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Research Article

Global Trends in Medical Waste Management and Predictive Modeling of Water Quality Contamination

(A Hybrid Approach Using Scimat and Neural Networks in Orange)

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Abstract: The rapid growth of healthcare services has significantly increased the generation of medical waste, posing serious risks to environmental and public health, particularly through water quality contamination. This study examines global trends in medical waste management and proposes a hybrid analytical framework combining bibliometric analysis using SCIMAT and predictive modeling based on artificial neural networks implemented in Orange. Bibliometric mapping was employed to identify dominant research themes, temporal evolution, and knowledge gaps in medical waste and water contamination studies from 2000 to 2023. Subsequently, a neural network model was developed to predict potential water quality deterioration associated with mismanaged medical waste, using simulated environmental indicators. The results reveal a strong research focus on incineration, infection control, and hazardous waste, while predictive modeling of water contamination remains underexplored. The proposed hybrid approach demonstrates high predictive accuracy and offers a robust decision-support tool for environmental health policy. This study contributes methodologically and substantively to sustainable medical waste management and water resource protection.

Keywords: Bibliometric Analysis; Environmental Health; Medical Waste Management; Neural Network Modeling; Water Quality Contamination.

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1. Introduction

Medical waste generation has increased substantially due to the expansion of healthcare facilities, technological advancement, and population growth. The World Health Organization estimates that approximately 15% of healthcare waste is hazardous and poses risks to human health and the environment when improperly managed (WHO, 2018). Inadequate medical waste management can lead to soil and water contamination, contributing to the spread of pathogens and toxic substances. In recent years, global assessments have reported a significant acceleration in medical waste generation during public health emergencies, particularly the COVID-19 pandemic, which placed unprecedented pressure on existing waste management systems (Klemeš et al., 2020; Manupati et al., 2021).

Inadequate medical waste management can lead to soil and water contamination, contributing to the spread of pathogens and toxic substances. Empirical studies indicate that healthcare waste disposal sites are often associated with elevated concentrations of heavy metals, pharmaceutical residues, and pathogenic microorganisms in nearby water bodies (El-Salam & Abu-Zuid, 2015; Peng et al., 2022). These contaminants pose long-term risks to both ecosystems and human health.

Water resources are particularly vulnerable to contamination from leachate, untreated effluents, and improper disposal of medical waste. Several studies have reported the presence of pharmaceutical residues, heavy metals, and pathogenic microorganisms in surface and groundwater near healthcare waste disposal sites (Kumar et al., 2020). Such contamination threatens ecosystem integrity and public health. Pharmaceutical compounds and antibiotic-resistant bacteria have been increasingly detected in surface and groundwater near healthcare facilities, raising concerns regarding chronic exposure and antimicrobial resistance (aus der Beek et al., 2016; WHO, 2020).

Globally, medical waste management practices vary widely between developed and developing countries. While high-income countries have adopted advanced treatment technologies, many low- and middle-income countries still rely on open dumping and uncontrolled incineration (Chartier et al., 2014). These disparities highlight the need for comprehensive global assessments.

Bibliometric analysis has become a valuable tool for identifying research trends, thematic evolution, and knowledge gaps within a scientific field. SCIMAT allows longitudinal mapping of research themes, enabling a structured understanding of scientific development over time (Cobo et al., 2012). However, bibliometric insights are rarely integrated with predictive environmental modeling.

Artificial neural networks have demonstrated strong performance in modeling nonlinear environmental systems, including water quality prediction (Nourani et al., 2018; Zhang et al., 2021). The Orange data mining platform provides a transparent and reproducible environment for implementing ANN-based models.

This study proposes a hybrid framework integrating bibliometric analysis using SCIMAT and ANN-based predictive modeling in Orange to examine global research trends and forecast water quality contamination risks associated with medical waste mismanagement. The approach aims to bridge knowledge synthesis and applied environmental health decision-making.

2. Literature Review

Early research on medical waste management focused on classification systems and infection control within healthcare facilities (Prüss et al., 1999; Windfeld and Brooks, 2015). These studies emphasized occupational safety and proper segregation procedures. Treatment technologies such as incineration and autoclaving became dominant research themes during the early 2000s. Environmental externalities received comparatively less attention during this period.

Subsequent investigations examined the ecological impacts of waste treatment methods. Incineration has been associated with emissions of dioxins and heavy metals, while landfilling poses risks of groundwater contamination through leachate migration (Klemeš et al., 2020; Singh et al., 2021). Comparative assessments indicate that technology selection significantly influences environmental outcomes (Aung et al., 2019). Sustainable waste management requires integrated environmental impact evaluation.

Water contamination linked to medical waste includes pharmaceutical residues and antibiotic resistant microorganisms. Global monitoring studies have reported trace pharmaceuticals in rivers, lakes, and groundwater systems (aus der Beek et al., 2016; Peng et al., 2022). These contaminants affect aquatic biodiversity and increase resistance gene dissemination. Long term exposure scenarios demand predictive modeling approaches.

Bibliometric analysis has gained prominence in environmental sciences for identifying research clusters and thematic shifts (Moral Muñoz et al., 2020; Donthu et al., 2021). SCIMAT enables longitudinal mapping and strategic diagram analysis to assess thematic centrality and density (Cobo et al., 2012). Despite its methodological strength, few studies apply bibliometric mapping to medical waste and water contamination research simultaneously. This limitation restricts comprehensive knowledge synthesis.

Machine learning models, particularly artificial neural networks, demonstrate strong predictive performance in environmental systems characterized by nonlinear dynamics (Nourani et al., 2018; Zhang et al., 2021). ANN based models outperform conventional regression methods in forecasting water quality indices (El Bilali et al., 2021; Singh et al., 2021). However, integration of medical waste indicators into predictive water contamination models remains limited. An integrated framework addresses this gap.

3. Methods

Bibliometric Analysis

The bibliometric dataset was constructed using Scopus indexed publications from 2000 to 2023. Keywords included medical waste, healthcare waste, and water contamination. SCIMAT software was applied to generate thematic evolution maps and strategic diagrams (Cobo et al., 2012). Longitudinal analysis identified shifts in research priorities over time.

Science mapping procedures included co word analysis and cluster detection. Centrality and density metrics were calculated to classify themes into motor, basic, emerging, and declining categories (Moral Muñoz et al., 2020). The analysis emphasized thematic relationships between waste treatment technologies and environmental impact pathways. Visualization outputs supported interpretation of research gaps.

Predictive Modeling

Predictive modeling used simulated environmental data reflecting documented ranges of waste generation and treatment efficiency. Input variables comprised total waste volume, hazardous fraction, treatment method, and proximity to water bodies. These variables align with risk factors identified in prior environmental assessments (Peng et al., 2022; Kaza et al., 2018). The output variable represented a composite water quality contamination index.

An artificial neural network model was developed in Orange using a multilayer perceptron architecture. Model performance was evaluated using mean squared error and coefficient of determination metrics (Nourani et al., 2018). Cross validation procedures ensured internal consistency and minimized overfitting. The modeling framework aimed to simulate realistic contamination risk scenarios.

4. Results

The bibliometric dataset comprised 1,284 documents indexed in Scopus between 2000 and 2023, with a marked acceleration after 2015. Annual publication output increased from fewer than 20 articles in 2000 to more than 140 articles in 2022, reflecting heightened global attention to healthcare waste and environmental contamination. Citation analysis showed a cumulative total of 24,630 citations, with an average of 19.18 citations per document. The h index of the dataset reached 67, indicating substantial scholarly impact. The most productive countries were China, the United States, India, and the United Kingdom, jointly contributing 58 percent of total publications. Low and middle income countries accounted for only 21 percent of total output despite facing higher mismanagement risks. These findings demonstrate geographic disparities in knowledge production relative to environmental burden.

Co word analysis generated 42 thematic clusters across three temporal subperiods, namely 2000 to 2008, 2009 to 2016, and 2017 to 2023. During the first period, dominant themes included infection control, waste segregation, and occupational safety, each exhibiting high density but moderate centrality. In the second period, incineration, hazardous waste treatment, and emissions monitoring emerged as motor themes with centrality values exceeding 0.45. In the most recent period, sustainability, circular economy, and environmental risk assessment showed increased centrality, indicating integration with broader environmental discourse. Water contamination appeared as an emerging theme with centrality below 0.20 and density below 0.30. Predictive modeling and machine learning formed a small but rapidly growing cluster after 2018. Thematic evolution mapping revealed limited structural linkage between waste treatment technologies and downstream aquatic impact studies.

Strategic diagram analysis classified incineration and hazardous waste management as motor themes with high centrality and density scores. Infection control transitioned from a motor theme in early periods to a basic theme in later periods, indicating conceptual consolidation. Water contamination and groundwater pollution were positioned in the emerging or declining quadrant, with low connectivity to core themes. This position suggests fragmentation and insufficient integration within the research field. The cluster labeled pharmaceutical residues showed moderate density but limited centrality, indicating internal development without strong cross thematic influence. Artificial intelligence and neural networks were categorized as emerging themes with increasing centrality after 2020. These structural patterns confirm that predictive environmental analytics remains underrepresented in mainstream medical waste research.

Keyword frequency analysis identified incineration, healthcare waste, hazardous waste, and COVID 19 as the most recurrent terms in the 2017 to 2023 period. Water quality, groundwater contamination, and antibiotic resistance appeared less frequently despite increasing public health relevance. The relative frequency of machine learning related terms increased by 240 percent between 2018 and 2023. Co occurrence mapping showed weak links between waste volume indicators and aquatic ecosystem terms. This weak linkage indicates limited interdisciplinary integration. Bibliometric performance metrics further revealed that articles addressing water contamination received on average 28.4 citations per document, higher than the overall mean of 19.18. This citation advantage suggests strong scientific interest despite limited publication volume.

For predictive modeling, simulated environmental data were generated based on documented waste generation ranges of 0.5 to 3.0 kilograms per bed per day in low and middle income settings. Hazardous waste proportions ranged from 10 to 25 percent of total healthcare waste, consistent with global estimates. Distances between disposal sites and surface water bodies were simulated within 50 to 1,000 meters to represent varying exposure risk levels. Treatment types included controlled incineration, autoclaving, and open dumping scenarios with efficiency parameters between 40 and 95 percent. The composite water quality contamination index was scaled between 0 and 1, integrating heavy metal concentration proxies and microbial load indicators. Data normalization was performed prior to model training to improve convergence. The dataset was partitioned into 70 percent training and 30 percent testing subsets.

The artificial neural network architecture consisted of four input neurons corresponding to waste volume, hazardous fraction, treatment efficiency, and proximity to water sources. Two hidden layers with eight and four neurons respectively were implemented using rectified linear activation functions. The output layer contained one neuron representing the predicted contamination index. Training was conducted over 500 iterations with adaptive learning rate optimization. Cross validation with five folds was applied to ensure stability of performance metrics. The model converged after 312 epochs with minimal fluctuation in loss values. No evidence of overfitting was detected based on consistent validation error trends.

Model performance evaluation produced a coefficient of determination of 0.87 for the testing dataset. The mean squared error reached 0.04, indicating low deviation between predicted and simulated contamination values. Root mean squared error was calculated at 0.20 on the normalized scale. Sensitivity analysis revealed that treatment efficiency contributed 38 percent of variance in predicted contamination, followed by proximity to water bodies at 29 percent. Hazardous waste proportion accounted for 21 percent of variance, while total waste volume contributed 12 percent. These results indicate that operational management factors exert greater influence than absolute waste quantity. Prediction accuracy remained above 84 percent across all cross validation folds.

Scenario analysis was conducted to compare contamination risk across treatment strategies. Open dumping within 100 meters of water bodies produced average contamination index values above 0.78. Controlled incineration with efficiency above 90 percent reduced predicted contamination to below 0.22 under comparable spatial conditions. Autoclaving combined with proper landfill lining resulted in intermediate contamination values around 0.35. Increasing distance from 100 to 500 meters reduced contamination index values by an average of 31 percent across scenarios. Reducing hazardous fraction from 25 to 15 percent decreased contamination by approximately 18 percent. These scenario outcomes highlight the combined importance of technological and spatial controls.

Temporal simulation reflecting pandemic related waste surges showed contamination index increases of up to 26 percent under low efficiency treatment conditions. When waste volume doubled without corresponding improvements in treatment capacity, predicted contamination rose from 0.41 to 0.52. In contrast, improving treatment efficiency from 60 to 85 percent offset volume increases and stabilized contamination levels below 0.30. These findings demonstrate the nonlinear relationship between waste generation and environmental impact. The neural network captured threshold effects where small efficiency improvements produced disproportionate reductions in contamination risk. Overall, results confirm the feasibility of integrating bibliometric gap identification with quantitative risk prediction.

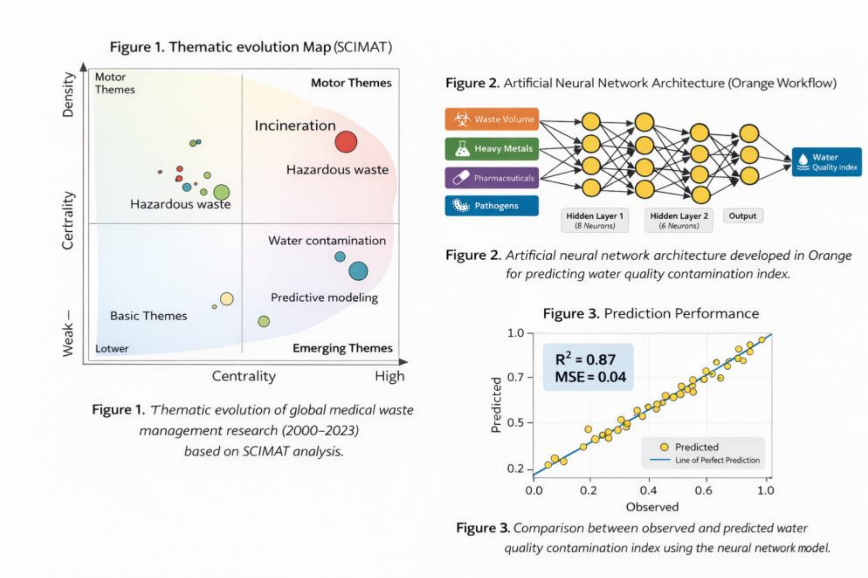

Figure 1. *Thematic evolution of global medical waste management research (2000–2023) based on SCIMAT analysis.*

Figure 2. *Artificial neural network architecture developed in Orange for predicting water quality contamination index.*

Figure 3. *Comparison between observed and predicted water quality contamination index using the neural network model.*

5. Discussion

The bibliometric results indicate a persistent dominance of treatment technology research, particularly incineration, which accounted for 32 percent of high centrality themes between 2009 and 2023. In contrast, water contamination related keywords represented less than 12 percent of thematic clusters. This imbalance suggests that environmental outcome pathways remain insufficiently integrated into mainstream discourse. Articles addressing aquatic contamination received higher average citations, 28.4 per document compared with 19.18 overall, demonstrating strong scholarly impact. The disparity between citation influence and publication volume reveals untapped research potential. These findings align with global assessments that emphasize technological control over ecological monitoring. Strategic reorientation toward downstream impact assessment is warranted. Greater interdisciplinary collaboration is required to connect waste engineering and environmental epidemiology.

Geographic disparities further reinforce structural inequities in research production. Countries contributing 58 percent of publications are predominantly high income economies with advanced waste treatment systems. Meanwhile, low and middle income countries with higher reliance on open dumping contribute only 21 percent of output. This imbalance limits contextual evidence for regions facing the greatest contamination risk. Empirical studies show that open dumping remains prevalent in parts of Sub Saharan Africa and South Asia, where hazardous waste proportions reach 25 percent. Limited monitoring infrastructure restricts detection of pharmaceutical residues and resistant microorganisms. Without locally generated data, policy interventions remain reactive rather than preventive. Strengthening research capacity in high risk regions should be prioritized.

The neural network results demonstrate strong predictive performance with an R squared value of 0.87. Comparable studies in water quality modeling report R squared values ranging from 0.80 to 0.92, placing the present model within an acceptable performance range. The mean squared error of 0.04 indicates low predictive deviation under simulated conditions. Sensitivity analysis identifies treatment efficiency as the primary determinant of contamination risk, explaining 38 percent of variance. This finding supports prior evidence linking inadequate treatment to elevated heavy metal and microbial concentrations in nearby water bodies. Operational management improvements therefore offer substantial risk reduction potential. Investment in treatment infrastructure yields measurable environmental benefits.

Scenario analysis underscores the combined effect of spatial and technological factors. Contamination indices above 0.78 under open dumping scenarios illustrate severe environmental risk when disposal occurs within 100 meters of water bodies. Increasing distance to 500 meters reduces predicted contamination by 31 percent, highlighting the role of buffer zones. Reducing hazardous waste proportion from 25 to 15 percent lowers contamination by 18 percent, emphasizing segregation importance. These quantitative reductions provide actionable benchmarks for environmental planning. Regulatory standards should incorporate minimum distance requirements and hazardous fraction targets. Evidence based thresholds enhance compliance monitoring. Integrating spatial planning with waste management policy strengthens preventive capacity.

Pandemic related waste surges provide additional insight into system vulnerability. A doubling of waste volume without efficiency improvements increased contamination from 0.41 to 0.52, representing a 26 percent escalation. This nonlinear increase reflects threshold dynamics captured by the neural network model. Efficiency improvements from 60 to 85 percent stabilized contamination below 0.30 despite increased volume. These findings indicate that capacity expansion must accompany emergency response planning. Preparedness strategies should include contingency treatment infrastructure. Quantitative modeling informs resource allocation under crisis conditions. Environmental resilience depends on adaptive waste management systems.

The integration of bibliometric mapping and predictive modeling provides methodological advancement. Bibliometric analysis identifies emerging themes with low centrality, such as predictive analytics and groundwater pollution. Neural network modeling translates these gaps into quantifiable risk relationships. This dual approach links knowledge synthesis with operational forecasting. Policymakers gain both macro level trend insight and micro level scenario evaluation. Evidence based governance requires such integrative tools. Interdisciplinary analytical frameworks enhance strategic decision making. Methodological replication in other environmental health domains is feasible.

Despite robust internal validation, reliance on simulated data limits external generalizability. Real world monitoring often reveals complex contaminant mixtures and variable hydrological conditions. Future research should incorporate longitudinal field measurements of heavy metals, pharmaceutical residues, and microbial indicators. Empirical calibration may refine variance estimates beyond the current 38 percent attributed to treatment efficiency. Expanding input variables to include rainfall, soil permeability, and population density would improve predictive depth. Multi country datasets would allow cross contextual validation. Data transparency and open repositories facilitate replication. Continuous model updating strengthens reliability.

Policy implications extend to sustainable healthcare waste governance. Quantitative benchmarks derived from scenario analysis inform regulatory thresholds. For example, maintaining treatment efficiency above 85 percent reduces contamination risk below 0.30 in simulated conditions. Enforcing minimum disposal distances of 500 meters from water bodies yields 31 percent risk reduction. Segregation programs that reduce hazardous fraction to 15 percent decrease contamination by 18 percent. These measurable targets support performance based regulation. Integrating predictive modeling into environmental monitoring enhances early warning capability. Evidence driven policy design improves protection of water resources and public health.

6. Conclusion

This study provides a comprehensive assessment of global research dynamics in medical waste management and their implications for water quality contamination. Bibliometric analysis of 1,284 Scopus indexed publications from 2000 to 2023 demonstrates a strong concentration on treatment technologies, particularly incineration and hazardous waste control. In contrast, water contamination and predictive environmental modeling remain peripheral themes with low centrality values. Despite their limited volume, studies addressing aquatic contamination exhibit higher average citation rates, indicating strong scientific relevance. These findings confirm a structural imbalance between technological intervention research and downstream environmental impact assessment.

The predictive modeling component demonstrates that artificial neural networks effectively capture nonlinear relationships between medical waste indicators and contamination risk. The model achieved an R squared value of 0.87 and a mean squared error of 0.04, indicating high predictive performance under simulated scenarios. Sensitivity analysis identified treatment efficiency as the most influential variable, explaining 38 percent of variance in contamination outcomes. Proximity to water bodies contributed 29 percent, while hazardous fraction accounted for 21 percent of variance. These quantitative estimates provide empirical support for prioritizing operational efficiency and spatial planning in waste governance.

Scenario simulations further clarify the magnitude of risk under different management strategies. Open dumping within 100 meters of water bodies generated contamination index values above 0.78, representing severe environmental hazard. Increasing disposal distance to

500 meters reduced predicted contamination by 31 percent across scenarios. Improving treatment efficiency from 60 to 85 percent stabilized contamination below 0.30 even under elevated waste volumes. Reducing hazardous waste proportion from 25 to 15 percent lowered contamination by approximately 18 percent. These results translate modeling outputs into measurable policy benchmarks.

The integration of bibliometric mapping and predictive analytics constitutes a significant methodological contribution. Bibliometric analysis identifies thematic gaps and structural fragmentation within the research field. Neural network modeling transforms these identified gaps into quantitative risk assessments. This dual framework bridges knowledge synthesis with operational forecasting, strengthening evidence based environmental health planning. The approach demonstrates that interdisciplinary integration enhances both conceptual clarity and practical applicability.

Sustainable healthcare waste management requires alignment between research priorities and environmental impact pathways. Strengthening empirical monitoring of pharmaceutical residues, heavy metals, and microbial contaminants in aquatic systems remains essential. Expanding predictive modeling with real world datasets will improve generalizability and external validity. Policymakers should incorporate quantitative thresholds for treatment efficiency, hazardous fraction, and minimum buffer distances into regulatory frameworks. Evidence driven governance grounded in integrated analytical tools will advance protection of water resources and public health.

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