.04 | 3.90 | 2.4 | 0.3 |
| Post 2022 | Soil II | 8.20 | 1.6 | 14.30 | 0.08 | 2.10 | 0.31 | 5.30 | 0.50 | 0.12 | 3.1 | 1.2 |
| Pre 2022 | Soil III | 2.25 | 0.48 | 3.90 | 0.23 | 0.12 | 0.9 | 5.60 | 0.02 | 3.20 | 4.6 | 0.03 |
| Post 2022 | Soil III | 6.30 | 2.1 | 6.20 | 0.10 | 0.5 | 0.6 | 6.10 | 0.05 | 0.70 | 2.8 | 0.5 |

BLQ – Below Limit of Quantification

Tin was notably high in pre-monsoon Soil III (5.64 mg/kg) and remained above 4 mg/kg in other post-monsoon samples, suggesting its lateral transport through surface runoff. Cobalt, which was below detection in many early samples, peaked at 2.5 mg/kg in Soil I (post-2022) and showed elevated levels in Soil II and III during pre- and post-monsoon 2022. In contrast, Soil III, located further along the drainage path, showed more moderate but detectable concentrations, indicating downstream migration of contaminants. To visualize these trends more effectively, Figure 8 illustrates a heatmap of normalized heavy metal concentrations. The color gradients depict hotspots of contamination in Soil I and Soil II, especially during post-monsoon 2022, where multiple elements, including Pb, Zn, Cr, and Ni, converged at high intensity.


**Figure 8: Heatmap of Heavy Metal Concentrations in Soil Samples by Site and Season (2021–2022)**

The clustering patterns in the heatmap further suggest that certain metals, such as chromium (Cr), cadmium (Cd), and copper (Cu), may share a common leachate source or mobilization mechanism. The high post-monsoon values also indicate enhanced percolation and leaching following rainfall, which facilitates vertical and lateral contaminant transport.

These results underscore the critical need for engineered containment systems, especially in the uncapped sections of the landfill, to mitigate further leachate escape. The persistent detection of methyl mercury and arsenic, both highly toxic and mobile, raises potential concerns for biomagnification and public health risks, especially in agrarian zones near Soil III.

The distribution of heavy metals across seasons and sites highlights the cumulative and seasonal nature of contamination, particularly near the landfill source. High concentrations of lead (15.00 mg/kg), zinc (13.60 mg/kg), and chromium (9.10 mg/kg) in Soil I in the post-monsoon of 2022 prove the increased mobility of leachates after rain, which has also been reported by Choudhury et al. (2021). The regular occurrence of cobalt and tin, as well as the spikes in methyl mercury and arsenic, is a cause of concern because of their toxicity and persistence in the environment. These results support the conclusions of Naeem et al. (2022), who pointed out the danger of bioaccumulation and trophic transfer of contaminated soils. The pre-monsoon levels of tin in Soil III (5.64 mg/kg) also indicate that the lateral migration occurs through the surface runoff, whereas the post-monsoon increases in most metals support the increased percolation pathways as discussed by Koliyabandara et al. (2024). The heatmap also indicates the clustering patterns that imply the common sources or co-mobilization processes, which emphasizes the necessity of engineered containment (Shadi et al., 2020) and prolonged monitoring. On the whole, these findings indicate the spatial scale of the heavy metal migration caused by leachates, which requires immediate remedial actions and policy responses to prevent the adverse effects of the migration on downstream ecosystems and human health.

## 5. CONCLUSION

At a time when uncontrolled waste disposal is increasingly becoming a threat to both environmental and human health, the present study provides a critical geochemical assessment of soils around the Jawahar Nagar dumpsite, which throws light on the extent and dynamics of contamination due to landfills. The study identified that Soil I, which was nearest to the landfill, was the most severely ionically enriched with sulphates reaching 6100 mg/kg and potassium 1550 mg/kg during the pre-monsoon seasons, indicating intrusion of leachate during dry seasons. The most significant organic load was observed in Soil II, which is in a low-lying area, with TOM of 4.32 percent in Pre-2022, whereas Soil III, which is downstream, had a hybrid profile with a nitrate concentration of up to 837 mg/kg, indicating the movement of pollutants through surface runoff. Heavy metal profiling underscored significant accumulation, particularly in post-monsoon samples from Soil I, where lead (15.0 mg/kg), chromium (9.1 mg/kg), and zinc (13.6 mg/kg) concentrations reflected acute anthropogenic pressure. Cadmium and arsenic were also consistently present across sites and seasons, underscoring potential ecological and human health concerns. The study's core contribution lies in its spatially and temporally resolved framework that not only quantifies the extent of contamination but unpacks the geochemical mechanisms underlying it, driven by topography, hydrology, and waste load. These findings provide vital empirical evidence for guiding landfill buffer zoning, remediation planning, and regulatory oversight. Furthermore, the work establishes a scientific foundation for predictive pollution modelling, long-term ecological risk forecasting, and the integration of soil monitoring into regional solid waste management strategies. As urban sprawl intensifies and legacy waste burdens grow, such research will be indispensable in shaping sustainable policies for land rehabilitation and environmental restoration in landfill-affected landscapes.

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