

Spatial Contamination Gradient and Electrical Conductivity as a Proxy Indicator for Landfill Leachate Impact on Himalayan Soils

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Spatial Contamination Gradient and Electrical Conductivity as a Proxy Indicator for Landfill Leachate Impact on Himalayan Soils

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Abstract

Uncontrolled landfill leachate represents a critical but quantitatively uncharacterised environmental threat in the global South, particularly in topographically complex, ecologically vulnerable mountain regions. Bhutan, despite maintaining carbon-negative status and strong environmental commitments, operates 25 unengineered open dumpsite landfills without functional leachate treatment systems, yet lacks empirical contamination baselines. This study provides a spatially resolved pedological assessment of the impact of landfill leachate in a Himalayan context, establishing a methodology applicable to resource-constrained regions. We quantified soil chemical contamination around the Omtékha landfill (Punakha, Bhutan) across a 200-metre spatial gradient using a systematic transect design (30 soil samples; 4 distance intervals: 50, 100, 150, 200 m along downslope and upper-slope transects). Analysis revealed a clear contamination gradient with electrical conductivity (EC) declining from 115.81 $\mu\text{S}/\text{cm}$ at 50 m to 35.28 $\mu\text{S}/\text{cm}$ at 150 m, confirming topographic control of leachate migration. Electrical conductivity emerged as a rapid, cost-effective proxy for leachate contamination, with strong correlations to potassium ($\rho = 0.655$, $p < 0.001$) and pH ($\rho = 0.470$, $p = 0.009$). Contamination extended approximately 100–150 m beyond the landfill boundary. Downslope areas exhibited 3.2-fold higher contamination than upslope reference zones, validating topographic-hydrological models of contaminant transport in uncontrolled landfill environments. This study delivers the first quantitative baseline for Himalayan landfill soil contamination and establishes electrical conductivity monitoring as a low-cost, field-deployable tool for environmental governance in developing economies. The spatial-transect methodology provides a replicable framework for rapid delineation of contamination boundaries in complex topography, directly informing waste management policy in Bhutan and offering a transferable solution for environmental risk assessment across resource-limited mountain regions facing mounting waste crises.

Keywords: Electrical Conductivity, Landfill Leachate, Spatial Contamination Gradient, Soil Chemical Signature, Mountain Environmental Governance, Himalayan Soil Contamination

Introduction

The exponential growth of municipal solid waste (MSW) is an increasingly critical environmental challenge in rapidly urbanising regions, including the ecologically sensitive Himalayan nations. Globally, total waste generation reached approximately 2.01 billion tonnes in 2017 and is projected to grow to 4.6 billion tonnes by 2050 (Maalouf & Mavropoulos, 2023). Landfilling remains the predominant waste disposal method worldwide, generating leachate—a toxic, chemically complex liquid— that is among the primary contributors to landfill instability and environmental contamination (Zhou et al., 2024).

Bhutan, recognised globally for its Gross National Happiness (GNH) philosophy and status as the world's only carbon-negative country, faces a mounting contradiction. Despite its commitment to environmental conservation and sustainable development (National Environment Commission, 2016), increasing urbanisation and per-capita waste generation are outpacing existing waste management infrastructure. According to the 2016 report by the Bureau of Statistics and Environment (BSE), Bhutan has 25 open dumpsites, most of which lack engineered leachate treatment and management systems (Norbu, 2010). This deficiency is particularly relevant in highland contexts where topography and climate amplify the risk of leachate migration into surrounding soils and water bodies (Sharma et al., 2025).

Leachate, formed when precipitation and waste-derived fluids percolate through landfill waste layers, constitutes a concentrated carrier of dissolved organic matter, inorganic nutrients, heavy metals such as lead (Pb), copper (Cu), and cadmium (Cd), and increasingly recognised micropollutants including microplastics (Tadsuwan et al., 2022; Vaidh et al., 2025). If inadequately managed, landfill leachate can infiltrate surrounding soils and groundwater, facilitating the dispersion of toxic pollutants into terrestrial and aquatic environments (Sun et al., 2021). Leachate-contaminated soils experience profound alterations in physicochemical properties, microbial community structure, and overall ecosystem function, with cascading impacts on plant health and adjacent vegetation (Zych et al., 2025).

The spatial impact of leachate on soil is characterised by a contamination gradient, where the highest pollutant concentrations occur nearest the landfill source and decline progressively with distance as contaminants are diluted, adsorbed, or transformed by soil processes (Chonattu et al., 2016). Electrical Conductivity (EC) is universally recognised as the most rapid and effective indicator or the chemical signature of leachate in soils, as leachate is inherently high in dissolved ionic species, including Na^+ , K^+ , Cl^- , SO_4^{2-} , and NH_4^+ , which directly elevate EC (Sintorini et al., 2021; Wdowczyk & Szymańska-Pulikowska, 2021). Soil pH, Soil Organic Carbon (SOC), and available macronutrients

(N, P, K) co-vary with EC along the contamination gradient, reflecting the multifaceted chemical signature of leachate impact (Vegi et al., 2025).

Despite the established global literature on the impacts of landfill leachate, there is a pronounced lack of localised, pedological studies in Bhutan. Existing reports have focused primarily on Thimphu and have confirmed contamination of soil and water near the Memelakha landfill (Rai, 2024). Yet, no study has quantified the spatial extent of leachate contamination for sites such as the Punakha landfill. This knowledge gap limits Bhutan's capacity to evaluate environmental risks and implement evidence-based waste management strategies.

This study addresses this critical gap by providing the first detailed spatial analysis of soil chemical properties around the Omtekha landfill in Punakha. The specific objectives were: (1) to characterise the spatial variation of EC as a proxy for leachate contamination with increasing distance from the landfill boundary; (2) to assess the co-variation of soil pH, SOC, and available macronutrients (N, P, K) along downslope and upper slope transects; and (3) to quantify the statistical relationships between EC and other soil chemical properties. It was hypothesised that soil properties would exhibit a measurable, statistically significant spatial gradient, with contamination levels highest near the landfill boundary and declining progressively with increasing distance from it.

Materials and Methods

Study Area

The study was conducted around the operational landfill located in Omtekha, Lingmukha Gewog, Punakha Dzongkhag, Bhutan (27.534769° N, 89.881428° E). The landfill covers an area of approximately 6,439.8 m² and faces south-west. Established in 2012, it receives approximately 135.55 metric tonnes of municipal solid waste per month from adjacent gewogs including Barp, Guma, and Lobesa, as well as from Khurutang town (District Environmental Officer, personal communication, 17 February 2026). The elevation of the study area ranges from 1,325 m above sea level at the lower slope to 1,414.9 m at the upper slope. Lingmukha Gewog experiences a subtropical climate with cool winters and warm, humid summers; annual rainfall ranges from 500 mm to 1,500 mm, and temperatures range from 5°C to 30°C (Dzongkhag Administration, Punakha, 2024).

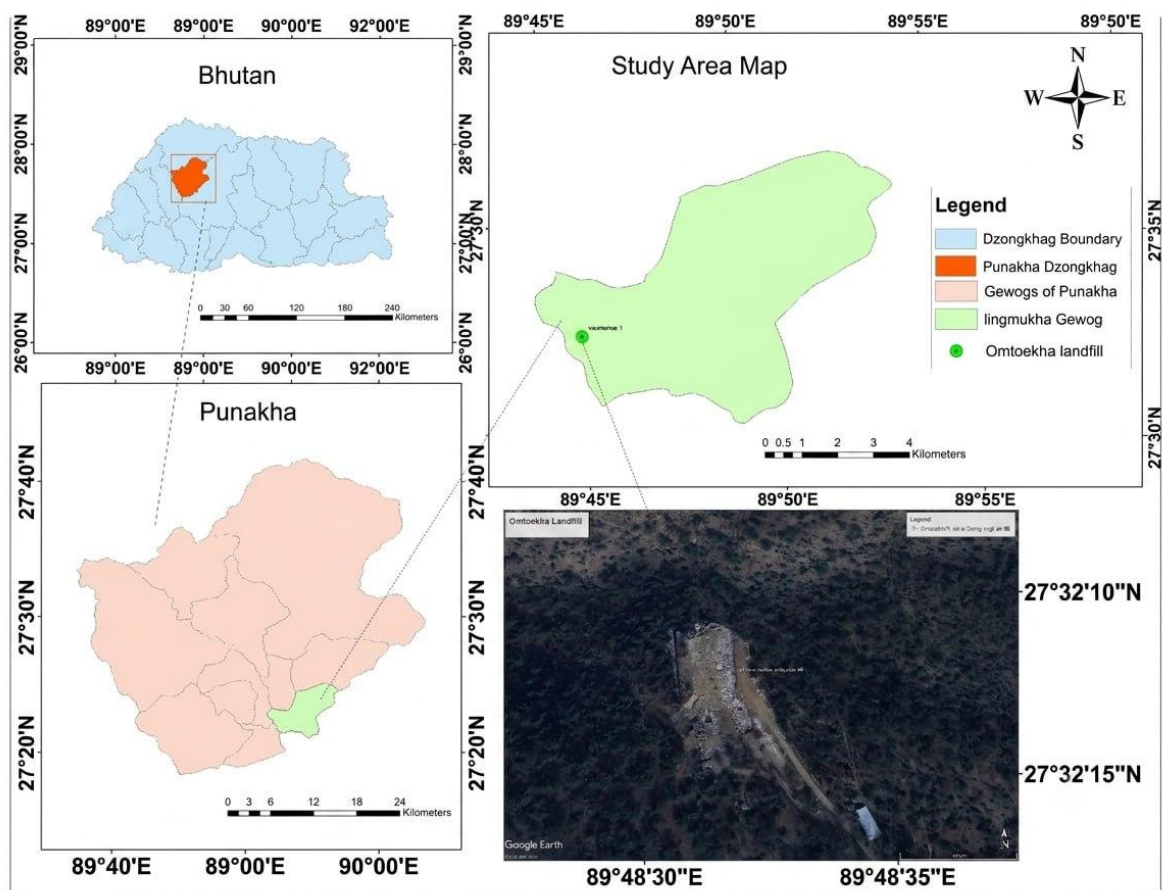


Figure 1: Study area of Omtokha Landfill

Sampling Design

A systematic sampling strategy was implemented along two 200-metre transects originating from the downslope boundary of the landfill: one extending directly downslope (following the presumed hydraulic gradient) and one extending upslope, which served as a comparative reference transect. Along each transect, soil samples were collected at fixed intervals of 50 m, 100 m, 150 m, and 200 m from the landfill boundary. A total of 30 soil samples were collected (15 per transect, $n = 3$ per sampling point per transect where feasible), providing sufficient statistical power to detect large spatial effects between the two groups (Statistical Learning and Selective Inference | PNAS, n.d.).

Sample Collection and Preparation

At each designated sampling point, soil samples were extracted using a soil auger to a depth of 30 cm. For sandy soils, multiple subsamples within a 30 cm radius were composited to ensure representativeness. Samples were collected in labelled zip-lock plastic bags with date, plot ID, GPS coordinates, slope, and aspect recorded for each point. Following collection, soil samples were air-dried at ambient temperature for two weeks to minimise alteration of physicochemical properties, an approach recommended as an alternative to oven-drying to prevent decomposition of soil organic

matter (Moktan, 2024; Sparks et al., 2020). After air-drying, samples were sieved through a 2 mm mesh (FAO, 2019), gently ground using a porcelain mortar for two minutes, and stored in sealed plastic containers prior to analysis.

Laboratory Analysis

All physicochemical analyses were conducted at the College of Natural Resources (CNR) laboratory at the Royal University of Bhutan. Electrical conductivity (EC) was measured using a digital EC meter calibrated with 0.01 M potassium chloride solution. A soil-to-water ratio of 1:2.5 (20 g soil in 50 mL distilled water) was used for EC determination (Gurumurthy, n.d.). Soil pH was measured with a calibrated digital pH meter and standard buffer solutions (pH 4.01 and 7.01), following the same 1:2.5 soil-to-water ratio (Panda, 2019). Soil Organic Carbon (SOC) and available nitrogen (N) were determined using the Loss on Ignition (LOI) method, whereby soil samples (5 g) were combusted in a muffle furnace at 500°C for 4 hours (Moktan, 2024). Available phosphorus (P) was determined using the Bray and Kurtz No. 1 method (0.25 M HCl and 0.03 M NH₄F extraction), with absorbance measured spectrophotometrically at 882 nm (Moktan, 2024). Available potassium (K) was determined using the ammonium acetate extraction method and measured using a flame photometer (Moktan, 2024).

Statistical Analysis

Statistical analysis was performed using IBM SPSS Statistics (Version 28), with raw data managed in Microsoft Excel. To address research question 1 (EC variation with distance), descriptive statistics, normality testing (Shapiro-Wilk and Kolmogorov-Smirnov tests), and simple linear regression were applied. For research question 2 (variation in physicochemical properties with distance), descriptive statistics, normality tests, Mann-Whitney U tests, and M-estimators of central tendency were used to compare transect results. For research question 3 (relationship between EC and other soil chemical properties), Spearman's rank correlation (for non-normally distributed data) and linear regression were applied. All statistical tests were conducted at a 95% confidence level ($\alpha = 0.05$, two-tailed).

Results and Discussion

Descriptive statistics for all 30 soil samples revealed substantial spatial variability across all measured parameters (Table 1). EC ranged from 18.70 $\mu\text{S}/\text{cm}$ to 432.00 $\mu\text{S}/\text{cm}$ (mean: 64.01 $\mu\text{S}/\text{cm}$), elevated relative to typical uncontaminated forest soils in Bhutan (Ghemiray et al., 2025). Soil pH ranged from 6.00 to 7.50 (mean: 6.61, SD: 0.43), indicating conditions from moderately acidic to slightly alkaline. SOC showed the greatest range (1.03%–49.31%, mean: 17.77%), with available N

showing extreme variability (1.80–1000.00 mg/kg). Available P ranged from 0.04 to 3.92 mg/kg, while K ranged from 0.05 to 36.47 mg/kg.

Table 1

Descriptive Statistics of all measured soil parameters (n = 30)

Parameter	N	Minimum	Maximum	Mean $\pm$ SD
pH	30	6.00	7.50	6.61 $\pm$ 0.43
EC (μ S/cm)	30	18.70	432.00	64.01 $\pm$ 87.63
SOC (%)	30	1.03	49.31	17.77 $\pm$ 15.40
Available N (mg/kg)	30	1.80	1000.00	91.06 $\pm$ 219.68
Available P (mg/kg)	30	0.04	3.92	0.84 $\pm$ 0.87
Available K (mg/kg)	30	0.05	36.47	1.70 $\pm$ 5.85

Spatial Variation of Electrical Conductivity (EC)

EC, serving as the primary proxy for leachate contamination, displayed a clear spatial gradient with increasing distance from the landfill (Table 2). The highest EC values were recorded at 50 m (mean: 115.81 μ S/cm, SD: 142.82 μ S/cm), declining progressively to 50.31 μ S/cm at 100 m and 35.28 μ S/cm at 150 m along the downslope transect, before a marginal stabilisation at 200 m (38.64 μ S/cm). In contrast, EC across the upper-slope transect remained comparatively stable throughout (18.7–43.0 μ S/cm), with no pronounced distance-dependent gradient. This pattern supports the alternative hypothesis that EC exhibits a significant negative gradient as distance from the landfill increases.

The elevated EC near the landfill reflects the high concentration of dissolved ionic species derived from leachate, consistent with findings by Przydatek & Kanownik (2019) and Vijayalakshmi et al. (2020). Leachate from landfills is inherently hyper-saline due to the dissolution of inorganic components from decomposing waste undergoing acidogenesis; this high ionic concentration—comprising Na^+ , K^+ , Cl^- , SO_4^{2-} , and NH_4^+ —directly elevates EC readings (Sintorini et al., 2021). The downslope transects showed substantially higher mean EC (97.47 μ S/cm) compared to the upper slope (30.55 μ S/cm), confirming that topography plays a critical role in directing leachate migration along hydraulic gradients, consistent with the literature (Osasogie Obasuyi et al., 2024).

Table 2EC values at varying distances from the landfill (Mean $\pm$ SD)

Distance (m)	N	Downslope (N)	Upper (N)	Slope	Mean ($\mu\text{S/cm}$)	EC	Range ($\mu\text{S/cm}$)
50	9	5	4		115.81 142.82	$\pm$	29.80 – 432.00
100	8	4	4		50.31 $\pm$ 40.55		25.20 – 141.00
150	8	4	4		35.28 $\pm$ 17.34		18.70 – 73.00
200	5	2	3		38.64 $\pm$ 13.39		29.70 – 62.00

Variation of Soil pH

Soil pH exhibited an initial elevation at 50 m and 100 m along the downslope transect (mean pH: 6.68 and 6.81, respectively), followed by a decline toward more acidic conditions at greater distances (150 m: 6.49; 200 m: 6.36). Across both transects, pH ranged from 6.00 to 7.50 and remained within the normal range throughout, with the downslope plots at 50 m and 100 m recording slightly higher values (Table 3). The relatively alkaline character of the leachate at these proximal distances is consistent with a mature, stabilised landfill (Longe & Balogun, 2010), as landfills established for more than a decade produce alkaline leachate (pH 8.0–8.5) due to the dominance of ammonium and bicarbonate derived from anaerobic decomposition (El-Fadel et al., 2002). The Omtexha landfill, established in 2012, is approximately 14 years old, supporting this interpretation.

The significance of soil pH extends beyond its direct value: higher pH suppresses metal mobility in soil while increasing metal availability, such that the elevated pH at 100 m may indicate higher availability of leachate-borne metals in the soil at this distance (Sintorini et al., 2021). The overall pH remained within the range considered favourable for most nutrient availability (6.0–7.0; Lauchli & Grattan, 2012), suggesting that pH alone may not constitute an acute threat to soil productivity in the study area. However, the alkaline influence of leachate at proximal distances warrants long-term monitoring.

Table 3Soil pH at varying distances from the landfill (Mean $\pm$ SD)

Distance (m)	N	Downslope (N)	Upper Slope (N)	Mean pH	Range
50	9	5	4	6.68 $\pm$ 0.46	6.00 – 7.50
100	8	4	4	6.81 $\pm$ 0.46	6.34 – 7.40
150	8	4	4	6.49 $\pm$ 0.14	6.28 – 6.70
200	5	2	3	6.36 $\pm$ 0.20	6.18 – 6.61

Soil Organic Carbon (SOC) Distribution

SOC exhibited the most dramatic spatial variation among all measured parameters. Concentrations were highest at 100 m (25.00 $\pm$ 19.05%), followed by 50 m (20.73 $\pm$ 18.12%), with substantial decreases at 150 m (12.76%) and 200 m (8.90%; Table 4). Notably, mean SOC on the upper slope (27.91%) was approximately 3.7 times higher than on the downslope transect (7.63%), reflecting natural organic matter accumulation in upper-slope positions typical of undisturbed forest vegetation rather than leachate inputs (Hua-jun, 2005; Ghemiray et al., 2025).

The elevated SOC in the 50–100 m range on the upper slope is attributable to natural inputs, including leaf litter, root turnover, and small-animal residues from intact vegetation cover. At the same time, below the landfill, additional organic matter derived from landfill runoff, leachate deposition, and early-stage plant colonisation of leachate-affected areas may contribute to SOC enrichment (Ghemiray et al., 2025). The literature generally supports the conclusion that SOC and total organic matter content in soils immediately adjacent to landfills are higher than at distal sites, as a direct consequence of the microbial metabolism of MSW components (Vijayalakshmi et al., 2020; Vegi et al., 2025). However, the quality of leachate-derived organic carbon is often chemically unstable and characterised by high C: N ratios, which can promote microbial nitrogen immobilisation and restrict plant growth in the short term (Parvin & Tareq, 2021).

Table 4Soil Organic Carbon (SOC) at varying distances from the landfill (Mean $\pm$ SD)

Distance (m)	N	Downslope (N)	Upper Slope (N)	Mean SOC (%)	Range (%)
50	9	5	4	20.73 $\pm$ 18.12	1.03 – 40.69

Distance (m)	N	Downslope (N)	Upper (N)	Slope	Mean (%)	SOC	Range (%)
100	8	4	4		25.00 ± 19.05		5.86 – 49.31
150	8	4	4		12.76 ± 10.25		7.24 – 37.93
200	5	2	3		8.90 ± 1.78		6.55 – 11.38

Available Nitrogen (N) Distribution

Available nitrogen exhibited the highest variability among all measured parameters, with mean values at 50 m (273.90 ± 366.00 mg/kg) strongly influenced by an extreme outlier of 1,000.00 mg/kg recorded at one downslope plot immediately adjacent to the landfill (Table 5). A dramatic decline was observed at 100 m (9.55 ± 6.45 mg/kg), representing approximately a 96.5% reduction, with values remaining comparatively stable at 150 m (13.16 mg/kg) and 200 m (17.00 mg/kg). This pattern of a sharp decline followed by relative stabilisation reflects both the rapid dilution of leachate-borne nitrogen and the efficient capture, transformation, and removal of nitrogen by the soil system, which acts as a buffer, filter, and bioreactor (He et al., 2017).

The extremely elevated nitrogen at the proximal downslope distance reflects the high ammonium and nitrate content characteristic of landfill leachate (Parvin & Tareq, 2021). The broader literature consistently documents nitrogen enrichment in leachate-contaminated soils, attributed to the decomposition of nitrogenous waste components and the high ammonia concentrations in mature leachate (Vegi et al., 2025). The very weak and non-significant correlation between N and EC (Spearman's $\rho = -0.118$, $p = 0.533$) is scientifically expected, as nitrogen species (NO_3^- , NH_4^+) typically occur at lower concentrations relative to major cations and anions that dominate total ionic strength and EC readings (Young, 2012).

Table 5

Available Nitrogen (N) at varying distances from the landfill (Mean ± SD)

Distance (m)	N	Downslope (N)	Upper (N)	Slope	Mean (mg/kg)	N	Range (mg/kg)
50	9	5	4		273.90 ± 366.00	13.00	– 1000.00
100	8	4	4		9.55 ± 6.45		2.30 – 19.00
150	8	4	4		13.16 ± 8.49		2.90 – 24.30

Distance (m)	N	Downslope (N)	Upper (N)	Slope	Mean (mg/kg)	N	Range (mg/kg)
200	5	2	3		17.00 ± 24.51		1.80 – 58.70

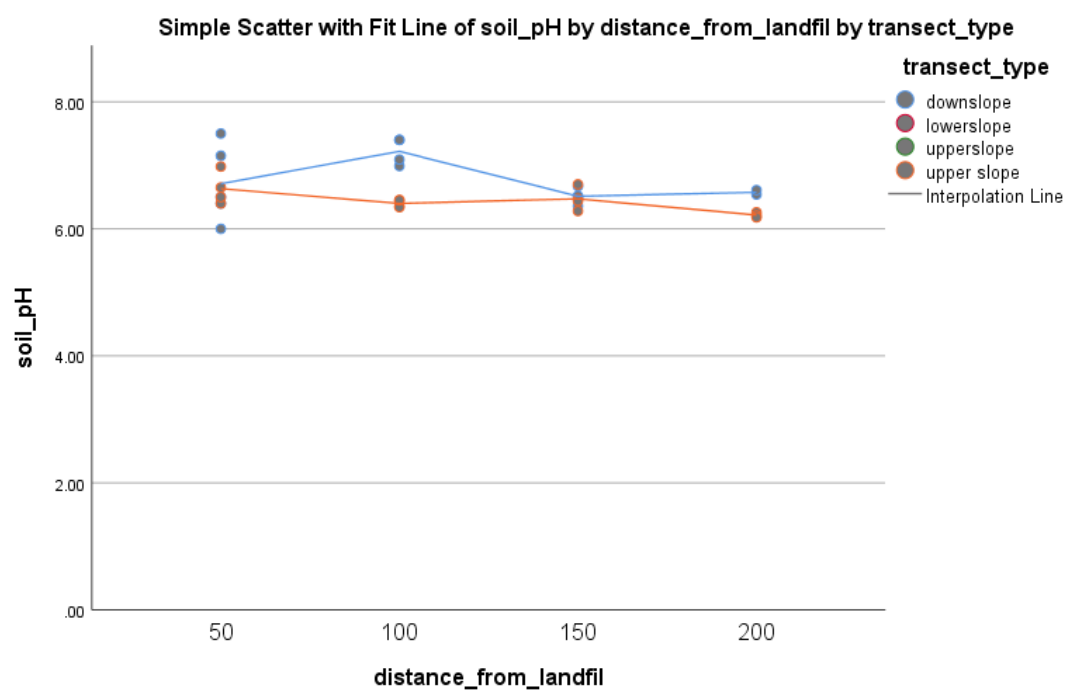
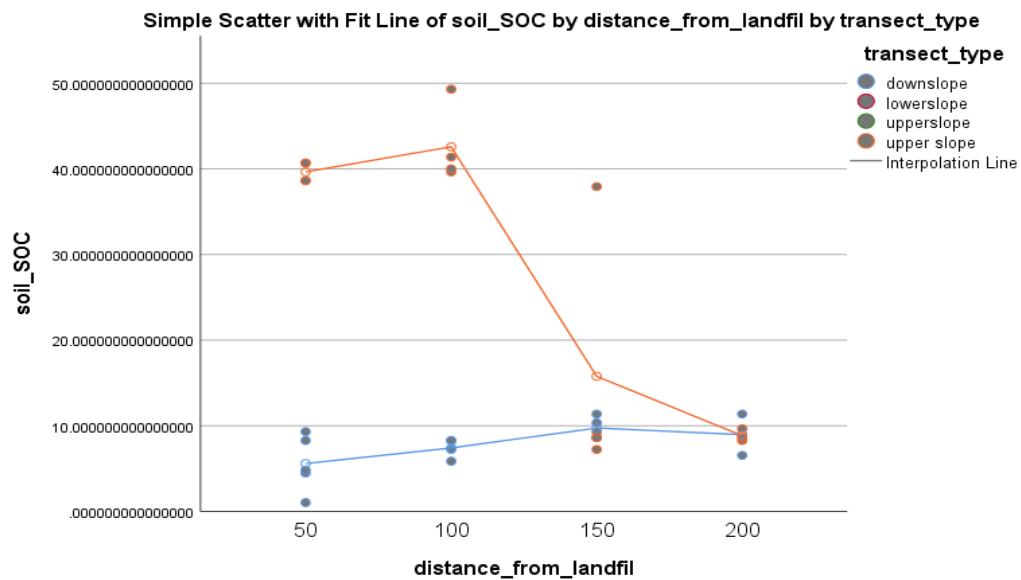
Available Phosphorus (P) and Potassium (K) Distribution

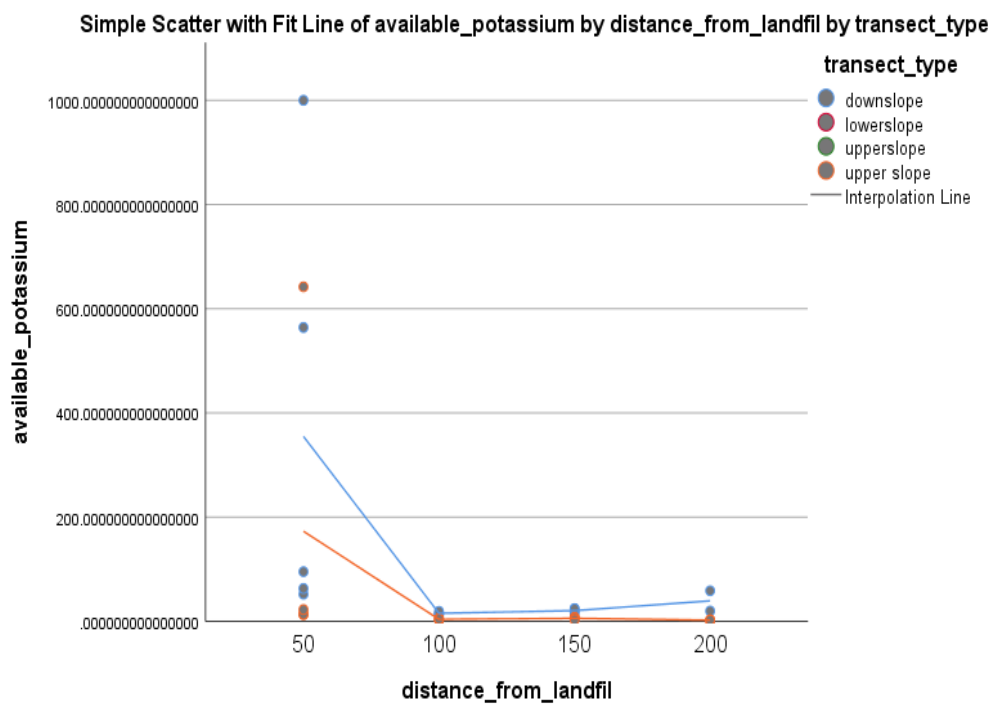
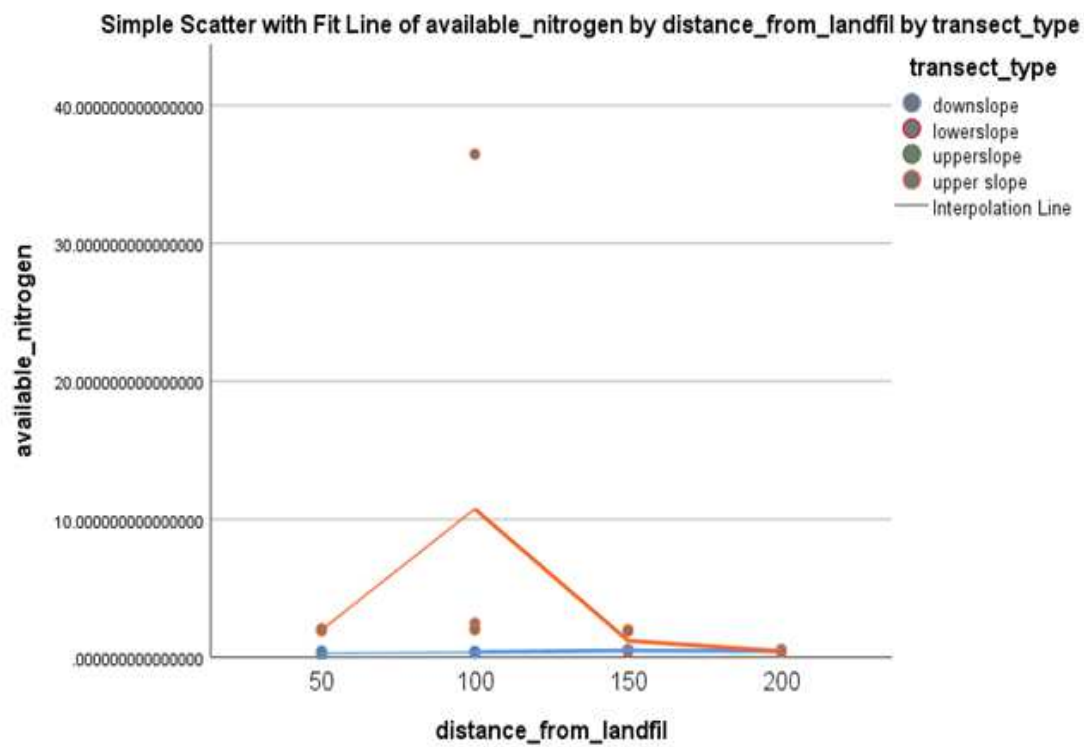
Available phosphorus concentrations were relatively low and showed no pronounced distance-dependent gradient in the downslope transect (range: 0.58–1.05 mg/kg across distances; Table 6). Notably, the upper-slope transects exhibited mean P concentrations approximately 3.2 times higher than those in the downslope transect, indicating that phosphorus enrichment in the study area reflects natural pedogenic processes rather than leachate inputs. This finding is supported by the literature, which documents that phosphorus does not rank among the major ionic constituents of landfill leachate (Singh et al., 2024) and that phosphorus leaching shows no general correlation with soil test P or sorption indices (Djodjic et al., 2004). The non-significant correlation between P and EC (Spearman's $\rho = -0.299$, $p = 0.108$) further supports this interpretation and is consistent with the rapid fixation and precipitation of phosphate in many soil types (Young, 2012).

Available potassium showed the clearest spatial gradient after EC, with highest concentrations at 50 m (5.56 ± 12.52 mg/kg) declining progressively to 0.44 ± 0.09 mg/kg at 200 m (Table 7). The strong positive correlation between K and EC (Spearman's $\rho = 0.655$, $p = 0.000$) confirms potassium's role as a major contributor to leachate ionic strength, consistent with the well-documented presence of K^+ as one of the dominant cations in landfill leachate (Singh et al., 2024; Andrade Neto et al., 2012). This relationship validates the utility of EC as a reliable proxy for tracking potassium-mediated leachate contamination. It confirms that available K is a primary driver of elevated ionic strength in leachate-affected soils.

Spatial Variability Along Transects

A comparison between the downslope and upper slope transects revealed fundamental differences in contamination patterns. The downslope transects exhibited substantially higher mean EC ($97.47 \mu\text{S/cm}$) compared to the upper slope ($30.55 \mu\text{S/cm}$). In contrast, the upper slope showed higher mean SOC (27.91%) and available P (1.28 mg/kg) relative to the downslope (7.63% and 0.40 mg/kg, respectively; Table 8). This asymmetry confirms that gravitational flow directs leachate migration downslope, consistent with the spatial contamination gradient model (Chonattu et al., 2016) and similar findings from the broader leachate literature (Osasogie Obasuyi et al., 2024).





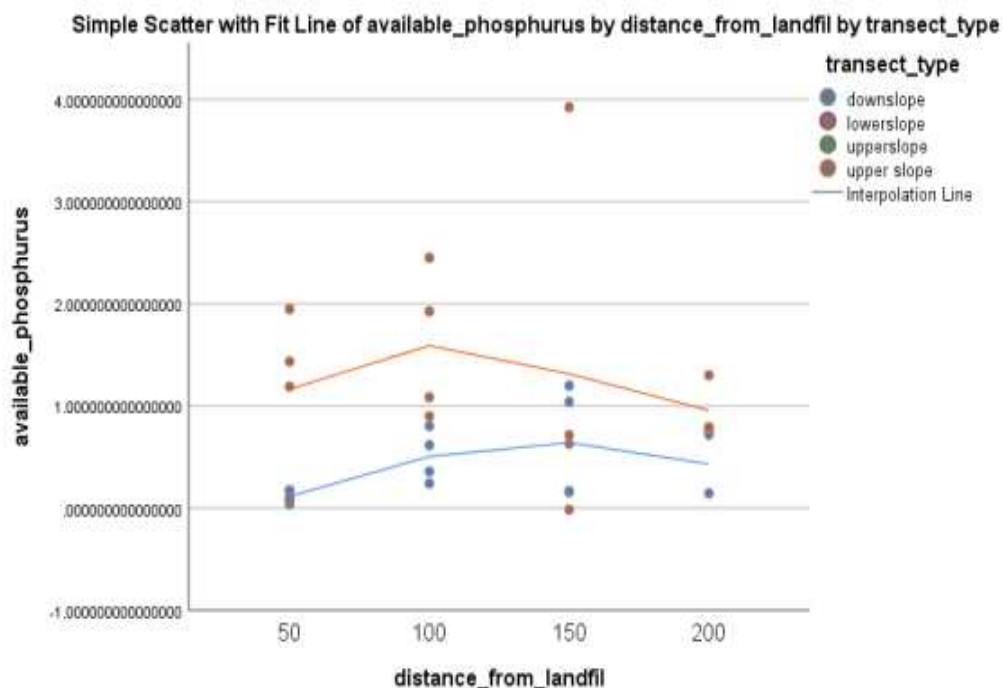


Figure 2: *Graphs showing relationship between soil parameters and distances from the landfill*

The higher SOC and P on the upper slope reflect the accumulation of natural organic matter and nutrient cycling in undisturbed upslope vegetation. At the same time, lower SOC downslope suggests soil disturbance, compaction, and mixing associated with proximity to the landfill. These patterns highlight the importance of transect-based study designs in accurately characterising leachate contamination zones and distinguishing anthropogenic impacts from natural pedogenic variation.

Table 6

Soil properties by transect type (Mean $\pm$ SD)

Parameter	Downslope (n = 15)	Upper Slope (n = 15)
pH	6.78 $\pm$ 0.45	6.44 $\pm$ 0.21
EC (μ S/cm)	97.47 $\pm$ 113.01	30.55 $\pm$ 6.51
SOC (%)	7.63 $\pm$ 2.77	27.91 $\pm$ 16.51
Available N (mg/kg)	133.07 $\pm$ 277.07	49.05 $\pm$ 164.13
Available P (mg/kg)	0.40 $\pm$ 0.38	1.28 $\pm$ 0.99
Available K (mg/kg)	0.38 $\pm$ 0.14	3.80 $\pm$ 9.07

Relationship Between EC and Soil Chemical Properties

Correlation analysis quantified the relationships between EC and other soil chemical properties (Table 7). A significant positive correlation was identified between EC and pH ($\rho = 0.470$, $p = 0.009$), indicating that higher leachate contamination is associated with more alkaline soil conditions. The strong positive correlation between EC and available K ($\rho = 0.655$, $p < 0.001$) confirms that potassium is a principal contributor to leachate ionic strength, consistent with Andrade Neto et al. (2012). SOC showed a weak, non-significant negative correlation with EC ($\rho = -0.281$, $p = 0.132$), whereas available N and P showed very weak, non-significant correlations ($\rho = -0.118$, $p = 0.533$; $\rho = -0.299$, $p = 0.108$, respectively).

The absence of significant correlations between EC and N, P, or SOC is scientifically consistent: nitrogen and phosphorus species contribute minimally to total soluble ion concentration relative to the dominant cations (Ca^{2+} , Mg^{2+} , Na^+ , K^+) and anions (Cl^- , SO_4^{2-} , HCO_3^-) that drive EC in leachate-affected soils (Young, 2012). Furthermore, available P is rapidly fixed or precipitated in soil matrices, rarely persisting in solution at concentrations sufficient to influence EC. These patterns collectively validate EC as a reliable, cost-effective integrating marker for overall pedological changes induced by migrating leachate.

Table 7

Spearman correlation coefficients between EC and soil chemical properties

Parameter	Spearman's ρ	p-value
pH	0.470*	0.009
SOC (%)	-0.281	0.132
Available N (mg/kg)	-0.118	0.533
Available P (mg/kg)	-0.299	0.108
Available K (mg/kg)	0.655**	0.000

* Significant at $p < 0.05$; ** Significant at $p < 0.001$

Regression Analysis

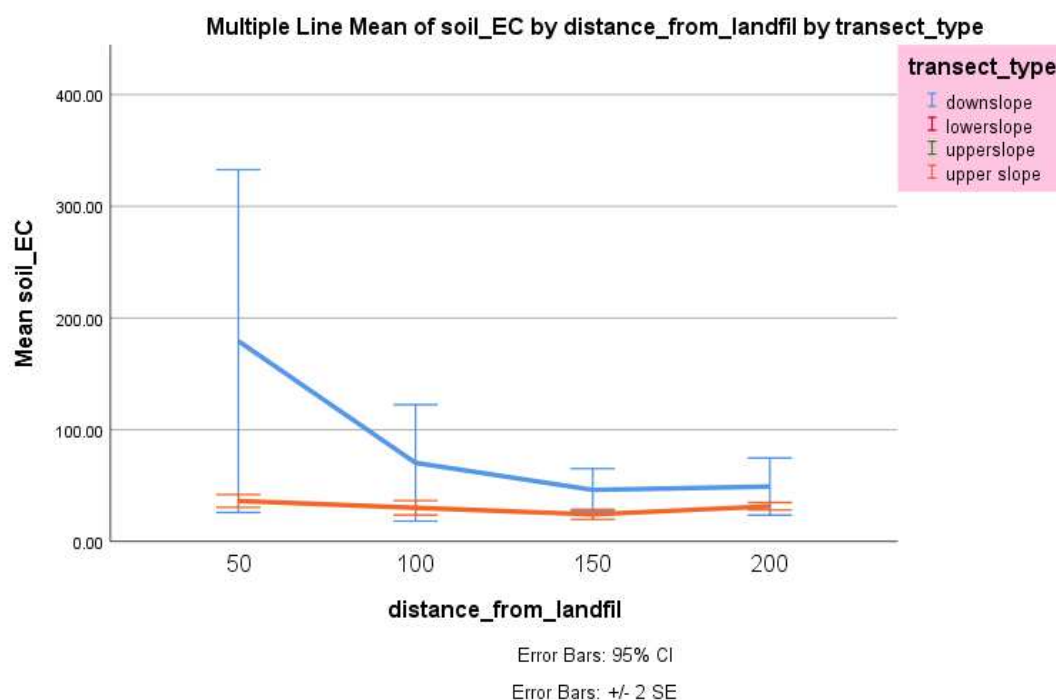


Figure 3: Graph showing mean EC values of the two slopes at varying Distance gradient

Simple linear regression modelling the relationship between EC and distance from the landfill yielded the following equations: for the downslope transect, $EC = 205.803 - 0.985(\text{Distance})$ ($R^2 = 0.222, p = 0.076$); for the upper-slope transect, $EC = 36.244 - 0.047(\text{Distance})$ ($R^2 = 0.167, p = 0.130$). Both models indicate a negative relationship between EC and distance, with a considerably steeper gradient on the downslope transect. For the downslope transect, EC decreases by approximately 0.985 $\mu\text{S}/\text{cm}$ per metre increase in distance from the landfill. The R^2 value of 0.222 indicates that while distance accounts for approximately 22% of EC variability, other soil factors—including soil texture, moisture, and natural pedogenic variation—also contribute to EC variation. The p-value of 0.076 represents a directionally consistent trend that, when considered alongside the broader spatial pattern and correlation data, provides meaningful evidence for a contamination gradient (Czyżyk et al., 2014).

Conclusion and Recommendations

This study provides the first pedological baseline characterisation of leachate-induced soil contamination at the Omtekha landfill, Punakha, Bhutan. A measurable spatial contamination gradient was identified, with EC, potassium, and nitrogen exhibiting the clearest distance-dependent decline from the landfill boundary. The contamination zone extends approximately 100–150 m from the boundary along the downslope transect, with the highest contamination levels nearest the source. Topographic position exerts critical control over leachate migration, with the downslope transect

consistently showing higher contamination indicators (EC: 97.47 $\mu\text{S}/\text{cm}$) than the upper slope (EC: 30.55 $\mu\text{S}/\text{cm}$).

The significant positive correlations between EC and pH ($r = 0.470$, $p = 0.009$) and between EC and K ($r = 0.655$, $p < 0.001$) support EC as a reliable, rapid, and cost-effective proxy for monitoring leachate contamination in Bhutanese landfill soils. Soil pH remained within the normal range (6.36–6.81) throughout, reflecting the mature, alkaline character of the Omtékha leachate. SOC distribution was primarily governed by topographic position and natural vegetation inputs rather than leachate enrichment. Available P showed no significant enrichment in leachate.

Future studies should incorporate seasonal sampling across at least four quarters to capture monsoon-driven leachate migration dynamics, which likely represent the highest risk period for contamination. Extension of transect distances to 500 m or beyond, along with the inclusion of cross-slope transects and truly independent control sites, would improve delineation of the contamination zone. Heavy metal analysis, particularly for Pb, Cd, Cu, Zn, and Cr, is essential for fully characterising long-term soil health risks, as these non-biodegradable contaminants pose sustained threats to ecosystems and human health. Groundwater quality assessment at varying distances from the landfill is also recommended, particularly for downstream communities that rely on groundwater for drinking. Phytotoxicity assessment of adjacent vegetation would further establish the ecological risk boundary of the leachate plume. These data are urgently needed to support evidence-based waste management policy and the design of appropriate leachate treatment and remediation interventions in Bhutan's fragile Himalayan ecosystems.

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