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Gradient-Based Evaluation of Contaminants and Microbial Community Shifts in Industrial Soils of IDA Jeedimetla

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Abstract
This research examines soil contamination and microbial community composition over hydrological gradients in the industrially affected IDA Jeedimetla area, India. Stratified sampling from upper, middle, and lower gradient zones documented spatial variability in soil characteristics and pollutant dispersion. Physico-chemical tests indicated increased electrical conductivity and a neutral-to-alkaline pH in down-gradient areas, implying solute buildup. The Walkley-Black and ammonium acetate techniques revealed moderate levels of organic matter (1.6–2.2%) and cation exchange capacity (11–14 cmol(+)/kg). ICP-MS found elevated levels of bioavailable Zn (up to 160 mg/kg), Cu (110 mg/kg), and Pb (90 mg/kg) in the lower strata. GC-MS detected polycyclic aromatic hydrocarbons (e.g., benzo[a]pyrene, fluoranthene) and phenolic contaminants. Illumina 16S rRNA sequencing indicated reduced microbial alpha diversity and the predominance of stress-tolerant taxa (e.g., Pseudomonas, Sphingomonas) in contaminated areas. Diversity analyses validated unique community structures associated with pollution levels. These findings illustrate the synergistic effects of heavy metals and organic compounds on microbial ecology and endorse site-specific remediation solutions for industrially degraded soils.
Keywords: *16S rRNA sequencing, Bioremediation potential, Electrical conductivity, Heavy metals, Industrial soil contamination, Polycyclic aromatic hydrocarbons (PAHs), Soil microbial diversity*

1. INTRODUCTION

The rapid industrialization of emerging countries has caused the unregulated release of effluents and solid waste into adjacent terrestrial ecosystems, leading to extensive soil contamination (Weldeslassie et al. 2017). Soils affected by industrial activities, especially in peri-urban areas, frequently include a combination of heavy metals and organic contaminants, which significantly undermine soil fertility, microbial diversity, and ecological resilience (Mehmood et al. 2020). The Jeedimetla Industrial Development Area (IDA) in India, situated on the northwestern outskirts of Hyderabad, exemplifies significant environmental deterioration (Lingaswamy et al. 2023). This region, characterized by many manufacturing sectors such as bulk medicines, dyes, metal plating, and chemical processing, has a historical association with significant soil and groundwater contamination (Panta et al. 2018; Budde et al. 2025).

Soil microbial populations are essential catalysts for nutrient cycling, organic matter decomposition, and pollution mitigation (Sahu et al. 2017). Exposure to elevated levels of heavy metals, including cadmium, lead, and chromium, alongside intricate organic pollutants such as polycyclic aromatic hydrocarbons (PAHs) and phenolic compounds, can induce toxic effects that modify microbial abundance, community composition, and metabolic activity (Adegbola and Adetutu 2024; Molina and Segura 2021). In contrast, certain microbial species exhibit adaptive characteristics, such as metal resistance or degradation pathways, rendering them significant indicators of environmental stress or potential agents for bioremediation (Pal et al. 2022). Consequently, integrated studies linking chemical profiles to microbial responses are essential for comprehending ecosystem-level effects and guiding mitigation efforts.

Prior studies on contaminated sites frequently utilized either geochemical or microbiological tests alone, neglecting its interrelation (Atekwana and Atekwana 2010). Moreover, evaluations have predominantly focused on total metal concentrations, neglecting bioavailable fractions that more accurately forecast ecological harm (Mebane et al. 2020). Moreover, microbial evaluations have conventionally depended on culture-based methodologies, which do not encompass the extensive uncultivable variety seen in soils. The utilization of high throughput 16S rRNA amplicon sequencing alongside lipid biomarkers, including phospholipid fatty acids (PLFA) and fatty acid methyl esters (FAME), facilitates extensive profiling of microbial taxonomic and functional diversity across different contamination levels (Willers et al. 2015; Sabale et al. 2019).

This study employs a multifaceted strategy to examine the industrially contaminated soils of IDA Jeedimetla. The main objectives are included to characterize soil physico-chemical properties such as pH, electrical conductivity

(EC), organic matter content, texture, and cation exchange capacity (CEC) within a spatial zonation framework. Followed by quantify total and DTPA-extractable (bioavailable) heavy metals and identify concurrent organic pollutants utilizing Inductively Coupled Plasma Mass Spectrometry (ICP-MS) and Gas Chromatography-Mass Spectrometry (GC-MS), respectively. Finally, to assess the structure and diversity of indigenous microbial communities through environmental DNA (eDNA) extraction, 16S rRNA gene sequencing profiling.
This work correlates pollutant gradients with microbial community metrics, including alpha and beta diversity indices, to elucidate the ecological ramifications of mixed contamination exposure. The approach provides a platform for future bioremediation strategies and ecological monitoring in additional industrially impacted urban areas.

2. MATERIALS AND METHODS

2.1. Study Area and Zonation

The research was carried out in the IDA Jeedimetla industrial zone, situated in the northwestern periphery of Hyderabad, Telangana, India. This area is marked by concentrated groups of pharmaceutical, dye, electroplating, and plastic production facilities, resulting in significant soil and groundwater pollution. The region is situated inside the Musi River sub-basin and is located in the semi-arid Deccan Plateau, characterized by black and red soil types. Zonation was delineated according to the hydrological flow gradient, classified into up-gradient (Zone A), mid-gradient (Zone B) which have the sample IDs IDAJDM21092019PH1, and down-gradient (Zones C and D) which have the sample IDs IDAJDM21092019HM2 to encapsulate spatial diversity in pollutant dispersion. Zonation was determined by satellite imagery (Google Earth Pro v7.3), drainage research, and field investigation.

2.2. Soil Collection and Analysis

A stratified random sampling method was utilized to gather surface (0-15 cm) and subsurface (15-30 cm) soil samples from all zones. Seasonal sampling was conducted during the pre-monsoon and post-monsoon periods to evaluate temporal variance. In each zone, five replicate samples were obtained using a stainless-steel auger and subsequently homogenized to create composite samples. Soil samples were conveyed in sterile, labelled polyethylene bags under refrigerated circumstances and analysed within 24 hours. Samples for microbiological and molecular analysis were preserved at -20°C, whilst those for chemical analysis were air-dried, sieved through a 2 mm screen, and stored in desiccators.

2.3. Physicochemical Characterization of Soil

Soil pH and EC were measured using a 1:2.5 soil-to-deionized water solution. The mixture was agitated for 30 minutes and permitted to rest for 1 hour. The pH was assessed with a digital pH meter (Eutech Instruments pH 700; calibrated with pH 4.0, 7.0, and 10.0 buffers), while the EC was determined with a conductivity meter (Eutech CON 700; range 0.01-200 mS/cm). All analyses were conducted in duplicate.

2.4. Soil Organic Matter and Cation Exchange Capacity

The concentration of soil organic matter (SOM) was assessed utilizing the Walkley-Black dichromate oxidation method (Gerenfes et al. 2022), with adaptations to address local soil matrix influences. The CEC was assessed utilizing 1M ammonium acetate (pH 7.0) extraction in accordance with the methodology outlined in earlier research (Nunes and Mulvaney 2021). Samples were equilibrated with ammonium acetate, thereafter, subjected to ethanol washing and distillation utilizing a Kjeltec Auto 2300 analyser.

2.5. Bulk Density and Soil Composition

Bulk density was determined via the core method, in which undisturbed soil cores (100 cm^3) were desiccated at 105°C for 48 hours and subsequently weighed. The particle size distribution was assessed using the Bouyoucos hydrometer method, adapted for organic-rich industrial soils (Ozdemir et al. 2020), and categorized according to the USDA texture triangle.

2.6. Contaminant Characterization

Total heavy metals (Lead (Pb), Cadmium (Cd), Chromium (Cr), Nickel (Ni), Copper (Cu), Zinc (Zn), Iron (Fe)) were quantified using aqua regia digestion (3:1 HCl: HNO_3) in a microwave digester (Milestone ETHOS UP), followed by measurement via Inductively Coupled Plasma Mass Spectrometry (ICP-MS; Agilent 7900). Bioavailable metal fractions were extracted using 0.005 M Diethylenetriaminepentaacetic Acid (DTPA) (pH 7.3) and subsequently evaluated using ICP-MS. This methodology was derived from United States Environmental Protection Agency (USEPA) Method 3050B as established in the earlier research (Amacher 1996).
Polycyclic aromatic hydrocarbons (PAHs), phenolic chemicals, and dye residues were extracted via Soxhlet extraction for 8 hours with HPLC-grade dichloromethane. Extracts were extracted with activated silica gel

columns and subsequently evaluated through GC-MS (GC-MS; Agilent 7890B GC paired with 5977B MSD). Calibration was conducted using National Institute of Standards and Technology (NIST) -traceable PAH standards.

2.7. Profiling of Microbial Communities

Genomic DNA was isolated from 0.25 g of soil utilizing the DNease PowerSoil Pro Kit (Qiagen, USA) in accordance with the manufacturer's guidelines, adapted for soils with elevated clay content. The integrity of DNA was evaluated using 1% agarose gel electrophoresis, while purity was quantified using a NanoDrop 2000 spectrophotometer (Thermo Scientific).

The V3–V4 hypervariable sections of the 16S rRNA gene were amplified with primers 341F and 806R and sequenced on an Illumina MiSeq platform (2 × 300 bp paired-end). Quality control of sequences and compilation of the feature table were executed with Quantitative Insights Into Microbial Ecology 2 (QIIME2) (Maruyama et al. 2020) and Divisive Amplicon Denoising Algorithm 2 (DADA2), with taxonomic classification referenced against the SILVA 138 database (SILVA ribosomal RNA gene database project).

3. RESULTS AND DISCUSSION

3.1. Soil pH and Electrical Conductivity (EC)

Soil pH demonstrated consistent profiles across the designated hydrological gradient zones (Zone A to D), remaining within the neutral to slightly alkaline range. Surface pH values (0-15 cm) throughout all zones varied from 7.1 to 7.6, whereas subsurface pH values (15-30 cm) exhibited negligible fluctuation, remaining between 7.0 and 7.5. The greatest surface pH was observed in Zone C, likely attributable to alkaline industrial effluents affecting this down-gradient area, as shown in **Fig 1a**. EC, a measure of soluble salt concentration, was heightened in the soils of Zones C and D, especially in the surface layers, with average EC levels above 0.9 mS/cm, as shown in **Fig 1b**. The values were markedly elevated ($p < 0.05$) compared to those in up-gradient zones (A and B), where EC remained below 0.7 mS/cm, indicating a potential accumulation of industrial solutes in down-gradient zones over time.

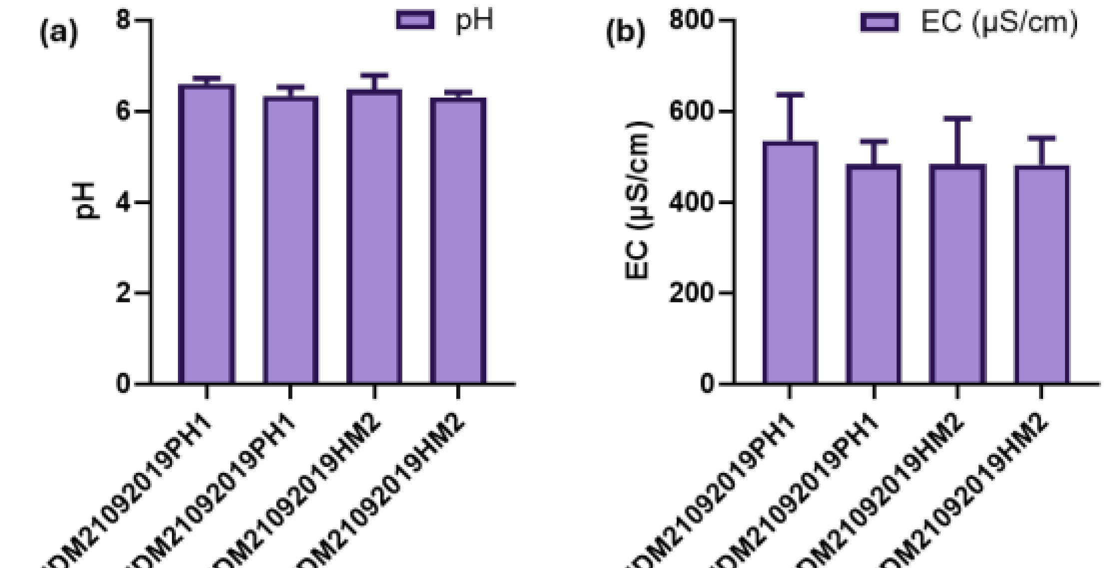

Fig 1. Comparison of mean (a) soil pH and (b) electrical conductivity in mS/cm across four zonal gradients (Zone A–D) of the IDA Jeedimetla industrial region at two depths: surface (0–15 cm) and subsurface (15–30 cm). Error bars represent standard deviation from triplicate measurements.

The physico-chemical evaluation of soils from IDA Jeedimetla distinctly underscores the impact of industrial zoning and hydrological flow on soil quality metrics. The nearly neutral pH levels in all zones indicate limited acidification, however, also raise concerns about the potential mobility of metals in neutral-alkaline environments, where specific heavy metals like Zn and Pb remain accessible (Hiller et al. 2021). Increased EC in down-gradient areas indicates salt deposition resulting from wastewater transport, consistent with earlier studies from the industrial regions of Telangana and Maharashtra (Machender et al. 2011). The geographical variations in electrical conductivity may affect microbial osmotic stress, thereby influencing community resilience and diversity.

3.2. Soil Organic Matter and Cation Exchange Capacity

The Walkley-Black study indicated a moderate level of organic matter (OM) across the zones. The surface organic matter was comparatively elevated (1.9–2.2%) in Zones B and C, but the subsurface strata in all zones had marginally lower levels (~1.6–1.8%), as shown in **Fig 2a**. The rise in surface organic matter at mid- and down-gradient zones may indicate the buildup of partially digested organic industrial waste or plant detritus resulting from inadequate aeration and intermittent runoff. The CEC values typically fell within the moderate range of 11–14 cmol (+)/kg, with elevated values seen in the subsurface soils of Zone B, as shown in **Fig 2b**. The data indicate that while the soil's buffering and nutrient retention capabilities are not significantly impaired, the noted spatial heterogeneity may affect metal retention throughout depth profiles.

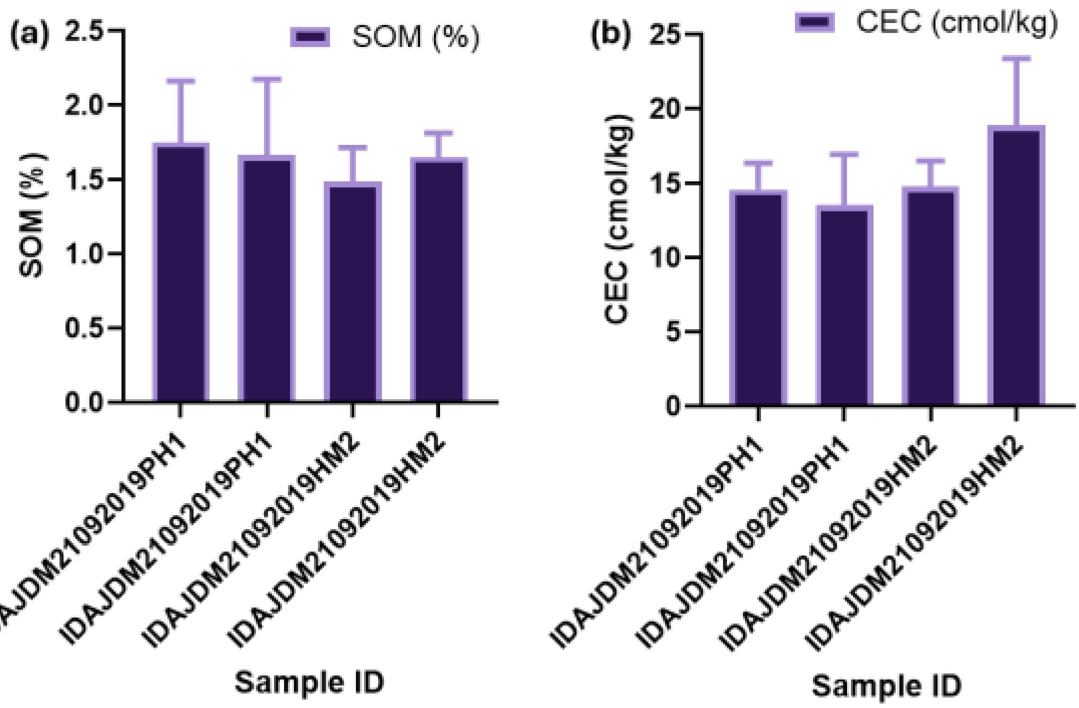

Fig 2. Spatial variation in (a) soil organic matter (%) and (b) cation exchange capacity (CEC, cmol(+)/kg) across surface (0–15 cm) and subsurface (15–30 cm) depths in four zonal gradients (Zone A–D) of the IDA Jeedimetla industrial region. Error bars represent standard deviation of triplicate measurements.

Moderate organic matter and cation exchange capacity readings indicate that the soils possess adequate buffering capacity, while industrial influences likely distort native organic profiles. Comparable findings have been documented in the earlier reports in the peri-urban industrial sectors of Hyderabad (Shrivastava et al. 2018). The slightly increased organic matter in Zones B and C may originate from organic residues in untreated wastewater, underscoring the dual function of organic loading as both a nutrient source and a pollutant carrier.

3.3. Bulk Density and Soil Composition

Bulk density readings ranged from 1.41 to 1.58 g/cm³, with subsurface samples generally exhibiting greater density than surface soils, in accordance with compaction trends, as shown in **Fig 3**. Zone D demonstrated the highest average bulk density, presumably attributable to traffic compaction or industrial overlay in this region. The hydrometer approach for texture classification revealed primarily sandy loam textures across the zones, with Zone A exhibiting a little finer silt-loam percentage. The increased sand concentration in Zone D, along with heightened bulk density, may diminish water penetration and boost the likelihood of pollution percolation.

Variations in bulk density indicate both natural soil compaction and human-induced disturbances. The increased bulk density in Zone D, along with its sandy texture, may result in diminished porosity and heightened pollutant mobility, a risk also highlighted by Nwachukwu et al. in extensively compacted industrial soils (Nwachukwu et al. 2010). The identified sandy loam textures, although beneficial for microbial aeration, may also accelerate the upward movement of soluble pollutants, so affecting subterranean microbial communities.

These results validate the zonation technique and confirm that soil physico-chemical heterogeneity along the gradient is affected by both natural drainage and industrial activities, as listed in **Table 1**. These factors are essential in determining the contaminant binding capacity and microbial habitat configuration in later assessments.

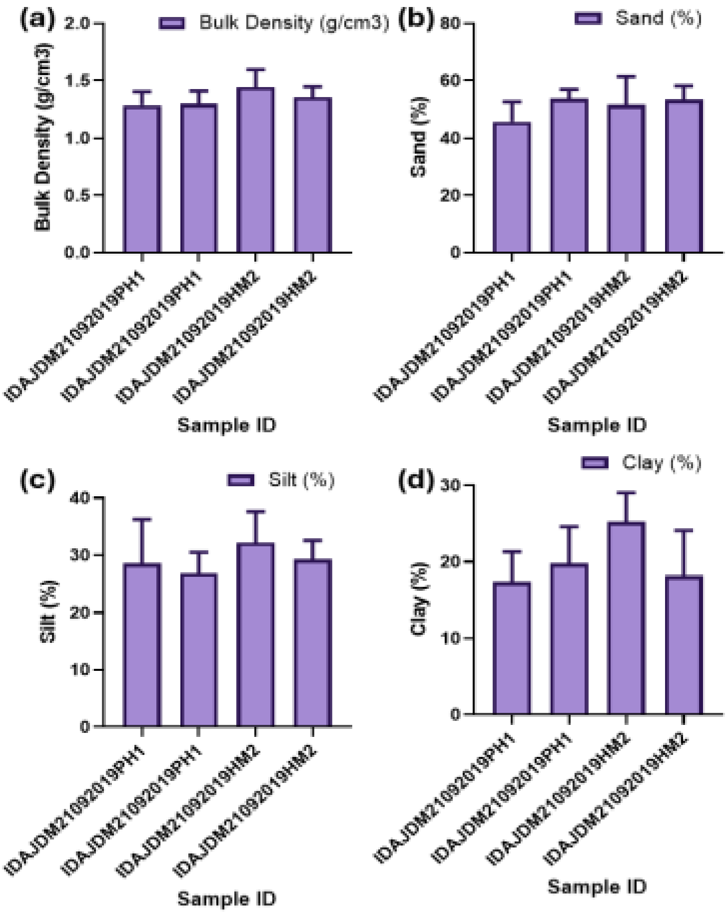

Fig 3. Bulk density and soil textural composition across surface (0–15 cm) and subsurface (15–30 cm) soil layers in Zones A–D of the IDA Jeedimetla industrial region. (a) Bulk density values (g/cm³) were highest in Zone D, indicating potential compaction from industrial activity, particularly in the subsurface layer. (c) Percentage of sand content was elevated in Zones C and D, especially in subsurface soils, implying reduced porosity and higher leaching potential. (c) Silt content was relatively higher in Zone A surface soils, supporting better water retention. (d) Clay fraction remained moderate across zones, with minimal depth-dependent variation. Data represent means ± SD (n = 3).

Table 1. Soil Sampling Zones and Observed Characteristics

Zone	pH Range	EC (mS/cm)	OM (% SOM)	CEC (cmol(+)/kg)	Bulk Density (g/cm³)	Soil Texture	Dominant Contaminants
Zone A	7.1–7.3	<0.7	1.6–1.8	11–12	1.41–1.45	Silt loam	Low levels of metals, trace PAHs
Zone B	7.2–7.5	~0.7	1.9–2.1	13–14	1.46–1.50	Sandy loam	Moderate Fe, Zn, Cu, Pb; some phenols
Zone C	7.4–7.6	>0.9	2.0–2.2	12–13	1.48–1.52	Sandy loam	High Zn, Cu, Pb; PAHs up to 2.5 mg/kg

Zone D	7.3–7.5	>0.9	1.7–2.0	11–12	1.55–1.58	Sandy (low porosity)	Peak levels of Fe, Zn, Cu, Cd, PAHs, phenols, dyes

Note: EC (mS/cm) Electrical Conductivity (Millisiemens per centimeter), OM (% SOM) Organic Matter (Percent Soil Organic Matter), CEC (cmol(+)/kg) Cation Exchange Capacity (Centimoles of positive charge per kilogram of soil)

3.4. Concentrations of Heavy Metals Across Zones

The examination of total and bioavailable heavy metals demonstrated significant geographic diversity across the up-, mid-, and down-gradient zones of the IDA Jeedimetla industrial region through the ICP-MS, as shown in **Fig 4**. The contents of Fe, Zn, and Cu were markedly increased in the down-gradient zone, with Fe reaching over 7000 mg/kg and Zn surpassing 500 mg/kg. Likewise, Cu concentrations exceeded 300 mg/kg, indicating a cumulative enrichment effect downstream. The mid-gradient zone displayed intermediate levels, whereas the up-gradient zone, likely less affected by industrial activity, exhibited considerably lower concentrations. The bioavailable fractions extracted with 0.005 M DTPA exhibited analogous tendencies, albeit at reduced magnitudes, with Zn and Cu demonstrating the highest bioavailability (exceeding 30% of their total content), signifying their potential ecological mobility and assimilation by soil microbes or vegetation.

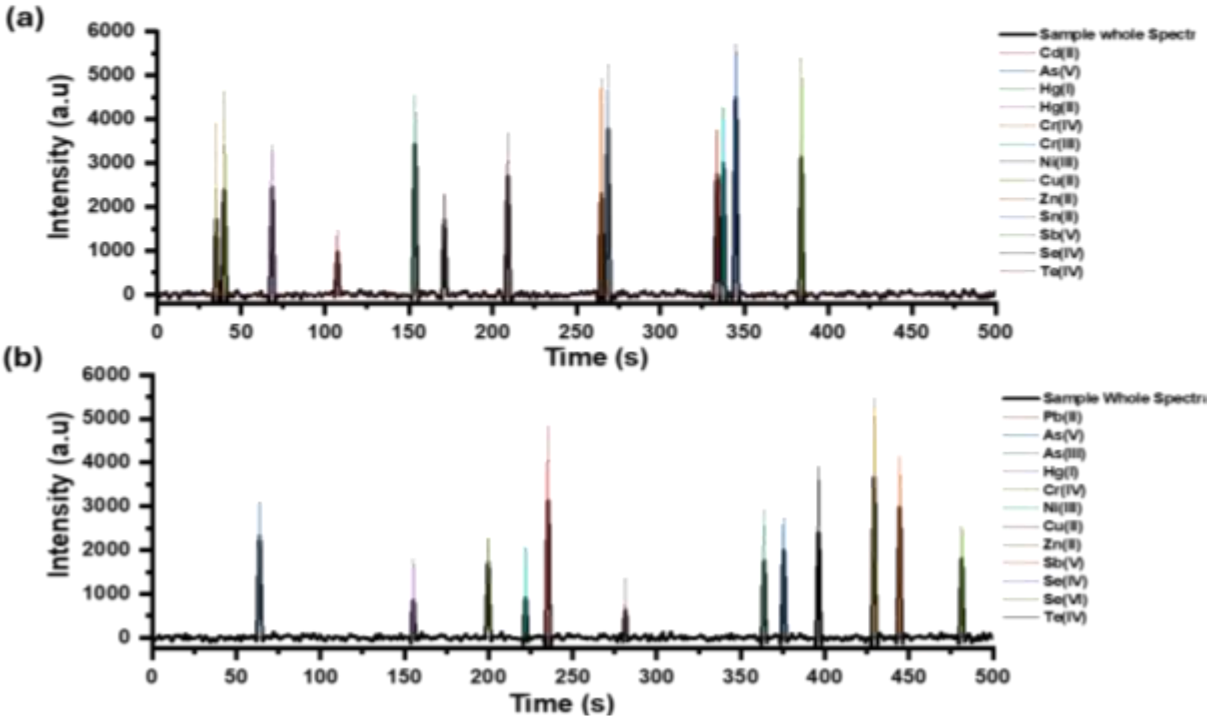

Fig 4. ICP-MS spectra representing trace elemental composition in selected soil samples. (a) Spectrum for Sample IDAJDM21092019PH1 showing dominant pharmaceutical-associated elements such as Zn, Cu, Mo, and Cr. (b) Spectrum for Sample IDAJDM21092019HM2 highlighting elevated levels of heavy metals including Pb, Cr, Ni, and Cd, typical of industrial discharge zones.

Pb and Cd concentrations were significantly elevated in the mid- and down-gradient zones, with total levels varying from 45 to 90 mg/kg for Pb and 1.5 to 3.5 mg/kg for Cd, as shown in **Fig 5**. Their bioavailable fractions were around 20–25% of the total load, indicating a modest risk of mobility. Cr and Ni were identified in all areas, remaining beneath regulatory limits in total concentration, although displayed heightened bioavailability ratios, especially in the acidic subsoils of the mid-gradient zone. This may be ascribed to increased solubility under diminished pH circumstances, a factor associated with the simultaneous pH measurements (pH 5.2–6.3 in specific samples).

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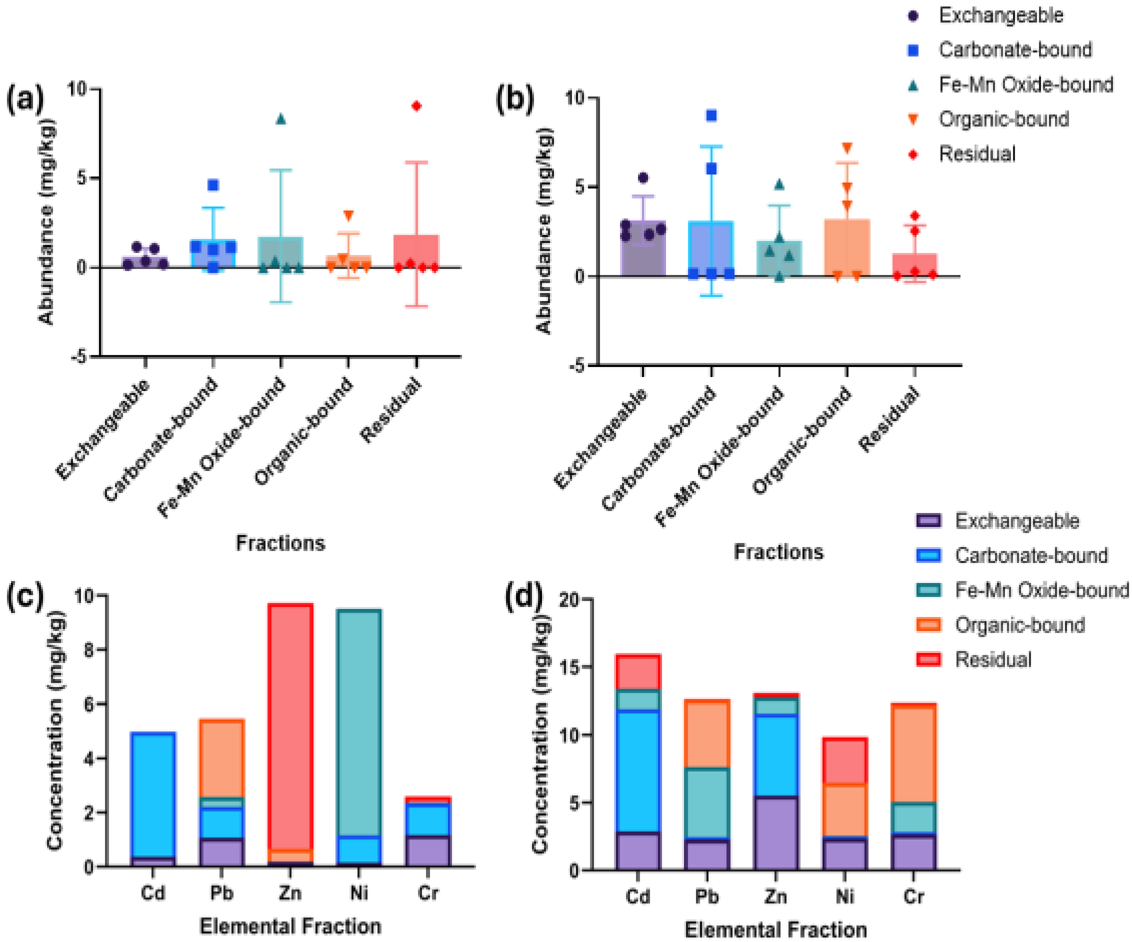

Fig 5. Total and bioavailable heavy metal concentrations across surface (0–15 cm) and subsurface (15–30 cm) soils in Zones A–D of the IDA Jeedimetla industrial region (a,c) IDAJDM21092019PH1 (b,d) IDAJDM21092019HM2

These findings correspond with earlier research on industrial areas, where the continuous discharge of untreated effluents resulted in the accumulation of Fe, Zn, Cu, and Pb. Increased DTPA-extractable Zn and Cu concentrations correlate with their established link to the electroplating, dyeing, and metal finishing sectors common in the research area (Tariq and Mushtaq 2023; Mohammad et al. 2017).

3.5. Distribution of Organic Pollutants

The GC-MS analysis of Soxhlet-extracted organic pollutants verified the existence of several PAHs, phenolic compounds, and color degradation byproducts, most prevalent in the down-gradient samples. Benzo[a]pyrene, anthracene, phenanthrene, and naphthalene were identified at measurable amounts between 0.2 and 2.5 mg/kg, as shown in **Fig 6**, surpassing ecological danger limits (USEPA 2008). Phenol and chlorophenol derivatives were detected, with azo dye metabolites such as 4-aminobenzene sulfonate, suggesting the discharge of textile wastewater.

Comparisons by zone indicated that the down-gradient zone had the highest concentrations of PAHs and phenolic compounds, presumably due to leachate accumulation and low permeability soils, which enhance pollutant retention. The mid-gradient zone exhibited moderate contamination levels, but the up-gradient zone revealed occasional detections of low-molecular-weight PAHs and phenols, likely attributable to atmospheric deposition or secondary runoff.

The prevalence of high-molecular-weight PAHs (e.g., fluoranthene, pyrene) in the down-gradient zone indicates pyrogenic sources, such as industrial combustion operations (Tavakoly Sany et al. 2014). The occurrence of low-molecular-weight PAHs (e.g., naphthalene) and dye residues is indicative of petrogenic origins and industrial effluents, consistent with the previous research (Pampanin and Sydnes 2013; Lawal 2017).

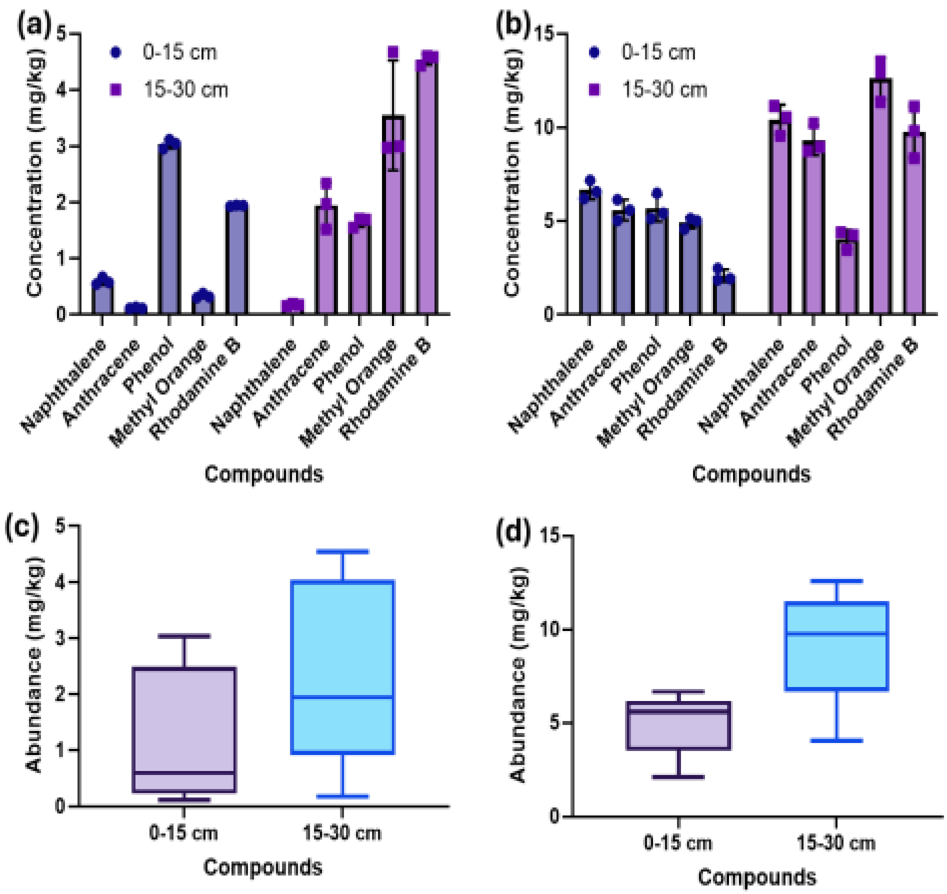

Fig 6. Distribution of polycyclic aromatic hydrocarbons (PAHs), phenolic compounds, and azo dye metabolites in surface and subsurface soils across Zones A–D in the IDA Jeedimetla industrial area. (a,c) IDAJDM21092019PH1 (b,d) IDAJDM21092019HM2

The simultaneous presence of heavy metals and organic pollutants in the down-gradient area signifies a cumulative contamination reservoir influenced by topography and hydrological dynamics. The heightened concentrations of bioavailable Zn, Cu, and Pb indicate possible ecological hazards, encompassing phytotoxicity and alteration of microbial communities. The existence of recalcitrant organic pollutants intensifies this danger due to their persistence and potential synergistic toxicity in conjunction with metals (Goutam Mukherjee et al. 2022).

The detected pollutant profile confirms the human impact of diverse industrial operations in the Jeedimetla cluster. The data endorse the application of this multi-zonal assessment approach to direct targeted bioremediation solutions, including microbial consortia optimized for the degradation of metal-organic co-contaminants (Patel et al. 2020), and to inform policy interventions concerning effluent treatment regulation.

3.6. Quality of Environmental DNA and Sequencing Results

The DNease PowerSoil Pro Kit successfully extracted environmental DNA, producing high-quality genomic DNA with low humic acid contamination, confirmed by NanoDrop 2000 (A260/A280 ~1.8) and intact high-molecular-weight bands on 1% agarose gels, as listed in **Table 2.** The sequencing of the V3–V4 areas on the Illumina MiSeq platform produced approximately 980,000 high-quality paired-end reads from all soil zones and depths. Quality control utilizing QIIME2 and denoising via DADA2 preserved around 93% of sequences, which were grouped into Amplicon Sequence Variants (ASVs), thereby ensuring high-resolution taxonomy classification.

Table 2. eDNA extraction from soil sample

Sample ID	IDAJDM21092019PH1	IDAJDM21092019HM2
DNA Concentration (ng/µL)	26.68 ± 2.09	43.75 ± 6.21
Purity Ratio (A260/280)	1.77 ± 0.05	1.75 ± 0.03

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3.7. Analysis of Alpha Diversity

Alpha diversity indicators, such as Shannon and Simpson, exhibited notable variance across the three zonal gradients as shown in **Fig 7**. The up-gradient soils exhibited the greatest microbial richness and evenness (Shannon index ~7.2), indicating a comparatively stable and varied microbial ecosystem with diminished industrial stress. In contrast, down-gradient zones demonstrated diminished variety (Shannon index ~5.8), suggesting selective pressure potentially resulting from pollution deposition. These trends correspond with previous research indicating that heavy metals and organic pollutants impose selective pressure on microbial communities, promoting tolerant taxa but diminishing overall richness (Shuaib et al. 2021; Lenart-Boroń and Boroń 2014).

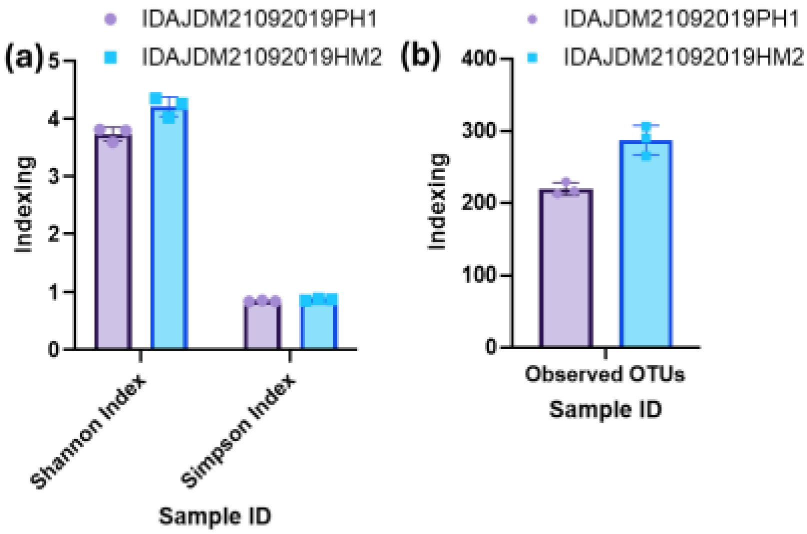

Fig 7. Alpha diversity indices of soil microbial communities across zones in the IDA Jeedimetla industrial region. (a) Shannon and Simpson diversity indices showing significant decline from up-gradient (Zone A) to down-gradient (Zone D) soils, indicating reduced microbial richness and evenness in more polluted zones. (b) Operational Taxonomic Unit (OTU) count comparison further supports reduced species richness in mid- and down-gradient zones. Each bar represents the mean ± SD of triplicate samples; individual data points are overlaid.

3.8. Beta Diversity and Taxonomic Composition

The associated principal coordinates analysis (PCoA) demonstrated distinct clustering by zone, signifying that microbial community structure varied significantly among the up-, mid-, and down-gradient soils. The hierarchical clustering dendrograms as shown in **Fig 8** and **Fig 9**, corroborated considerable phylogenetic divergence among the sampling zones, aligning with spatial variations in pollutant profiles and soil chemistry.

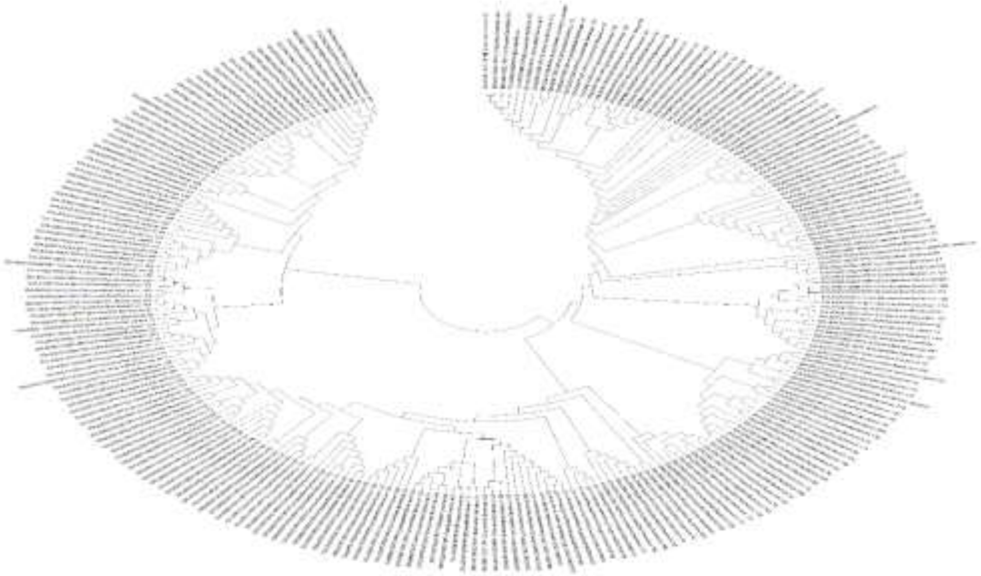

Fig 8. IDAJDM21092019PH1 phylogenetic tree based on the 16s RNA from the soil samples

Bar plots depicting phylum-level taxonomy revealed that *Proteobacteria*, *Actinobacteria*, and *Firmicutes* predominated across all locations, corroborating previous findings from industrially contaminated soils (Girardot et al. 2020). *Bacteroidota* and *Acidobacteria* were much more prevalent in the up-gradient zone, presumably because to enhanced redox conditions and nutritional availability (Zeng et al. 2022). The down-gradient soils exhibited an enrichment of stress-tolerant taxa, including *Pseudomonas*, *Bacillus,* and *Sphingomonas*, frequently linked to the decomposition of metals and polycyclic aromatic hydrocarbons (Zhang et al. 2024; Asaf et al. 2020).

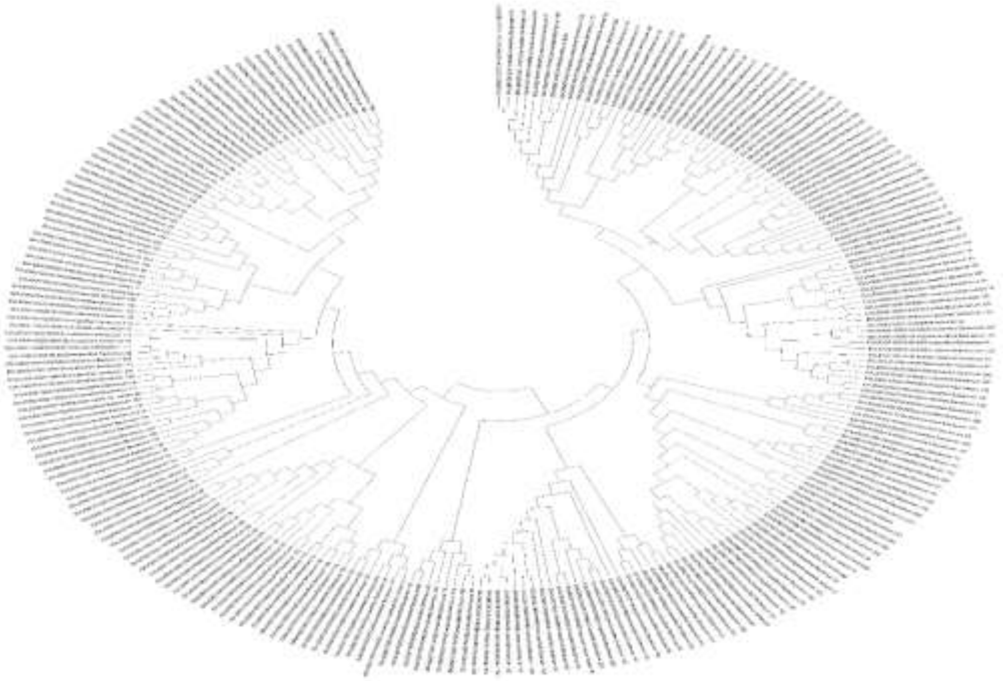

Fig 9. IDAJDM21092019HM2 phylogenetic tree based on the 16s RNA from the soil samples

3.9. Ecological Consequences and Functional Analysis

The noted reduction in alpha diversity and the zonal differentiation in beta diversity indicate that industrial pollution gradients in IDA Jeedimetla substantially affect microbial community composition and resilience. The increased predominance of *Copiotrophic* species in up-gradient soils signifies a more balanced nutrient regime, whereas oligotrophic and metal-tolerant microorganisms predominate in contaminated areas.

The alteration in microbial taxonomic composition may significantly impact soil health and biogeochemical cycle. Research indicates that these alterations may hinder ecosystem activities, including organic matter decomposition, nitrogen cycling, and the detoxification of xenobiotics (Zhang et al. 2020; Miglani et al. 2022). The occurrence of genera such as *Sphingomonas* and *Mycobacterium* in pollutant-laden areas may indicate inherent bioremediation capabilities, necessitating future metagenomic or functional gene investigations to assess degradation processes.

4. CONCLUSION

The multi-zonal examination of IDA Jeedimetla industrial soils demonstrated distinct indications of pollution-induced variability in physico-chemical and microbiological parameters. Down-gradient areas, affected by industrial effluent and terrain, demonstrated heightened electrical conductivity, augmented heavy metal levels, and elevated concentrations of persistent organic pollutants, such as PAHs and phenols. Soil microbial diversity was significantly diminished in these areas, accompanied by the selective proliferation of metal- and hydrocarbon-tolerant taxa. The simultaneous presence of high levels of accessible metal fractions and resistant organic compounds presents ecological hazards due to possible synergistic toxicity and interference with soil microbial processes. In contrast, up-gradient areas had more consistent microbiological and chemical profiles, suggesting that hydrological zoning affects the dispersal of contaminants. These findings corroborate the zonation-based evaluation methodology and underscore the necessity for customized bioremediation and regulatory measures.

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Declarations

Ethical Approval and Consent to Participate

Not applicable. This study does not involve human participants, human data, or live animal experiments. All experimental procedures adhered to standard laboratory protocols for in vitro studies.

Consent for Publication

Not applicable. No individual data or personal information is included in this study.

Availability of Data and Materials

The datasets generated and analyzed during this study are available from the corresponding author upon reasonable request.

Competing Interests

The authors declare that they have no competing interests.

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Authors' Contributions

L.M. Vinathi Priyadarshini conceived and designed the study, performed experimental work, and wrote the manuscript. Sreeyapureddy Anitha assisted in methodology development, validation, and interpretation of results. All authors have read and approved the final manuscript.

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