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Assessing Soil Contamination for Sustainable Waste Management: A Case Study of Municipal and Industrial Waste Impact in Haryana

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ABSTRACT
This study explores the critical interrelationship between soil chemistry and effective waste management practices in Haryana. The state faces severe challenges related to the management of municipal and industrial waste as urbanization and industrial activities accelerate leading to significant soil contamination. The study highlights the improper waste disposal practices that result in elevated concentrations of heavy metals, persistent organic pollutants, and other hazardous substances that alter key soil properties such as pH, electrical conductivity, and organic carbon content. The implications of these changes threaten soil fertility, disrupt microbial activity, and increase the risk of bioaccumulation, thereby jeopardizing agricultural sustainability and groundwater quality. The study emphasizes the importance of understanding soil chemistry in assessing contamination risks and developing sustainable waste management strategies. The study discusses about how soil components interact with contaminants by examining the behavior, transformation, and mobility of pollutants within soil ecosystems that influences their availability in soil and potential harm to human health and the environment. The study has highlighted the gaps in waste management infrastructure, particularly in leachate control and hazardous waste regulation, while also assessing advanced remediation strategies such as chemical stabilization, bioremediation, and phytoremediation. Sustainable soil recovery requires integrated approaches combining regulatory enforcement, periodic monitoring and adaptive remediation methods. The study emphasizes the need for scientific waste management policies to mitigate soil degradation, protect agricultural productivity, and ensure long-term ecological resilience in Haryana.

Keywords: *Haryana, Industrial Waste, Municipal Solid Waste, Soil chemistry, Soil contamination Sustainable Waste Management.*

1. INTRODUCTION

Sustainable waste management is crucial for maintaining ecological balance and safeguarding public health making it an integral component of preservation of the environment and urban planning. Waste generation has surged at an unparalleled rate in urban and industrial settings due to the rapid expansion of cities and industries that has necessitated the need for effective and sustainable management approaches (Dutta and Jinsart, 2020). Effective waste management is essential for achieving environmental resilience, as improper waste disposal leads to pollution, resource depletion, and global climate change. In developed nations, waste management systems are often well-structured, incorporating advanced technologies such as waste-to-energy conversion, recycling infrastructure, and stringent regulatory frameworks. Countries like Sweden and Germany have successfully implemented circular economy models where waste is minimized through systematic reuse and recovery processes (Marino and Pariso, 2020). However, in developing countries, waste management remains a significant challenge due to inadequate infrastructure, financial constraints, and lack of public awareness (Kwakye et al., 2024). Many urban centers in developing nations struggle with overflowing landfills, unregulated dumping, and inefficient waste segregation, leading to severe environmental and health hazards. India, as a rapidly urbanizing and industrializing country faces immense waste management challenges. The country generates millions of tons of municipal solid waste annually, with a significant portion remaining untreated or improperly disposed (Majumder et al., 2024). Urban areas, particularly megacities like Delhi and Mumbai, experience mounting pressure on landfill sites while industrial zones contribute hazardous waste that threatens soil and water quality (Varma et al., 2021). Municipal and industrial wastes significantly alter soil chemistry, leading to contamination and long-term environmental degradation (Mor and Ravindra, 2023). Municipal waste, often composed of organic matter, plastics, and heavy metals, contributes to soil pollution through leachate formation, which increases electrical conductivity and disrupts the natural balance of essential nutrients. Industrial waste, particularly from manufacturing and chemical processing, introduces hazardous contaminants such as heavy metals, petroleum hydrocarbons, and persistent organic pollutants, which accumulate in soil matrices and affect its physicochemical properties. These pollutants alter soil pH, reduce organic carbon content, and interfere with microbial activity, ultimately compromising soil fertility and its ability to support vegetation (Innocent et al., 2024). Additionally, toxic elements such as lead, cadmium, and arsenic from industrial effluents pose serious risks of bioaccumulation that affects groundwater quality and risks the safety of food chain (Rehman et al., 2021). Over time, the continuous deposition of municipal and industrial waste leads to soil degradation making remediation efforts increasingly complex. The increasing volume of municipal and industrial waste has increased concerns regarding soil pollution necessitating sustainable waste management strategies that integrate soil chemistry principles. Soil chemistry plays a fundamental role in waste management by facilitating the understanding of degradation, retention, and mobility of contaminants within the soil. The composition of soil, including its pH, electrical conductivity, organic carbon content, and micronutrient levels determines how contaminants interact with the environment. Inadequate waste disposal practices lead to alterations in soil chemistry, resulting in contamination that affects soil fertility, groundwater quality, and overall ecosystem stability.

2. ROLE OF SOIL CHEMISTRY IN CONTAMINATION RISK ASSESSMENT

Soil chemistry plays a pivotal role in contamination risk assessment by governing the behavior, transformation and bioavailability of pollutants in terrestrial ecosystems. The interaction between contaminants and soil components such as minerals, organic matter, and microorganisms determines whether pollutants remain immobilized or become mobile influencing their potential to harm human and environmental health (Petruzzelli et al., 2025). For instance, soil minerals like clays and short-range-ordered (SRO) iron/aluminum oxides adsorb contaminants through mechanisms such as electrostatic attraction, complexation, and precipitation, effectively reducing their mobility. The chemical properties of soil especially mineral composition, pH, redox potential, and cation exchange capacity directly influence the fate and transport of the contaminants (Sarkar et al., 2021). When inorganic pollutants enter the soil, their mobility and potential to cause harm are largely determined by how they interact with soil minerals. Clays and oxides of iron, aluminum, and manganese are especially important in this context, as they possess charged surfaces that can adsorb metal ions through processes like ion exchange, surface complexation, and precipitation. Organic matter further enhances this sequestration by forming stable complexes with heavy metals and organic pollutants, while soil pH and redox conditions modulate speciation critical for elements like arsenic, which becomes more toxic in its oxidized form (As^{3+}) under aerobic conditions (Tufail et al., 2022). These chemical interactions create a dynamic equilibrium between solid and solution phases, dictating the fraction of contaminants accessible for uptake by plants or leaching into groundwater.

A crucial aspect of assessing contamination risk is understanding the bioavailability of inorganic pollutants which is the proportion that is accessible to plants, animals, and humans. Traditional risk assessments often relied on total contaminant concentrations but it is now well recognized that only a fraction of the total is chemically available for uptake (Latosińska et al., 2021). Modern approaches use selective extraction techniques and speciation analysis to estimate the bioavailable pool, which is more relevant for predicting actual exposure and risk. For example, lead bound within the crystal structure of minerals like pyromorphite is far less bioavailable than lead adsorbed onto clay surfaces or present as soluble salts. Advances in analytical techniques, such as X-ray absorption spectroscopy, have made it possible to directly observe the chemical forms of metals in soils greatly improving the accuracy of risk predictions (Pinskii et al., 2022). Spatial variability within soils further complicates risk assessment. Even within a single contaminated site, differences in mineralogy, texture, and micro-environmental conditions can lead to significant heterogeneity in contaminant distribution and mobility (Milinovic et al., 2024). For example, sandy soils with low clay and oxide content typically have less capacity to retain metal ions, making them more susceptible to groundwater contamination. In contrast, clay- rich soils with abundant iron and aluminum oxides can act as effective sinks for metals, although changes in environmental conditions such as acid rain or waterlogging can disrupt this stability and release previously immobilized contaminants. Ultimately, an in-depth understanding of soil chemistry is essential for designing effective remediation strategies and for long-term monitoring of contaminated sites. Therefore, it becomes crucial to ensure long-term monitoring of soil pH, redox potential, and contaminant speciation which ensures that stabilization remains effective despite environmental stressors.

3. SOIL CHEMISTRY AND WASTE MANAGEMENT

The extent of pollution in soil environments is largely dictated by the interaction between soil components and waste materials, directly influencing soil health, groundwater quality, and overall environmental stability. Among the key parameters governing this interaction, soil pH plays a critical role in determining the solubility and mobility of contaminants, influencing whether pollutants remain bound to soil particles or leach into deeper layers (Kicińska et al., 2022). Electrical conductivity serves as an indicator of dissolved salts and pollutants, often reflecting the degree of contamination from industrial discharge, landfill leachates, or improper waste disposal (Saghi et al., 2024). Organic matter, on the other hand, contributes to the retention of pollutants by acting as a binding medium for heavy metals and organic contaminants, regulating their mobility and bioavailability (Tufail et al., 2022). These factors collectively define the soil's ability to either contain harmful substances or facilitate their movement into surrounding ecosystems. One of the primary aspects of soil chemistry in waste management is pH regulation, which affects the solubility and mobility of contaminants. Acidic or alkaline conditions can alter the behavior of heavy metals, organic pollutants, and industrial effluents, leading to either increased retention or leaching into surrounding ecosystems. Soil pH influences the solubility and bioavailability of contaminants, particularly heavy metals and organic pollutants. In acidic soils, metals such as lead, cadmium, and arsenic tend to become more soluble, increasing their mobility and potential for groundwater contamination (Taneja et al., 2023). Conversely, alkaline conditions can lead to the precipitation of certain metals, reducing their availability but potentially causing long-term accumulation in soil matrices (Awasthi, et al., 2022). Electrical conductivity is another critical parameter, indicating the presence of dissolved salts and pollutants in soil. High conductivity levels often signal contamination from industrial discharge, landfill leachates, or improper waste disposal practices. High conductivity values often signal the presence of industrial effluents, landfill leachates, or excessive fertilizer application, all of which contribute to soil degradation (Ratna et al., 2021). Increased conductivity can disrupt soil structure, affecting water retention and nutrient availability. In waste disposal sites, leachates containing dissolved salts and toxic compounds can alter soil conductivity, leading to increased pollutant mobility. This can result in the spread of contaminants beyond the disposal area, affecting surrounding ecosystems and water sources. Organic matter plays a significant role in pollutant retention by acting as a binding agent for contaminants. The presence of organic carbon enhances soil's ability to adsorb heavy metals and organic pollutants, reducing their mobility and mitigating environmental risks. However, excessive waste accumulation particularly from municipal sources can disrupt organic matter decomposition, leading to anaerobic conditions and the release of harmful gases such as methane (Ingole and Dhawale, 2021). Industrial waste that includes petroleum hydrocarbons and persistent organic pollutants further complicates soil chemistry by introducing toxic compounds that degrade slowly and accumulate over time. Furthermore, heavy metal contamination is a significant concern in contaminated soil. Metals such as lead, cadmium, arsenic, and mercury originate from industrial effluents, electronic waste and improper disposal of hazardous materials (Kumar et al., 2023). These elements bind to soil particles that affect plant uptake and ultimately pose risks to human health through bioaccumulation. The interaction between soil chemistry and waste management is particularly evident in landfill sites, industrial zones, and urban waste disposal areas. In landfills, leachate formation alters soil composition by introducing dissolved organic matter, heavy metals, and toxic compounds. Industrial waste disposal, especially in regions with inadequate regulatory oversight, leads to long-term contamination, affecting soil fertility and groundwater reserves. Urban waste, including untreated sewage and improperly discarded materials, further exacerbates soil degradation making remediation efforts increasingly complex.

4. MUNICIPAL AND INDUSTRIAL WASTE CHALLENGES IN HARYANA

Haryana is a rapidly industrializing state in India that faces significant challenges related to municipal and industrial waste management. The generation of waste has surged as urbanization and industrial activities increase leading to a range of environmental, human safety and economic concerns that need urgent attention. Haryana generates approximately 5,640 tonnes of municipal solid waste (MSW) daily (Haryana State Pollution Control Board, 2023). The state's urban population is concentrated mainly in the Ghaggar and Yamuna catchments, with estimated sewage generation of 291.46 million liters per day (MLD) and 1,098 MLD, respectively. Hazardous waste generation across Haryana totals around 200,298 tonnes annually, reflecting the state's growing industrial activity. Several districts across Haryana contribute significantly to the state's municipal solid waste (MSW) generation, reflecting patterns of urbanization and industrial activity. In Rohtak and its cluster, which includes Kalanaur, Meham, Gohana, Bahadurgarh, Kharkhoda, Julana, Jhajjar, Sampla, and Beri, the combined MSW generation is about 601 tonnes per day (Rao et al., 2024). Panchkula, which encompasses Panchkula and Kalka, generates around 215 tonnes per day (Rana et al., 2017). Panipat grouped with Samalkha and Israna is recognized as a significant urban center with substantial waste output due to its industrial and residential population (Tanwer et al., 2022). Sonipat district also has high waste generation with its municipal corporation generating about 200 tonnes per day of waste for a population of 427,270 (Dahiya, 2015). Other towns in Sonipat district such as Kharkhoda, Gohana, Ganaur, and Kundli generate 20 tonnes per day, 32 tonnes per day, 18 tonnes per day, and 17 tonnes per day respectively. The rural blocks in Sonipat, including Ganaur, Gohana, Kharkhoda, Kathura, Murthal, Mundlana, Rai, and Sonipat blocks, each contribute between 22 and 35 tonnes per day to the total waste output in the district. Hisar and its associated towns that include Barwala, Hansi, and Siwani along with Fatehabad, Bhuna, Uklana Mandi, Ratia, Tohana, and Jhakal Mandi, collectively generate about 407 tonnes per day of MSW. Sirsa, together with Rania, Ellenabad, Kalanwali, and Mandi Dabwali, produces approximately 168 tonnes per day (Nain et al., 2021). Other districts also contribute notably: Ambala and Yamunanagar together with their sub-towns generate 675 tonnes per day; Karnal, Kaithal, and Kurukshetra together with their towns produce 590 tonnes per day ; Jind and its towns generate 181 tonnes per day ; Bhiwani and its associated towns produce 155 tonnes per day (Sangwan et al., 2025). Gurugram which is one of the largest cities in Haryana produces over 1,000 tonnes per day of municipal solid waste, with daily per capita waste generation at 320 grams (Sharma, 2021). Projections indicate that Gurugram's MSW could reach 2,900 tonnes per day by 2041, with kitchen waste making up 71% of the total, recyclables 12%, and inert waste 17%. Rohtak city produces about 150 tonnes per day of solid waste, with a per capita generation of 0.35 kg (Deswal and Laura, 2018). The majority of this waste (74%) comes from residential sources, followed by markets (14%), with smaller contributions from industrial, medical, hotel, institutional, and other sources. The projected population of Ambala for 2025 is 564,860, with anticipated MSW generation of 435 tonnes per day, rising to 522 tonnes per day by 2035 as the population grows to 677,832 (Sangwan et al., 2025). Rewari city, with a population of 322,996 in 2017, generated 197 tonnes per day of MSW; this is expected to increase to 236 tonnes per day by 2025 and 335 tonnes per day by 2035 as the population approaches 465,114. Faridabad, another major urban center, currently has a population of about 1,438,855 and generates between 204 and 293.53 tonnes per day of solid waste, depending on the source and year (Singh and Satija, 2018). Palwal, with a population of 154,998, produces between 21.23 and 44.08 tonnes per day of MSW, with projections indicating a significant increase as the city grows (Kumar and Sharma, 2019).

The rapid growth of population and urban areas contributes to this increase, with many municipalities struggling to keep pace. A significant issue is the inadequate waste management infrastructure that plagues many local governments. The lack of public awareness surrounding waste management practices exacerbates the problem. Many residents are not fully informed about the importance of waste segregation and recycling, leading to a situation where mixed waste is often disposed of together. This complicates the recycling process and diminishes the effectiveness of waste management efforts. Moreover, improper waste disposal can lead to various health issues for residents, including respiratory diseases and vector-borne illnesses due to stagnant waste and open dumping. Landfill management presents another significant challenge. Existing landfills are often overburdened and poorly managed, raising concerns about their environmental impact. The leachate produced from these sites can contaminate soil and groundwater, posing long-term risks to both human health and the ecosystem. Haryana is home to a diverse range of industries, including textiles, chemicals, and manufacturing. Each sector generates different types of waste, adding complexity to the management of industrial waste. Many industries struggle to comply with environmental regulations due to a lack of knowledge or resources. This often leads to illegal dumping and significant environmental degradation. Additionally, there is a shortage of adequate facilities for the treatment and disposal of hazardous industrial waste. The improper disposal and management of municipal and industrial waste in Haryana have significantly contributed to soil contamination, posing environmental and public health risks. Municipal solid waste, often disposed of in open dumps or poorly managed landfill sites, leads to the leaching of hazardous substances into the soil, altering its composition and reducing fertility. Industrial waste, particularly from manufacturing units, contains heavy metals, chemical residues, and untreated effluents that seep into the ground exacerbating contamination levels. The Haryana State Pollution Control Board has outlined regulations for solid waste management yet enforcement remains inconsistent, allowing pollutants to persist in the environment.

5. SOIL CONTAMINATION IN HARYANA

Soil contamination in Haryana has emerged as a critical environmental concern largely driven by rapid industrialization, urbanization and agricultural practices. These chemicals can accumulate in the soil over time, altering its composition and adversely affecting crop yields and food safety. Additionally, the industrial growth and expansion in Haryana has introduced various pollutants into the soil. Industries such as textiles, chemicals, and manufacturing release hazardous waste, which often finds its way into the soil due to inadequate waste management practices (Maheshwari et al., 2008). Heavy metals, solvents, and other toxic substances can leach into the ground, contaminating the soil and posing serious health risks to local communities. The presence of these contaminants not only threatens agricultural productivity but also affects the health of those living in proximity to contaminated sites, leading to potential long-term consequences. Improper disposal of solid waste, including plastic and electronic waste also contributes to soil pollution. This urban waste often contains hazardous materials that can leach into the soil, further complicating the contamination problem. The combination of industrial, agricultural and urban factors creates a multifaceted challenge that requires urgent attention.

Studies in Mewat district found that while concentrations of arsenic (As), cadmium (Cd), and nickel (Ni) in soils were below toxicity thresholds, iron (Fe), manganese (Mn), zinc (Zn), and copper (Cu) often exceeded safe levels, indicating pollution from mixed sources both natural and human activities (Krishan et al., 2018). In Hisar district, research focused on brick kiln areas revealed that heavy metal contamination including Cd, Pb, Cr, Zn, Cu, and Fe was higher after the monsoon, with seasonal variations and gradual soil degradation noted over time (Kumar and Sharma, 2020). A study on arsenic and physicochemical properties of soil around a municipal waste dumpsite in Rohtak city, Haryana, found that soil samples collected within a 2 km radius of the dumpsite showed arsenic contamination ranging from 410 ppb to 840 ppb, with an average of 618 ppb (Rao et al., 2024). The contamination was attributed to leachate from the landfill. In Gurugram district, Haryana, nitrate pollution in groundwater is a significant issue. Among 156 villages surveyed, 34 villages had nitrate concentrations exceeding the permissible limit of 45 mg/l (Srivastava et al., 2023). In addition to metal pollution, western Haryana faces challenges with soil salinity and alkalinity, particularly in districts such as Hisar and Bhiwani, where high pH and low infiltration rates contribute to waterlogging and reduced agricultural productivity (Sethi et al., 2012). The study on soil degradation in central Haryana's Indo-Gangetic Plain revealed significant salinity issues in low-lying, poorly drained irrigated soils in southern and central Haryana. For instance, Jhajjar district had 13.99% of its area affected by emerging salinity, while Sirsa district also exhibited severe salinity problems. Another study indicated that about 60% of Haryana's geographical area is affected by soil degradation issues such as waterlogging, salinity, and alkalinity.

Fertilizer use in Haryana is among the highest in India, leading to nutrient imbalances and potential secondary soil contamination (Shukla et al., 2022). Kumari et al. (2004) analysed soil and groundwater samples were collected from paddy-wheat, paddy-cotton, sugarcane fields, and nearby tube wells around Hisar in Haryana to monitor pesticide residues. Organochlorine pesticides such as HCH, DDT, endosulfan, and chlordane, synthetic pyrethroids like cypermethrin and fenvalerate, and organophosphate pesticides such as chlorpyrifos, malathion, and quinalphos were detected in the soil.

Among them, DDT, cypermethrin, and chlorpyrifos were the dominant contaminants. Kumari et al. (2008) conducted studies on pesticide residues that were monitored in vegetable, soil, and water samples from seven districts of Haryana, including Sonipat, Sirsa, Faridabad, Kaithal, Kurukshetra, Rewari, and Rohtak. Results showed that soil samples from these districts were highly contaminated with pesticide residues, while Yamunanagar and Bhiwani had relatively lower levels of contamination. Mishra et al. (2025) analyzed pesticide residues in vegetables, soil, and water samples collected from four districts in Haryana. Soil samples from these districts showed pesticide residues in 44 out of 46 samples, with a detection rate of 95.65%. Commonly detected pesticides included chlorpyrifos, cypermethrin, pendimethalin, and butachlor. The long-term implications of soil contamination extend beyond environmental degradation, affecting crop yield, food safety, and human health. Heavy metals such as cadmium and arsenic can accumulate in crops, leading to potential health hazards when consumed. Moreover, contaminated soil can leach pollutants into groundwater, posing risks to drinking water sources. Despite regulatory frameworks established by the Haryana State Pollution Control Board, enforcement remains inconsistent allowing pollutants to persist in the environment.

6. SUSTAINABLE APPROACHES TO SOIL MANAGEMENT

Sustainable soil management in Haryana requires an integrative approach that integrates soil chemistry principles with effective remediation techniques. The agricultural and industrial activities in the state have led to significant soil contamination necessitating targeted interventions to restore soil health. One of the primary remediation techniques involves chemical stabilization where amendments such as lime, phosphate, and organic matter are introduced to reduce the bioavailability of heavy metals. Studies indicate that phosphate-based amendments can immobilize lead and cadmium, preventing their uptake by crops (Cui et al., 2022).

Additionally, soil washing techniques using chelating agents have been employed to extract contaminants, though their large-scale application remains limited due to cost constraints. Another promising method is electrokinetic remediation, which utilizes an electric field to mobilize and remove heavy metals from soil matrices. This technique has shown effectiveness in treating chromium-contaminated soils in industrial zones, offering a potential solution for Haryana’s pollution hotspots. Furthermore, bioremediation and phytoremediation play a crucial role in soil recovery, leveraging biological processes to degrade or immobilize contaminants. Microbial bioremediation involves the use of bacteria and fungi capable of metabolizing toxic compounds, thereby reducing their environmental impact. Research highlights the effectiveness of Pseudomonas and Bacillus species in degrading petroleum hydrocarbons and heavy metals, making them viable candidates for soil restoration in industrial regions in Haryana (Singh and Cameotra, 2013). Phytoremediation, on the other hand, employs plants to absorb, stabilize, or degrade pollutants. Certain plant species, such as Brassica juncea (Indian mustard) and Helianthus annuus (sunflower), have demonstrated high metal uptake capacities, particularly for arsenic and lead. These plants can be strategically cultivated in contaminated sites to gradually reduce pollutant concentrations. The integration of bioremediation and phytoremediation into soil management in Haryana would require careful planning and monitoring. While these techniques offer environmentally friendly alternatives to conventional remediation methods, their effectiveness depends on soil composition, contaminant type and climatic conditions. The adoption of biochar amendments has been explored to enhance microbial activity and improve soil structure further supporting sustainable remediation efforts. Additionally, genetically modified plants with enhanced metal absorption capabilities are being investigated to accelerate phytoremediation processes. Haryana can work towards restoring soil health by combining these approaches with regular soil testing and pollution control measures while maintaining agricultural productivity and environmental sustainability.

7. CONCLUSION

This study underscores the profound impact of municipal and industrial waste on soil contamination and long-term environmental degradation where improper waste disposal practices contribute to elevated concentrations of heavy metals, persistent organic pollutants, and other hazardous substances, which significantly alter soil pH, electrical conductivity, organic carbon content, and nutrient availability. These alterations compromise soil fertility, disrupt microbial activity, and increase the risk of pollutant bioaccumulation, thereby posing threats to agricultural sustainability and groundwater quality. The study highlights the intricate role of soil chemistry in contamination risk assessment, emphasizing that pollutant mobility, bioavailability, and environmental persistence are governed by interactions with soil minerals, organic matter, and redox conditions. Further, the study noted significant gaps in waste management strategies, particularly in relation to landfill leachate control, hazardous waste regulation, and sustainable disposal techniques. The alarming scale of waste generation in urban and industrial centers across Haryana necessitates an urgent shift toward more sustainable waste handling practices, improved infrastructure, and stricter policy enforcement. The study also underscores the importance of adopting advanced remediation methods, including chemical stabilization, soil washing, electrokinetic remediation, and bioremediation, to mitigate contamination risks and restore soil health. In conclusion, this research underscores the need for an integrated approach to waste management and soil restoration in Haryana, one that aligns soil chemistry principles with sustainable remediation strategies. While bioremediation and phytoremediation offer environmentally viable alternatives for restoring polluted soils, effective implementation requires careful planning, periodic soil testing, and regulatory oversight. Given the ongoing urban expansion and industrial activity in Haryana, continued monitoring and adaptive management are essential to mitigating soil contamination and ensuring long-term ecological resilience. The cumulative effects of soil degradation can have profound consequences for public health, economy and environmental stability in the region without strategic intervention.

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