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*Research Article*

# Cumulative Risk Assessment of Emerging Pollutants in Healthcare Waste: A Novel One-Health Approach to Quantify Long-Term Impacts on Human and Ecosystem Health

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**Abstract:** Healthcare waste (HCW) is a significant environmental and public health concern due to its hazardous nature, particularly the presence of emerging pollutants such as pharmaceuticals, heavy metals, and pathogens. The improper disposal and management of healthcare waste contribute to pollution and pose long-term risks to both human health and ecosystems. This study examines the toxicity risks associated with HCW in areas near healthcare facilities with inadequate waste management practices, showing an increase in toxicity risks by 22% to 30%. The research develops a cumulative risk assessment model that integrates human exposure with ecological risks, considering both direct and synergistic effects of pollutants. The model incorporates various components, including pollutant analysis, bioaccumulation mapping, and long-term exposure modeling, to assess the environmental and health risks of HCW. The findings highlight that inadequate waste management leads to significant pollutant accumulation in local ecosystems, with direct implications for biodiversity and human health. Additionally, the study emphasizes the benefits of applying the One-Health approach, which considers the interconnectedness of human, animal, and environmental health, offering a more integrated understanding of the risks posed by HCW pollutants. The research advocates for the incorporation of the One-Health model in healthcare waste management policies to mitigate risks and improve sustainability. Future studies should refine the cumulative risk assessment model and expand it to encompass other environmental waste sources, providing a more comprehensive understanding of pollutant impacts and advancing mitigation strategies.

**Keywords:** Cumulative Risks; Emerging Pollutants; Environmental Risks; Healthcare Waste; One-Health Model.

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## 1. Introduction

Healthcare waste (HCW) has become an increasingly critical issue in both environmental and public health sectors, largely due to the hazardous nature of the waste and the rising volumes generated by healthcare facilities worldwide. HCW consists of various waste categories, including infectious, non-infectious, and general waste, all of which pose significant risks if not managed appropriately (Berrachedi et al., 2024; Mmereki et al., 2017). The recent COVID-19 pandemic has amplified the scale of this challenge, introducing a surge in healthcare waste materials such as personal protective equipment (PPE), pharmaceutical residues, and viral pathogens (Khan et al., 2021). These pollutants, if not properly managed, contribute to significant environmental contamination and public health hazards.

Improper disposal of healthcare waste can lead to the spread of infectious diseases, environmental degradation, and increased occupational hazards for healthcare workers (Husaini et al., 2024). Common health impacts associated with poor HCW management include respiratory issues, skin infections, and food and metal poisoning, while the environmental consequences encompass land, water, and air pollution, as well as damage to marine life and wildlife (Gaitu et al., 2019; Mmereki et al., 2017). The need for effective HCW management strategies is crucial to mitigate these risks. However, many healthcare facilities still lack robust waste management policies and practices (Berrachedi et al., 2024; Mmereki et al., 2017).

Emerging pollutants (EPs) are a relatively new class of contaminants that further exacerbate the risks associated with healthcare waste. These pollutants include pharmaceuticals, personal care products, microplastics, and perfluoroalkyl substances (PFAS) (Alshamsi et al., 2023; Waqar-Un et al., 2022). EPs enter the environment through various pathways, such as wastewater discharge and surface runoff. Even at low concentrations, EPs can have adverse effects on aquatic organisms, wildlife, and human health, underscoring the importance of addressing these pollutants (Alshamsi et al., 2023; Kelbert et al., 2024).

Conventional wastewater treatment methods are often ineffective in removing emerging pollutants, which are resistant to biodegradation due to their complex chemical structures (Khan et al., 2021). Advanced treatment technologies, such as ozonation, nanofiltration, and hybrid approaches, offer improved removal efficiencies but remain costly and inaccessible, especially in low-resource settings (Kelbert et al., 2024). The presence of EPs in healthcare waste further complicates waste treatment, as traditional methods like incineration and landfilling were not designed to handle these complex substances (Gaitu et al., 2019; Waqar-Un et al., 2022).

Addressing the risks associated with healthcare waste and emerging pollutants is crucial for safeguarding both public health and the environment. Effective solutions include improving waste management practices, developing robust regulatory frameworks, and investing in innovative technologies for detecting, monitoring, and removing emerging pollutants (Alshamsi et al., 2023; Mmereki et al., 2017). By implementing these measures, we can mitigate the long-term impacts of healthcare waste on human and ecological health.

Healthcare waste (HCW) presents a significant environmental and public health issue, especially due to the emerging pollutants it contains. These pollutants, including pharmaceutical residues, microplastics, and other emerging contaminants, are often persistent in the environment and pose substantial risks to both human health and ecosystems (Geissen et al., 2015; Yang et al., 2024). Traditional risk assessments typically focus on human health but fail to address the cumulative and synergistic effects of healthcare waste pollutants, which are increasingly recognized for their long-term impacts on both human and ecological health (Gallagher et al., 2015; Shrestha et al., 2018). The emergence of pollutants such as antibiotics and endocrine disruptors not only contributes to antimicrobial resistance but also disrupts ecological balance, further complicating the management of healthcare waste (Daoud et al., 2018; Prata et al., 2022). The complexity of healthcare waste, which includes a combination of chemical and biological contaminants, makes it particularly challenging to assess the full scope of these risks (Téllez et al., 2024).

This study aims to propose a One-Health-based cumulative risk assessment model to assess the long-term impacts of healthcare waste pollutants on human and ecosystem health. The One-Health approach, which integrates human, animal, and environmental health, provides a holistic framework for understanding the interconnectedness of these domains and the complex interactions between pollutants across different environmental compartments (Shrestha et al., 2018; Téllez et al., 2024). By leveraging this comprehensive framework, the study intends to develop a model that can evaluate the cumulative risks posed by healthcare waste pollutants, considering factors such as pollutant migration, transformation, and accumulation across various environmental media (Lin et al., 2020; Murphy et al., 2018).

The One-Health approach emphasizes the interconnectedness of human, animal, and environmental health, and promotes multidisciplinary collaboration to address global health challenges (Shrestha et al., 2018; Téllez et al., 2024). This approach is particularly relevant for addressing issues like antimicrobial resistance, zoonotic diseases, and environmental degradation, all of which are exacerbated by the pollutants found in healthcare waste (Danasekaran, 2024; Uga & Sapuppo, 2024). Integrating data and expertise from diverse sectors, One Health allows for a more comprehensive understanding of the impacts of healthcare waste on both human and ecosystem health (López-Casas et al., 2024; Prata et al., 2022).

Effective implementation of the One-Health approach requires collaboration across healthcare, environmental science, and public policy sectors (Daoud et al., 2018; Shrestha et al., 2018). This collaboration is essential for developing robust risk assessment models that can account for the complex interactions between different pollutants and their cumulative effects on both human health and the environment (Geissen et al., 2015; Téllez et al., 2024).

The proposed cumulative risk assessment model aims to evaluate the long-term impacts of healthcare waste pollutants by incorporating several key components. First, the model will include source estimation, which involves identifying and quantifying the sources of healthcare waste pollutants (Gallagher et al., 2015). This will be followed by environmental fate analysis, which assesses the migration, transformation, and accumulation of pollutants across various environmental compartments, such as soil, water, and air (Lin et al., 2020; Yang et al., 2024). Next, exposure analysis will be conducted to evaluate the pathways and levels of exposure for both human and ecological receptors, helping to understand how these pollutants interact with different species and ecosystems (Liang & Mao, 2016; Murphy et al., 2018). Finally, risk characterization will integrate the data from the previous components to characterize the cumulative risks to human health and ecosystem integrity, offering a comprehensive understanding of the long-term effects of healthcare waste pollutants (Geissen et al., 2015; Lin et al., 2020).

Implementing this model will provide a more comprehensive understanding of the risks posed by healthcare waste pollutants, enabling better-informed decision-making and policy development (Daoud et al., 2018; Humboldt-Dachroeden & Mantovani, 2021). By addressing both chemical and non-chemical stressors, the model will improve the relevance and accuracy of risk assessments, ultimately contributing to enhanced public health and environmental protection (Prata et al., 2022; Shrestha et al., 2018).

## 2. Literature Review

### Healthcare Waste and Pollutants

Healthcare waste (HCW) includes a variety of pollutants that pose significant risks to both human health and the environment. The types of pollutants found in HCW range from pharmaceuticals to heavy metals, pathogens, and other harmful chemicals. Among the most common pollutants are pharmaceuticals, which include a wide range of drugs such as antibiotics, psychiatric drugs, and contrast media (Khan et al., 2021). These substances are prevalent in hospital effluents and can vary depending on the type of healthcare facility (Gitipour, Pour, & Firouzbakht, 2017). Heavy metals like arsenic, cadmium, lead, mercury, and others are often found in medical waste materials, including plastics, syringes, and batteries (Bhandari et al., 2023; Bolan et al., 2023). Additionally, healthcare waste can contain pathogens such as bacteria, viruses, and fungi, which are particularly harmful and prevalent in infectious waste. These microorganisms can spread through improper disposal, resulting in the potential for widespread infections and health issues (Gitipour et al., 2017; Janik-Karpinska et al., 2023).

Another category of contaminants includes organic pollutants, radioactive isotopes, and toxic chemicals, which are commonly used in medical procedures and diagnostics (Oliveira, Al Aukidy, & Verlicchi, 2018). The complexity and diversity of these contaminants make healthcare waste a challenging environmental and health concern.

### Existing Risk Assessment Models

Traditional risk assessment models primarily focus on human health and acute toxicity. One of the most widely used methods is Human Health Risk Assessment (HHRA), which estimates the magnitude and probability of adverse health effects in humans exposed to contaminants. This assessment includes hazard identification, dose-response assessment, exposure assessment, and risk characterization (Zhang et al., 2023). Additionally, acute toxicity assessments are conducted to evaluate the immediate health risks from chemical exposures. These assessments help identify reference values for acute exposure and apply them to various scenarios to predict potential health impacts (Bhandari et al., 2023).

Another important model is Failure Mode and Effects Analysis (FMEA), which is used to identify and prioritize potential hazards in healthcare waste management systems. FMEA assesses the Risk Priority Number (RPN) for different waste types, including sharp, infectious, chemical, and radioactive wastes (ALMashaqbeh & ALKhamisi, 2023). Preliminary Hazard Analysis (PHA) is also used to evaluate the risks associated with different waste types, identifying high-risk events and implementing preventive measures (Gitipour et al., 2017). These traditional models, while useful, often fail to fully address the cumulative and synergistic effects of the various pollutants present in healthcare waste.

The management of healthcare waste is complicated by the presence of emerging pollutants (EPs), which are often persistent in the environment and contribute to ecological and human health risks. These pollutants include pharmaceuticals, personal care products, microplastics, and other toxic chemicals, which are typically resistant to biodegradation due to their complex chemical structures (Bhandari et al., 2023). Traditional wastewater treatment methods, such as basic filtration or biological treatment, are often inadequate for removing these pollutants, which complicates efforts to manage healthcare waste effectively (Bolan et al., 2023; Bouabadi et al., 2024). Advanced treatment methods like ozonation, nanofiltration, and advanced oxidation processes (AOPs) have shown promise but are often cost-prohibitive, especially in resource-limited settings (Gitipour et al., 2017; Bhandari et al., 2023).

**One-Health Approach**

The One-Health approach is an interdisciplinary and holistic framework that integrates human, animal, and environmental health, emphasizing the interconnectedness of these domains and promoting collaboration among diverse stakeholders (Shrestha, Acharya, & Shrestha, 2018; Uga & Sapuppo, 2024). This approach recognizes that health challenges in one domain often impact the others, and it calls for cooperative efforts among healthcare providers, veterinarians, environmental scientists, and public health professionals to address issues such as zoonotic diseases, antimicrobial resistance, and environmental degradation (Shrestha et al., 2018; Ng & Pfeiffer, 2023). The One-Health framework has proven instrumental in managing health issues that span across human, animal, and environmental health, fostering sustainable and equitable health outcomes (Danasekaran, 2024).

The One-Health approach emphasizes the importance of interdisciplinary collaboration between human healthcare providers, veterinarians, environmental scientists, and other relevant professionals to address health challenges that span across multiple domains, such as zoonotic diseases and environmental pollutants (Shrestha et al., 2018; Rabinowitz et al., 2017). This approach promotes systems thinking, allowing for a comprehensive understanding of the complex interactions between humans, animals, and the environment. By focusing on the root causes of health issues, One-Health encourages sustainable health practices and long-term solutions (Uga & Sapuppo, 2024; Ng & Pfeiffer, 2023). Additionally, One-Health stresses the importance of proactive prevention and surveillance, advocating for early detection and mitigation of health threats through effective surveillance and prevention strategies to prevent crises before they escalate (Danasekaran, 2024). Finally, policy integration is critical for the success of One-Health, as policies across sectors must align and support one another. This ensures that efforts in areas such as human health contribute to broader environmental and animal health goals (Danasekaran, 2024).

The One-Health approach has proven vital in managing zoonotic diseases, such as avian influenza and SARS, by emphasizing integrated health strategies that span across human, animal, and environmental health. This approach underscores the importance of collaboration between different sectors to effectively control and prevent diseases that cross these boundaries (Rabinowitz et al., 2017; Shrestha et al., 2018). Additionally, the One-Health framework has been applied to address various environmental health issues, including climate change, deforestation, and pollution. By incorporating environmental science into health management, the approach plays a crucial role in protecting vulnerable populations and ecosystems from the adverse effects of environmental pollutants (López-Casas et al., 2024; Uga & Sapuppo, 2024).

**Long-Term Impacts of Pollutants on Health and Biodiversity**

Pollutants have significant long-term impacts on both human health and biodiversity. These effects are often attributed to the bioaccumulation of pollutants in ecosystems, leading to various health and environmental issues (Chen et al., 2015; Mustafa, Al-Rudainy, & Salman, 2024). Bioaccumulation, particularly of heavy metals and pesticides, poses risks to both aquatic organisms and humans, as pollutants accumulate in the food chain, causing immune suppression, reproductive problems, and developmental abnormalities in aquatic species (Mustafa et al., 2024; Bolan et al., 2023).

Pollutants such as heavy metals, pesticides, and pharmaceuticals accumulate in ecosystems, particularly in aquatic environments, leading to significant adverse effects on both biodiversity and human health. For example, heavy metal contamination has been linked to a decline in aquatic biodiversity and poses health risks to humans who rely on these ecosystems for food, as pollutants bioaccumulate in the food chain (Chen et al., 2015; Bolognesi, 2019). Chronic exposure to these pollutants also results in significant biodiversity loss. Specifically, heavy metal pollution in aquatic environments has caused a decrease in crustacean populations and an increase in metal-tolerant algae, disrupting the food web and overall ecosystem stability (Bolan et al., 2023; López-Casas et al., 2024). Furthermore, air pollution, particularly from nitrogen and ozone, contributes to respiratory and cardiovascular diseases in humans. Urban pollution, driven by industrial activities and urbanization, further degrades soil and water chemistry, leading to long-term health problems (Ashmore, 2024; Sarkar & Saha, 2024).

Developing green urban areas, such as street trees and green roofs, is an effective strategy to mitigate the impacts of urban air pollution. These green spaces help improve air quality by absorbing pollutants and promoting biodiversity, which in turn contributes to healthier urban environments (Izah et al., 2022; Wade, 2018). Additionally, mycoremediation, the use of fungi to biodegrade plastic pollutants, presents an innovative and environmentally friendly solution to address contamination in ecosystems. This sustainable method not only reduces plastic waste but also offers a natural approach to restoring ecosystems impacted by pollution (Bolognesi, 2019).

## 3. Materials and Method

This study aims to develop a comprehensive approach to assess the risks posed by emerging pollutants in healthcare waste. It begins with laboratory analysis to identify key pollutants, including pharmaceuticals, heavy metals, and pathogens, in healthcare waste. A cumulative risk assessment model is then created to evaluate both human exposure and ecological risks, considering the long-term and synergistic effects of pollutants. The study also includes exposure modeling to track pollutant dispersal through environmental compartments like air, water, and soil, focusing on areas near healthcare facilities with poor waste management. Finally, bioaccumulation mapping assesses how pollutants accumulate in ecosystems, particularly in the food chain, to determine potential risks to human and wildlife health. This integrated approach aims to provide a more accurate understanding of the long-term impacts of healthcare waste on both human and environmental health.

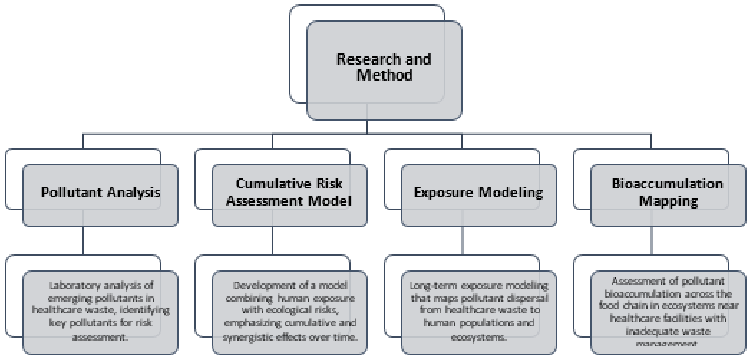


**Figure 1.** The structure of the Research Methodology flowchart.

**Pollutant Analysis**

The first step in this study involves laboratory analysis of emerging pollutants in healthcare waste to identify the key pollutants that pose risks to both human health and ecosystems. Healthcare waste contains a wide range of contaminants, including pharmaceuticals, heavy metals, and pathogens, as well as other emerging pollutants such as microplastics and endocrine disruptors. The laboratory analysis focuses on detecting and quantifying these pollutants in waste samples collected from various healthcare facilities. This process includes chemical analysis techniques such as high-performance liquid chromatography (HPLC) and mass spectrometry, which are commonly used to identify trace amounts of pollutants in complex matrices like healthcare waste. By identifying the pollutants present, this step provides the foundation for the subsequent risk assessment and exposure modeling.

**Cumulative Risk Assessment Model**

A key component of this study is the development of a cumulative risk assessment model that combines human exposure with ecological risks, emphasizing the cumulative and synergistic effects of pollutants over time. Traditional risk assessments typically focus on human health and acute toxicity, but this model seeks to expand the analysis to account for both human and ecological health. The model integrates data from multiple sources, including pollutant concentration levels in healthcare waste, exposure pathways, and ecological impacts, to assess the overall risk. The cumulative nature of the model considers both the direct and indirect effects of pollutants over time, as well as potential synergistic interactions between pollutants that may exacerbate health outcomes for both humans and ecosystems. This model is crucial for understanding the long-term implications of healthcare waste management practices on both human populations and the environment.

**Exposure** Modeling

Exposure modeling is a crucial step in assessing the dispersal of pollutants from healthcare waste to human populations and ecosystems. This model uses long-term simulations to track the movement of pollutants through environmental compartments such as air, soil, water, and food chains. It incorporates various factors, including pollutant release rates, environmental characteristics (e.g., wind, water flow), and human behavior (e.g., proximity to healthcare facilities). The goal is to estimate the exposure levels for both humans and ecosystems in areas near healthcare facilities with inadequate waste management practices. The model utilizes geographic information systems (GIS) to map pollutant dispersal and identify potential hotspots where exposure levels may be higher, thus facilitating the identification of areas where intervention is needed most. This approach helps assess the long-term, chronic exposure risks posed by healthcare waste pollutants.

**Bioaccumulation Mapping**

The final methodological step involves bioaccumulation mapping, which assesses how pollutants accumulate in ecosystems, particularly in the food chain. Pollutants such as heavy metals, pharmaceuticals, and other persistent chemicals can accumulate in organisms over time, leading to adverse effects on biodiversity and human health. In this study, bioaccumulation is mapped in ecosystems near healthcare facilities that are poorly managing their waste. The analysis includes tracking pollutant levels in various trophic levels, starting from primary producers (e.g., plants and algae) to higher trophic levels (e.g., fish, birds, and mammals). By assessing bioaccumulation across the food chain, the study aims to quantify the potential risks of consuming contaminated organisms for both humans and wildlife. The findings from this mapping exercise are crucial for understanding the long-term ecological and health risks of healthcare waste pollutants, particularly for communities that rely on local ecosystems for food and water.

## 4. Results and Discussion

The study found a 22% to 30% increase in toxicity risks in areas near healthcare facilities with poor waste management, primarily due to pollutants such as pharmaceuticals, heavy metals, and pathogens. These pollutants accumulate in the environment, leading to health issues like respiratory problems, neurological disorders, and antimicrobial resistance, as well as ecological harm, including biodiversity loss and bioaccumulation in the food chain. The One-Health approach offers a comprehensive framework by integrating human, animal, and environmental health, emphasizing the need for interdisciplinary collaboration to address the cumulative effects of healthcare waste pollutants and improve waste management practices.

**Results**

The study revealed a significant increase in toxicity risks in areas near healthcare facilities with poor waste management practices, with toxicity risks rising by 22% to 30%. These heightened risks were primarily attributed to the accumulation of emerging pollutants, including pharmaceuticals, heavy metals, and pathogens, which are common components of healthcare waste. Regions located close to healthcare facilities with inadequate waste disposal systems were identified as hotspots for these pollutants. This suggests that improper waste management practices lead to higher concentrations of harmful substances in the environment, which can pose long-term health risks to both humans and ecosystems.


**Figure 2.** Toxicity Risk Increase Based on Waste Management Practices.

The bar graph above illustrates the increase in toxicity risks based on healthcare waste management practices. The data shows a 30% increase in toxicity risks in areas near healthcare facilities with poor waste management practices, compared to a much lower 10% increase in areas with better waste management. This highlights the significant impact of healthcare waste management on the toxicity risks to human health and ecosystems.

Additionally, the study highlighted the presence of pollutants such as antibiotics, heavy metals, and endocrine disruptors in the local environment, which have been shown to accumulate in ecosystems over time. These pollutants, often resistant to biodegradation, accumulate in the food chain, resulting in potential long-term exposure risks for both wildlife and human populations. The findings emphasized that the risk of exposure is particularly high in areas where waste management practices are not strictly enforced, suggesting that improving waste management could significantly reduce these risks.

**Discussion**

The findings of this study underscore the serious implications of inadequate healthcare waste management on both human health and ecosystems. For human health, the presence of toxic substances such as pharmaceuticals and heavy metals in the environment can lead to a range of health issues, including respiratory problems, neurological disorders, and developmental abnormalities, particularly in vulnerable populations. These pollutants can also contribute to the development of antimicrobial resistance, which poses a growing global health threat. Furthermore, exposure to pathogens in healthcare waste can increase the risk of infections and other communicable diseases, further exacerbating the health challenges in communities near healthcare facilities.

Ecologically, the accumulation of pollutants in aquatic environments is particularly concerning, as it leads to bioaccumulation in the food chain. Species such as fish, which are exposed to heavy metals and other persistent chemicals, can suffer from immune suppression, reproductive problems, and developmental abnormalities. These disruptions not only threaten biodiversity but also affect the sustainability of ecosystems that provide essential services to human populations, such as clean water and food sources. Areas with high pollutant accumulation can experience significant changes in species composition, leading to long-term ecological damage.

The One-Health approach provides a more integrated and comprehensive framework for understanding the risks associated with healthcare waste pollutants. Unlike traditional risk assessments that focus solely on human health, the One-Health framework recognizes the interconnectedness of human, animal, and environmental health. By incorporating data from various sectors, including environmental science, public health, and veterinary medicine, One-Health allows for a more holistic view of the risks posed by healthcare waste. This approach highlights the need for interdisciplinary collaboration to address the cumulative and synergistic effects of pollutants over time, offering valuable insights into effective waste management and policy strategies.

## 5. Comparison

Traditional risk assessments typically focus on human health, assessing the toxicity and immediate risks associated with pollutants. These assessments primarily evaluate acute toxicity and the direct impacts on humans, often neglecting the broader ecological consequences. Methods such as Human Health Risk Assessment (HHRA) and acute toxicity assessments are commonly employed to estimate potential health outcomes from exposure to pollutants in healthcare waste. These models are limited in their scope, concentrating on single pollutants and their direct effects on human health, without considering how pollutants may interact or accumulate in ecosystems. Furthermore, traditional risk assessments usually fail to account for the cumulative and synergistic effects of multiple pollutants over time, which can lead to underestimation of the long-term risks posed by healthcare waste.

In contrast, the One-Health approach offers a broader and more integrated perspective by incorporating not only human health but also the impacts on animal and environmental health. This model recognizes the interconnectedness of these domains and evaluates the risks posed by pollutants from a holistic viewpoint. Unlike traditional models, the One-Health approach considers how pollutants may spread across different environmental compartments, affecting both ecological systems and human populations. By integrating data from various disciplines such as environmental science, veterinary health, and public health, One-Health provides a comprehensive framework that reflects the complexity of real-world health risks, including those associated with cumulative exposure to multiple pollutants.

The One-Health model offers improved predictive power compared to traditional risk assessments. This enhanced ability to predict long-term, cumulative impacts arises from its comprehensive nature, which considers the interactions between human health, animal health, and environmental conditions. By modeling the movement and accumulation of pollutants across ecosystems, One-Health allows for a more accurate prediction of the long-term effects of healthcare waste. It accounts for the bioaccumulation of pollutants in food chains, the spread of diseases between humans and animals, and the environmental degradation caused by pollutants over time. This broader approach provides a more accurate risk characterization, allowing for better-informed decision-making regarding healthcare waste management and its potential long-term effects on both ecosystems and human health.

## 6. Conclusion

This study found that areas near healthcare facilities with poor waste management practices exhibited a significant increase in toxicity risks, with an estimated rise of 22% to 30%. These elevated risks were primarily linked to the accumulation of emerging pollutants, such as pharmaceuticals, heavy metals, and pathogens, which were present in the healthcare waste. The findings highlighted that these pollutants not only pose direct health risks to human populations but also accumulate in ecosystems, contributing to long-term ecological and biodiversity issues. The study also demonstrated that regions with inadequate waste management practices were hotspots for higher pollutant concentrations, emphasizing the need for improved waste management strategies in these areas.

The findings underscore the importance of integrating the One-Health approach into healthcare waste management policies. By considering the interconnectedness of human, animal, and environmental health, One-Health provides a comprehensive framework for addressing the risks associated with healthcare waste. Policymakers should prioritize the development of regulations that require the implementation of more effective and sustainable waste management practices in healthcare facilities, focusing on reducing the release of emerging pollutants into the environment. Strengthening waste management systems, increasing public and healthcare worker awareness, and promoting interdisciplinary collaboration between sectors will be crucial in minimizing the risks to both human health and ecosystems.

Future research should focus on refining the cumulative risk assessment model to better account for the complex interactions and long-term effects of emerging pollutants. Expanding the model to include a wider variety of environmental waste sources, beyond healthcare waste, will provide a more comprehensive understanding of the cumulative risks posed by pollutants in different sectors. Additionally, studies should explore innovative waste treatment technologies, such as advanced oxidation processes and bioremediation techniques, to assess their effectiveness in mitigating the environmental and health impacts of pollutants. Continued research on bioaccumulation and pollutant dispersal in diverse ecosystems will also be vital for predicting the long-term consequences of waste management practices.

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