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Scoping Review on Mitigating the Silent Threat of Toxic Industrial Waste: Eco-Rituals Strategies for Remediation and Ecosystem Restoration

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Abstract

Background: The problem of toxic industrial waste impacting soil and water quality remains a significant environmental threat, yet comprehensive solutions are lacking. This review addresses this gap by exploring the effects of industrial waste on ecosystems and proposing strategies for remediation. Its aim is to provide a thorough understanding of the issue and suggest actionable solutions to minimize environmental damage.
Methods: A comprehensive scoping review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. Data were sourced from major academic databases, including Science Direct, Scopus, PubMed, Academic Search Premier, Springer Link, Google Scholar, and Web of Science. A total of 105 relevant articles were included based on strict eligibility criteria. The review process encompassed identification, screening, and eligibility checks, followed by data abstraction and analysis.
Results: The scoping review highlights the severe impact of toxic industrial waste on soil and water quality, emphasizing pollutants such as heavy metals (cadmium, lead, chromium), organic contaminants, and excess nutrients (nitrogen and phosphorus). These pollutants degrade aquatic ecosystems, causing acidification, eutrophication, and oxygen depletion, leading to biodiversity loss and the mobilization of toxic metals. Soil health is similarly compromised, with heavy metal contamination reducing fertility and disrupting microbial communities essential for nutrient cycling. Mitigation strategies, including cleaner production technologies, effluent treatment, bioremediation, and phytoremediation, offer promising solutions. These eco-friendly approaches effectively reduce pollutants, restore ecosystems, and enhance environmental sustainability, thus mitigating the long-term risks posed by industrial waste on soil and water quality.

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Conclusions and recommendations: The findings confirm that toxic industrial waste is a critical environmental threat that impacts both aquatic ecosystems and terrestrial soils. Immediate action is necessary to address ecological degradation. Recommended strategies include banning harmful raw materials, pre-treatment of waste, riparian buffering, bioremediation, and stricter regulations to control pollution and safeguard ecosystems.

Keywords
industrial waste remediation, soil and water pollution, eco-friendly mitigation strategies, heavy metal contamination, environmental sustainability

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Introduction

The rapid increase in industrialization across the globe raised alarms about its profound effects on the environment, particularly concerning the health of natural ecosystem.[1] The production of industrial waste, which includes hazardous chemicals, heavy metals, and radioactive materials, has become one of the most pressing environmental issues of the 21st century.[2,3] These waste materials are often disposed of improperly, with industrial effluents being released into surrounding soil and water bodies without adequate treatment or containment.[4,5] As a result, toxic industrial waste has emerged as a significant environmental threat, contributing to widespread soil and water contamination endangering both human health and biodiversity.[6]

Industrial activities, spanning various sectors including manufacturing, mining, and chemical production, generate large quantities of waste in solid, liquid, and gaseous forms.[7,8] These wastes often contain harmful pollutants that possess carcinogenic, bio-accumulative, and reactive properties.[9] Such pollutants, when discharged into the environment, can persist for long periods, leading to the gradual degradation of soil and water quality.[10,11] This environmental contamination can result in toxic exposure to both wildlife and local populations, compromising the health of ecosystems and the quality of resources vital for human survival.[12,13]

One of the primary pathways through which industrial waste contaminates the environment is through the release of effluents into water bodies.[14,15] Surface water sources such as rivers, lakes, and streams can become severely polluted, altering key water quality parameters such as pH, electrical conductivity, and dissolved oxygen levels.[16,17] These changes can have devastating impacts on aquatic life, disrupting food chains and reducing biodiversity.[18] Toxic substances such as heavy metals and chemical solvents present in industrial effluents are known to bio accumulate in aquatic organisms, posing a risk to human populations that rely on these water sources for drinking and irrigation.[19]

In addition to water contamination, the impacts of toxic industrial waste extend to the soil, where pollutants can degrade soil properties and disrupt its natural functions.[20,21] Toxic chemicals released into the soil can lead to a reduction in soil fertility, harming agricultural productivity and threatening food security.[22,23] Soil contamination can also compromise the health of plants and animals, as toxic substances are absorbed into the food chain.[12] Furthermore, industrial waste often contains substances that are difficult to remove or neutralize, creating long-term challenges for soil remediation and restoration.[12,24]

Despite the growing recognition of the dangers posed by industrial waste, many industries still lack proper waste management systems and infrastructure to prevent or mitigate contamination.[25] Small-scale industries, in particular, are often exempt from strict environmental regulations and may discharge untreated effluents directly into local ecosystems.[26]

The silent threat of toxic industrial waste lies in its gradual accumulation and delayed yet devastating impact on both the environment and public health. Unlike sudden pollution events, these contaminants—such as heavy metals, persistent organic compounds, and hazardous chemicals—seep into soil, water, and air over time, leading to long-term ecological damage. As these toxins bioaccumulate in food chains, they pose severe risks, contributing to chronic illnesses, developmental disorders, and biodiversity loss. What makes this threat particularly dangerous is its subtlety; its effects often go unnoticed until irreversible harm has already occurred. Beyond environmental degradation, the contamination of natural resources by industrial waste has profound socio-economic consequences, affecting livelihoods, food security, and public health systems.[27]

Contaminated water sources can lead to waterborne diseases, affecting local communities that depend on these resources for drinking and irrigation.[28,29] Agricultural communities are particularly vulnerable, as soil contamination can reduce crop yields and expose farmers to health risks from toxic substances.[30,31] Additionally, the remediation of polluted sites requires significant financial investments, which many countries and industries are ill-equipped to handle, exacerbating the long-term effects of industrial pollution.[32]

Addressing the issue of toxic industrial waste requires a multi-faceted approach that involves both preventive and remedial measures.[33-35] Prevention can be achieved through the implementation of cleaner production techniques, such as the substitution of hazardous materials and the adoption of sustainable manufacturing practices.[36,37] For existing contaminated sites, bioremediation technologies and riparian buffering techniques offer potential solutions for restoring soil and water quality.[38] Furthermore, regulatory frameworks and stricter enforcement of environmental policies are essential to ensure that industries are held accountable for the disposal of toxic waste.[39]

This comprehensive scoping review seeks to evaluate the impacts of toxic industrial waste on surrounding soil and surface water quality, with an emphasis on the ecological consequences and the long-term effects on human health.[40] Through an analysis of current literature, this review will highlight the need for urgent action to address this silent environmental threat, focusing on effective management strategies to prevent contamination, promote sustainable industrial practices, and restore affected ecosystems.

Methods

Data Sources and Study Design

This comprehensive scoping review was conducted to evaluate the impacts of toxic industrial waste on surrounding soil and surface water quality. A systematic approach was followed, adhering to the preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines.[41] This method ensures a transparent and replicable process for identifying, screening, and analyzing relevant literature. A broad range of databases were utilized to gather empirical research articles, including ScienceDirect, Scopus, PubMed, Academic Search Premier, SpringerLink, Google Scholar, and Web of Science. These databases were chosen based on their extensive coverage of peer-reviewed journals related to environmental science, toxicology, and industrial waste management.

Eligibility and Exclusion Criteria

Several eligibility and exclusion criteria were established to ensure the inclusion of relevant studies and the exclusion of irrelevant or low-quality publications. First, literature type was a key consideration. Only peer-reviewed journal articles, including original research and review articles, were included in the review. Emphasis was placed on articles containing empirical data that directly addressed the impact of toxic industrial wastes on soil and surface water. Publications such as books, book chapters, and national reports were excluded due to their limited scope or lack of empirical data.

In terms of language, only studies published in English were considered to maintain clarity and ensure accurate analysis. Non-English articles were excluded to avoid challenges in translation and interpretation.

Regarding the timeframe, the review focused on articles published between 2000 and 2024. This period was selected to capture both recent developments in industrial waste management practices and environmental impact, while also ensuring a broad historical context for the review.

Finally, relevance to the review objectives was a critical criterion. Only studies that directly examined the impact of toxic industrial waste on surrounding soil and surface water were included. Articles that addressed broader environmental concerns or lacked empirical evidence on the effects of industrial chemicals were excluded. These criteria were carefully applied to ensure that the review encompassed high-quality, relevant, and focused literature.

Systematic Review Process

The systematic review was conducted in 4 stages to ensure a rigorous selection of relevant literature. In the identification stage, 1057 records were retrieved from databases like PubMed and registers using keywords such as “industrial toxics,” “impacts of industrial chemicals on soil and water,” and “management of industrial chemical waste.” After removing 507 duplicates and 37 irrelevant records, 537 studies proceeded to screening, where 230 were excluded based on title and abstract. In the eligibility assessment, 283 reports were sought for retrieval, but 120 were unavailable, leaving 163 for full-text review. Of these, 58 were excluded due to irrelevance or insufficient data. Finally, in the inclusion stage, 105 studies were selected and categorized into 4 themes: common contaminants of industrial waste, impacts on water and soil quality, and mitigation strategies (Figure 1).

Data Abstraction and Analysis

The final set of 105 articles was thoroughly assessed and analyzed through a systematic data abstraction process, which involved extracting key information from the selected studies, such as study design, methodologies, and results. The focus was placed on studies that specifically addressed the impacts of toxic industrial waste on soil and water quality, as well as those that explored management approaches aimed at mitigating these impacts. In terms of qualitative analysis, common themes were identified across the articles, including the types of toxic substances most frequently associated with industrial waste, their specific effects on soil and water quality, and the socio-economic consequences of contamination. This thematic analysis provided a deeper understanding of the issue and highlighted areas that warrant further research. In addition, quantitative analysis was performed on studies that provided numerical data, enabling the assessment of contamination levels, concentrations of toxic chemicals in soil and water, and the effectiveness of various waste management strategies. The results of both analyses were synthesized to provide a comprehensive view of the environmental impacts of industrial waste and the efficacy of different interventions. Through this systematic process, the review offers valuable insights into the current state of research on toxic industrial waste, pinpointing key findings and gaps in the literature. This analysis will be instrumental in guiding future policy recommendations and developing management strategies aimed at mitigating the adverse effects of industrial waste on soil and water quality.

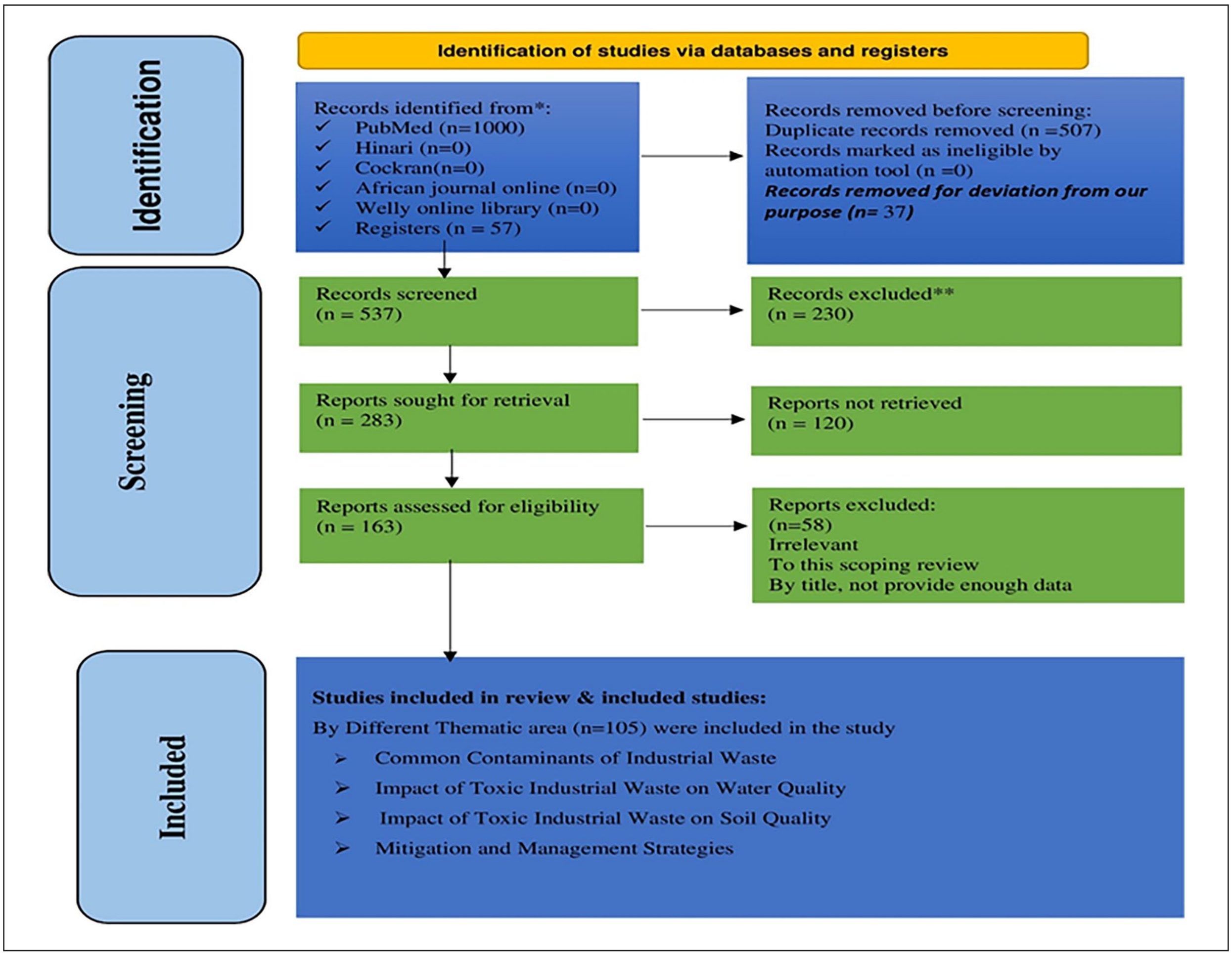

Figure 1. PRISMA flow diagram of articles on silent threat of toxic industrial waste.

Table 1. Common pollutants and sources from industrial effluents.

Pollutants	Industries responsible	Major impact	Reference
Cadmium (Cd), Lead (Pb), Chromium (Cr), Nickel (Ni)	Electroplating, tanneries, mining	Toxic to aquatic life, bioaccumulation in food chains	Kareem et al[42]
Ammonium (NH_4^+), Nitrates (NO_3^-), Phosphates (PO_4^{3-})	Fertilizers, agricultural runoff	Eutrophication, oxygen depletion in aquatic systems	Rahman and Singh,[43] Vardhan et al[44]
Sulfates (SO_4^{2-}), Sulfides (S^{2-})	Pulp and paper, chemical industries	Soil acidity, reduced soil fertility	Agrawal et al[45]
Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD)	Textile, leather, food processing	Oxygen depletion, aquatic life mortality	Ngatia et al[46]
Pesticides, Solvents, Phenols	Textile, leather, and paper industries	Toxicity to aquatic and terrestrial life, disruption of microbial communities	Chowdhary et al[47]

Results and Discussion

Overview of Contaminants in Industrial Waste

As indicated below (Table 1), industrial waste contains a range of pollutants that vary depending on the type of industry, the chemicals used, and the production processes involved.[42] Common pollutants include heavy metals such as cadmium (Cd), lead (Pb), chromium (Cr), arsenic (As), mercury (Hg), and nickel (Ni), which are highly toxic even at low concentrations.[43,44] These metals typically originate from industries such as electroplating, mining, and tanneries.[45] Additionally, nutrients like nitrogen (N) and phosphorus (P) from fertilizers, detergents, and agricultural effluents can cause eutrophication in water bodies, leading to ecological imbalances.[46] Organic pollutants, including solvents, oils, phenols, and dyes, are mainly found in textile, leather, and paper industries, and can negatively affect aquatic ecosystems and soil microbial health.[47] Inorganic chemicals, such as Ammonium (NH_4^+), Sulfates (SO_4^{2-}), and Phosphates (PO_4^{3-}) are often discharged in large quantities by industries like fertilizers, cement, and mining, further contributing to environmental degradation.[48]

Impact of Toxic Industrial Waste on Water Quality

Water quality is profoundly impacted by the discharge of industrial waste. The following aspects of water quality are affected:

PH Alterations. It is highly sensitive to industrial waste, particularly from sectors such as mining, electroplating, and textiles.[49] Industrial toxic waste in wastewater significantly impacts the environment, as reflected in key water quality parameters such as COD (250-1500 mg/l), BOD (100-600 mg/l), and heavy metals (Pb: 0.5-2.5 mg/l, Cd: 0.1-0.8 mg/l), indicating severe pollution levels. These contaminants can cause both acidification and alkalinization of water bodies, leading to aquatic ecosystem disruptions, biodiversity loss, and serious public health risks. Implementing stringent regulatory measures and advanced treatment technologies is crucial to mitigating these adverse effects and ensuring sustainable water quality management.[50] Acidic discharges, commonly arising from metal plating processes (eg, chromium and cadmium), can lower the pH of water, creating a hostile environment for pH-sensitive aquatic species.[51] Acidification can also trigger the mobilization of heavy metals present in sediments, making them more bioavailable and potentially toxic to aquatic organisms.[52] On the other hand, alkalinization, which may result from certain industrial effluents, increases the solubility of toxic metals like mercury, further exacerbating the threat to aquatic species by allowing these harmful substances to enter the food chain. Both acidification and alkalinization compromise the health and biodiversity of aquatic ecosystems.[53]

Eutrophication and Algae Blooms. Excessive nutrients, especially nitrogen and phosphorus, contribute to eutrophication, a process in which water bodies become overly enriched with nutrients, resulting in excessive algae growth.[54,55] This algal bloom can have severe ecological impacts.[56,57] First, the decomposition of algae consumes large amounts of dissolved oxygen, leading to hypoxic conditions or "dead zones," where oxygen levels are so low that aquatic organisms cannot survive.[58] Furthermore, certain algal species, such as cyanobacteria, produce toxins that can be harmful to both aquatic life and humans.[59] These toxins can contaminate drinking water, affect fish populations, and pose significant health risks, including liver damage and neurological issues in humans.[60] Eutrophication, therefore, disrupts aquatic ecosystems, leading to a loss of biodiversity and negatively impacting water quality[61] (Figure 2).

Alteration of Water Parameters. Key water quality parameters, such as Electrical Conductivity (EC), Total Dissolved Solids (TDS), and Dissolved Oxygen (DO), are significantly influenced by industrial effluent discharges.[62,63] High EC values are indicative of the presence of dissolved salts and minerals, including chlorides and sulfates, which are often the result of industrial processes.[64] Elevated EC levels are typically associated with poor water quality and a reduction in biodiversity, as many aquatic species are sensitive to changes in salinity and mineral content.[65] This disruption can alter the composition of aquatic ecosystems, favoring salt-tolerant species while harming others.[66] Similarly, the discharge of organic pollutants, such as Chemical Oxygen Demand (COD) and Biochemical Oxygen Demand (BOD), into water bodies can lead to a significant decrease in DO.[67] Low DO levels impair the respiration of aquatic organisms, leading to oxygen-deprived conditions that can cause fish kills and disrupt the entire aquatic food chain.[68] Reduced DO availability hinders the growth and survival of many aquatic species, leading to long-term ecological imbalances[69] (Table 2).

Impact of Toxic Industrial Waste on Soil Quality

Industrial waste not only affects water quality but also has a significant impact on soil health, fertility, and productivity.[70,71]

Changes in Soil pH. Heavy metals and acidic discharges from industries such as electroplating, mining, and chemical manufacturing contribute to soil acidification, which has several negative effects on soil health.[72] Acidic soils reduce the availability of essential nutrients, making them less accessible to plants, which can stunt growth and significantly lower crop yields.[30] In addition, the increased concentration of toxic metals like lead, mercury, and cadmium in the soil not only decreases soil fertility but also harms beneficial soil microorganisms.[30] These microorganisms, which play a critical role in nutrient cycling and maintaining soil structure, are particularly sensitive to these toxic metals, leading to a disruption in soil ecosystem functions.[73]

Soil Contamination and Reduced Fertility. Soil contamination with heavy metals and industrial effluents significantly reduces soil fertility and poses a threat to food safety.[74,75] Heavy metals such as cadmium (Cd) and chromium (Cr) can bioaccumulate in plants, leading to harmful effects on crops.[43,76] Cadmium, for instance, is known to accumulate in leafy vegetables, posing long-term health risks when consumed by humans.[77,78] Similarly, chromium reduces plants' ability to absorb essential nutrients, leading to stunted growth and toxicity.[79] These contaminants not only degrade soil quality but also endanger the food supply, affecting both agricultural productivity and human health.[80]

Soil Microbial Disruption. As shown in Table 3, industrial effluents can severely disrupt the balance of soil microorganisms, which are crucial for nutrient cycling and the decomposition of organic matter.[81,82] Heavy metals like

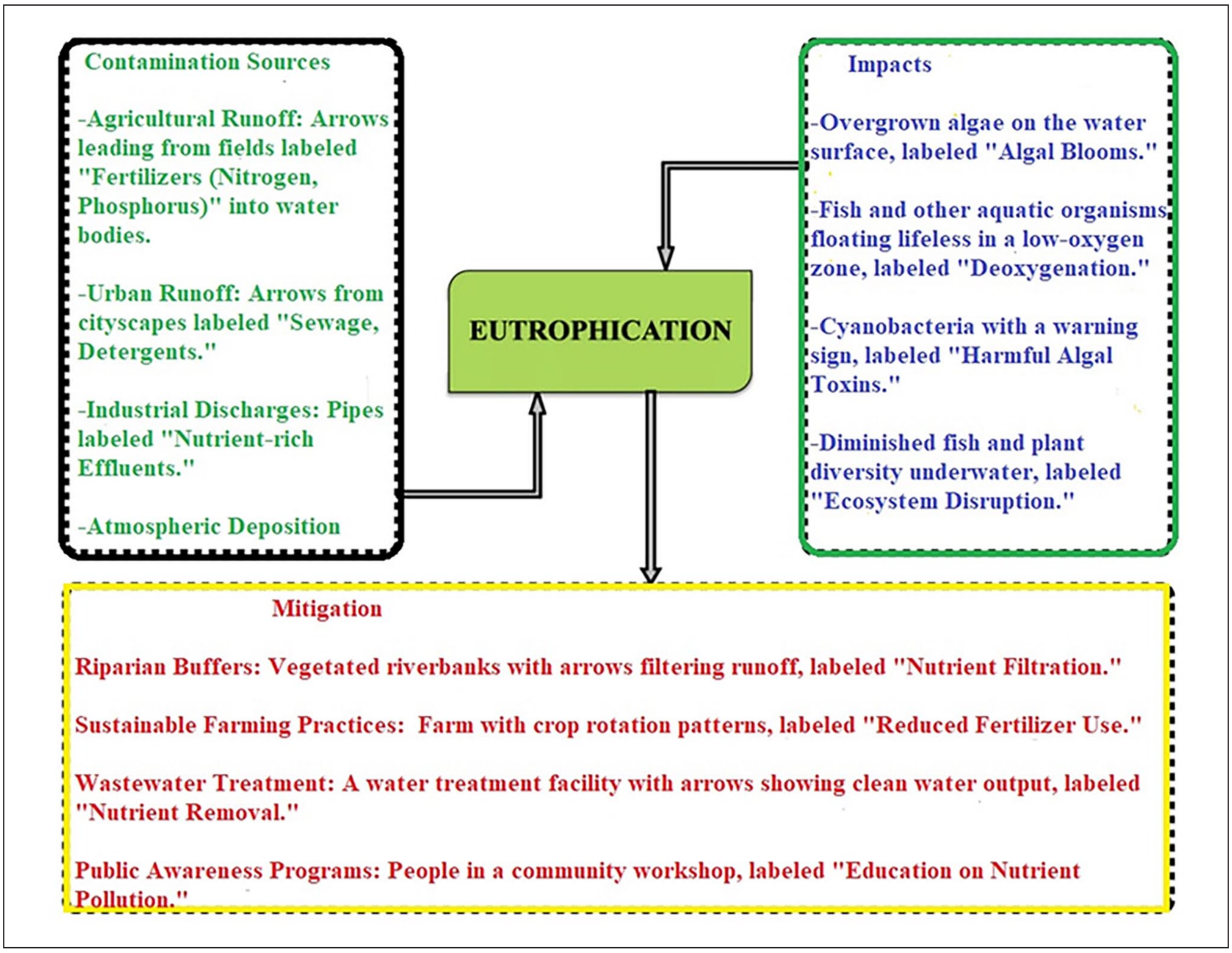

Figure 2. Sources, impact and mitigation measure of eutrophication.

Table 2. Key Water quality parameters affected by industrial toxic waste.

Parameter	Industrial source	Impact on aquatic ecosystems	Reference
pH	Electroplating, mining, textile industries	Acidification or alkalinization, mobilization of heavy metals	Gbarakoro et al,[62] Osode and Okoh[63]
Electrical Conductivity (EC)	Cement, chemical industries, textile wastewater	Increased salt and metal content, which can be harmful to aquatic life	Patil et al[64]
Dissolved Oxygen (DO)	Textile, paper industries, food processing	Low oxygen levels, leading to fish kills and hypoxia	Nielsen et al[65]
Chemical Oxygen Demand (COD)	Textile, leather, chemical industries	Reduced oxygen availability for aquatic organisms	Maddah[67]
Nutrient Levels (N, P)	Fertilizer, agricultural runoff, food processing	Eutrophication, algae blooms, reduced biodiversity	Kannel et al[69]

zinc, copper, and lead are toxic to soil microbes, reducing microbial biodiversity and negatively impacting soil health.[30] These metals interfere with microbial enzymatic activities, hindering essential processes such as nitrogen fixation.[83] Toxic industrial wastes, including cyanides in coking wastewater, pose significant environmental and public health risks. Cyanides, even in low concentrations, can be highly toxic to aquatic life and soil microorganisms. In coking wastewater treatment, cyanides often persist in the secondary effluent, where they can remain mobile under aerobic conditions, contaminating water bodies and soil.[84] The presence of heavy metals and other pollutants further exacerbates their toxicity, affecting ecosystems by disrupting biochemical cycles, reducing biodiversity, and impacting agricultural productivity. Proper treatment and management are essential to mitigate the harmful effects of these pollutants on both ecosystems and human health.[85]

Table 3. Effects of heavy metals on soil microbial communities.

Heavy metal	Impact on soil microbes	Resulting effect on soil health	Reference
Cadmium (Cd)	Inhibits microbial growth, limit enzymatic activity, and reduces microbial diversity	Reduced decomposition of organic matter, decreased soil fertility, and poor nutrient cycling	Srivastava et al,[77] Wang et al[78]
Lead (Pb)	Toxic to soil fungi, bacteria, and invertebrates; affects microbial diversity	Disrupted nutrient cycling, decreased soil productivity, and reduced microbial resilience	Sharma et al[79]
Zinc (Zn)	Alters microbial structure, diversity, and functional diversity	Reduced nitrogen fixation, diminished soil nutrient availability, and imbalanced microbial community dynamics	Udeigwe et al[80]
Cyanide (CN)	Inhibits microbial metabolic processes and decrease microbial diversity	Disrupted nutrient cycling, decreased soil fertility, and potential toxic effects on soil organisms	Huang et al,[81] Lipczynska-Kochany[82]

Impact of Industrial Waste on Ecosystems and Human Health

Industrial waste not only harms ecosystems but also poses serious risks to human health. Contaminants such as heavy metals, including lead (Pb) and cadmium (Cd), can accumulate in aquatic organisms, entering the food chain and ultimately affecting human health through consumption of contaminated seafood. These heavy metals have been linked to various health issues, including neurological disorders, kidney damage, and cancer. Furthermore, the elevated levels of chemical oxygen demand (COD) and biological oxygen demand (BOD) in industrial wastewater can lead to oxygen depletion in water bodies, creating hypoxic or anoxic environments that disrupt aquatic life. Acidification or alkalinization of water bodies due to industrial emissions can also make water uninhabitable for many species, reducing biodiversity and impacting ecosystem services. Humans relying on contaminated water for drinking or agriculture are at risk of waterborne diseases and long-term health impacts. Therefore, effective wastewater management and regulatory measures are crucial for protecting both ecosystems and human health.[86]

Human health risks due to industrial pollutants can be related to the investigation of heavy metals in wastewater treatment systems, particularly the study on the fate of heavy metals in an A-O_1-H-O_2 biological coking wastewater treatment system. In industrial zones, pollutants such as heavy metals and persistent organic pollutants (POPs) are prevalent in wastewater, contributing to serious health issues such as kidney damage, neurological disorders, and developmental defects through direct exposure and bioaccumulation in the food chain. Similarly, the biological coking wastewater treatment system aims to address the fate of these heavy metals by evaluating how they are distributed across different chemical phases during the treatment process. The treatment system's effectiveness in removing or neutralizing these contaminants plays a crucial role in preventing their accumulation in the environment and food sources. If the wastewater treatment is not properly managed, as seen in coking industries, these metals may remain in the effluent and pose risks to human health and ecosystems, emphasizing the need for advanced and efficient wastewater treatment technologies to reduce the spread of industrial pollutants. By effectively controlling heavy metal concentrations and ensuring their safe removal during treatment, the public health concerns associated with contaminated water sources can be alleviated, underscoring the importance of regulatory measures in industrial wastewater management.[87]

Mitigation and Management Strategies

Mitigation and management strategies for the silent threat of toxic industrial waste on soil and water quality focus on a combination of innovative approaches.[88] Cleaner production technologies emphasize waste minimization by optimizing production processes, reducing the use of harmful materials, and enhancing resource efficiency.[89,90] Treatment of industrial effluents, such as physicochemical and biological methods, plays a crucial role in removing contaminants, including heavy metals and organic pollutants, before they are discharged into the environment.[91] Additionally, bioremediation and phytoremediation offer eco-friendly solutions by utilizing microorganisms and plants to degrade or absorb toxic substances, respectively, thus restoring contaminated soils and water bodies.[92] These strategies, when implemented effectively, can significantly reduce the harmful impact of industrial waste on ecosystems and public health[93] (Figure 3).

Cleaner Production Technologies. Adopting cleaner production methods is crucial in minimizing the generation of toxic waste and mitigating its environmental impact.[37] Key strategies include waste minimization, which focuses on reducing waste at the source by optimizing production processes and using less harmful materials.[89] Additionally, recycling and reuse play a significant role in sustainable practices, such as recycling water and by-products, which helps minimize waste generation and reduces the discharge of harmful chemicals into the environment.[94] These strategies not only contribute to a cleaner environment but also promote resource efficiency and cost savings for industries.[95]

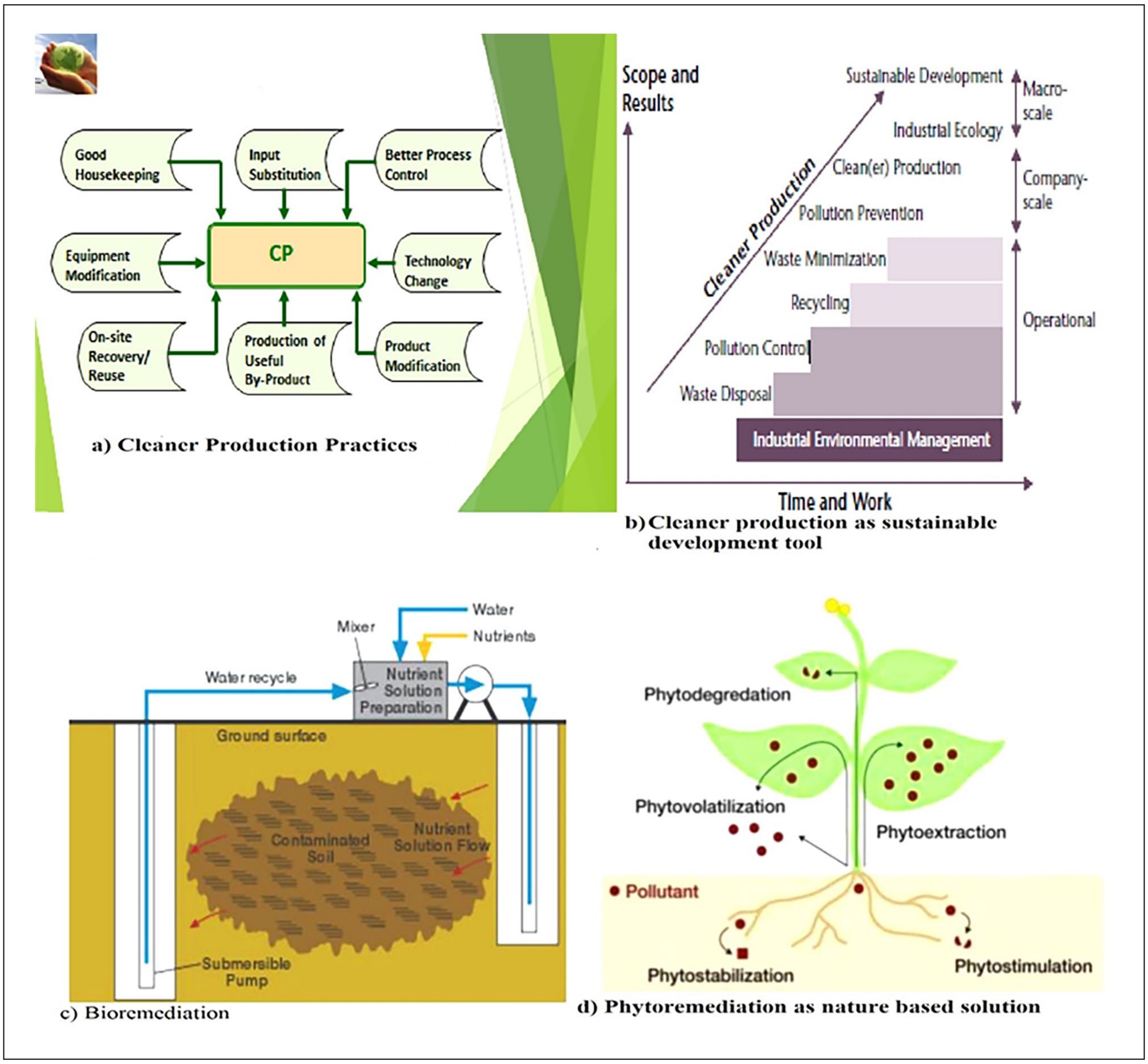

Figure 3. Integrated mitigation and management strategies for silent threat of toxic industrial waste.[89,90]

Treatment of Industrial Effluents. Effluent treatment technologies play a critical role in reducing the environmental impact of industrial discharges.[96] Physicochemical treatment methods, such as filtration, adsorption, and precipitation, effectively remove heavy metals and other contaminants from wastewater before it is released into the environment.[97] These methods help to prevent the contamination of water bodies and protect aquatic life.[98] Biological treatment, on the other hand, uses microorganisms to degrade organic pollutants and treat nutrient-rich wastewater.[99,100] This approach is particularly effective for removing excess nitrogen and phosphorus, which can lead to eutrophication, and is a sustainable solution for managing industrial effluents.[101]

Bioremediation and Phytoremediation. Bioremediation and phytoremediation are promising, eco-friendly approaches for treating contaminated soil and water.[102] Bioremediation involves using microorganisms to detoxify pollutants, particularly organic contaminants, by breaking them down into less harmful substances.[102] This method is particularly effective for treating oil spills, pesticides, and other organic chemicals.[103] Phytoremediation, on the other hand, utilizes plants to absorb and accumulate heavy metals from contaminated soils, effectively removing toxic elements such as cadmium, lead, and mercury.[104] Both methods provide sustainable and cost-effective alternatives to traditional remediation techniques, helping to restore ecosystems and protect human health.[105]

Conclusion and Recommendation

Conclusions

The study highlights the severe environmental and health repercussions of toxic industrial waste, which degrades soil and water quality, disrupts ecosystems, and threatens agricultural productivity and public health. Heavy metals, organic pollutants, and nutrient-rich discharges from industries such as electroplating, mining, tanneries, fertilizers, and detergents contribute to eutrophication, oxygen depletion, and biodiversity loss in aquatic systems, while soils suffer acidification, heavy metal accumulation, and reduced microbial diversity. These pollutants bioaccumulate in food chains, posing chronic health risks, and jeopardizing food security. Addressing this pervasive threat necessitates integrated strategies that encompass pollution prevention, advanced treatment technologies, and ecological restoration to safeguard ecosystems and human well-being.

Recommendations

Addressing the challenges of industrial toxic waste pollution requires a multifaceted approach. Industries must adopt cleaner production technologies, emphasizing waste minimization, resource efficiency, and recycling, supported by regular audits and incentives. Advanced effluent treatment systems, including physicochemical methods for heavy metal removal and biological systems for organic waste degradation, are essential to prevent eutrophication and water quality degradation. Eco-friendly remediation techniques, such as bioremediation and phytoremediation, offer sustainable solutions for detoxifying contaminated sites. Governments must enforce stringent environmental regulations, impose penalties for non-compliance, and foster public-private partnerships to fund innovative waste management solutions. Public awareness campaigns are vital to educating stakeholders about the environmental and health risks of industrial pollution and promoting sustainable practices.

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Statements and Declarations

Ethics Approval and Consent to Participate

This study is a scoping review; therefore, it did not require an ethical review.

Consent for Publication

Not applicable.

Author Contributions/CRediT

A.G.Y., G.M.B., H.M. and C.H.Y. wrote the main manuscript text. Z.A.Y., A.T., A.S.E., G.Y., T.D.T., S.S.T, A.A.G., Z.A.A., A.G.E., A.F.A., and R.M.A prepared figures and tables. All authors reviewed and write the manuscript.

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Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Data Availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

References

1. Anderson K. *What was the Industrial Revolution's Environmental Impact?* Greenly Earth. 2023;10.
2. Manahan SE. *Industrial Ecology: Environmental Chemistry and Hazardous Waste*. Routledge; 2017.
3. Krishnan S, Zulkapli NS, Kamyab H, et al. Current technologies for recovery of metals from industrial wastes: an overview. *Environ Technol Innov*. 2021;22:101525.
4. Gautam PK, Gautam RK, Banerjee S, Chattopadhyaya M, Pandey J. *Heavy Metals in the Environment: Fate, Transport, Toxicity and Remediation Technologies*. Vol. 60. Nova Sci Publishers; 2016:101-130.
5. Padhye LP, Srivastava P, Jasemizad T, et al. Contaminant containment for sustainable remediation of persistent contaminants in soil and groundwater. *J Hazard Mater*. 2023;455:131575.
6. Mishra S, Bharagava RN, More N, et al. Heavy metal contamination: an alarming threat to environment and human health. *Environ Biotechnol Sustain Futur*. 2019;(2):103-125.
7. Heveling J. Heterogeneous catalytic chemistry by example of industrial applications. *J Chem Educ*. 2012;89(12):1530-1536.
8. Küfeoğlu S. *Industrial Process Emissions. Net Zero: Decarbonizing the Global Economies*. Springer; 2024:341-414.
9. Chormare R, Kumar MA. Environmental health and risk assessment metrics with special mention to biotransfer, bioaccumulation and biomagnification of environmental pollutants. *Chemosphere*. 2022;302:134836.
10. Akram R, Turan V, Hammad HM, et al. Fate of organic and inorganic pollutants in paddy soils. *Environmental pollution of paddy soils*. 2018;197-214.
11. Holt MS. Sources of chemical contaminants and routes into the freshwater environment. *Food Chem Toxicol*. 2000;38(1 Suppl):S21-27.
12. Okereafor U, Makhatha M, Mekuto L, et al. Toxic metal implications on agricultural soils, plants, animals, aquatic life and human health. *Int J Environ Res Public Health*. 2020;17(7):2204.
13. Singh PK, Kumar U, Kumar I, et al. Critical review on toxic contaminants in surface water ecosystem: sources, monitoring, and its impact on human health. *Environ Sci Pollut Res*. 2024;31(45):56428-56435.
14. Mokarram M, Saber A, Sheykhi V. Effects of heavy metal contamination on river water quality due to release of industrial effluents. *J Clean Prod*. 2020;277:123380.
15. Rajaram T, Das A. Water pollution by industrial effluents in India: discharge scenarios and case for participatory ecosystem specific local regulation. *Futures*. 2008;40(1):56-69.
16. Igwe P, Chukwudi C, Ifenatuorah F, Fagbeja I, Okeke C. A review of environmental effects of surface water pollution. *Int J Adv Eng Res Sci*. 2017;4(12):128-137.

17. Khatri N, Tyagi S. Influences of natural and anthropogenic factors on surface and groundwater quality in rural and urban areas. *Front Life Sci*. 2015;8(1):23-39.
18. Fanzo J, Miachon L. Harnessing the connectivity of climate change, food systems and diets: taking action to improve human and planetary health. *Anthropocene*. 2023;42:100381.
19. Ali H, Khan E, Ilahi I. Environmental chemistry and ecotoxicology of hazardous heavy metals: environmental persistence, toxicity, and bioaccumulation. *J Chem*. 2019; 2019:1-6730305.
20. Biswas B, Qi F, Biswas JK, et al. The fate of chemical pollutants with soil properties and processes in the climate change paradigm—a review. *Soil Systems*. 2018;2(3):51.
21. Cachada A, Rocha-Santos T, Duarte AC. Soil and pollution: an introduction to the main issues. *Soil pollution*. 2018;(3):1-28.
22. Bisht N, Chauhan PS. Excessive and disproportionate use of chemicals cause soil contamination and nutritional stress. In: *Soil Contamination-Threats and Sustainable Solutions*. Vol. 2020. 2020:1-10.
23. Kopittke PM, Menzies NW, Wang P, McKenna BA, Lombi E. Soil and the intensification of agriculture for global food security. *Environ Int*. 2019;132:105078.
24. Sonone SS, Jadhav S, Sankhla MS, Kumar R. Water contamination by heavy metals and their toxic effect on aquaculture and human health through food Chain. *Lett Appl NanoBioScience*. 2020;10(2):2148-2166.
25. Dutta D, Arya S, Kumar S. Industrial wastewater treatment: current trends, bottlenecks, and best practices. *Chemosphere*. 2021;285:131245.
26. Brunner PH, Rechberger H. Waste to energy–key element for sustainable waste management. *Waste Manag*. 2015;37:3-12.
27. Listorti J, Doumani F. *Energy and Environmental Health: A Literature Review and Recommendations*. World Bank, Energy Sector Management Assistance Programmer (ESMAP); 2004.
28. Manetu WM, Karanja AM. Waterborne disease risk factors and intervention practices: a review. *OALib J*. 2021;8(5):1-11.
29. Rose JB, Epstein PR, Lipp EK, et al. Climate variability and change in the United States: potential impacts on water-and foodborne diseases caused by microbiologic agents. *Environ Health Perspect*. 2001;109(2):211-221.
30. Alengebawy A, Abdelkhalek ST, Qureshi SR, Wang MQ. Heavy metals and pesticides toxicity in agricultural soil and plants: Ecological risks and human health implications. *Toxics*. 2021;9(3):42.
31. Khalid S, Shahid M, Bibi I, et al. A review of environmental contamination and health risk assessment of wastewater use for crop irrigation with a focus on low and high-income countries. *Int J Environ Res Public Health*. 2018;15(5):895.
32. Liu X, Sathishkumar K, Zhang H, et al. Frontiers in environmental cleanup: recent advances in remediation of emerging pollutants from soil and water. *J Hazard Mater Adv*. 2024;16:100461.
33. Chen S, Ding Y. Tackling heavy metal pollution: evaluating governance models and frameworks. *Sustainability*. 2023;15(22):15863.
34. Patil KD, De J, Patil VK, Kulkarni MM. Environmental effects and threats of waste: understanding threats and challenges to ecosystem, health, and sustainability and mitigation strategies. In: *From Waste to Wealth*. Springer; 2024:37-69.
35. Ogbeide O, Henry B. Addressing heavy metal pollution in Nigeria: evaluating policies, assessing impacts, and enhancing remediation strategies. *J Appl Sci Environ Manag*. 2024;28(4):1007-1051.
36. Almeida CMVB, Bonilla SH, Giannetti BF, Huisingh D. Cleaner production initiatives and challenges for a sustainable world: an introduction to this special volume. *J Clean Prod*. 2013;47:1-10.
37. Hens L, Block C, Cabello-Eras JJ, et al. On the evolution of "cleaner production" as a concept and a practice. *J Clean Prod*. 2018;172:3323-3333.
38. Pavlidis G, Karasali H. Natural remediation techniques for water quality protection and restoration. In: *Methods for Bioremediation of Water and Wastewater Pollution*. Springer; 2020:327-340.
39. Wang H, Wang T, Xue G, et al. Key technologies and equipment for contaminated surface/groundwater environment in the rural river network area of China: integrated remediation. *Environ Sci Eur*. 2021;33(1):16.
40. Zhou W, Li M, Achal V. A comprehensive review on environmental and human health impacts of chemical pesticide usage. *Emerg Contam*. 2024;11(1):100410.
41. Parums DV. Review articles, systematic reviews, meta-analysis, and the updated preferred reporting items for systematic reviews and meta-analyses (PRISMA) 2020 guidelines. *Med Sci Monit*. 2021;27:e934475.
42. Kareem HA, Riaz S, Sadia H, Mehmood R. Industrial waste, types, sources, pollution potential, and country-wise comparisons. In: *Waste Problems and Management in Developing Countries*. Apple Academic Press; 2023:169-203.
43. Rahman Z, Singh VP. The relative impact of toxic heavy metals (THMs) (arsenic (As), cadmium (Cd), chromium (Cr) (VI), mercury (Hg), and lead (Pb)) on the total environment: an overview. *Environ Monit Assess*. 2019;191(7):419-421.
44. Vardhan KH, Kumar PS, Panda RC. A review on heavy metal pollution, toxicity and remedial measures: current trends and future perspectives. *J Mol Liq*. 2019;290:111197.
45. Agrawal A, Kumar V, Pandey BD. Remediation options for the treatment of electroplating and leather tanning effluent containing chromium—a review. *Miner Process Extractive Metall Rev*. 2006;27(2):99-130.
46. Ngatia L, Grace JM, Moriasi D, Taylor R. Nitrogen and phosphorus eutrophication in marine ecosystems. *Monit Mar Pollut*. 2019;1(6):1-17.
47. Chowdhary P, Bharagava RN, Mishra S, Khan N. Role of industries in water scarcity and its adverse effects on environment and human health. Environmental concerns and sustainable development: volume 1: air. *Water and Energy Resources*. 2020;(4):235-256.
48. Onwordi CT. Physicochemical characteristics and amenability to bench scale treatments of some industrial effluents and sediments in lagos metropolis. 2014.
49. Dhal B, Thatoi HN, Das NN, Pandey BD. Chemical and microbial remediation of hexavalent chromium from contaminated soil and mining/metallurgical solid waste: a review. *J Hazard Mater*. 2013;250:272-291.
50. Billé R, Kelly R, Biastoch A, et al. Taking action against ocean acidification: a review of management and policy options. *Environ Manag*. 2013;52(4):761-779.
51. Lydersen E, Löfgren S, Arnesen RT. Metals in Scandinavian surface waters: effects of acidification, liming, and potential reacidification. *Crit Rev Environ Sci Technol*. 2002;32(2-3):73-295.

52. de Orte MR, Sarmiento AM, Basallote MD, et al. Effects on the mobility of metals from acidification caused by possible CO2 leakage from sub-seabed geological formations. *Sci Total Environ*. 2014;470:356-363.
53. Mohammed-Nour A, Al-Sewailem M, El-Naggar AH. The influence of alkalization and temperature on ammonia recovery from cow manure and the chemical properties of the effluents. *Sustainability*. 2019;11(8):2441.
54. Khan MN, Mohammad F. Eutrophication: challenges and solutions. In: *Eutrophication: Causes, Consequences and Control*. Vol. 2. 2014:1-15.
55. Purohit R. Eutrophication: harmful algal blooms. *Int J Multidiscip Res Sci*. 2018;1(1):267-278.
56. Dolah FMV, Roelke D, Greene RM. Health and ecological impacts of harmful algal blooms: risk assessment needs. *Hum Ecol Risk Assess*. 2001;7(5):1329-1345.
57. Hallegraeff G. Harmful algal blooms: a global overview. In: *Manual on Harmful Marine Microalgae*. Vol. 33. 2003;1-22.
58. Yan T, Li X-D, Tan Z-J, Yu R-C, Zou J-Z. Toxic effects, mechanisms, and ecological impacts of harmful algal blooms in China. *Harmful Algae*. 2022;111:102148.
59. Paerl HW, Fulton RS, Moisander PH, Dyble J. Harmful freshwater algal blooms, with an emphasis on cyanobacteria. *ScientificWorldJournal*. 2001;1:76-113.
60. Rastogi RP, Madamwar D, Incharoensakdi A. Bloom dynamics of cyanobacteria and their toxins: environmental health impacts and mitigation strategies. *Front Microbiol*. 2015;6:1254.
61. Rathore SS, Chandravanshi P, Chandravanshi A, Jaiswal K. Eutrophication: impacts of excess nutrient inputs on aquatic ecosystem. *IOSR J Agric Vet Sci*. 2016;9(10):89-96.
62. Gbarakoro SL, Gbarakoro TN, Eebu WL. Impact of industrial effluent discharge on the physico-chemical properties of Aleto Stream, Eleme, Rivers State, Nigeria. *Annu Res Rev Biol*. 2020;35(1):79-89.
63. Osode AN, Okoh AI. Impact of discharged wastewater final effluent on the physicochemical qualities of a receiving watershed in a suburban community of the Eastern Cape Province. *Clean*. 2009;37(12):938-944.
64. Patil P, Sawant D, Deshmukh R. Physico-chemical parameters for testing of water–a review. *Int J Environ Sci*. 2012;3(3):1194-1207.
65. Nielsen DL, Brock MA, Rees GN, Baldwin DS. Effects of increasing salinity on freshwater ecosystems in Australia. *Aust J Bot*. 2003;51(6):655-665.
66. Pinheiro JPS, Windsor FM, Wilson RW, Tyler CR. Global variation in freshwater physico-chemistry and its influence on chemical toxicity in aquatic wildlife. *Biol Rev*. 2021;96(4):1528-1546.
67. Maddah HA. Predicting optimum dilution factors for BOD sampling and desired dissolved oxygen for controlling organic contamination in various wastewaters. *Int J Chem Eng*. 2022;2022:1-14.
68. Daniel MHB, Montebelo AA, Bernardes MC, et al. Effects of urban sewage on dissolved oxygen, dissolved inorganic and organic carbon, and electrical conductivity of small streams along a gradient of urbanization in the Piracicaba river basin. *Water Air Soil Pollut*. 2002;136(1/4):189-206.
69. Kannel PR, Lee S, Lee Y-S, Kanel SR, Khan SP. Application of water quality indices and dissolved oxygen as indicators for river water classification and urban impact assessment. *Environ Monit Assess*. 2007;132(1-3):93-110.
70. Akinbile CO, Erazua AE, Babalola TE, Ajibade FO. Environmental Implications of animal wastes pollution on agricultural soil and water quality. *Soil Water Res*. 2016; 11(3):172-180.
71. De Silva S, Carson P, Indrapala DV, Warwick B, Reichman SM. Land application of industrial wastes: impacts on soil quality, biota, and human health. *Environ Sci Pollut Res*. 2023;30(26):67974-67996.
72. Lenart-Boroń A, Boroń P. *The Effect of Industrial Heavy Metal Pollution on Microbial Abundance and Diversity in Soils—A Review*. IntechOpen; 2014.
73. Morgado RG, Loureiro S, González-Alcaraz MN. Changes in soil ecosystem structure and functions due to soil contamination. *Soil pollution*. 2018;(1):59-87.
74. Hou D, O'Connor D, Igalavithana AD, et al. Metal contamination and bioremediation of agricultural soils for food safety and sustainability. *Nature Reviews Earth & Environment*. 2020;1(7):366-381.
75. Oves M, Khan MS, Zaidi A, Ahmad E. *Soil Contamination, Nutritive Value, and Human Health Risk Assessment of Heavy Metals: An Overview*. Springer; 2012.
76. Shankar SR. Effect of heavy metals on growth and development of cultivated plants with reference to cadmium, chromium and lead–a review. *Journal of Stress Physiology & Biochemistry*. 2020;16(3):84-102.
77. Srivastava D, Tiwari M, Dutta P, et al. Chromium stress in plants: toxicity, tolerance and phytoremediation. *Sustainability*. 2021;13(9):4629.
78. Wang M, Chen Z, Song W, et al. A review on cadmium exposure in the population and intervention strategies against cadmium toxicity. *Bull Environ Contam Toxicol*. 2021;106(1):65-74.
79. Sharma A, Kapoor D, Wang J, et al. Chromium bioaccumulation and its impacts on plants: an overview. *Plants*. 2020;9(1):100.
80. Udeigwe TK, Teboh JM, Eze PN, et al. Implications of leading crop production practices on environmental quality and human health. *J Environ Manag*. 2015;151:267-279.
81. Huang P-M, Wang M-K, Chiu C-Y. Soil mineral–organic matter–microbe interactions: impacts on biogeochemical processes and biodiversity in soils. *Pedobiologia*. 2005; 49(6):609-635.
82. Lipczynska-Kochany E. Humic substances, their microbial interactions and effects on biological transformations of organic pollutants in water and soil: a review. *Chemosphere*. 2018;202:420-437.
83. Naz M, Dai Z, Hussain S, et al. The soil pH and heavy metals revealed their impact on soil microbial community. *J Environ Manag*. 2022;321:115770.
84. Chen A, Guan X, Pang Z, et al. Function and direction of cyanide in coking wastewater: from water treatment to environmental migration. *ACS ES&T Water*. 2023;3(12):3980-3991.
85. Chen A, Guan X, Pang Z, et al. Catalytic oxidation of biorefractory cyanide-containing coking wastewater by deconjugation effect of bimetal copper-loaded activated carbon. *J Environ Chem Eng*. 2023;11(6):111283.
86. Cheng X, Wei C, Ke X, et al. Nationwide review of heavy metals in municipal sludge wastewater treatment plants in China: sources, composition, accumulation and risk assessment. *J Hazard Mater*. 2022;437:129267.
87. Kong Q, Li Z, Zhao Y, et al. Investigation of the fate of heavy metals based on process regulation-chemical reaction-phase distribution in an A-O1-H-O2 biological coking wastewater treatment system. *J Environ Manag*. 2019;247:234-241.

88. Dehkordi MM, Nodeh ZP, Dehkordi KS, et al. Soil, air, and water pollution from mining and industrial activities: sources of pollution, environmental impacts, and prevention and control methods. *Results in Engineering*. 2024;23:102729.
89. Giannetti B, Agostinho F, Eras JC, Yang Z, Almeida C. Cleaner production for achieving the sustainable development goals. *J Clean Prod*. 2020;271:122127.
90. Hilson G. Defining “cleaner production” and “pollution prevention” in the mining context. *Miner Eng*. 2003;16(4):305-321.
91. Kato S, Kansha Y. Comprehensive review of industrial wastewater treatment techniques. *Environ Sci Pollut Res*. 2024;31(39):51064-51097.
92. Sathya K, Nagarajan K, Carlin Geor Malar G, Rajalakshmi S, Raja Lakshmi P. A comprehensive review on comparison among effluent treatment methods and modern methods of treatment of industrial wastewater effluent from different sources. *Appl Water Sci*. 2022;12(4):70.
93. Palani G, Arputhalatha A, Kannan K, et al. Current trends in the application of nanomaterials for the removal of pollutants from industrial wastewater treatment—a review. *Molecules*. 2021;26(9):2799.
94. Abubakar IR, Maniruzzaman KM, Dano UL, et al. Environmental sustainability impacts of solid waste management practices in the global South. *Int J Environ Res Public Health*. 2022;19(19):12717.
95. Cesar da Silva P, Cardoso de Oliveira Neto G, Ferreira Correia JM, Pujol Tucci HN. Evaluation of economic, environmental and operational performance of the adoption of cleaner production: survey in large textile industries. *J Clean Prod*. 2021;278:123855.
96. Madhav S, Ahamad A, Singh P, Mishra PK. A review of textile industry: wet processing, environmental impacts, and effluent treatment methods. *Environ Qual Manag*. 2018;27(3):31-41.
97. Kurniawan TA, Chan GYS, Lo WH, Babel S. Physico–chemical treatment techniques for wastewater laden with heavy metals. *Chem Eng J*. 2006;118(1-2):83-98.
98. Barakat MA. New trends in removing heavy metals from industrial wastewater. *Arab J Chem*. 2011;4(4):361-377.
99. Ob A, Muchie M. Remediation of heavy metals in drinking water and wastewater treatment systems: processes and applications. *Int J Phys Sci*. 2010;5(4):1807-1817.
100. Gunatilake S. Methods of removing heavy metals from industrial wastewater. *Methods*. 2015;1(1):14.
101. Azimi A, Azari A, Rezakazemi M, Ansarpour M. Removal of heavy metals from industrial wastewaters: a review. *ChemBioEng Rev*. 2017;4(1):37-59.
102. Lavanya MB, Viswanath DS, Sivapullaiah PV. Phytoremediation: an eco-friendly approach for remediation of heavy metal-contaminated soils-a comprehensive review. *Environ Nanotechnol Monitor Manag*. 2024;22:100975.
103. Kuppan N, Padman M, Mahadeva M, Srinivasan S, Devarajan R. A comprehensive review of sustainable bioremediation techniques: eco friendly solutions for waste and pollution management. *Waste Management Bulletin*. 2024;2(3):154-171.
104. Ansari AA, Naeem M, Gill SS, AlZuaibr FM. Phytoremediation of contaminated waters: an eco-friendly technology based on aquatic macrophytes application. *Egypt J Aquat Res*. 2020;46(4):371-376.
105. Bhalla G, Bhalla B, Kumar V, Sharma A. Bioremediation and phytoremediation of pesticides residues from contaminated water: a novel approach. In: *Pesticides Remediation Technologies From Water and Wastewater*. Elsevier; 2022: 339-363.