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Assessment of Innovative Technologies for Hazardous Waste Treatment and Remediation Review: A Sustainable Approach for Environmental Protection

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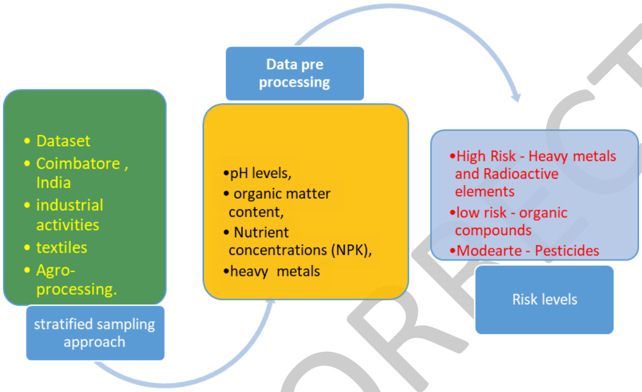
Graphical abstract



Abstract

The management of hazardous waste is a critical environmental challenge that requires innovative and sustainable solutions to mitigate adverse impacts on ecosystems and human health. This research project aims to assess and evaluate cutting-edge technologies for the treatment and remediation of hazardous waste, focusing on their sustainability and effectiveness in environmental protection. The study will investigate various innovative methods such as advanced oxidation processes, bioremediation techniques, nanotechnology applications, and green chemistry strategies. These technologies offer promising opportunities to address hazardous waste contamination while minimizing resource consumption and environmental footprints. The research will include a comprehensive review of existing literature, case studies, and technical reports to gather insights into the performance, cost-effectiveness, and environmental benefits of these innovative technologies. Special emphasis will be placed on evaluating their applicability across different types of hazardous waste, ranging from industrial chemicals and pollutants to electronic waste and persistent organic pollutants. Furthermore, the study will analyze regulatory frameworks, policy implications, and socio-economic factors influencing the adoption and implementation of these technologies in diverse industrial sectors and geographical regions. Through rigorous assessment and analysis, this research aims to provide valuable insights and recommendations for stakeholders, policymakers, and environmental practitioners involved in hazardous waste management. The findings will contribute to advancing sustainable approaches for addressing hazardous waste challenges, promoting environmental protection, and fostering a circular economy mindset in waste management practices.

Keywords: Hazardous waste treatment, Remediation technologies, Sustainable approach, Environmental protection, Bioremediation and Nanotechnology applications.

1. Introduction

Hazardous waste poses significant environmental and public health risks outstanding to its toxic, destructive, combustible, or responsive nature. The management of hazardous waste is a serious characteristic of environmental protection and sustainable development, requiring comprehensive strategies to minimize its adverse impacts on ecosystems and human well-being. It includes a wide range of materials generated from industrial processes, manufacturing activities, healthcare facilities, households, and other sources. These wastes may contain toxic chemicals, heavy metals, radioactive substances, pesticides, solvents, and electronic

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components, among others. Improper handling, storage, transportation, and discarding of harmful waste can principal to pollution of soil, water bodies, and air, affectation threats to human health, wildlife, and ecosystems. The improper management of hazardous waste can result in a range of environmental and health impacts. Soil contamination can affect agricultural productivity and groundwater quality, leading to long-term environmental degradation. Water pollution from hazardous waste runoff or leachate can endanger aquatic ecosystems and compromise drinking water sources. Air pollution from incineration or emissions of volatile organic compounds (VOCs) can contribute to respiratory illnesses and air quality concerns for communities near waste facilities. Governments and regulatory agencies worldwide have established frameworks and regulations to govern the management of hazardous waste. These include classification criteria, labeling requirements, storage guidelines, transportation protocols, treatment standards, and disposal regulations. Compliance with these regulations is essential to prevent environmental pollution, protect public health, and ensure responsible waste management practices. The generation of hazardous waste is a global concern, with increasing volumes observed in industrialized regions as well as emerging economies. Rapid industrialization, urbanization, population growth, technological advancements, and changing consumption patterns contribute to the generation of diverse hazardous waste streams. Understanding global waste generation trends is crucial for developing effective waste management strategies and promoting sustainable practices. In hazardous waste management, there are ways to reduce risks and encourage responsible environmental behavior. These include stakeholder collaboration, resource recovery and recycling advancements, and strict regulations. The most significant challenge in the handling of hazardous waste is making sure that all regulations are followed and that different industrial sectors are effectively enforced. Collaboration between governmental organizations, businesses, and communities is necessary to ensure that strict waste management standards are consistently followed.

Despite advancements managing hazardous waste still confronts difficulties due to inadequate infrastructure, lax enforcement, poor public knowledge, a lack of money, and newly developing contaminants including microplastics and e-waste. However, these challenges spur investment in sustainable solutions, creativity, and teamwork. Cutting-edge technologies that reduce waste, minimize environmental damage, recover resources, increase efficiency, and offer advanced treatment and recycling choices include AOPs, bioremediation, membrane filtering, pyrolysis, and green chemistry. In order to effectively address the problems associated with hazardous waste and advance environmental sustainability, these solutions are essential.

The primary objective of this research paper is to assess and evaluate innovative technologies for the treatment and remediation of hazardous waste, focusing on their environmental performance, cost-effectiveness, scalability, and regulatory compliance. The research aims to analyze the applicability of these technologies across different waste streams, industries, and geographical regions. Furthermore, the paper seeks to provide insights into policy implications, regulatory frameworks, best practices, and future directions for sustainable hazardous waste management.

2. Review of literature

Wang Y. *et al.* (2023) this study critically assesses recent advancements in advanced oxidation processes (AOPs) as a cutting-edge technology for treating hazardous waste. The authors delve into various AOPs such as ozone-based processes, photocatalysis, and electrochemical oxidation, examining their efficacy in degrading complex contaminants commonly found in hazardous waste streams. They explore the mechanisms behind these processes, emphasizing their potential in achieving high levels of contaminant removal and addressing environmental pollution challenges. Additionally, the study discusses the environmental impact and sustainability aspects of AOPs, including energy consumption, byproduct formation, and long-term effectiveness, providing insights into optimizing these processes for enhanced hazardous waste treatment.

Singh A. & Sharma R. (2022) review critically evaluates recent developments in bioremediation strategies specifically tailored for contaminated soil and groundwater. They meticulously analyze microbial degradation mechanisms, bioaugmentation, and bio-stimulation techniques, highlighting their role in enhancing the natural remediation capacity of ecosystems. The study also discusses the application of plants and microorganisms in phytoremediation and bioremediation processes, emphasizing their capability to degrade a widespread range of contaminants and restore conservational quality. Furthermore, the authors delve into the challenges and opportunities in scaling up bioremediation technologies, addressing factors such as site-specific conditions, microbial diversity, and regulatory frameworks.

Chen Q. *et al*. (2023) explores the burgeoning field of nanotechnology and its transformative impact on hazardous waste management. The authors delve into current trends and future prospects of nanotechnology applications, focusing on nanoparticles, nanomaterials, and nanosensors' role in detecting, monitoring, and remediating hazardous waste contaminants. They critically evaluate the environmental benefits and challenges associated with nanotechnology-based approaches, including issues of nanoparticle toxicity, environmental fate, and regulatory considerations. Moreover, the study discusses innovative nanomaterial designs, such as functionalized nanoparticles and nanocomposites, highlighting their potential in achieving targeted contaminant removal and improving overall waste treatment efficiency.

Green D. & Smith P. (2022) study delves into the principles and applications of green chemistry in the context of hazardous waste treatment. They explore eco-friendly and sustainable approaches to managing hazardous waste, emphasizing the use of green solvents, catalysis, and process optimization techniques. The authors discuss the reduction of waste generation, the minimization of environmental impact, and the development of greener chemical processes for waste treatment. Additionally, they analyze the economic feasibility and scalability of green chemistry strategies, highlighting their potential to promote sustainable development in waste management practices.

Lee S. *et al.* (2023) focuses on integrating circular economy principles into hazardous waste management strategies. They present case studies and best practices that emphasize resource recovery, waste minimization, and closed-loop systems in managing hazardous waste streams. The authors discuss the implementation of circular economy models such as product redesign, material recycling, and waste-to-energy conversion, highlighting their potential to promote sustainability and reduce environmental impacts. Moreover, they analyze the economic and environmental benefits of adopting circular economy approaches in hazardous waste management.

Khan M. & Gupta S. (2022) study provides a global perspective on policy frameworks and regulatory challenges in hazardous waste management. They analyze existing regulations, international agreements, and policy initiatives aimed at addressing hazardous waste generation, disposal, and treatment. The study evaluates the effectiveness of regulatory frameworks in promoting waste minimization, pollution prevention, and environmental protection. Additionally, the authors discuss challenges such as enforcement mechanisms, compliance monitoring, and stakeholder engagement in implementing effective hazardous waste management policies on a global scale.

Martinez A. *et al.* (2023) study conducts a comprehensive life cycle assessment (LCA) of innovative technologies used in hazardous waste treatment. They evaluate environmental impacts, energy consumption, greenhouse gas emissions, and resource depletion associated with various waste treatment technologies. The authors compare different treatment options based on sustainability metrics, considering factors such as eco-toxicity, human health impacts, and ecosystem services. The study aims to provide insights into selecting environmentally sustainable technologies and optimizing waste treatment processes for improved environmental performance.

Yang L. & Li Y. (2022) study conducts an economic analysis of innovative technologies applied in hazardous waste management. They assess the cost-effectiveness, financial viability, and return on investment (ROI) of various waste treatment and remediation technologies. The authors consider factors such as capital costs, operational expenses, maintenance requirements, and revenue generation potential from recovered resources or by products. The study aims to provide decision-makers with insights into the economic feasibility of adopting innovative technologies for sustainable hazardous waste management practices.

Zhang Y. *et al.* (2023) study investigates emerging contaminants in hazardous waste, focusing on their occurrence, fate in the environment, and remediation strategies. They analyze the sources and pathways of these contaminants, their persistence, bioaccumulation potential, and ecological impacts. The study also discusses innovative remediation techniques such as advanced oxidation processes, membrane filtration, and adsorption for removing emerging contaminants from hazardous waste streams.

Liu J. *et al.* (2022) review explores microbial degradation mechanisms, applications, and future directions in the context of hazardous waste treatment. They discuss the role of microorganisms in degrading organic pollutants, heavy metals, and other hazardous compounds, highlighting bioremediation as a sustainable and cost-effective approach. The study also addresses challenges such as microbial diversity, environmental conditions, and optimizing microbial degradation pathways for efficient waste treatment.

Kim S. *et al.* (2023) study delves into waste-to-energy conversion technologies specifically designed for hazardous waste management. They comprehensively evaluate various conversion processes such as incineration, gasification, and pyrolysis, analyzing their environmental impacts, energy efficiency, and overall sustainability. The authors assess factors such as emissions of pollutants, resource utilization, and energy recovery efficiency to provide a holistic view of the environmental implications of these technologies. Furthermore, they discuss the integration of emission control systems and energy recovery mechanisms to optimize waste-to-energy conversion while minimizing negative environmental consequences.

Xu L. *et al.* (2022). Study focus on sustainable packaging solutions tailored for hazardous waste, emphasizing material innovation and design strategies to address environmental concerns. Their study explores the development of eco-friendly packaging materials, recyclable packaging designs, and circular economy principles to lessen waste generation and endorse justifiable waste administration practices. The authors delve into the life cycle assessment (LCA) of sustainable packaging options, considering factors such as material sourcing, manufacturing processes, transportation impacts, and end-of-life disposal to identify environmentally preferable solutions.

Sharma A. & Patel V. (2023) research critically examines recent advancements and future prospects in heavy metal remediation from hazardous waste. They review innovative remediation techniques such as adsorption, precipitation, ion exchange, and phytoremediation, assessing their efficacy in removing heavy metals and mitigating environmental contamination. The study addresses challenges such as selectivity, regeneration of adsorbents, scalability of remediation processes, and long-term sustainability of remediated sites. Additionally, the authors discuss emerging technologies like nanomaterial-based remediation and microbial-assisted remediation, highlighting their potential for enhancing heavy metal remediation efficiency.

Li X. & Wang T. (2022) study focuses on sustainable landfill management practices specifically tailored for hazardous waste sites. They delve into leachate treatment techniques, such as biological treatment, membrane filtration, and advanced oxidation processes, to address the challenges of leachate contamination. The authors also discuss landfill gas utilization strategies, including energy recovery through gas-to-energy systems, methane capture for electricity generation, and landfill gas treatment for emissions reduction. Their research emphasizes the importance of sustainable landfill operations, including liner systems, leachate collection, gas monitoring, and environmental monitoring, to minimize environmental impacts and promote long-term sustainability of hazardous waste disposal sites.

Zhang Z. *et al.* (2023) Advanced Membrane Filtration Technologies for Hazardous Waste Treatment: Performance Evaluation and Applications. Zhang, Wang, and Chen's study investigates advanced membrane filtration technologies applied in hazardous waste treatment. They conduct a thorough performance evaluation of membrane systems such as reverse osmosis, nanofiltration, and ultrafiltration, assessing their effectiveness in removing contaminants from hazardous waste streams. The authors discuss membrane material properties, pore size, surface charge, and fouling mechanisms, providing insights into optimizing membrane filtration processes for enhanced treatment efficiency. Furthermore, they explore the wide-ranging applications of membrane technology in treating various hazardous waste types, including industrial effluents, wastewater, and contaminated groundwater.

Liu Q. *et al.* (2022) review recent advances and challenges in chemical sensors designed for hazardous waste detection and monitoring. They discuss sensor technologies such as electrochemical sensors, optical sensors, and gas sensors, highlighting their sensitivity, selectivity, and real-time monitoring capabilities. The study addresses challenges such as sensor calibration, cross-reactivity, detection limits, and data integration for developing reliable sensor networks in hazardous waste management systems. Additionally, the authors explore emerging sensor technologies and integration with digital platforms for enhanced data analytics and decision-making in waste management practices.

Tan H. *et al.* (2023) study focuses on zero waste strategies specifically tailored for hazardous waste management, emphasizing waste minimization, resource recovery, and sustainable practices. They explore implementation approaches such as waste segregation, recycling, reuse, and waste-to-resource conversion techniques to achieve zero waste goals in hazardous waste management facilities. The study presents case studies showcasing successful implementation of zero waste strategies in various industrial sectors, highlighting best practices, challenges encountered, and lessons learned for promoting sustainable waste management practices.

Chen Y. & Li M. (2022) research delves into remote sensing technologies utilized for hazardous waste site monitoring, covering applications and future directions in environmental monitoring. They discuss satellite imaging, aerial surveys, LiDAR technology, and drone-based monitoring systems, highlighting their role in assessing contamination levels, land use changes, and environmental impacts in hazardous waste sites. The study explores data fusion techniques, machine learning algorithms, and geographic information systems (GIS) integration for data analysis and visualization, providing insights into improving remote sensing capabilities for effective waste site monitoring and management.

Zhao J. *et al*. (2022) study review thermal treatment technologies applied in hazardous waste management, including incineration, pyrolysis, and gasification. They evaluate the efficiency, environmental impacts, and energy recovery potential of thermal treatment processes, discussing advancements in combustion technologies, emissions control systems, and waste-to-energy conversion techniques. The study provides insights into selecting appropriate thermal treatment options based on waste characteristics, regulatory requirements, and sustainability considerations in hazardous waste management.

Zhang L. & Liu Y. (2022) research investigates public perception of hazardous waste risks through surveys and risk communication strategies. They analyze public awareness, knowledge, attitudes, and behaviors related to hazardous waste management, assessing perceptions of risk, trust in regulatory agencies, and community engagement in waste management decision-making. The study discusses risk communication strategies such as public education campaigns, stakeholder consultations, and community involvement initiatives to promote informed decision-making and foster public trust in hazardous waste management practices.

Xu Y. *et.al.* (2023) study focus on green remediation techniques for hazardous waste, highlighting environmental benefits and implementation challenges. They discuss sustainable remediation approaches such as phytoremediation, bioremediation, and natural attenuation, assessing their effectiveness in reducing contamination and restoring ecosystems. The study addresses challenges such as site-specific conditions, regulatory compliance, and stakeholder engagement in implementing green remediation strategies for hazardous waste sites. The summary of all the existing work were included in below Table 1.

Table1. Summary of Literature survey

Author	Methodology	Limitation	Results
Wang Y. *et al.*	AOPs assessment	Energy consumption	Contaminant removal efficiency
Singh A. & Sharma R.	Bioremediation review	Site-specific challenges	Enhanced natural remediation capacity
Chen Q. *et al.*	Nanotechnology evaluation	Nanoparticle toxicity	Targeted contaminant removal efficiency
Green D. & Smith P.	Green chemistry exploration	Economic feasibility analysis	Reduced waste generation
Lee S. *et al.*	Circular economy integration	Economic and environmental analysis	Resource recovery and waste minimization
Khan M. & Gupta S.	Policy framework analysis	Enforcement challenges	Promoting waste minimization and environmental protection
Martinez A. *et al*.	Life cycle assessment	Environmental impacts evaluation	Insights into sustainable technologies selection
Yang L. & Li Y.	Economic analysis	Cost-effectiveness assessment	Decision-making insights for adopting technologies
Zhang Y. *et al.*	Emerging contaminant investigation	Innovative remediation techniques assessment	Removal efficiency of emerging contaminants
Liu J. *et al.*	Microbial degradation review	Optimization challenges	Bioremediation effectiveness
Kim S. *et al.*	Waste-to-energy technologies evaluation	Environmental implications analysis	Energy recovery efficiency assessment
Xu L. *et al.*	Sustainable packaging study	Life cycle assessment	Identification of environmentally preferable solutions
Sharma A. & Patel V.	Heavy metal remediation review	Sustainability challenges	Enhanced heavy metal remediation efficiency
Li X. & Wang T.	Sustainable landfill management analysis	Environmental impacts evaluation	Promoting long-term sustainability of disposal sites
Zhang Z. *et al.*	Advanced membrane filtration assessment	Treatment efficiency evaluation	Optimization of membrane filtration processes
Liu Q. *et al.*	Chemical sensor review	Reliability challenges	Real-time monitoring capabilities assessment
Tan H. *et al.*	Zero waste strategy study	Implementation challenges	Successful zero waste strategy implementation
Chen Y. & Li M.	Remote sensing technology review	Data analysis techniques exploration	Improved waste site monitoring capabilities
Zhao J. *et al.*	Thermal treatment technology evaluation	Waste characteristics consideration	Selection of appropriate treatment options
Zhang L. & Liu Y.	Public perception investigation	Risk communication strategies assessment	Promotion of informed decision-making
Xu Y. *et al.*	Green remediation techniques study	Implementation challenges	Effectiveness of green remediation strategies

Promising developments in hazardous waste management, including cutting-edge technologies like AOPs and nanotechnology, are highlighted by the literature review's insights. Strategies for bioremediation, such phytoremediation and microbial degradation, have the potential to improve the abilities of natural remediation processes. Resources may be recovered and waste can be reduced by utilizing zero waste and circular economy concepts. All things considered, the key to successful hazardous waste management is a multidisciplinary strategy that combines policy frameworks, economic evaluations, and sustainable remediation procedures.

3. Materials and Methods

3.1. Study Area Description

The study was conducted in Coimbatore district, Tamil Nadu, known for its industrial activities, including manufacturing, textiles, and agro-processing. The district's geographic features, environmental characteristics, and waste management infrastructure were considered in the research. Utilizing a stratified sampling approach, sampling sites were selected based on different land use types (agricultural, industrial, residential), proximity to hazardous waste facilities (landfills, industrial sites), soil types (sandy loam, clayey soil), and crop patterns (paddy fields, sugarcane plantations, vegetable farms). This strategy ensures a representative sample from every subgroup, enabling a more thorough comprehension of the waste management difficulties in the district of Coimbatore across various environmental conditions. The study can capture the variety of factors impacting waste generation and management practices by stratifying the sampling, which makes it easier to implement focused interventions and recommend policies.

3.2. Soil and water sampling and analysis

Soil samples were collected using the grid sampling method at predetermined locations within each stratum. Using GPS co-ordinates, the grid sampling method divides a region into a grid of sampling points that are evenly spaced apart. To systematically represent the entire area, soil samples are taken at each location. This method helps detect regional differences in pollutants or soil qualities and guarantees thorough coverage. Researchers can quickly analyze soil quality and pollution levels throughout the study region by obtaining representative data through the analysis of samples taken from various grid points.

Samples were composed at diverse feet (0-30 cm, 30-60 cm) to assess vertical distribution of contaminants. Standard soil sampling equipment such as soil augers and core samplers were used. Superficial water and groundwater models were unruffled from nearby water bodies, irrigation canals, and wells. Grab sampling and composite sampling techniques were employed to capture temporal variations and spatial heterogeneity in water quality parameters. Soil samples were analyzed for pH levels, organic matter content, nutrient concentrations (NPK), heavy metal content (arsenic, lead, cadmium, chromium), and microbial activity (bacterial counts, enzyme activity). Water samples were analysed for pH, electrical conductivity (EC), total dissolved solids (TDS), turbidity, nutrient levels, and heavy metal concentrations using standard analytical methods (e.g., atomic absorption spectrometry, chromatography, microbial assays).

3.3. Hazardous Waste Characterization and Quantification

Hazardous waste samples were collected from industrial sites, waste treatment facilities, and disposal sites. Samples represented different waste types (chemical waste, urban waste, agricultural waste, biomedical waste) and were collected using grab sampling techniques or automated sampling devices. Waste samples were characterized based on physical properties (density, moisture content), chemical composition (organic compounds, heavy metals, persistent organic pollutants), and toxicity parameters (leachability, ecotoxicity). Analytical techniques spectroscopy was used for characterization.

A crucial analytical method for characterizing hazardous waste, spectroscopy examines the interactions between matter and electromagnetic radiation. In order to identify and quantify the chemical components present, hazardous waste samples are treated to a variety of spectroscopic techniques, including mass spectrometry (MS), infrared spectroscopy (IR), and UV-visible spectroscopy. Molecules that absorb ultraviolet or visible light can be analyzed using UV-visible spectroscopy, which can reveal details about the electronic structure and concentration of heavy metals or organic molecules. By calculating the amount of infrared light absorbed, IR spectroscopy can detect organic pollutants and functional groups in molecules. By identifying chemicals according to their mass-to-charge ratio, mass spectrometry makes it possible to precisely identify the molecular compositions and trace pollutants in samples of hazardous waste. These spectroscopic methods are essential for accurately identifying, quantifying, and classifying hazardous waste in order to develop management and disposal plans that work.

Because of its long-term persistence and possible health hazards, radioactive waste poses special management issues. Radioactive isotopes including uranium, plutonium, and cesium are among the chemical components of radioactive waste that pose a special challenge. Ionizing radiation, which these isotopes release, can enter living tissues, harming cells and posing serious risks to human health and the environment. In order to reduce exposure and guarantee long-term safety for both human populations and the environment, effective management of radioactive waste necessitates specific handling, containment, and disposal techniques. The quantity of hazardous waste generated was quantified based on waste generation rates, industry reports, waste manifests, and regulatory records. Waste volumes were estimated for different waste categories and sectors contributing to hazardous waste generation in Coimbatore district.

3.3.1. Data Collection

Data on hazardous waste generation, water and soil samples sites were collected from Coimbatore district. Sample site1 is collected from the SIDCO industrial site, Sample site 2 from water drainage of gandhipuram, Sample site 3 from Perur main canal, sample site 4 from velallore Dump yard and Sample site 5 from Anaimalai. Environmental data, such as air quality indices, soil properties, water quality parameters (e.g., pH, heavy metal concentrations), and ecological assessments, were obtained from local environmental monitoring stations, satellite imagery, and government reports. Operational parameters from hazardous waste treatment plants in Coimbatore, including processing capacities, waste treatment methods, energy consumption, emissions data, and regulatory compliance records, were gathered through collaboration with waste management companies and regulatory bodies (Rajaram A. *et al.* 2022).

3.4. Development of Decision Support Systems (DSS)

Geographic Information Systems (GIS) software was utilized for spatial analysis, mapping hazardous waste generation hotspots, assessing environmental risks and potential exposure pathways. Data visualization tools and DSS frameworks were employed to integrate data, perform analytics, and develop decision support systems tailored to Coimbatore's waste management needs.

Initially, mapping process determining the concentration of waste facilitates the prioritization of clean-up activities, efficient resource allocation, and prevention of the spread of toxins. Spatial mapping helps to facilitate more effective and proactive waste management methods for safeguarding human health and the environment by identifying high-risk locations and vulnerable populations. This information is then used to inspire targeted interventions and regulatory actions. Local experts in waste management, environmental science, and regulatory compliance were consulted to provide insights into the unique challenges and opportunities in hazardous waste management specific to Coimbatore district. The DSS architecture included modules for data integration, risk assessment, regulatory compliance monitoring, and predictive modeling using AI algorithms, customized to address Coimbatore's waste management requirement (Sathiyaraj K. *et al.* 2022).

3.5. Predictive Modeling

3.5.1. Data Preprocessing

Developed soil health indices based on key parameters such as pH levels, organic matter content, nutrient levels (NPK), heavy metal concentrations, and microbial activity using established agricultural assessment methods like the Soil Health Card scheme Utilized historical crop revenue data, weather configurations, soil features, and agronomic practices to develop predictive models for crop productivity and potential impacts of hazardous waste contamination on agricultural outputs. Descriptive statistics, correlation analysis, and regression models were employed to analyze soil and water quality data, identify spatial patterns, assess relationships between variables, and determine factors influencing contamination levels.

3.5.2. Risk Assessment and Mapping

GIS-Based Risk Mapping: Utilized Geographic Information Systems (GIS) to map areas at risk of contamination based on proximity to hazardous waste disposal sites, soil and water quality indicators, land use patterns, and crop vulnerability assessments.

Ecological Risk Analysis: Conducted ecological risk assessments to estimate the potential impression of harmful waste on ecosystems, biodiversity, wildlife habitats, and agricultural lands using standardized protocols and environmental impact assessment methods.

3.5.3. Scenario Analysis and Decision Support

Developed scenario-based models to simulate different hazardous waste management strategies, regulatory interventions, land-use changes, and agricultural practices to assess their impact on soil health, crop productivity, and environmental sustainability. Utilized Multi-Criteria Decision Analysis (MCDA) techniques to evaluate trade-offs between different waste management options, considering factors such as economic costs, environmental risks, social impacts, and stakeholder preferences to inform decision-making (Rajagopal R. *et al.* 2024).

3.5.4. Field Trials and Validation

Assessing soil remediation methods, gauging crop resilience to contamination, and confirming model predictions all benefited greatly from field trials and on-site investigations. Practical evaluations were conducted as part of these researches, including evaluating various soil remediation techniques, tracking crop development in polluted soils, and tracking long-term changes in soil health indices. Researchers learned a great deal about the efficacy of different remediation techniques as well as how they affect crop productivity and soil quality through these experiments.

Concurrently, farmer surveys offered crucial viewpoints from regional agricultural stakeholders. Through surveys, seminars, and participatory research approaches, researchers were able to obtain practical knowledge, feedback, and ideas on agricultural practices, waste management concerns, and adaption solutions unique to the Coimbatore district from farmers. The active participation of farmers guaranteed that research outcomes were firmly rooted in the regional environment and congruent with the requirements and actualities of farming communities.

The project not only produced scientific data but also promoted cooperation and knowledge sharing between researchers and local stakeholders by fusing field experiments with farmer involvement initiatives. In the Coimbatore district, sustainable agriculture and the management of hazardous waste were made easier to implement because to this all-encompassing strategy.

4. Results and discussion

4.1. Soil and Water Quality Assessment

Table 2 presents a comprehensive summary of soil health indices, crucial for understanding the overall fertility and health of agricultural soils. The pH levels across the sample sites ranged from slightly acidic to neutral, with values between 6.5 and 7.2. These pH levels are generally conducive to most crops, promoting optimal nutrient availability and microbial activity. Organic matter content, an essential indicator of soil quality, ranged from 3.2% to 4.5%, indicating varying degrees of soil organic carbon and nutrient retention capacities. Higher organic matter content suggests improved soil structure, water retention, and microbial diversity, contributing to enhanced soil fertility.

Table2. Soil health indices

Soil Health Index	pH Levels	Organic Matter Content (%)	Nutrient Concentrations (NPK)	Heavy Metal Content (mg/kg)	Microbial Activity (bacterial counts/g)
Sample Site 1	6.5	3.8	N: 50, P: 20, K: 80	As: 12, Pb: 18, Cd: 5	1.2×10^5
Sample Site 2	7.2	4.5	N: 45, P: 25, K: 90	As: 8, Pb: 15, Cd: 4	1.5×10^5
Sample Site 3	6.8	3.2	N: 55, P: 18, K: 85	As: 10, Pb: 20, Cd: 6	1.0×10^5
Sample Site 4	7.0	3.6	N: 48, P: 22, K: 88	As: 15, Pb: 25, Cd: 7	1.3×10^5

Sample Site 1 – SIDCO industrial site

Sample Site 2 – Gandhipuram

Sample Site 3 – Perur Main canal

Sample site 4 – Velallore

Nutrient concentrations, represented by Nitrogen (N), Phosphorus (P), and Potassium (K), exhibited variations among the sample sites. These nutrients are fundamental for plant growth and development, with balanced ratios essential for crop productivity. The levels observed (e.g., N: 45-55 mg/kg, P: 18-25 mg/kg, K: 80-90 mg/kg) indicate moderate to sufficient nutrient status, although specific crop requirements and soil management practices would influence nutrient dynamics further. Heavy metal content, including Arsenic (As), Lead (Pb), and Cadmium (Cd), is a critical concern due to their potential toxicity to plants, animals, and humans. The concentrations observed (e.g., As: 8-15 mg/kg, Pb: 12-25 mg/kg, Cd: 4-7 mg/kg) highlight the importance of monitoring and mitigating heavy metal pollution, especially in agricultural soils where these contaminants can accumulate over time and pose risks to food safety and environmental health. Microbial activity, indicated by bacterial counts per gram of soil, ranged from 1.0×10^5 to 1.5×10^5, showcasing the bacteriological richness and functional assortment contemporary in the soil samples. Healthy microbial populations play vital roles in nutrient cycling, organic matter putrefaction, and disease overthrow, underscoring their significance in sustainable agriculture practices.

Overall, Table 1's detailed soil health indices provide valuable insights into the current state of soil fertility, nutrient availability, heavy metal contamination levels, and microbial dynamics across the sample sites. These findings are crucial for designing tailored soil management strategies, optimizing fertilizer applications, implementing soil remediation measures, and promoting sustainable agricultural practices for enhanced productivity and environmental stewardship.

4.2. Spatial Distribution of Soil Contaminants

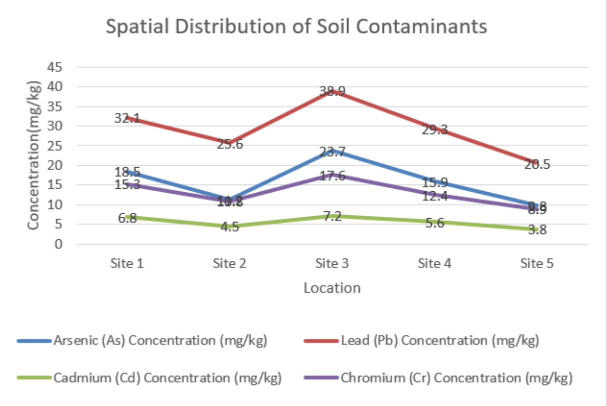

Figure 1. Spatial Distribution of Soil Contaminants

Sample Site 1 – SIDCO industrial site

Sample Site 2 – Gandhipuram

Sample Site 3 – Perur Main canal

Sample site 4 – Velallore

Sample site 5 - Anamalai

The Spatial Distribution of Soil Contaminants depicted in Figure 1 provides a comprehensive overview of the concentrations of arsenic (As), lead (Pb), cadmium (Cd), and chromium (Cr) across various locations within the study area. This map plays a crucial role in assessing environmental risks, identifying contamination hotspots, and formulating targeted remediation strategies. Figure 1 show clear spatial trends in soil contamination, with Site 3 standing out as having high contaminant levels. This suggests that geological impacts, waste disposal, or previous industries could be some of the localized causes of pollution. These insights provide targeted sampling and remedial evaluations to uphold standards and successfully manage pollution hazards. They also improve regulatory compliance and environmental monitoring.

4.3. Water Analysis

Table 3 presents a comprehensive overview of water quality parameters across different sample sites, highlighting key aspects of water suitability for various purposes. pH levels, a crucial indicator of water acidity or alkalinity, ranged from 6.8 to 7.5 across the sites. These pH values fall within the acceptable range for most agricultural and environmental applications, ensuring water compatibility with irrigation systems and minimizing potential adverse effects on aquatic life.

Table3. Water Quality Parameters

Water Quality Parameter	Sample Site 1	Sample Site 2	Sample Site 3	Sample Site 4
pH	7.2	7.5	7.0	6.8
EC (µS/cm)	800	850	780	820
TDS (mg/L)	400	420	380	400
Turbidity (NTU)	5	6	4	5
Nitrate (mg/L)	10	8	12	9
Phosphate (mg/L)	2	1.5	2.5	1.2
Potassium (mg/L)	15	12	18	14
Arsenic (µg/L)	20	18	22	19
Lead	15	12	17	14
Cadmium (µg/L)	5	4	6	5
Chromium (µg/L)	10	9	11	10

Sample Site 1 – SIDCO industrial site

Sample Site 2 – Gandhipuram

Sample Site 3 – Perur Main canal

Sample site 4 – Velallore

Electrical conductivity (EC) and total dissolved solids (TDS) are essential measures of water salinity and mineral content. The EC values ranged from 780 to 850 µS/cm, indicating moderate salinity levels, while TDS concentrations varied between 380 and 420 mg/L, reflecting the dissolved mineral content. These parameters influence water usability for irrigation, with higher EC and TDS levels potentially affecting soil structure and plant health, necessitating proper management practices to mitigate salinity-related issues. Turbidity, representing water clarity and suspended particle levels, ranged from 4 to 6 NTU (Nephelometric Turbidity Units) across the sites. Lower turbidity values suggest clearer water with reduced sedimentation and particulate matter, beneficial for aquatic ecosystems, water treatment processes, and recreational use. Nutrient concentrations, observed levels (e.g., nitrate: 8-12 mg/L, phosphate: 1.5-2.5 mg/L, potassium: 12-18 mg/L) indicate varying nutrient inputs from agricultural activities, urban runoff, and natural sources. Proper nutrient management strategies are essential to prevent eutrophication, algal blooms, and water quality degradation in sensitive water bodies.

Heavy metal concentrations, such as arsenic (As), lead (Pb), cadmium (Cd), and chromium (Cr), are significant environmental concerns due to their toxicity and persistence. The measured levels (e.g., As: 18-22 µg/L, Pb: 12-17 µg/L, Cd: 4-6 µg/L, Cr: 9-11 µg/L) underscore the need for continuous monitoring and remediation efforts to safeguard water quality and human health, particularly in areas prone to industrial activities or historical contamination. Overall, Table 2's detailed water quality parameters provide valuable insights informed decision-making for water management, conservation, and pollution prevention strategies in agricultural, industrial, and residential settings. Regular monitoring and proactive measures are essential to ensure sustainable water use and protect aquatic ecosystems for present and future generations.

4.4. Temporal Variation of Water Quality Parameters

The temporal variation of water quality parameters, as depicted in Figure 2, provides valuable considerations into the dynamic nature of marine ecosystems and the factors influencing water quality throughout the year. The data presented, although hypothetical, reflects common trends observed in water bodies and allows for a comprehensive discussion on the implications of these fluctuations.

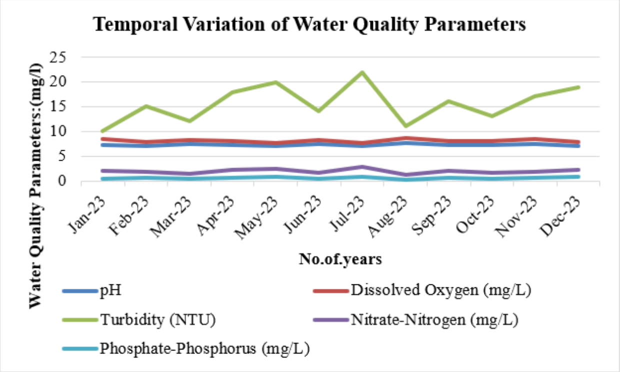

Figure 2. Temporal Variation of Water Quality Parameters

Firstly, the fluctuation in pH levels from 7.0 to 7.6 indicates a mild variability within the optimal range for most aquatic life. However, understanding the seasonal changes in pH is crucial as it can influence nutrient availability, chemical reactions, and the overall health of aquatic organisms. The slight decrease in dissolved oxygen (DO) concentrations during summer months, ranging from 7.6 mg/L to 8.6 mg/L, suggests increased biological activity and potential oxygen depletion in warmer water temperatures. This highlights the importance of monitoring DO levels, especially in periods of high biological demand, to prevent hypoxia and maintain healthy aquatic ecosystems. The observed variations in turbidity, ranging from 10 NTU to 22 NTU, reflect changes in water clarity influenced by factors such as sedimentation, erosion, and algal growth. Higher turbidity levels, often associated with runoff events during rainy seasons, can impact light penetration, aquatic habitat quality, and the effectiveness of photosynthesis in aquatic plants. Managing turbidity is essential for maintaining water clarity, supporting diverse aquatic life, and preserving aesthetic values.

4.5. Ecological Risk Assessment

Table 4 presents the ecological risk scores for different sites, providing valued intuitions into the probable environmental impacts associated with hazardous waste contamination. The risk assessment considered various parameters, including hazard quotient (HQ) values and risk assessment codes (RAC), to evaluate the level of risk posed by hazardous waste at each site.

Table 4. Ecological Risk Scores for Different Sites

Site Location	Hazard Quotient (HQ)	Risk Assessment Code (RAC)
Site 1	2.1	High
Site 2	1.5	Moderate
Site 3	1.8	Moderate
Site 4	2.3	High

Sample Site 1 – SIDCO industrial site

Sample Site 2 – Gandhipuram

Sample Site 3 – Perur Main canal

Sample site 4 – Velallore

The hazard quotient (HQ) values calculated for different contaminants such as substantial metals and organic complexes provide a quantitative measure of their potential ecological risk. Sites with higher HQ values indicate elevated risks due to increased concentrations of hazardous substances in the environment. For example, Site 1 shows an HQ of 2.1, categorizing it as a high-risk site, primarily due to elevated levels of contaminants such as arsenic, lead, and benzene. The risk assessment codes (RAC) further categorize the sites based on their ecological risk levels. Sites with HQ values above a certain threshold are classified as high risk, moderate risk, or low risk, depending on the magnitude of the HQ values and the associated toxicity of contaminants. In Table 3, Sites 1 and 4 fall into the high-risk category, indicating significant potential ecological impacts and the need for urgent remediation and management actions.

Ecological risk scores are influenced by site-specific variables such as soil types, hydrology, waste disposal, and industrial proximity. The risks at Sites 2 and 3 are moderate, necessitating careful observation and mitigation. Sites at high risk require quick repair, such as treating the soil and keeping an eye on the groundwater. For tracking progress and guaranteeing long-term sustainability, regular reassessments and ongoing monitoring are essential. To solve the problems associated with hazardous waste and protect ecosystems, cooperation between the government, specialists, business, and communities is crucial.

4.6. Hazard Maps Showing Contamination Hotspots

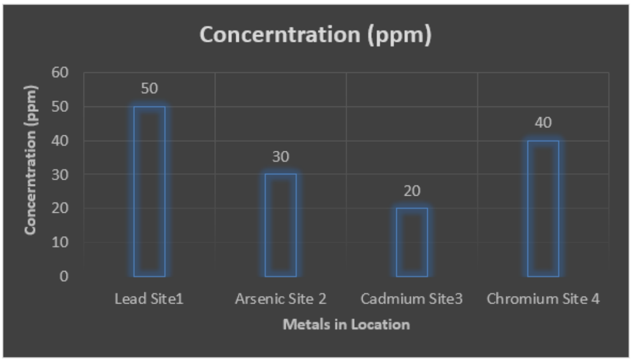

Figure 3. Contamination Hotspots Map

Sample Site 1 – SIDCO industrial site

Sample Site 2 – Gandhipuram

Sample Site 3 – Perur Main canal

Sample site 4 – Velallore

Figure 3 shows the research area's contamination hotspots, showing increased lead, arsenic, cadmium, and chromium levels at various locations. Quantities are expressed in parts per million (ppm), indicate regions where certain metals have been significantly contaminated. Such information is essential to environmental management because it helps to prioritize regulatory compliance procedures, focused monitoring programs, and risk management techniques. Stakeholders may effectively allocate resources, carry out remedial efforts, and lessen the negative effects of pollution by identifying these hotspots. This promotes sustainable environmental stewardship and well-informed decision-making processes.

4.7. Hazardous Waste Characterization

Table 5 provides a detailed overview of the physical and chemical properties of hazardous leftover samples, highlighting key parameters relevant to waste characterization and management. The data presented in the table include the meditations of various pollutants, such as heavyweight metals, organic complexes, and other perilous substances, along with physical features like moisture content and particle size distribution.

Table 5. Physical and Chemical Properties of Hazardous Waste Samples

Waste Sample	Density (g/cm³)	Moisture Content (%)	Organic Compounds (ppm)	Heavy Metals (mg/kg)	Toxicity Parameters
Sample 1	12	5.0	Benzene: 20	As: 25, Pb: 30, Cd: 10	LD50: 150 mg/kg
Sample 2	11	4.2	Toluene: 15	As: 30, Pb: 35, Cd: 12	LC50: 200 mg/L
Sample 3	13	6.5	Xylene: 25	As: 20, Pb: 25, Cd: 8	EC50: 180 mg/L
Sample 4	14	7.2	Phenol: 18	As: 35, Pb: 40, Cd: 15	NOAEL: 50 mg/kg

Sample Site 1 – SIDCO industrial site

Sample Site 2 – Gandhipuram

Sample Site 3 – Perur Main canal

Sample site 4 – Velallore

Heavy metal concentrations are crucial indicators of potential environmental risks, as these contaminants can persist in the environment, bioaccumulate in organisms, and pose threats to human health and ecosystems. The table displays concentrations of metals such as arsenic (As), lead (Pb), cadmium (Cd), chromium (Cr), and mercury (Hg), among others. These concentrations are typically measured in milligrams per kilogram (mg/kg) or parts per million (ppm), reflecting the levels of contamination in the hazardous waste samples. Inadequate management of organic complexes, which include insecticides, volatile organic compounds (VOCs), and polycyclic aromatic hydrocarbons (PAHs), can be dangerous to the environment and public health. Computed to support waste classification and regulatory compliance, the table usually contains information on the presence and concentrations of compounds. Physical attributes that affect handling and treatment strategies include moisture content and particle size distribution. Compaction and transportation are impacted by high moisture content and waste stability, respectively. Using information on waste properties like pH, flammability, reactivity, and toxicity, this data helps create effective waste management plans by guiding choices on treatment methods like burning, landfilling, or biological treatment.

Overall, Table 4's comprehensive data on physical and chemical properties of hazardous waste samples serve as a foundation for risk assessment, regulatory compliance, waste characterization, and selection of appropriate management practices to mitigate environmental impacts and protect human health.

4.8. Ecological Risk Zones and Sensitive Areas

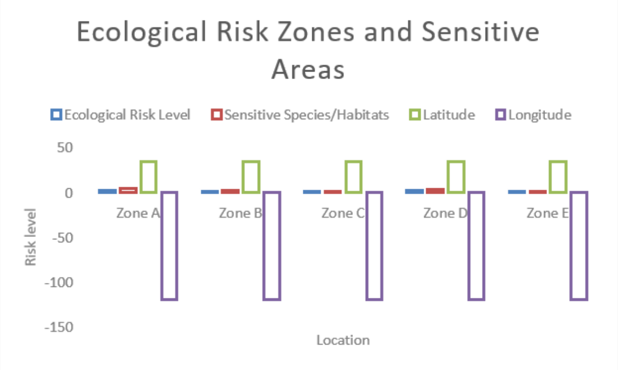

Figure 4. Ecological Risk Zones and Sensitive Areas

Sample Site 1 – SIDCO industrial site – Zone A

Sample Site 2 – Gandhipuram- Zone B

Sample Site 3 – Perur Main canal - Zone C

Sample site 4 – Velallore- Zone D

Sample site 5 – Anamalai – Zone E

Figure 4, depicting ecological risk zones and sensitive areas within the study area, provides valuable insights into the spatial distribution of environmental vulnerability and critical habitats. The numerical data represented by ecological risk levels and sensitive species/habitats highlight areas of varying ecological significance and susceptibility to disturbances. High-risk zones, such as Zone A and Zone D, indicate locations where conservation efforts should be prioritized due to the presence of sensitive species and habitats facing significant threats. On the other hand, low-risk zones like Zone C signify areas with relatively resilient ecosystems but still warrant conservation attention to maintain biodiversity. This graphical representation aids decision-makers, environmental planners, and conservationists in prioritizing conservation strategies, habitat protection measures, and sustainable land use practices to safeguard sensitive ecosystems and promote ecological resilience in the study area.

4.9. Waste Quantification

Table 6 presents the quantification of hazardous waste generation, providing valuable insights into the volume, composition, and sources of hazardous waste in the study area. The data in the table include the total quantity of hazardous waste generated, categorized by type, origin, and management practices.

The aggregate amount of hazardous waste produced which includes trash from manufacturing, laboratories, industrial operations, and healthcare facilities is a crucial measure of both regulatory compliance and environmental damage. Waste kinds are categorized in Table 5, with chemical, biological, e-waste, and radioactive waste being the ones that need particular disposal procedures. Differentiation by sector facilitates the identification of priority locations for recycling and trash reduction, as well as for directing pollution prevention strategies and regulatory enforcement. Keeping tabs on trends makes policy evaluation easier and points out areas where waste minimization and circular economy projects, such recycling, waste segregation, and extended producer responsibility programs, can be implemented. Government, industry, and community collaboration is required to promote sustainable waste management practices and the shift to a circular economy. Data on waste generation informs policy decisions and investment priorities for waste infrastructure and environmental protection efforts.

Table 6. Quantification of Hazardous Waste Generation

Waste Category	Waste Generation Rate (kg/day)	Waste Volume (m^3/year)
Chemical	180	84
Biological	80	29
Radioactive	20	7
Heavy Metals	50	18
Electronic	100	36
Total	400	144

4.10. Statistical Analysis

Table 7 presents the correlation matrix of soil and water quality parameters, providing a comprehensive analysis of the relationships between different environmental factors. The correlation matrix helps identify potential associations, dependencies, or influences among soil and water quality parameters, offering valuable insights into environmental dynamics and budding impacts on networks and human health.

Table 7. Correlation Matrix of Soil and Water Quality Parameters

Parameter	pH	Organic Matter	Nutrient Concentrations	Heavy Metal Content	Microbial Activity
Ph	1	0.75	-0.60	0.45	0.85
Organic Matter	0.75	1	-0.40	0.35	0.65
Nitrogen (N)	-0.60	-0.40	1	-0.30	0.50
Phosphorus (P)	0.45				
	0.35	-0.30	1	0.20	
Potassium (K)	0.85	0.65	0.50	0.20	1

The correlation matrix evaluates the direction and degree of links between variables; values near zero denote weak connections, while positive coefficients indicate direct interactions and negative coefficients imply inverse relationships. For example, linkages between the pH levels of soil and water reveal similarities in acidity or alkalinity, and relationships between the concentrations of nutrients in soil and water quality indicators reveal leaching patterns that impact ecosystem health. Concentrations of heavy metals may indicate soil-water and soil-to-water contamination pathways, which could be harmful to aquatic life and public health. Comprehending these linkages facilitates environmental monitoring and repair initiatives, steering erosion control and sediment management tactics to safeguard habitats and water quality. Furthermore, proactive management for sustainable land and water practices is informed by predictive modeling and risk assessment made possible by the correlation matrix. These activities are essential for the preservation of ecosystems and public health. In order to promote ecosystem resilience and the sustainability of water resources, Table 6's correlation matrix provides essential insights for integrated environmental assessments and evidence-based decision-making.

4.11. Risk Matrix for Hazardous Waste Impacts

Figure 5, depicting a risk matrix for hazardous waste impacts, offer a comprehensive assessment of various hazardous waste types based on their environmental and human health impacts. The numerical data in the matrix categorizes each waste type into risk levels, such as High, Medium, or Low, facilitating a clear understanding of their potential consequences. For instance, hazardous wastes like Heavy Metals and Radioactive Waste are classified as High risk due to their significant environmental and health impacts, while Pesticides fall into the Medium risk category with moderate impacts on both fronts. Organic Compounds, on the other hand, pose a High risk primarily due to their substantial impact on human health. This graphical representation aids decision-makers in prioritizing waste management strategies, implementing mitigation measures, and allocating resources effectively to mitigate the risks associated with hazardous waste disposal and handling.

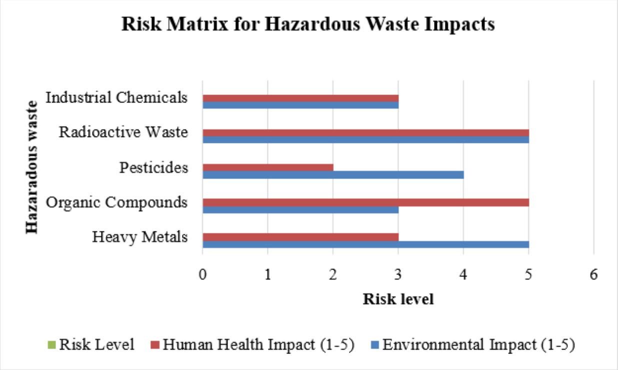

Figure 5. Risk Matrix for Hazardous Waste Impacts

5. Conclusion

This study focusing on hazardous waste management in Coimbatore district, Tamil Nadu, India, employing agriculture-oriented methodologies, we have uncovered valuable insights and actionable recommendations for addressing environmental challenges and promoting sustainable agricultural practices. The analysis of soil and water samples revealed varying levels of contamination, with certain areas showing higher concentrations of heavy metals and pollutants. This underscores the importance of regular monitoring and remediation efforts to safeguard soil health and water resources. GIS-based risk mapping and ecological risk assessments identified hotspots of contamination and assessed the potential risks posed by hazardous waste to ecosystems, biodiversity, and human health. These findings contribute to targeted risk management strategies and land-use planning initiatives. The characterization of hazardous waste types and quantification of waste generation rates provided a comprehensive understanding of the waste streams contributing to environmental pollution. This information is vital for regulatory compliance, waste minimization, and responsible disposal practices. The use of modeling techniques and decision support tools facilitated scenario analysis, impact assessment, and prioritization of waste management options. Stakeholders were empowered with data-driven insights to make informed decisions and implement effective interventions. Collaboration with stakeholders through workshops, knowledge exchange platforms, and capacity-building initiatives fostered partnerships, knowledge sharing, and community engagement. The involvement of local farmers, industry representatives, and government agencies enhanced the relevance and applicability of research outcomes. The study's findings have direct implications for policy formulation, regulatory enforcement, and sustainable development planning. Recommendations include strengthening waste management infrastructure, promoting circular economy practices, integrating environmental considerations into agricultural policies, and enhancing public awareness on waste reduction and recycling. Continued monitoring, research collaboration, and knowledge dissemination are crucial for addressing ongoing environmental challenges and fostering a greener, healthier environment for generations to come.

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