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Investigation of Electroplating Industrial Wastewater Quality and Its Environmental Impact on Surrounding Soils in Haldia, West Bengal

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Abstract

The electroplating industry plays a significant role in the manufacturing sector by providing corrosion resistance, improved surface finish, and enhanced durability to metallic products. However, the process generates substantial quantities of industrial wastewater containing toxic heavy metals, acids, alkalis, cyanides, and suspended solids, which pose serious environmental concerns if discharged without adequate treatment. Haldia, one of the major industrial hubs of West Bengal, accommodates numerous engineering, chemical, petrochemical, and metal-finishing industries where electroplating operations contribute significantly to industrial effluent generation. Improper disposal of untreated or partially treated electroplating wastewater has emerged as a major source of soil and groundwater contamination in the surrounding areas. Heavy metals such as chromium (Cr), nickel (Ni), copper (Cu), zinc (Zn), lead (Pb), and cadmium (Cd) tend to accumulate in soils due to their non-biodegradable nature, adversely affecting soil fertility, microbial activity, agricultural productivity, and ecosystem health.

The present study aims to investigate the physicochemical characteristics of electroplating industrial wastewater and evaluate its environmental impact on surrounding soils in Haldia, West Bengal. The study proposes the collection of wastewater samples from selected electroplating industries and soil samples from adjacent locations at varying distances from the discharge points. Physicochemical parameters including pH, electrical conductivity (EC), total dissolved solids (TDS), total suspended solids (TSS), biological oxygen demand (BOD), chemical oxygen demand (COD), dissolved oxygen (DO), chloride, sulphate, nitrate, phosphate, hardness, alkalinity, and heavy metal concentrations will be analysed using standard methods prescribed by the American Public Health Association (APHA). Soil samples will be assessed for texture, pH, organic carbon, cation exchange capacity, electrical conductivity, nutrient status, and heavy metal accumulation. Statistical analyses, including descriptive statistics, correlation analysis, and comparative evaluation with national and international environmental standards, will be employed to interpret the findings.

The study is expected to provide comprehensive information regarding the extent of industrial pollution and its influence on soil quality in the Haldia industrial region. The outcomes will assist policymakers, environmental regulatory agencies, and industrial stakeholders in formulating sustainable wastewater management strategies, strengthening

pollution control measures, and promoting environmentally responsible industrial development. Furthermore, the research will contribute valuable baseline information for future environmental monitoring and remediation programmes in industrial regions of eastern India.

Keywords

Electroplating wastewater; Heavy metals; Soil contamination; Environmental pollution; Physicochemical analysis; Industrial effluents; Haldia; West Bengal; Soil quality; Wastewater management.

1. Introduction

Industrialisation has been one of the major driving forces of economic development worldwide. The rapid expansion of manufacturing industries has significantly improved infrastructure, employment opportunities, and technological advancement. However, this industrial growth has simultaneously resulted in the generation of enormous quantities of industrial wastes that threaten environmental sustainability. Among various industrial sectors, the electroplating industry is recognised as one of the major contributors to environmental pollution because of the complex chemical composition of its wastewater. Electroplating processes involve coating metallic surfaces with another metal using electrolytic deposition to improve corrosion resistance, hardness, appearance, electrical conductivity, and wear resistance. During these operations, substantial amounts of wastewater containing toxic chemicals are generated through cleaning, rinsing, pickling, degreasing, plating, and finishing processes.

Electroplating wastewater is characterised by high concentrations of heavy metals such as chromium (Cr), nickel (Ni), copper (Cu), zinc (Zn), cadmium (Cd), lead (Pb), iron (Fe), and manganese (Mn). In addition, industrial effluents often contain cyanides, fluorides, chlorides, sulphates, nitrates, acids, alkalis, detergents, complexing agents, suspended solids, and organic pollutants. The composition of wastewater depends upon the type of electroplating operation, production capacity, chemicals used, and wastewater treatment facilities available in the industry. Because most heavy metals are non-biodegradable, persistent, and capable of bioaccumulation, their discharge into the environment represents a significant ecological and public health concern.

The discharge of untreated or inadequately treated electroplating wastewater into natural water bodies or open land has become a major environmental challenge in developing countries. Industrial wastewater alters the physicochemical characteristics of receiving water bodies and surrounding soils, thereby reducing environmental quality. Soil acts as a natural sink for contaminants due to its ability to adsorb dissolved metals and chemical compounds. Continuous disposal of industrial wastewater results in the gradual accumulation of toxic

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elements in soil, adversely affecting soil fertility, microbial diversity, enzymatic activities, nutrient cycling, and agricultural productivity. Elevated concentrations of heavy metals can inhibit seed germination, retard plant growth, reduce crop yields, and eventually enter the food chain through agricultural produce.

Heavy metals exhibit varying mobility depending upon soil pH, organic matter content, cation exchange capacity, moisture, and redox conditions. Acidic soils generally enhance metal solubility, increasing their availability to plants and microorganisms. Chromium exists mainly in trivalent [Cr(III)] and hexavalent [Cr(VI)] forms, with the latter being highly toxic and carcinogenic. Nickel toxicity affects plant metabolism and microbial activities, whereas excessive copper concentrations interfere with enzymatic functions. Cadmium is regarded as one of the most hazardous heavy metals because of its high toxicity even at low concentrations. Lead accumulation causes irreversible damage to neurological, reproductive, and cardiovascular systems in humans while also reducing plant growth and microbial diversity.

In India, industrialisation has accelerated rapidly during the last three decades, resulting in increasing concerns regarding industrial wastewater management. The electroplating sector comprises thousands of small, medium, and large-scale industries engaged in automobile manufacturing, engineering products, electrical components, electronics, household appliances, defence equipment, and decorative metal finishing. Many small-scale electroplating industries operate with limited financial resources and inadequate wastewater treatment facilities, leading to indiscriminate discharge of toxic effluents into drains, canals, rivers, and agricultural lands.

West Bengal is among the industrially advanced states of eastern India, hosting diversified industries including petrochemicals, fertilisers, engineering, shipbuilding, thermal power generation, pharmaceuticals, textiles, food processing, and metal industries. Haldia, situated in Purba Medinipur district along the banks of the Haldi River, has emerged as one of the state's most important industrial centres. The Haldia industrial complex comprises petrochemical industries, chemical manufacturing units, engineering industries, oil refineries, fertiliser plants, metal fabrication industries, and ancillary engineering workshops. Electroplating operations associated with these industries generate wastewater rich in heavy metals and inorganic pollutants. Improper management of industrial wastewater may contribute significantly to soil degradation and environmental contamination in the surrounding areas.

Soil quality is a crucial component of sustainable ecosystems because it directly influences agricultural productivity, biodiversity, groundwater recharge, and ecological balance. Industrial pollutants alter the physical, chemical, and biological properties of soils by changing pH, electrical conductivity, nutrient availability, organic carbon content, and microbial populations. Continuous accumulation of heavy metals reduces soil productivity

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and increases ecological risks. Therefore, regular monitoring of soil quality in industrial regions has become an essential component of environmental management.

Physicochemical analysis provides a scientific basis for evaluating wastewater quality and identifying pollution sources. Parameters such as pH, electrical conductivity, total dissolved solids, total suspended solids, dissolved oxygen, biological oxygen demand, chemical oxygen demand, chlorides, sulphates, nitrates, phosphates, hardness, alkalinity, and heavy metal concentrations serve as important indicators of industrial pollution. Similarly, soil parameters including pH, organic carbon, cation exchange capacity, texture, moisture content, nutrient status, and metal accumulation provide valuable information regarding environmental degradation.

The Central Pollution Control Board (CPCB), State Pollution Control Boards (SPCBs), and the Ministry of Environment, Forest and Climate Change (MoEFCC) have established regulatory standards for industrial wastewater discharge in India. Nevertheless, effective implementation and continuous environmental monitoring remain major challenges due to rapid industrial expansion and increasing production activities. Scientific assessment of wastewater quality and soil contamination is therefore essential for evaluating compliance with environmental standards and identifying appropriate pollution control measures.

Several researchers have reported elevated concentrations of heavy metals in industrial wastewater and surrounding soils near electroplating industries across India and abroad. These studies indicate that chromium, nickel, copper, zinc, cadmium, and lead frequently exceed permissible limits, posing risks to ecosystems and human health. However, limited systematic investigations have specifically focused on the Haldia industrial region despite its significant industrial importance. A comprehensive assessment integrating wastewater quality with soil physicochemical characteristics is therefore required to understand the environmental implications of electroplating activities in this region.

The present study has been designed to investigate the physicochemical characteristics of electroplating industrial wastewater and evaluate its impact on surrounding soil properties in Haldia, West Bengal. The research intends to generate baseline scientific information regarding wastewater composition, heavy metal contamination, and soil quality deterioration. The findings are expected to contribute to sustainable industrial wastewater management, environmental monitoring, pollution control planning, and formulation of appropriate remediation strategies. Furthermore, the study will support policymakers, environmental scientists, industrial managers, and regulatory authorities in promoting environmentally responsible industrial development while ensuring the protection of soil resources and ecological health.

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2. Review of Literature

2.1 Introduction

Electroplating industries are among the major contributors to industrial pollution due to the discharge of wastewater containing high concentrations of heavy metals, acids, alkalis, cyanides, and various inorganic salts. These contaminants significantly alter the physicochemical properties of soil and water, leading to ecological imbalance and potential risks to human health. Numerous researchers have investigated the characteristics of electroplating wastewater, heavy metal contamination, soil quality degradation, and appropriate remediation strategies. The following review summarizes selected studies relevant to the present investigation.

2.2 Review of Previous Studies

Study 1: Fu and Wang (2011)

Fu and Wang (2011) reviewed the occurrence, toxicity, and removal technologies for heavy metals in industrial wastewater. Their study highlighted that electroplating industries generate wastewater containing chromium, nickel, copper, zinc, cadmium, and lead at concentrations that may exceed permissible discharge standards. The authors discussed chemical precipitation, ion exchange, adsorption, membrane filtration, and electrochemical treatment as major removal techniques. They concluded that heavy metals are persistent pollutants requiring integrated treatment approaches for effective environmental protection.

Relevance to the present study: Provides the scientific basis for analysing heavy metal contamination in electroplating wastewater.

Study 2: Barakat (2011)

Barakat (2011) investigated recent advances in heavy metal removal from industrial wastewater. The study emphasized that electroplating wastewater is one of the principal sources of toxic metal contamination worldwide. Conventional treatment technologies were found to be effective under controlled conditions, although operational cost and sludge generation remain significant limitations. The author recommended combining physicochemical and biological treatment methods to improve removal efficiency.

Research implication: Highlights the need for regular wastewater quality assessment before disposal into the environment.

Study 3: Tchounwou et al. (2012)

Tchounwou and co-workers (2012) examined the toxicological effects of heavy metals on human health and ecosystems. The study reported that chromium, cadmium, lead, mercury, arsenic, and nickel exhibit significant toxicity due to bioaccumulation and biomagnification. Long-term exposure may cause neurological disorders, kidney damage, respiratory diseases, reproductive abnormalities, and cancer. The authors emphasized continuous environmental monitoring in industrial regions.

Research implication: Demonstrates why heavy metal monitoring is essential around electroplating industries.

Study 4: Alloway (2013)

Alloway (2013) presented a comprehensive discussion on heavy metals in soils, including their sources, transport mechanisms, accumulation patterns, and environmental behaviour. Industrial wastewater, atmospheric deposition, mining, and municipal wastes were identified as major contributors to soil contamination. Soil pH, organic matter, clay content, and cation exchange capacity were reported as critical factors controlling metal mobility.

Research implication: Supports the evaluation of soil physicochemical properties in the present investigation.

Study 5: Jaishankar et al. (2014)

Jaishankar et al. (2014) reviewed the environmental and human health effects associated with heavy metal exposure. The authors reported that electroplating wastewater contributes significantly to chromium, nickel, copper, cadmium, and lead contamination. Heavy metals were found to inhibit microbial activity, reduce soil fertility, and adversely affect agricultural productivity. The study recommended strict industrial wastewater management practices.

Research implication: Provides evidence linking industrial effluents with soil degradation.

Study 6: Saha et al. (2017)

Saha and colleagues (2017) assessed heavy metal contamination in industrial areas of eastern India using pollution indices and ecological risk assessment methods. Elevated concentrations of chromium, lead, copper, and zinc were detected in soils near industrial installations. The study concluded that prolonged industrial discharge leads to significant deterioration of soil quality and increases ecological risk.

Research implication: Supports pollution index–based assessment for industrial soils.

Study 7: Kumar et al. (2018)

Kumar et al. (2018) investigated physicochemical characteristics and heavy metal concentrations in industrial wastewater from metal-finishing industries. Wastewater samples showed elevated electrical conductivity, total dissolved solids, chemical oxygen demand, and heavy metal concentrations compared with regulatory standards. The study emphasized periodic monitoring to minimize environmental risks.

Research implication: Demonstrates the importance of analysing key wastewater quality parameters.

Study 8: Singh et al. (2019)

Singh et al. (2019) evaluated the influence of industrial effluents on agricultural soils surrounding industrial estates. Significant changes in soil pH, electrical conductivity, organic carbon, and nutrient availability were observed in contaminated locations. Heavy metal accumulation was higher near wastewater discharge channels and gradually decreased with increasing distance from the source.

Research implication: Supports spatial sampling of soils around electroplating industries.

Study 9: Kumar and Maiti (2020)

Kumar and Maiti (2020) examined industrial wastewater management in eastern India with particular emphasis on heavy metal pollution and sustainable treatment practices. The authors stressed that industrial clusters require continuous environmental monitoring, effective effluent treatment plants, and compliance with environmental regulations. Failure to implement these measures could result in long-term soil and groundwater degradation.

Research implication: Reinforces the need for environmental monitoring in industrial hubs such as Haldia.

Study 10: Gupta et al. (2022)

Gupta et al. (2022) investigated the impact of industrial wastewater irrigation on soil physicochemical properties and heavy metal accumulation. The researchers reported increased concentrations of chromium, nickel, copper, zinc, and lead in irrigated soils, along with changes in soil pH, salinity, and nutrient status. The study recommended regular environmental surveillance and sustainable wastewater management to protect soil health.

Research implication: Provides recent evidence on the environmental consequences of industrial wastewater disposal.

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2.3 Comparative Summary of Previous Studies

Author(s)	Year	Study Area	Major Focus	Key Findings
Fu & Wang	2011	Review	Heavy metal removal	Heavy metals are persistent pollutants requiring integrated treatment methods.
Barakat	2011	Review	Industrial wastewater treatment	Conventional treatment methods have operational limitations; combined approaches improve efficiency.
Tchounwou et al.	2012	Global	Heavy metal toxicity	Heavy metals pose serious ecological and human health risks.
Alloway	2013	Global	Heavy metals in soils	Soil properties strongly influence heavy metal mobility and retention.
Jaishankar et al.	2014	Review	Heavy metal contamination	Heavy metals reduce soil fertility and threaten ecosystem health.
Saha et al.	2017	Eastern India	Soil contamination	Industrial activities significantly increase heavy metal concentrations in soils.
Kumar et al.	2018	India	Wastewater quality	Industrial wastewater often exceeds permissible physicochemical limits.
Singh et al.	2019	India	Soil quality	Wastewater discharge alters soil physicochemical characteristics.
Kumar & Maiti	2020	Eastern India	Wastewater management	Continuous monitoring and treatment are essential for pollution control.
Gupta et al.	2022	India	Soil pollution	Long-term wastewater exposure increases heavy metal accumulation and soil degradation.

2.4 Research Gap

The literature demonstrates that electroplating industries are important sources of heavy metal pollution and that untreated industrial wastewater can adversely affect soil quality. Although numerous investigations have evaluated electroplating effluents in different industrial regions, comprehensive studies integrating wastewater physicochemical characteristics with surrounding soil properties remain limited for the Haldia industrial region of West Bengal. In particular, there is a lack of location-specific information on wastewater quality, heavy metal accumulation, and their influence on soil physicochemical properties in this industrial cluster. The present study aims to address this gap by simultaneously assessing wastewater quality and soil characteristics to generate baseline environmental data that can support pollution control and sustainable industrial management.

3. Research Objectives

The present investigation has been undertaken with the following objectives:

General Objective

To investigate the physicochemical characteristics of electroplating industrial wastewater and evaluate its environmental impact on surrounding soil properties in Haldia, West Bengal.

Specific Objectives

1. To analyse the physicochemical characteristics of electroplating industrial wastewater.
2. To determine the concentration of selected heavy metals in wastewater.
3. To evaluate the physicochemical properties of soils surrounding electroplating industries.
4. To assess the accumulation of heavy metals in contaminated soils.
5. To compare the observed values with CPCB, BIS, and WHO permissible standards.
6. To evaluate the relationship between wastewater quality and soil degradation.
7. To recommend suitable wastewater management and pollution control strategies.

4. Research Hypotheses

H_0 (Null Hypothesis)

Electroplating industrial wastewater has no significant effect on the physicochemical properties of surrounding soils.

H_1 (Alternative Hypothesis)

Electroplating industrial wastewater significantly alters the physicochemical properties of surrounding soils.

5. Materials and Methods

5.1 Study Area

Haldia is situated in the Purba Medinipur district of West Bengal and is one of the largest industrial centres in eastern India. The industrial belt consists of petrochemical industries, engineering industries, shipbuilding units, fertilizer plants, oil refineries, chemical industries and metal finishing industries.

Several electroplating workshops are located within the industrial estate. Wastewater generated from these industries is discharged either into drainage channels or treated through effluent treatment plants before disposal.

The climatic condition is tropical with annual rainfall of approximately 1600–1700 mm. The dominant soil type is alluvial soil.

5.2 Collection of Wastewater Samples

Wastewater samples will be collected from:

- Inlet of electroplating unit
- Outlet of electroplating unit
- Final discharge point

Three replicate samples will be collected from each location.

Samples will be stored in sterilized polyethylene bottles and preserved at 4°C before laboratory analysis.

5.3 Collection of Soil Samples

Soil samples will be collected at different distances from wastewater discharge points.

Sampling Site	**Distance**
S1	0 m
S2	100 m
S3	250 m
S4	500 m
Control	Uncontaminated Area

Soil samples will be collected from a depth of 0–15 cm.

6. Laboratory Analysis

6.1 Wastewater Parameters

The following parameters will be analysed according to APHA (2023).

Parameter	**Method**
pH	Digital pH Meter
Electrical Conductivity	Conductivity Meter
Total Dissolved Solids	Gravimetric Method
Total Suspended Solids	Filtration Method

Dissolved Oxygen	Winkler Method
BOD	Five-day Incubation
COD	Dichromate Method
Chloride	Argentometric Method
Sulphate	Turbidimetric Method
Nitrate	UV Spectrophotometer
Phosphate	Spectrophotometer
Heavy Metals	Atomic Absorption Spectrophotometer (AAS)/ICP-OES

6.2 Soil Parameters

The following properties will be determined.

Parameter	**Method**
Soil pH	Digital pH Meter
EC	Conductivity Meter
Organic Carbon	Walkley–Black Method
Moisture Content	Oven Dry Method
Texture	Hydrometer Method
Available Nitrogen	Kjeldahl Method
Available Phosphorus	Olsen Method
Available Potassium	Flame Photometer
Heavy Metals	AAS/ICP-OES

7. Statistical Analysis

The experimental data will be statistically analysed using SPSS Version 26 and Microsoft Excel.

The following statistical techniques will be applied:

- Descriptive Statistics

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- Mean
- Standard Deviation
- Coefficient of Variation
- Pearson Correlation
- One-way ANOVA
- Principal Component Analysis (PCA) (optional)
- Pollution Index Calculation
- Geoaccumulation Index
- Contamination Factor
- Pollution Load Index

The level of significance will be considered at **$P < 0.05$**.

8. Results and Discussion (Hypothetical Data for Demonstration Only)

8.1 Physicochemical Characteristics of Electroplating Wastewater

Table 8.1 Physicochemical Characteristics of Electroplating Wastewater

Parameter	Unit	Observation	CPCB Standard	Status
pH	-	5.62	5.5–9.0	Within limit
Electrical Conductivity	µS/cm	2845	--	High
Total Dissolved Solids	mg/L	1850	2100	Within limit
Total Suspended Solids	mg/L	268	100	Above limit
Dissolved Oxygen	mg/L	2.8	>4	Low
BOD	mg/L	86	30	Above limit
COD	mg/L	324	250	Above limit
Chloride	mg/L	382	1000	Within limit

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Sulphate	mg/L	198	1000	Within limit
Nitrate	mg/L	18.6	50	Within limit
Phosphate	mg/L	7.8	--	Moderate

The illustrative results suggest that electroplating wastewater possesses a high organic and inorganic pollution load. Elevated BOD and COD indicate the presence of biodegradable and non-biodegradable contaminants, while high TSS reflects suspended particulate matter generated during plating and rinsing operations. The low dissolved oxygen level indicates poor water quality that could adversely affect aquatic ecosystems if discharged untreated.

8.2 Heavy Metal Concentration in Wastewater

Table 8.2 Heavy Metal Concentration

Heavy Metal	**Observation (mg/L)**	**CPCB Limit (mg/L)**	**Status**
Chromium (Cr)	2.35	2.0	Above
Nickel (Ni)	3.14	3.0	Slightly Above
Copper (Cu)	2.72	3.0	Within
Zinc (Zn)	4.95	5.0	Within
Lead (Pb)	0.41	0.10	Above
Cadmium (Cd)	0.12	0.01	Above

The hypothetical data indicate that chromium, lead, and cadmium exceed the permissible limits, suggesting a potential environmental risk. Nickel is marginally above the guideline value, whereas copper and zinc remain within the assumed permissible range. If such conditions were observed in practice, continuous discharge could contribute to long-term contamination of surrounding soils.

8.3 Soil Physicochemical Properties

Table 8.3 Soil Quality at Different Sampling Sites

Parameter	**Control**	**S1**	**S2**	**S3**	**S4**
pH	7.12	6.15	6.38	6.65	6.89
EC (µS/cm)	432	1165	984	735	548

Organic Carbon (%)	0.84	0.62	0.66	0.71	0.79
Available N (kg/ha)	286	218	236	252	271
Available P (kg/ha)	24.6	17.2	18.8	20.5	22.8
Available K (kg/ha)	242	184	195	208	226

The illustrative data suggest a decline in soil quality near the wastewater discharge point. Soil pH becomes slightly acidic, electrical conductivity increases substantially, and available nutrients decrease compared with the control site. These trends are consistent with the expected influence of industrial wastewater on soil properties.

8.4 Heavy Metal Accumulation in Soil

Table 8.4 Heavy Metal Concentration in Soil

Metal	**Control (mg/kg)**	**S1**	**S2**	**S3**	**S4**
Chromium	24	86	71	55	39
Nickel	18	69	55	42	28
Copper	21	64	56	44	30
Zinc	58	132	118	94	73
Lead	12	49	42	33	20
Cadmium	0.5	3.6	2.8	2.0	1.1

The illustrative soil data show the highest heavy metal concentrations at Site S1, closest to the discharge point, with concentrations decreasing progressively with distance. Such a pattern is commonly observed where wastewater is the principal source of contamination.

8.5 Correlation Analysis

Table 8.5 Pearson Correlation Matrix

Variable	**EC**	**TDS**	**BOD**	**COD**	**Cr**
EC	1.00	0.94	0.71	0.69	0.78
TDS	0.94	1.00	0.73	0.72	0.81
BOD	0.71	0.73	1.00	0.92	0.66
COD	0.69	0.72	0.92	1.00	0.64

Chromium	0.78	0.81	0.66	0.64	1.00

The illustrative correlation matrix suggests strong positive relationships between electrical conductivity, total dissolved solids, and chromium concentration. BOD and COD also exhibit a strong positive correlation, indicating that increases in organic pollution are associated with higher chemical oxygen demand.

Findings

- Wastewater exhibits high EC, BOD, COD, and TSS.
- Chromium, lead, and cadmium exceed assumed regulatory limits.
- Soil quality deteriorates near wastewater discharge locations.
- Heavy metal concentrations decrease with increasing distance from the source.
- Soil electrical conductivity is positively associated with heavy metal accumulation.

Conclusion

The present study highlights the environmental significance of monitoring electroplating industrial wastewater and its potential impact on surrounding soil quality in Haldia, West Bengal. The illustrative assessment indicates that electroplating wastewater may contain elevated concentrations of organic pollutants and heavy metals, which can adversely influence soil physicochemical properties when discharged without adequate treatment. Continuous exposure to such effluents may increase soil salinity, alter soil pH, reduce nutrient availability, and promote the accumulation of toxic metals, thereby affecting soil fertility, agricultural productivity, and ecosystem health. These findings emphasize the importance of efficient effluent treatment systems, regular environmental monitoring, and strict compliance with pollution control standards to minimize ecological risks. Sustainable wastewater management practices, coupled with periodic assessment of soil and water quality, are essential for protecting natural resources in industrial regions. Future investigations based on comprehensive field sampling and laboratory analyses will further strengthen the understanding of contamination patterns and support evidence-based environmental management and remediation strategies.

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