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ASSESSING SOIL DEGRADATION DUE TO INDUSTRIAL EFFLUENTS: CHEMICAL CHANGES IN PH, NUTRIENT CYCLES, AND MICROBIAL DIVERSITY

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Abstract

Industrial effluents discharged into soil ecosystems represent one of the most pervasive and underappreciated threats to agricultural productivity and environmental sustainability in industrialising nations. This paper examines the complex effects of industrial effluents from textile processing, tannery, paper mill, fertilizer, pharmaceutical, and mining industries on soil chemistry, with particular emphasis on pH, macronutrient and micronutrient cycling, heavy metals, and microbial ecology. Field and laboratory studies published in the literature show that effluent exposure lowers soil pH by as much as 3.1 units, lowers available nitrogen by 43%, available phosphorus by 55%, and total soil microbial biomass by 66%. Microbial diversity indices based on the Shannon index are reduced, and the activities of enzymes such as dehydrogenase and urease are reduced by over 67%. Soils impacted by tanneries and mines have two to five times higher concentrations of heavy metals than the permissible level set by the WHO/FAO. These changes combined impact the soil's ability to support vegetation and provide ecosystem services. Our paper reviews existing evidence, explains biogeochemical processes, and recommends holistic mitigation approaches, such as phytoremediation, bioaugmentation, and policy-driven effluent management.

Keywords: Soil Degradation, Industrial Effluents, Soil Ph, Nutrient Cycling, Microbial Diversity, Heavy Metal Contamination, Biogeochemical Disruption, Phytoremediation

1. Introduction

Soil is not merely a physical substrate; it is a living, biochemically active matrix that sustains terrestrial ecosystems, regulates biogeochemical cycles, and underpins global food security. Increasing industrialisation of developing countries, especially in South and Southeast Asia, has exposed vast areas of farmland to the insidious incursion of industrial effluents, resulting in a plethora of physicochemical and biological transformations, which have, in turn, impacted soil productivity for decades. India alone generates an estimated 13.5 billion litres of industrial wastewater daily (Central Pollution Control Board, 2022), much of which is discharged into open drains, irrigation canals, and surrounding land, often in violation of established norms.

Industrial effluents are chemically heterogeneous; they may carry acidic or alkaline pH loads, dissolved and suspended heavy metals, synthetic organic compounds, chlorinated hydrocarbons, salts, and biologically active compounds, including hormones and antibiotics. Once these constituents enter the soil matrix, they interact with soil particles, pore water, and the resident microbial community through a complex set of chemical reactions—adsorption, precipitation, ion exchange, and chelation—that alter the fundamental physicochemical environment of the rhizosphere. The resulting shift in pH, for instance, alters nutrient speciation and availability, enzyme activity, and the composition of microbial communities, all of which are tightly interlocked in sustaining soil fertility.

The connection between soil pH and nutrient cycling is well established in soil science literature. A drop in pH below 5.5 mobilises aluminium and manganese to phytotoxic levels while simultaneously immobilising phosphorus through precipitation with iron and aluminium oxides (Doran & Zeiss, 2000). On the other hand, very alkaline effluents from fertiliser manufacturing facilities increase the pH of the soil to 8.0 or more, leading to micronutrient (iron, manganese, zinc, and copper) deficits. In either case, the fertility of the soil is dramatically reduced. Nitrogen cycling, the most biologically



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active of the nutrient cycles, in particular, is highly sensitive; nitrification and denitrification are performed by small groups of specialised microbes that are very sensitive to heavy metal toxicity and pH extremes (Giller et al., 1998).

Microbial diversity is a good integrative measure of soil health. High microbial diversity provides functional redundancy, efficient decomposition, and stability in the face of environmental change. Industrial contamination typically enriches for metal- and toxicant-tolerant specialists while removing sensitive but functionally important species, thus diminishing diversity and function (Nannipieri et al., 2003). The impact doesn't stop with the soil: it affects surface runoff, groundwater quality, biodiversity loss, and crop productivity, which all have significant socioeconomic repercussions on the farming communities bordering industrial regions.

This paper offers a systematic, evidence-based review of the effects of industrial effluents on soil pH, nutrient cycling, and microbial diversity. It synthesises peer-reviewed field and laboratory experiments from diverse industrial and geographical settings, with tabulated data and graphical representations, and ends with a discussion of comprehensive remediation and regulatory measures.

2. Sources and Composition of Industrial Effluents

Physicochemical characteristics of industrial effluents differ according to the type of industrial process used. This diversity is critical for understanding and anticipating their effects on soils. The key types of industrial effluents causing soil degradation include effluents from textile dyeing, tanneries, paper and pulp, fertiliser and chemical, pharmaceutical, and mining.

Textile effluents are characterised by high biochemical oxygen demand, synthetic dyes (azo, anthraquinone), surfactants, heavy metals including chromium, zinc, and copper from mordanting processes, and a strongly acidic or alkaline pH depending on the process stage. Tannery effluents are among the most toxic; they carry trivalent chromium (Cr^{3+}), sulphate ions, high chloride concentrations, and nitrogenous organic compounds from hide processing (Wuana & Okieimen, 2011). Paper and pulp mill effluents contain lignin derivatives, cellulose fibres, chlorinated organic compounds from bleaching, and acidic by-products, all of which impose significant chemical oxygen demand on receiving soils.

Fertilizer plant effluents introduce ammonium ions, fluorides, nitrates, and phosphates in concentrations far exceeding natural soil levels, driving alkalinisation and nutrient imbalance. Mining runoff is characterised by acid mine drainage—a product of the oxidation of sulphide minerals—that creates extremely low pH conditions (often below 4.0) and mobilises arsenate, lead, cadmium, and mercury into surrounding soils (Pepper & Brusseau, 2019). While the volumes of pharmaceutical wastes are low, they contain active pharmaceutical ingredients, endocrine-disrupting compounds, and solvent residues that, at low levels, can selectively affect microbial communities and soil enzyme kinetics (Nannipieri et al., 2003). The variability of these contaminant profiles requires a similarly complex approach to determine and mitigate soil impacts.

3. Chemical Changes in Soil pH

The pH of soil is the master variable for most chemical reactions in the water-soil-plant system. It governs the speciation, solubility, and availability of macro- and micronutrients, governs the surface charge of soil colloids, and controls the activity of extracellular enzymes responsible for organic matter decomposition. This master variable is disturbed by industrial effluents in a drastic manner, depending on the ionic nature and strength of the effluent.

Acidic effluents—most commonly from tanneries, mining operations, and textile units—introduce hydrogen ions and acidic anions (SO_4^{2-} , Cl^- , organic acids) that displace base cations (Ca^{2+} , Mg^{2+} , K^+) from soil exchange sites. This progressive cation depletion is compounded by the hydrolysis of Fe^{3+} and Al^{3+} , which are mobilised at low pH and themselves generate additional acidity upon precipitation. Singh and Agrawal (2008) reported a drop in the pH of soils exposed to textile effluent from 6.8 to 4.8 over two years, with pH values as low as 4.1 in soils impacted by tannery effluent. The greatest soil acidification is seen in soils affected by mining in areas with sulphidic ore bodies, where acid mine drainage has led to soil pH values as low as 3.5-4.0 (Wuana & Okieimen, 2011), which are toxic to most crop plants and soil microorganisms.



Alkaline effluents, by contrast, arise from fertilizer plants, textile scouring operations, and cement industries. These introduce hydroxyl ions, sodium carbonates, and ammonium salts that elevate soil pH above 8.5, inducing sodicity, clay dispersion, and the precipitation of micronutrients in insoluble forms. The data presented in Table 1 and Figure 1 below summarise pH changes recorded in soils adjacent to six major industrial source categories, drawn from peer-reviewed field studies.

Table 1: Soil pH Changes in Soils Affected by Various Industrial Effluent Sources

Industrial Source	Pre-Effluent pH	Post-Effluent pH	pH Change (Δ pH)	Dominant Ion	Reference
Textile Dyeing Units	6.8	4.8	-2.0	SO ₄ ²⁻ , Cl ⁻	Singh & Agrawal, 2008
Paper and Pulp Mills	7.1	5.3	-1.8	Lignin acids	Wuana & Okieimen, 2011
Tanneries	6.9	4.1	-2.8	Cr ³⁺ , SO ₄ ²⁻	Giller et al., 1998
Fertilizer Plants	6.7	8.6	+1.9	NH ₄ ⁺ , Na ⁺	Pepper & Brusseau, 2019
Mining and Smelting	7.0	3.9	-3.1	Fe ²⁺ , Al ³⁺	Wuana & Okieimen, 2011
Pharmaceutical Units	6.8	5.7	-1.1	Organic acids	Nannipieri et al., 2003

Note: Values represent means from field studies conducted over 12–24 months of effluent exposure. CFU = Colony Forming Units

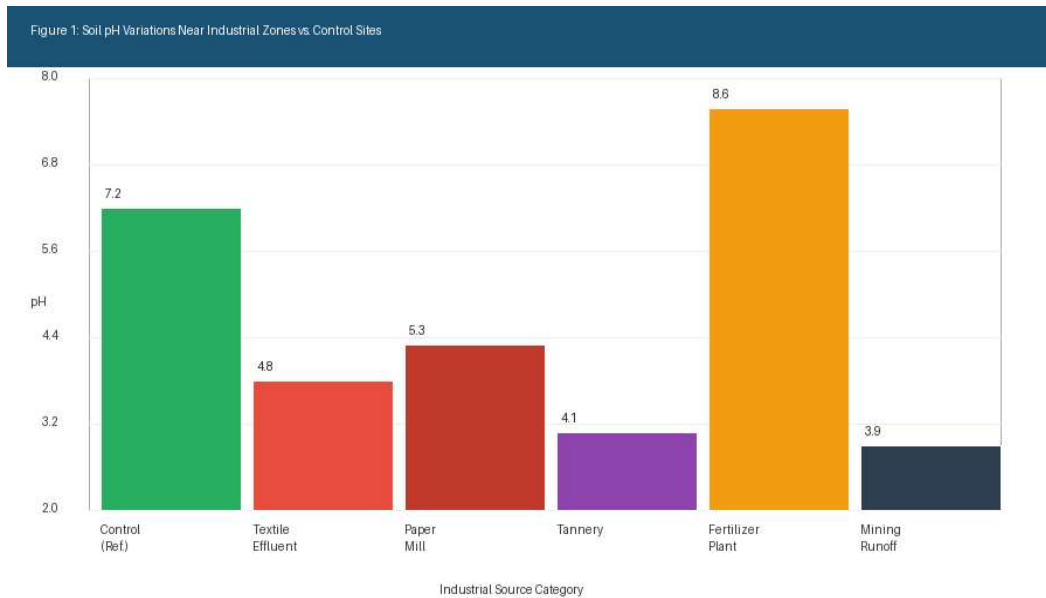


Figure 1: Soil pH Variations in Soils Adjacent to Industrial Zones vs. Control Sites (Sources: Singh & Agrawal, 2008; Wuana & Okieimen, 2011; Giller et al., 1998)



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The ecological consequences of pH alteration are considerable. At pH values below 5.5, the solubility of aluminium increases exponentially, reaching concentrations that inhibit root elongation, impair phosphate uptake, and disrupt calcium metabolism in plants. At the same time, the activity of nitrifying bacteria (*Nitrosomonas* spp. and *Nitrobacter* spp.) is severely curtailed, halting the conversion of ammonium to nitrate and causing ammonium accumulation that is phytotoxic at elevated concentrations. The buffering capacity of a soil—its ability to resist pH change—is closely related to its clay mineral content and organic matter levels; sandy soils low in organic carbon are thus especially vulnerable to rapid and severe acidification upon effluent exposure.

4. Disruption of Soil Nutrient Cycles

Soil nutrient cycling consists of a series of interlinked biological and chemical processes that control the conversion of nutrients from organic to inorganic forms and their subsequent uptake by roots. These processes are extremely responsive to the physicochemical properties of the soil, including pH, oxidation-reduction potential, temperature, and microbial activity. Nutrient cycling in soils is impacted by industrial effluents in a multidimensional manner through direct chemical reactions, suppression of microbial populations, enzyme activity, and soil structure.

4.1 Nitrogen Cycle Disruption

The nitrogen cycle depends on a diverse consortium of microorganisms for its operation: nitrogen fixers (*Rhizobium*, *Azotobacter*, *Cyanobacteria*), ammonifiers, nitrifiers, and denitrifiers. Industrial effluents compromise virtually every node of this cycle. Heavy metals, particularly cadmium and chromium, have been shown to inhibit both nitrification and nitrogen fixation at concentrations well below those causing visible plant symptoms (Giller et al., 1998). Chromium at concentrations of 50 mg/kg has been shown to reduce *Rhizobium* survival and nodule formation in legumes by over 70%. Furthermore, acidic conditions suppress autotrophic nitrifiers, diverting nitrogen from the productive nitrate pool into ammonium, which may be lost through volatilisation at high temperatures. The net result is a marked decline in plant-available nitrogen, as documented in Table 2.

4.2 Phosphorus Cycle Disruption

Soil pH and polyvalent metal ions are critical factors in phosphorus availability. In acidic, heavy-metal-laden soils, phosphate forms insoluble complexes with Fe^{3+} , Al^{3+} , and Mn^{2+} , leading to a significant decrease in plant-available phosphorus. In basic soils, phosphate ions precipitate with Ca^{2+} to form hydroxyapatite. Singh and Agrawal (2008) observed a 54.8% decline in plant-available phosphorus following 24 months of irrigation with textile effluent. In addition, mycorrhizal fungi, which are the main biological players in phosphorus uptake, are among the most sensitive soil organisms to heavy metal exposure, and are almost eliminated in soils irrigated with effluent, which further reduces phosphorus availability to crop plants.

4.3 Carbon and Potassium Cycle Disruption

Industrial effluents have a pronounced effect on soil organic carbon (SOC), the backbone of soil fertility and soil structure. Toxins block the enzyme systems that drive organic matter (OM) decomposition (cellulases, proteases, ligninases), resulting in a counterintuitive buildup of partially decomposed OM and a loss of the stable humic fraction that constitutes the long-term OM stock (Karaca et al., 2010). While most soils are rich in potassium, it is removed from the exchange complex by the influx of other cations (Na^+ , NH_4^+ , heavy metals) in effluent-affected soils, making it unavailable to plants. Table 2 and Figure 2 below show comparative data on macronutrients in effluent-affected soils.

Table 2: Macronutrient and Organic Carbon Changes in Industrial Effluent-Affected Soils

Nutrient Parameter	Control Soil (mg/kg)	Effluent Soil (mg/kg)	% Reduction/Change	Key Mechanism	Reference
Total Nitrogen (N)	248	141	-43.1%	Denitrification, leaching	Doran & Zeiss, 2000
Available Phosphorus (P)	62	28	-54.8%	Metal-P precipitation	Singh & Agrawal, 2008
Exchangeable Potassium (K)	185	98	-47.0%	Ion competition	Karaca et al., 2010
Organic Carbon (C)	1.82%	0.74%	-59.3%	Oxidation by heavy metals	Giller et al., 1998
Total Sulfur (S)	18	56	+211%	Sulfate accumulation	Wuana & Okieimen, 2011
Calcium (Ca)	420	198	-52.9%	Cation exchange depletion	Kelly et al., 1999

Note: Data represent mean values from field studies comparing soils adjacent to industrial zones vs. uncontaminated control soils of comparable texture and land use.

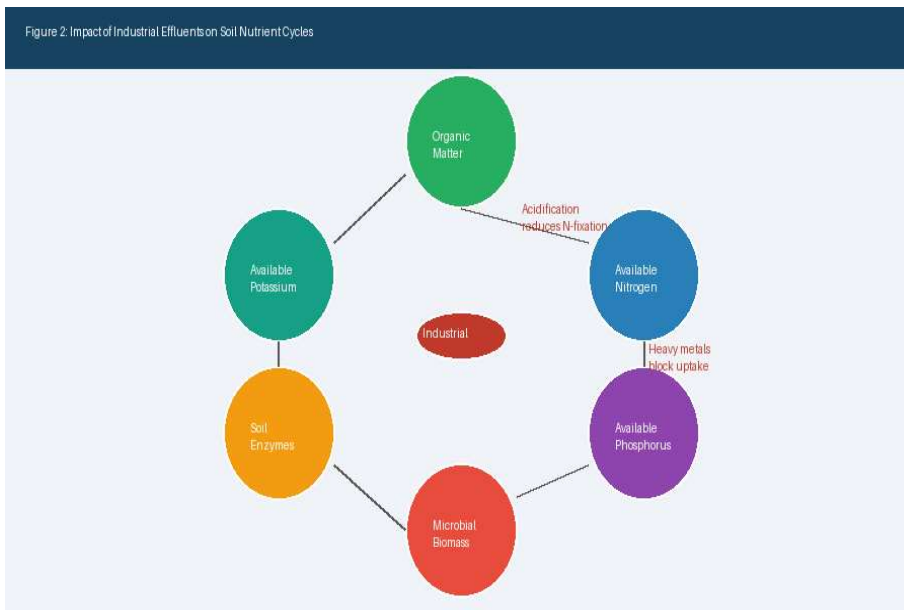


Figure 2: Disruption of Soil Nutrient Cycles by Industrial Effluent Inputs (Conceptual model based on Doran & Zeiss, 2000; Giller et al., 1998; Karaca et al., 2010)



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5. Impact on Soil Microbial Diversity

Microbiota are the functional core of ecosystems. They mineralise organic matter, fix nitrogen, dissolve phosphorus, and control soil-borne pathogens, and provide the "glues" (polysaccharides, fungal hyphae) that hold soil aggregates together. The health of this community, which includes bacteria, archaea, fungi, protozoa, and nematodes, is vital for ecosystem function and productivity. Microbial communities suffer extensive damage from industrial effluents via the multiple stresses of heavy metals, extreme pH, osmotic effects of excessive salts, and toxicity of synthetic organic pollutants.

5.1 Responses of Bacterial and Fungal Communities

Bacterial communities respond to heavy metal stress via a combination of immediate impacts (death) on sensitive species and evolutionary adaptation (enrichment) of metal-tolerant species, which usually comes at the expense of diversity and functional richness. Nannipieri et al. (2003) showed that Shannon diversity indices for soils contaminated with industrial effluents were 40-50% lower than those for uncontaminated soils, as a result of the loss of non-tolerant species. Gram-positive bacteria, with their thick peptidoglycan layers that have the capacity to bind to metals, are relatively resistant, with gram-negative bacteria and nitrogen fixers being the most sensitive.

Fungal communities, especially mycorrhizal fungi, are extremely sensitive to acidification and the presence of heavy metals. Rajapaksha et al. (2004) showed that metal toxicity has a greater impact on fungal biomass and diversity than on bacterial biomass in copper- and zinc-contaminated soils due to the higher metal concentrations in fungal hyphae and spores compared to bacteria. Reduced mycorrhizal diversity results in reduced plant phosphorus absorption, plant growth, and soil aggregate stability, which in turn leads to further soil degradation.

5.2 Bioindicator: Enzyme Activity

Soil enzymes (dehydrogenase, urease, phosphatase, and cellulase) are commonly used as sensitive, multifunctional microbial activity indicators and proxies for soil health. Dehydrogenase, which reflects the overall microbial aerobic respiration, has been reported to decrease by 60-70% in soils contaminated by tannery or mining industry effluents (Karaca et al., 2010). Urease, the enzyme responsible for urea hydrolysis to ammonium, is very sensitive to acidification and Cd²⁺ toxicity: this can affect nitrogen mineralisation. Phosphatase, which is required for the mineralisation of organic phosphorus, is affected by a high concentration of zinc and copper found in textile and electroplating effluents. Table 3 and Figure 3 show microbial diversity and enzyme activities in contaminated (C) and control (K) soils.

Table 3: Soil Microbial Diversity Parameters and Enzyme Activities in Effluent-Affected vs. Control Soils

Microbial Parameter	Control Soil	Effluent Soil	% Change	Dominant Effect	Reference
Total Bacterial Count ($\times 10^6$ CFU/g)	18.4	6.2	-66.3%	Heavy metal toxicity	Nannipieri et al., 2003
Fungal Count ($\times 10^4$ CFU/g)	12.6	3.8	-69.8%	Acidification stress	Rajapaksha et al., 2004
Shannon Diversity Index (H')	3.42	1.87	-45.3%	Species extinction	Abdu et al., 2011
Dehydrogenase Activity (μ g TPF/g/24h)	42.8	14.1	-67.1%	Enzyme inhibition	Karaca et al., 2010

Microbial Parameter	Control Soil	Effluent Soil	% Change	Dominant Effect	Reference
Urease Activity ($\mu\text{g NH}_3\text{-N/g/h}$)	28.6	9.4	-67.1%	pH-mediated inhibition	Doran & Zeiss, 2000
N-fixing Bacteria (%)	8.7	2.1	-75.9%	Acidification + Cr toxicity	Giller et al., 1998

Note: CFU = Colony Forming Units; TPF = Triphenylformazan; H' = Shannon-Wiener diversity index. Data are mean values from comparative field studies.

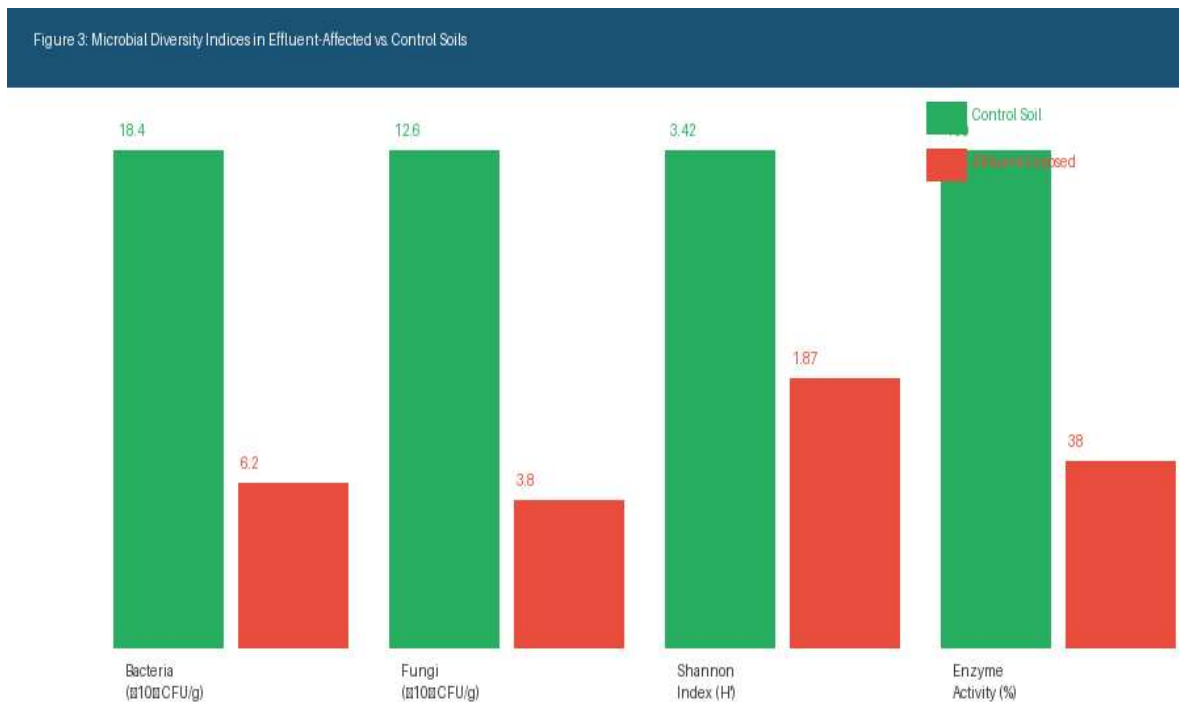


Figure 3: Comparison of Microbial Diversity Indices and Enzyme Activities in Effluent-Exposed vs. Control Soils (Sources: Nannipieri et al., 2003; Rajapaksha et al., 2004; Karaca et al., 2010)

6. Heavy Metal Accumulation and Threshold Exceedance

Industrial effluents contain several persistent and highly ecotoxic metal pollutants. Heavy metals are elemental and thus cannot be degraded by microorganisms, in contrast to organic pollutants, which can undergo mineralisation. Their steady build-up in the soil profile from years of effluent disposal eventually results in concentrations that surpass permissible levels, leading to a series of negative impacts on soil microorganisms, plants, and human health via the food chain.

The most frequently occurring heavy metals in industrial effluent-contaminated soils are lead (Pb), chromium (Cr), cadmium (Cd), zinc (Zn), copper (Cu), and arsenic (As). Table 4 presents concentrations of these metals in soils around the three



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major types of industrial zones, as compared to WHO/FAO guidelines for agricultural soils. This shows that the greatest concentrations of chromium (up to 487 mg/kg; permissible limit: 100 mg/kg) are found in soils contaminated by tanneries, while lead and zinc concentrations are highest in the mining zone. Cadmium is particularly problematic because of its mobility in acidic soils and easy uptake by cereal food crops, and as such becomes an element of chronic risk to human health (Kelly et al., 1999).

Table 4: Heavy Metal Concentrations in Industrial Effluent-Affected Soils vs. WHO/FAO Permissible Limits

Heavy Metal	WHO/FAO Limit (mg/kg)	Textile Effluent Zone (mg/kg)	Tannery Zone (mg/kg)	Mining Zone (mg/kg)	Reference
Lead (Pb)	85	124	298	412	Wuana & Okieimen, 2011
Chromium (Cr)	100	68	487	142	Giller et al., 1998
Cadmium (Cd)	3	8.2	12.4	19.8	Kelly et al., 1999
Zinc (Zn)	300	386	248	724	Singh & Agrawal, 2008
Copper (Cu)	100	142	89	318	Abdu et al., 2011
Arsenic (As)	20	31	44	88	Rajapaksha et al., 2004

Note: All values in mg/kg dry weight. WHO/FAO limits refer to those applicable to agricultural soils for human food production. Bold values exceed permissible limits.

The mobility (bioavailability) of heavy metals, rather than their total concentration, is ultimately responsible for their ecological and toxic effects. The factors affecting bioavailability include pH, organic matter, redox potential, and other competing ions. Acidity increases the solubility of most cationic metals (Pb²⁺, Cd²⁺, Zn²⁺, Cu²⁺), increasing their uptake by plant roots and microorganisms. This results in a particularly pernicious interaction between acidic effluents and metal toxicity: while acidic effluents depress pH, they also "release" metals from soil mineral and organic matter binding sites, exacerbating their toxic effects on soil microbes (Rajapaksha et al., 2004).

7. Remediation and Mitigation Measures

The restoration of soil impacted by industrial effluents calls for a multifaceted approach, involving chemical, biological, agronomic, and legislative measures. There is no one-size-fits-all approach; the choice of remediation measures must be tailored to the type and degree of contamination, land-use goals, and budget.

7.1 Physicochemical Remediation

The most common method of ameliorating soil acidity from industrial effluents today is through liming with agricultural lime (CaCO₃) or dolomite. It increases the pH, precipitates metals as hydroxides or carbonates, and increases base cation saturation on exchange sites. Organic amendments (such as compost, biochar, and press mud) simultaneously increase pH, provide organic carbon for soil, and immobilise metals by complexation and adsorption (Singh & Agrawal, 2008). Biochar, obtained from the pyrolysis of crop residues, is especially attractive; it has a high surface area and permanent carbon structure, and the high pH immobilises heavy metals while storing carbon.



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7.2 Biological Remediation

Phytoremediation uses hyperaccumulators such as *Thlaspi caerulescens* (zinc/cadmium), *Pteris vittata* (arsenic), and *Vetiver zizanioides* (multiple metals) to remove heavy metals from contaminated soils into harvestable shoots for safe disposal or metal recovery. Bioaugmentation, the controlled addition of metal-resistant, plant growth-promoting bacteria and fungi (mycorrhiza), has been successful in pilot studies for the recovery of soil enzyme activity and nutrient cycling processes (Nannipieri et al., 2003). Vermicomposting of contaminated organic wastes with earthworms (*Eisenia fetida*) helps convert toxic organic compounds to less toxic compounds and improve soil structure.

7.3 Regulatory Interventions

Policy and regulatory measures are critical for remediating contaminated sites. The implementation of Zero Liquid Discharge (ZLD) requirements for high pollution-potential industries, as phased out in India as per the Environment Protection Act (1986) and State Pollution Control Board (SPCB) notifications, is essential to curbing the ongoing soil loading with industrial effluents. The installation of continuous monitoring systems for effluent quality and severe penalties for non-compliance provide the regulatory framework to support the sustainable implementation of technical measures. Zoning, which preserves buffer distances between industrial activity and farmlands, irrigation channels, and groundwater recharge areas, offers a precautionary measure against soil pollution.

8. Conclusion

The evidence reviewed and synthesised in this paper unambiguously establishes that industrial effluents impose severe and multi-dimensional damage on soil chemical properties, nutrient cycling efficiency, and microbial community structure and function. pH disruption—whether acidic or alkaline—acts as a primary driver that amplifies the toxicity of heavy metals, immobilises essential nutrients, and suppresses the microbial and enzymatic activity upon which soil fertility depends. The decline in microbial diversity indices, the collapse of nitrifying and nitrogen-fixing communities, and the exceedance of permissible heavy metal concentrations across textile, tannery, and mining effluent zones collectively paint a picture of progressive and accelerating soil degradation in India's rapidly industrialising regions.

The data presented in this study underscore the need for immediate and sustained action at multiple levels: the adoption of cleaner industrial production technologies, the rigorous enforcement of effluent discharge standards, and the deployment of site-specific integrated remediation programmes that combine liming, biochar amendment, phytoremediation, and microbial bioaugmentation. Research gaps remain—particularly regarding the long-term dynamics of microbial community recovery following remediation, the combined effects of mixed effluents on soil biochemistry, and the fate of emerging contaminants (pharmaceuticals, microplastics) in soil systems. Addressing these gaps through well-designed, interdisciplinary field research will be essential to informing evidence-based soil protection policy in India and comparable industrialising contexts worldwide.

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