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Impact of Improper Healthcare Waste Management on the Spread of Infectious Microorganisms

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ABSTRACT

Improper management of healthcare waste (HCW) is a significant public health concern, as it facilitates the transmission of infectious microorganisms. This review focuses on the impact of improper healthcare waste management on the spread of infectious organisms, examining how inadequate handling, storage, and disposal contribute to microbial transmission. Healthcare facilities generate diverse types of waste, including communicable, sharps, pathological, pharmaceutical, chemical, and radioactive materials, many of which harbor pathogenic bacteria, viruses, fungi, and parasites. When HCW is inadequately segregated, stored, handled, or disposed of, it becomes a potential reservoir for microbial proliferation, facilitating the transmission of infections to healthcare workers, patients, waste handlers, and the surrounding community. Transmission occurs through direct contact, contaminated surfaces, airborne aerosols, vectors, and environmental contamination of soil and water. Common pathogens identified in improperly managed HCW include Staphylococcus aureus, Escherichia coli, Clostridium difficile, Human Immunodeficiency Virus (HIV), Hepatitis B Virus (HBV), Hepatitis C Virus (HCV), Candida spp., and parasitic organisms, many of which exhibit resistance to conventional treatments. The health implications of poor HCWM extend beyond occupational exposure, contributing to community-acquired infections, localized outbreaks, and the propagation of antimicrobial resistance. Environmental contamination resulting from open dumping or uncontrolled incineration further exacerbates the risk of disease spread. Effective mitigation strategies involve adherence to international and national HCWM guidelines, including proper segregation, safe storage, treatment via autoclaving or chemical disinfection, and environmentally sound disposal methods. Additionally, training of healthcare personnel, microbiological monitoring, technological innovations, and community education are crucial for minimizing microbial hazards. Strengthening these measures is essential to safeguard public health, reduce environmental contamination, and curb the transmission of infectious microorganisms associated with healthcare waste.

Keywords: Healthcare waste, Infectious microorganisms, Improper management, Pathogens, Microbial contamination, Waste treatment, Occupational exposure, Environmental contamination, Infection control, Antimicrobial resistance

1. INTRODUCTION

The management of healthcare waste (HCW) is an increasingly critical concern, closely intertwined with public health and infection control. Healthcare waste refers to the various types of waste generated in healthcare facilities, including general, hazardous, and infectious waste. With rising global healthcare demands and ongoing health crises such as the COVID-19 pandemic (Izah et al., 2020a,b), the volume of healthcare waste has escalated dramatically, posing severe risks to public health and the environment. Effective HCW management practices are essential to prevent the transmission of infectious microorganisms and protect both healthcare workers and patients.

Healthcare waste can be classified into several categories, including general, infectious, sharps, pathological, pharmaceuticals, and chemical waste. Each type comes from diverse sources, including hospitals, clinics, laboratories, and even home care settings (Adu et al., 2020). Megatrends such as urbanization, population growth, and increased demand for healthcare services have driven significant increases in HCW generation rates, estimated at up to 5.2 million tons annually worldwide (Yoon et al., 2022). Moreover, the COVID-19 pandemic has exacerbated these rates, leading to unprecedented levels of medical waste, particularly from personal protective equipment (PPE) and single-use medical supplies (Sami et al., 2022). The challenge lies not only in managing this waste locally but also in mitigating its environmental impacts and the transmission risks associated with improper disposal methods (Saadat et al., 2020).

The importance of proper healthcare waste management cannot be overstated, particularly for infection prevention and control. According to the World Health Organization (WHO), effective HCW management is crucial in minimizing the risk of healthcare-associated infections (HAIs) and protecting healthcare staff from occupational hazards (Durán-Manuel et al., 2021). Studies show that improper handling of infectious waste can facilitate the spread of resistant microorganisms, jeopardizing the safety of healthcare providers and patients (Shah et al., 2020). Moreover, public health efforts must incorporate stringent waste management protocols to protect the environment, as improperly disposed of medical waste can contaminate soil and water systems (Saadat et al., 2020).

Failures in HCW disposal practices can escalate the risk of transmission of various infectious microorganisms, impacting communities at large. Research indicates that during the COVID-19 pandemic, improper disposal of virus-related materials increased exposure among healthcare staff and waste management personnel (Shah et al., 2020). Additionally, evidence indicates ongoing risks of bacterial contamination from improperly handled waste in healthcare settings, exacerbating the burden of antimicrobial resistance (Collignon & McEwen, 2019). Therefore, understanding and improving healthcare waste management practices is imperative to launch effective responses to current and future infectious disease outbreaks.

The environmental implications of healthcare waste mismanagement extend beyond human health, impacting ecosystems as well. The massive increase in plastic waste from PPE and other medical supplies during the COVID-19 pandemic has led to serious environmental concerns, including plastic pollution in oceans and green spaces (Sami et al., 2022). This calls for an integrated approach that addresses waste management within healthcare settings while assessing and mitigating the broader ecological impacts (Huraimel et al., 2020). Innovations in waste treatment technologies and stricter regulations are urgently needed to align healthcare waste management with sustainability goals (Sami et al., 2022).

Healthcare workers (HCWs) are on the frontline in managing the risks they face, often bearing the brunt of potential exposure to infectious agents through their handling practices (Xiao et al., 2020). Protective measures, training, and awareness campaigns are fundamental for ensuring that HCWs are equipped to prevent the transmission of pathogens effectively (Chou et al., 2020). Furthermore, studies consistently show that enhanced safety protocols and proper waste disposal practices correlate with reduced transmission of infections in healthcare facilities (Huei et al., 2020). Thus, prioritizing the health and safety of HCWs through robust HCW management protocols is vital for effective infection control.

Despite the significant implications of healthcare waste, various challenges hinder effective management. These include inadequate infrastructure, insufficient training, weak regulations, and limited resources, particularly in low- and middle-income countries (Anderson et al., 2021). Furthermore, public awareness and cultural perceptions around waste management often influence the success of HCW practices, leading to inconsistent practices at community and hospital levels (Saadat et al., 2020; Islam et al., 2021).

This paper examines the impact of improper healthcare waste management on the spread of infectious microorganisms. It highlights the types of pathogens present in medical waste and the potential risks they pose to healthcare workers, communities, and the environment. The study emphasizes the role of healthcare waste in the emergence and dissemination of multidrug-resistant organisms. By identifying gaps in current waste management practices, the paper provides evidence-based recommendations for safer and more effective handling of medical waste. The findings aim to enhance public health protection, reduce infection risks, and support sustainable healthcare waste management strategies.

2.0. Classification and Characteristics of Healthcare Waste

Healthcare waste involves various categories, each with specific classifications based on their potential health risks. These include infectious waste, hazardous chemical waste, sharps waste, pharmaceutical waste, and general waste. In furtherance of this, Janik-Karpińska et al. (2023) classified healthcare waste into hazardous and non-hazardous categories, noting that approximately 85% of healthcare waste is non-hazardous, while the remaining 15% consists of hazardous materials that are infectious, radioactive, or toxic (Figure 1). Hospitals and related facilities—including medical centers, laboratories, veterinary clinics, research institutions, mortuaries, blood banks, and nursing homes—are the main generators of healthcare waste, with hazardous waste generation reaching nearly 11 kg/bed/day in high-income countries compared to up to 6 kg/bed/day in low-income settings (Janik-Karpińska et al., 2023). Cirstea et al. (2025) reported HCW hazardous wastes to include pathological waste, infectious waste, radioactive waste, pharmaceutical and cytotoxic waste, chemical waste, and sharps waste (Figure 2). These hazardous wastes have deleterious effects on both human and the ecosystem (Izah et al., 2024).

Figure 1. Standard waste composition in health facilities. Source: Janik-Karpinska et al. (2023)

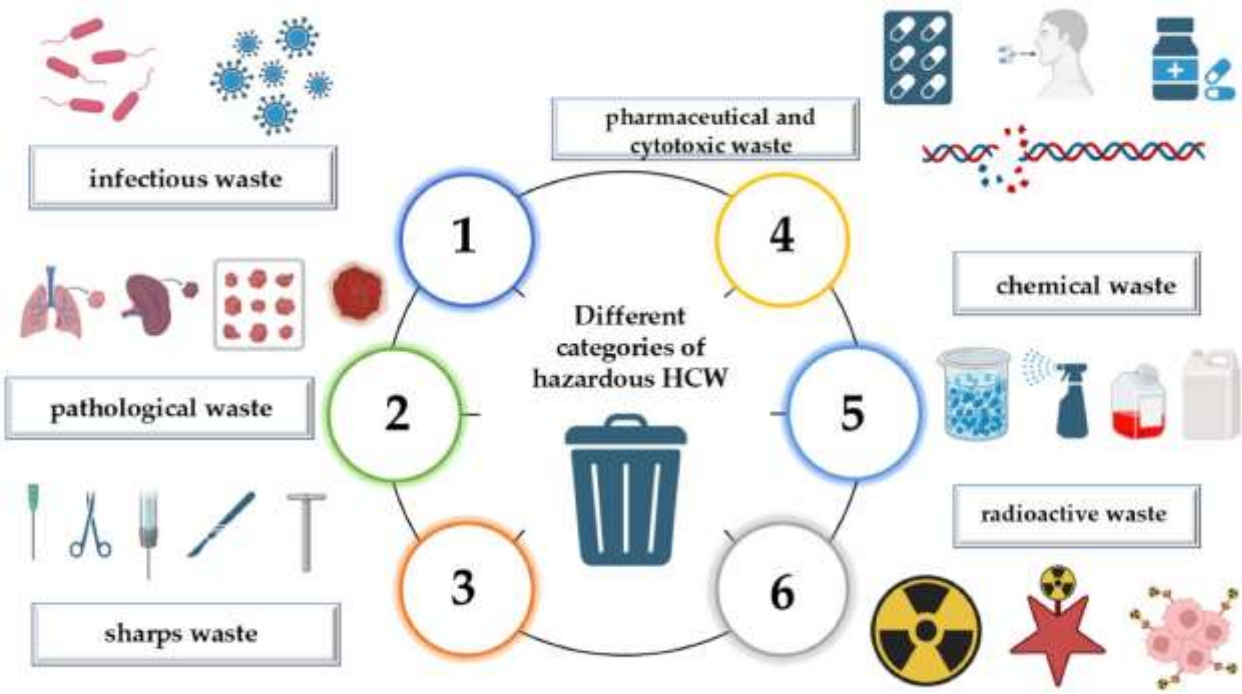

Figure 2: Categories of hazardous HCW. Source: Cirstea et al. (2025)

2.1 Major Categories of Healthcare Waste

Healthcare waste can be classified into several categories, each with distinct characteristics and associated risks. Infectious waste comprises materials contaminated with blood, bodily fluids, or excreta from patients, such as swabs and dressings. This type of waste has a high potential for transmitting pathogens, including bacterial, viral, and fungal agents, posing a significant infection risk in healthcare environments (Awodele et al., 2016; Ezeudu et al., 2022). Hazardous (chemical) waste includes laboratory reagents, solvents, and materials with chemical toxicity, such as formaldehyde and cytotoxic drugs. Improper handling of this waste can result in chemical burns, poisoning, and environmental pollution, further complicating waste management (Chisholm et al., 2021; Jangre et al., 2023). Sharps waste, including needles, scalpels, and broken glass, poses a substantial risk of transmitting bloodborne pathogens, underscoring the importance of stringent disposal protocols (Kenny & Priyadarshini, 2021; Pandey et al., 2021).

Other categories of healthcare waste include pharmaceutical waste and general waste. Pharmaceutical waste consists of expired or unused medications, including antibiotics and vaccines, which pose risks of environmental contamination and contribute to antimicrobial resistance if disposed of improperly (Sharma et al., 2019; El-Ramady et al., 2021). General waste, although typically posing minimal direct infectious risk, contributes to the overall burden of healthcare waste management due to its volume and the potential for cross-contamination (Bansod & Deshmukh, 2023). Effective classification and management of these waste types are essential to minimize infection risks, prevent environmental hazards, and ensure safe healthcare operations.

2.2 Microbiological Composition of Healthcare Waste

Healthcare waste is home to a wide range of microorganisms, including bacteria like Staphylococcus aureus and Escherichia coli, as well as pathogens such as HIV and Hepatitis B and C (Tesfahun et al., 2015; Wassie et al., 2022). The microbial load can vary significantly depending on the waste source—surgical, laboratory, or general patient care—thereby affecting infection and contamination risk (Leonard et al., 2022; Millanzi et al., 2023).

2.3 Potential for Harboring Pathogenic Microorganisms

Infectious and sharps waste can act as reservoirs for pathogenic microorganisms. Factors such as moisture, temperature, and the presence of organic matter influence pathogen survival on waste surfaces (Sehlapelo et al., 2025; Manupati et al., 2021). Inadequately managed waste can result in cross-contamination and increased healthcare-associated infections (HAIs), underscoring the need for strict management protocols (Goswami et al., 2021; Yazie et al., 2019).

Healthcare waste management remains crucial, particularly in high-risk settings such as hospitals and laboratories, where hazardous materials are more prevalent. Poor segregation and handling practices exacerbate the risk of infection transmission, making them a critical focus for public health initiatives (Moloisi & Onwubu, 2024; Carmona-Pomada et al., 2025).

3. Microbial Contamination in Improperly Managed Healthcare Waste

Healthcare waste commonly harbors a variety of pathogens that can adversely affect human health. Notable bacteria include Staphylococcus aureus, Escherichia coli, Pseudomonas aeruginosa, and Clostridium difficile, which are known for their role in nosocomial infections and their ability to form spores that contribute to environmental persistence (Wafula et al., 2019; Windfeld & Brooks, 2015). Viral threats include the Hepatitis B virus (HBV), Hepatitis C virus (HCV), and Human Immunodeficiency Virus (HIV), which pose significant exposure risks to healthcare workers and the general populace (Wafula et al., 2019; Khosla et al., 2022). Additionally, fungi such as Candida spp. and Aspergillus spp., as well as protozoan parasites such as Giardia lamblia, can survive in medical waste, complicating infection control efforts (Githinji et al., 2024; Windfeld & Brooks, 2015).

3.1 Survival and Persistence of Pathogens in Waste

Pathogens exhibit varying survival rates in healthcare waste, influenced by environmental conditions such as moisture, temperature, and waste composition. Bacteria can remain viable from hours to several months, while certain viruses can persist on contaminated surfaces for days to weeks, especially on plastics and fabrics (Liu et al., 2018; Mekonnen et al., 2021). Fungi are remarkably resilient, with spores capable of enduring dry conditions for extended durations (Githinji et al., 2024; Windfeld & Brooks, 2015). Furthermore, parasitic protozoa can survive in contaminated fluids and water, presenting secondary infection risks if they enter the water supply or are accessed by humans (Githinji et al., 2024; Mekonnen et al., 2021).

3.2 Factors Influencing Microbial Growth and Transmission

Microbial proliferation depends on several factors. Adequate moisture levels in waste significantly enhance bacterial survival and growth, whereas dry waste limits such proliferation (Steadmon et al., 2023; Moloisi & Onwubu, 2024). Elevated temperatures foster microbial activity, though some pathogens demonstrate heat resistance, complicating waste treatment processes (Awodele et al., 2016; Wafula et al., 2019). The pH environment also plays a crucial role; neutral to slightly alkaline conditions favor bacterial growth, while acidic environments may inhibit it (Steadmon et al., 2023; Moloisi & Onwubu, 2024). Organic matter, particularly body fluids and tissues, serves as a nutrient source for many pathogens, further exacerbating the risk of transmission (Windfeld & Brooks, 2015; Adu et al., 2020).

3.3 Implications of Microbial Contamination

The improper management of healthcare waste has profound implications for public health, contributing to increased rates of nosocomial infections and community-acquired diseases (Wafula et al., 2019; Khosla et al., 2022). The potential for disease outbreaks is heightened when contaminated waste enters water systems or soil, leading to widespread microbial exposure (Khosla et al., 2022; Mekonnen et al., 2021). Moreover, continual exposure to sub-lethal doses of antibiotics found in waste can promote antimicrobial resistance among various pathogenic strains, complicating treatment protocols (Githinji et al., 2024; Khosla et al., 2022).

3.4 Segregation and Management Practices

Adequate waste segregation and management are crucial for mitigating the risks of microbial contamination. Studies indicate that improper segregation enhances the potential for cross-contamination, thereby increasing health risks for waste handlers and the community at large (Adu et al., 2020; Ibáñez-Cruz et al., 2025). The absence of effective segregation technologies and color coding for waste types remains a significant barrier to safe waste management practices, particularly in developing regions (Wafula et al., 2019; Khan et al., 2019).

3.5 Cross-Contamination Risks

The risk of cross-contamination in healthcare facilities increases due to inadequate adherence to waste management protocols. Shared spaces and improper waste disposal methods heighten vulnerability not only for healthcare workers but also for patients and the community, as pathogens can be airborne or transmitted through contact (Windfeld & Brooks, 2015; Adu et al., 2020). Additionally, vectors such as pests and flies can facilitate the further spread of contaminants from waste to human populations and food sources, exacerbating public health threats (Githinji et al., 2024; Khalid et al., 2021).

3.6 Educations from the COVID-19 Pandemic

The COVID-19 pandemic highlighted systemic weaknesses in global healthcare waste management. Increased biomedical waste generation from protective equipment (PPE) necessitated urgent attention to waste treatment methods to prevent secondary infections and environmental pollution (Khosla et al., 2022; Singh et al., 2020). Improved protocols for the safe disposal and handling of infectious waste are essential to address the challenges sparked by the pandemic, underscoring the need for education and stricter regulatory guidelines (Moloisi & Onwubu, 2024; Khan et al., 2019).

4. Routes of Transmission and Public Health Implications

Routes of transmission describe the pathways through which infectious agents in improperly managed healthcare waste spread from their source to humans and the environment (Table 1). Understanding these routes is essential for designing effective infection prevention, environmental protection, and public health control measures.

Table 1: Routes of Transmission from Improperly Managed Healthcare Waste and Associated Public Health Implications

Route of Transmission	Exposure Pathways	Principal Public Health Implications
Occupational Exposure	Needle-stick/sharps injuries; direct contact with infectious waste; inhalation of bioaerosols; exposure through cuts and mucous membranes	Blood-borne and respiratory infections; increased healthcare costs; reduced workforce productivity; need for strict IPC and occupational safety measures
Environmental Contamination	Soil pollution from open dumping; water contamination via leachates and runoff; air contamination from open burning or poor incineration	Water- and air-borne diseases; ecosystem degradation; long-term environmental health risks; food and water safety threats
Community Exposure & Outbreaks	Contact with improperly disposed waste; use of contaminated water and food; vector-mediated transmission (flies, rodents)	Increased infectious disease burden; outbreaks (e.g., cholera, hepatitis); antimicrobial resistance spread; strain on public health systems

4.1 Occupational Exposure

Occupational exposure to healthcare waste is a critical public health concern that primarily affects healthcare workers, waste handlers, and cleaners. Direct contact with contaminated materials, such as blood-soiled dressings and improperly disposed needles, can lead to needle-stick injuries, which are prevalent sources of occupational infections like HIV, hepatitis B, and C (Bouya et al., 2020; Subramanian et al., 2017; Alaru et al., 2023). These injuries often occur due to inadequate personal protective equipment (PPE) during the handling and segregation of hazardous waste (Janik-Karpinska et al., 2023; Kanyal et al., 2021).

The exposure risk escalates when handling waste and can exacerbate injuries through cuts and abrasions, allowing pathogens to enter via mucous membranes (Reda et al., 2021). Furthermore, splashing infectious fluids during waste handling poses another significant risk, particularly in settings where PPE is compromised or not used (Alaru et al., 2023; Ibrahim et al., 2023).

Inhalation of bioaerosols, particularly during waste incineration or compaction, introduces airborne pathogens that can lead to respiratory infections, including tuberculosis (Jahangiri et al., 2016). Consequently, occupational health risks can considerably reduce productivity and contribute to psychological stress due to unsafe working conditions (Subramanian et al., 2017; Janik-Karpinska et al., 2023).

4.2 Environmental Contamination

Healthcare waste management has profound environmental implications, severely impacting soil, water, and air quality. Untreated or poorly managed waste can lead to soil contamination, where pathogenic microorganisms may survive and proliferate, posing long-term risks to ecosystems and human health (Janik-Karpinska et al., 2023; Kanyal et al., 2021). Similarly, when healthcare waste leaks into groundwater systems, it can contaminate domestic water supplies and increase the risk of waterborne diseases, such as cholera and enteric infections (Janik-Karpinska et al., 2023).

Moreover, air pollution originating from open burning or inadequate incineration of healthcare waste releases microbial aerosols and toxic gases into the atmosphere, posing further health risks to communities (Khalid et al., 2021; Oyekale & Oyekale, 2017). Consequently, the environmental ramifications extend beyond immediate public health concerns, disrupting local ecosystems and threatening biodiversity (Kanyal et al., 2021; Ibrahim et al., 2023).

4.3 Community Exposure and Disease Outbreaks

Community exposure to healthcare waste poses a significant public health challenge, with direct and indirect pathways of infection. Improper disposal of healthcare waste exposes nearby residents, including vulnerable groups such as children and informal waste pickers, to infectious materials (Khalid et al., 2021; Kanyal et al., 2021).

Indirect exposure can occur through the consumption of contaminated water or crops cultivated in polluted soil (Khalid et al., 2021; Janik-Karpinska et al., 2023). The risk of vector-mediated disease transmission, facilitated by pests breeding in waste-filled environments, further exacerbates health concerns within communities, potentially leading to outbreaks of diseases like diarrheal infections and typhoid fever (Reda et al., 2021; Janik-Karpinska et al., 2023).

Public health implications manifest as increased morbidity and mortality rates, especially among high-risk populations. Furthermore, these health crises can strain public health resources and economic structures due to increased healthcare expenditures, destabilizing community health and economic security (Ibrahim et al., 2023; Janik-Karpinska et al., 2023).

5. Antimicrobial Resistance and Healthcare Waste

The antimicrobial resistance risks associated with improper healthcare waste management arise from multiple interrelated components, including the presence of multidrug-resistant organisms (MDROs), inadequate waste disposal practices, and the potential for resistance gene spread in the environment. Table 2 summarizes these components, their descriptions, key examples, and the public health implications of each risk factor.

Table 2: Antimicrobial Resistance Risks Associated with Improper Healthcare Waste Management

Component	Narrative	Principal Examples	Public Health Implications
MDROs in Healthcare Waste	Presence of antibiotic-exposed and resistant pathogens in clinical and laboratory waste	MRSA, VRE, ESBL-producing *E. coli*/*Klebsiella*, carbapenem-resistant *Pseudomonas*/*Acinetobacter*	Acts as a reservoir for resistant organisms and resistance genes
Improper Waste Disposal	Poor segregation, open dumping, inadequate treatment, and unsafe wastewater discharge	Untreated hospital effluents, discarded sharps, and expired antibiotics	Environmental contamination and spread of resistance through soil and water
Spread of Resistance	Survival and transfer of resistance genes in waste environments	Horizontal gene transfer via plasmids and transposons	Amplification of antimicrobial resistance in communities
Treatment & Infection Control Impact	Reduced effectiveness of available antibiotics	Increased reliance on second-line and last-resort drugs	Higher morbidity, mortality, costs, and compromised infection control

The intersection of antimicrobial resistance (AMR) and healthcare waste management is a significant public health concern. Healthcare waste is recognized as a reservoir for multidrug-resistant organisms (MDROs), including Methicillin-resistant Staphylococcus aureus (MRSA) and Vancomycin-resistant Enterococci (VRE) (Larsson & Flach, 2021; Yazie et al., 2019). Contaminated materials, such as used syringes and laboratory cultures, can serve as hotspots for these resistant pathogens (Awodele et al., 2016). The continual presence of these organisms in hospital environments may contribute to an escalated risk of hospital-acquired infections.

Improper disposal methods exacerbate the AMR crisis. Practices such as open dumping and inadequate treatment of healthcare waste can lead to the environmental dissemination of resistant bacteria and resistance genes (Yazie et al., 2019; Bakon, 2025). Inadequate segregation of healthcare waste allows pathogens to persist and proliferate, ultimately spreading into soil and water and, consequently, into human communities, heightening exposure risks for both the public and healthcare workers (Alharbi et al., 2021).

The consequences of increasing AMR prevalence due to poor healthcare waste management are dire. They result in limited treatment options and higher healthcare costs, contributing to extended hospital stays and increased morbidity and mortality from infections that were once easily treatable (Yazie et al., 2019; Olaifa et al., 2018). Moreover, AMR undermines the efficacy of current infection control measures in healthcare settings, exacerbating the challenge of managing outbreaks effectively (Van Bijnen et al., 2015).

Sustainable waste management solutions are urgently needed to mitigate the adverse effects on public health. Implementation of strict protocols for the segregation, treatment, and disposal of healthcare waste is crucial (Awodele et al., 2016; Alharbi et al., 2021). Integrating surveillance for antibiotic resistance into waste management strategies could further help understand the spread of these resistant organisms and the genes associated with them (Nelson et al., 2025).

6. Regulatory Frameworks and Management Practices of healthcare wastes

Healthcare waste management (HCWM) is a critical area in public health, particularly concerning infectious microorganisms. The WHO provides global guidelines emphasizing the importance of waste minimization, adequate segregation, and environmentally sound disposal methods to mitigate health risks associated with HCW (Windfeld & Brooks, 2015). The WHO's waste hierarchy, which prioritizes minimization, segregation, treatment, and disposal, is crucial for preventing the potential spread of infections (Kenny & Priyadarshini, 2021). Segregation methods, such as color-coded waste systems, are encouraged globally to ensure safe management practices and protect healthcare personnel from occupational hazards (Janik-Karpinska et al., 2023).

International regulations, including the Basel and Stockholm Conventions, play significant roles in controlling the transboundary movement and disposal of hazardous healthcare waste, particularly persistent organic pollutants generated during treatment processes (Raubenheimer & McIlgorm, 2018). In line with these conventions, countries are increasingly developing national HCWM policies that align with WHO guidelines, thereby strengthening regulatory frameworks and institutional responsibilities at multiple levels (Fuzi et al., 2025). National policies involve establishing monitoring bodies and clear penalties for non-compliance to ensure adherence to health and environmental standards (Van Caneghem et al., 2025).

Despite the structured frameworks, implementation is often challenged by infrastructural deficiencies, particularly in low-resource settings. Many regions lack functional incinerators or adequate waste storage facilities, leading to unsafe disposal practices, such as open burning of waste (Abanyie et al., 2021). Gallo et al. (2018) highlighted that financial constraints hinder infrastructural development for HCWM, exacerbating the risks to public health and environmental quality.

Training for healthcare workers is vital for effective HCWM. Studies have shown that inadequate training and high staff turnover hinder compliance with established waste segregation and treatment protocols (Kanyal et al., 2021). Additionally, the lack of awareness regarding the health implications of improper waste management poses a significant barrier to effective HCWM (Chepchirchir & Ngoye, 2024). Addressing training gaps can significantly enhance HCWM by ensuring that staff are equipped with the necessary skills and knowledge to manage waste responsibly.

Environmental concerns from improper HCWM practices include hazardous exposure risks from infectious waste. Potential health impacts range from infections to systemic toxic effects, emphasizing the importance of effective HCWM systems to protect both healthcare workers and the community (Cirstea et al., 2025). The literature consistently emphasizes that improper waste management practices can lead to significant environmental contamination and public health crises (Janik-Karpinska et al., 2023).

Another prevalent issue is the variability in HCWM practices across different countries, particularly in developing regions. Factors such as cultural perceptions of waste risks and limited governmental oversight often lead to non-adherence to waste management protocols (Paudel et al., 2023). Context-specific studies indicate that tailored interventions are required to address local barriers and enhance HCWM efficiency (Paudel et al., 2023).

Many countries have successfully implemented structured HCWM categories and practices, which Nigeria can adapt to improve its own waste handling systems. As shown in **Figure 3**, these categories include guidelines, segregation, treatment methods, and final disposal, each with specific challenges and One Health implications. Adopting these measures can enhance occupational safety, reduce environmental contamination, and minimize the transmission of pathogens to humans, animals, and ecosystems.

Figure 3: Possible healthcare waste management in Nigeria: from guideline to One Health Impact

7. Recommendations and Future Directions for healthcare waste

Effective HCWM is essential not only for minimizing environmental impact but also for reducing microbial risks associated with infectious waste. Table 3 summarises the strategies for minimizing microbial risks and enhancing HCWM efficiency. One of the best practices involves strict segregation of waste at the point of generation, ensuring that contagious, sharps, pharmaceutical, and general waste are clearly categorized. Utilizing color-coded bins and clearly labeled containers further supports compliance and facilitates proper waste disposal, thereby minimizing potential hazards posed by microorganisms (Nwosu et al., 2024).

Table 3: Strategies for Minimizing Microbial Risks and Enhancing HCWM Efficiency

Category	Principal Recommendations / Strategies	Purpose / Outcome
Minimizing Microbial Risks	- Segregate waste at point of generation - Use color-coded bins and labeled containers - Regular staff training on HCWM - Employ engineering controls (closed transport, leak-proof containers) - Disinfect reusable materials; treat infectious waste properly - Ensure PPE usage - Minimize waste via reusable alternatives	Reduce exposure to pathogens; prevent infection transmission; improve safety of healthcare workers and patients
Microbiological Monitoring	- Conduct routine microbial surveillance of storage and treatment areas - Perform swab tests and culture analyses- Implement microbial risk assessment protocols - Use real-time detection technologies (biosensors) - Utilize monitoring data to guide policies and optimize treatment	Early detection of contamination; informed decision-making; improved compliance and efficiency
Research Gaps & Innovations	- Develop eco-friendly, energy-efficient treatment technologies (plasma pyrolysis, solar sterilization) - Design biodegradable and antimicrobial containers - Study microbial survival in various waste types and environments	Promote sustainable, safe, and innovative waste management practices; reduce environmental impact; guide future research and policy

	- Explore cost-effective solutions for low-resource settings - Implement circular economy approaches for safe recycling - Use digital tracking systems for waste management- Investigate policy and behavioral interventions for compliance	

Regular training for healthcare workers on safe handling, transport, and disposal of healthcare waste is crucial for maintaining safety standards. Education initiatives should reinforce the importance of proper waste segregation and the use of personal protective equipment (PPE) to mitigate risks associated with exposure to hazardous materials (Karim et al., 2020). Furthermore, engineering controls, such as closed waste transport systems and leak-proof containers, help prevent contamination during waste management processes (Kim et al., 2024).
Routine disinfection of reusable materials and proper treatment protocols for infectious waste, such as autoclaving, incineration, or chemical treatment, must be implemented to diminish microbial loads before disposal. Specifically, recent studies highlight the effectiveness of environmentally conscious methods, such as plasma pyrolysis and solar-assisted sterilization, as sustainable alternatives for waste treatment (Lee & Lee, 2022; Ahmad et al., 2021).
The integration of microbiological monitoring into HCWM strategies can identify contamination hotspots in waste management facilities. Regular microbial surveillance, including periodic swab tests and culture analyses, can inform healthcare operations about the levels of microbial risks present, thereby guiding necessary interventions and compliance measures (Islam & Bhuiyan, 2023). The adoption of real-time monitoring technologies, such as biosensors, enhances the ability to detect pathogens in healthcare waste rapidly (Nwosu et al., 2024).
Research gaps in HCWM highlight the need for innovations in biodegradable, antimicrobial materials for waste containers, which could significantly reduce environmental hazards associated with healthcare waste (Hu et al., 2020). The exploration of circular economy approaches, including the safe recycling of non-infectious materials, represents a promising area for future interventions in sustainable waste management (Antunes et al., 2022). As regulations evolve, continuous efforts in policy and behavioral interventions are required to improve compliance with established HCWM standards (Mhaddolkar et al., 2024).

8. CONCLUSION

The complex interplay between healthcare waste management and microbial contamination highlights the urgent need for comprehensive strategies in healthcare settings. Effective practices (such as proper segregation, safe storage, transport, and treatment of infectious waste) are essential to minimize occupational exposure, prevent environmental contamination, and protect community health. By integrating monitoring technologies and adhering to established safety standards, healthcare facilities can detect microbial risks promptly, enforce compliance, and strengthen infection prevention and control measures, ultimately reducing the reservoir of pathogens and mitigating the rise of antimicrobial resistance.
Moreover, continuous training and capacity building for healthcare personnel, alongside the adoption of innovative treatment methods like autoclaving, advanced chemical disinfection, and environmentally friendly incineration, are pivotal in shaping sustainable healthcare waste management. Embedding these strategies within robust regulatory frameworks ensures not only the protection of public health but also the preservation of environmental resources. A holistic approach that combines best practices, technological innovation, and education is therefore essential for fostering a safer, more sustainable, and resilient healthcare ecosystem.

REFERENCES

1. Abanyie, S. K., Amuah, E. E. Y., Douti, N. B., Amadu, C. C., & Bayorbor, M. (2021). Healthcare waste management in the Tamale Central Hospital, northern Ghana: An assessment before the emergence of the COVID-19 pandemic in Ghana. *Environmental Challenges, 5*, 100320.
2. Adu, R. O., Gyasi, S. F., Essumang, D. K., & Otabil, K. B. (2020). Medical waste-sorting and management practices in five hospitals in Ghana. *Journal of Environmental and Public Health*, *2020*(1), 2934296.
3. Ahmad, R. W., Salah, K., Jayaraman, R., Yaqoob, I., Omar, M., & Ellahham, S. (2021). Blockchain-based forward supply chain and waste management for COVID-19 medical equipment and supplies. *IEEE Access, 9*, 44905–44927.
4. Alaru, M., Kyiu, C., Yariga, F. Y., & Osman, A. (2023). Prevalence of needle stick injury among healthcare workers in Savelugu Municipal Hospital. *Asian Journal of Medicine and Health, 21*(12), 127–136.
5. Alharbi, N. S., Alhaji, J. H., & Qattan, M. Y. (2021). Toward sustainable environmental management of healthcare waste: A holistic perspective. *Sustainability, 13*(9), 5280.
6. Anderson, D. M., Cronk, R., Fejfar, D., Pak, E., Cawley, M., & Bartram, J. (2021). Safe healthcare facilities: A systematic review on the costs of establishing and maintaining environmental health in facilities in low-and middle-income countries. *International Journal of Environmental Research and Public Health, 18*(2), 817.
7. Antunes, J., Matos, K., Carvalho, I., Carvalho, S., Ferreira, F., & Cruz, S. M. (2022). Physical vapor deposition technology in personal protective equipment production: Improved antibacterial and hydrophobic character of textiles. *Coatings, 12*(10), 1399.
8. Awodele, O., Adewoye, A. A., & Oparah, A. C. (2016). Assessment of medical waste management in seven hospitals in Lagos, Nigeria. *BMC Public Health, 16*(1), 269.
9. Bakon, S. K., Zakaria, N. F. S., Jamilan, M. A., Hashim, H., & Mohamad, Z. A. (2025). City or suburb, resistance flows: Wastewater-borne ESKAPE and AMR genes in Malaysian hospitals. *Antibiotics, 14*(11), 1058.
10. Bansod, H. S., & Deshmukh, P. (2023). Biomedical waste management and its importance: A systematic review. *Cureus, 15*(2), e34589.
11. Bouya, S., Balouchi, A., Rafiemanesh, H., Amirshahi, M., Dastres, M., Moghadam, M. P., Behnamfar, N., Shyeback, M., Badakhsh, M., Allahyari, J., & Al Mawali, A. (2020). Global prevalence and device related causes of needle stick injuries among health care workers: A systematic review and meta-analysis. *Annals of Global Health, 86*(1), 35.
12. Carmona-Pomada, B., Diaz-Co, L., Azaroual El Bachiri, H., Nieto-Lorente, N., Muriel-Serrano, G., Zarza-Sánchez, L., Caro-Benito, C., & Monistrol, O. (2025). Segregation and recycling in the operating room: An intervention to accelerate the decarbonisation process in the health sector. *Journal of Clinical Nursing.*
13. Chepchirchir, C., & Ngoye, B. (2024). Assessment of the level of adherence to hazardous waste management policy frameworks among health workers in private hospitals in Nairobi County-Kenya. *International Journal of Health, Medicine and Nursing Practice, 6*(5), 1–18.
14. Chisholm, J. M., Zamani, R., Negm, A. M., Said, N., Abdel Daiem, M. M., Dibaj, M., & Akrami, M. (2021). Sustainable waste management of medical waste in African developing countries: A narrative review. *Waste Management & Research, 39*(9), 1149–1163.
15. Chou, R., Dana, T., Buckley, D. I., Selph, S., Fu, R., & Totten, A. M. (2020). Epidemiology of and risk factors for coronavirus infection in health care workers: A living rapid review. *Annals of Internal Medicine, 173*(2), 120–136.
16. Cirstea, I., Radu, A. F., Radu, A., Tit, D. M., & Bungau, G. S. (2025). Healthcare waste toxicity: From human exposure to toxic mechanisms and management strategies. *Journal of Xenobiotics, 15*(5), 155.
17. Collignon, P. J., & McEwen, S. A. (2019). One health—Its importance in helping to better control antimicrobial resistance. *Tropical Medicine and Infectious Disease, 4*(1), 22.
18. Durán-Manuel, E. M., Cruz-Cruz, C., Ibáñez-Cervantes, G., Bravata-Alcantará, J. C., Sosa-Hernandez, O., Delgado-Balbuena, L., León-García, G., Cortés-Ortíz, I. A., Cureño-Díaz, M. A., Castro-Escarpulli, G., & Vélez-Reséndiz, J. M. (2021). Clonal dispersion of Acinetobacter baumannii in an intensive care unit designed for patients with COVID-19. *The Journal of Infection in Developing Countries, 15*(01), 58–68.
19. El-Ramady, H., Brevik, E. C., Elbasiouny, H., Elbehiry, F., Amer, M., Elsakhawy, T., Omara, A. E. D., Mosa, A. A., El-Ghamry, A. M., Abdalla, N., & Rezes, S. (2021). Planning for disposal of COVID-19 pandemic wastes in developing countries: A review of current challenges. *Environmental Monitoring and Assessment, 193*(9), 592.
20. Ezeudu, O. B., Ezeudu, T. S., Ugochukwu, U. C., Tenebe, I. T., Ajogu, A. P., Nwadi, U. V., & Ajaero, C. C. (2022). Healthcare waste management in Nigeria: A review. *Recycling, 7*(6), 87.
21. Fuzi, M. Y. A., Yatim, S. R. M., Dom, N. C., Ilias, K., & Asfiradayati, R. (2025). Factors influencing healthcare waste management effectiveness: Challenges and interventions. *Environment-Behaviour Proceedings Journal, 10*(31), 197–203.
22. Gallo, F., Fossi, C., Weber, R., Santillo, D., Sousa, J., Ingram, I., Nadal, A., & Romano, D. (2018). Marine litter plastics and microplastics and their toxic chemicals components: The need for urgent preventive measures. *Environmental Sciences Europe, 30*(1), 13.
23. Githinji, M. J., Njogu, P. M., Nganga, Z., & Karama, M. (2024). Levels of polycyclic aromatic hydrocarbons (PAHs) in healthcare waste incinerators' bottom ash from five county hospitals in Kenya. *Journal of Environmental Protection, 15*(3), 318–337.

24. Goswami, M., Goswami, P. J., Nautiyal, S., & Prakash, S. (2021). Challenges and actions to the environmental management of bio-medical waste during COVID-19 pandemic in India. *Heliyon, 7*(3).
25. Hu, X. R., Han, M. F., Wang, C., Yang, N. Y., Wang, Y. C., Duan, E. H., Hsi, H. C., & Deng, J. G. (2020). A short review of bioaerosol emissions from gas bioreactors: Health threats, influencing factors and control technologies. *Chemosphere, 253*, 126737.
26. Huei, L., Ya-Wen, L., Chiu Ming, Y., Li Chen, H., Jong Yi, W., & Ming Hung, L. (2020). Occupational health and safety hazards faced by healthcare professionals in Taiwan: A systematic review of risk factors and control strategies. *SAGE Open Medicine, 8*, 2050312120918999.
27. Huraimel, A. K., Alhosani, M., Kunhabdulla, S., & Stietiya, M. H. (2020). SARS-CoV-2 in the environment: Modes of transmission, early detection and potential role of pollutions. *Science of the Total Environment, 744*, 140946.
28. Ibáñez-Cruz, A. J. A., Vergara-Florián, A. M. E., & Algoner, W. C. (2025). Hospital solid waste management strategies to prevent healthcare-associated infections from occupational exposure to bloodborne pathogens and improve occupational safety. *Frontiers in Public Health, 13*, 1499463.
29. Ibrahim, M., Kebede, M., & Mengiste, B. (2023). Healthcare waste segregation practice and associated factors among healthcare professionals working in public and private hospitals, Dire Dawa, Eastern Ethiopia. *Journal of Environmental and Public Health, 2023*(1), 8015856.
30. Islam, M. M., & Bhuiyan, Z. A. (2023). An integrated scalable framework for cloud and IoT based green healthcare system. *IEEE Access, 11*, 22266–22282.
31. Islam, S. D. U., Mondal, P. K., Ojong, N., Bodrud-Doza, M., Siddique, M. A. B., Hossain, M., & Mamun, M. A. (2021). Water, sanitation, hygiene and waste disposal practices as COVID-19 response strategy: Insights from Bangladesh. *Environment, Development and Sustainability, 23*(8), 11953–11974.
32. Izah, S. C., Chandel, S. S., Aigberua, A. O., Venkatachalam, T., & Verma, D. (2020a). Coronavirus disease 2019: The emergence of popular unverified myths and realities to its spread. *International Journal of Life Science and Pharma Research, 10*(5), 17–26.
33. Izah, S. C., Iniamagha, I., & Sylva, L. (2020b). Two months of COVID-19 pandemic in Nigeria: Distribution and responses of the Nigerian media. *Epidemiology International, 5*(2), 32–44.
34. Izah, S.C, Ogwu, M.C., Hait, M. (2025). Waste Management and Health: Addressing the Processes Behind Hazardous Waste and Pollution. In: Izah, S.C, Ogwu, M.C (eds) Innovative Approaches in Environmental Health Management. Environmental Science and Engineering. (PP. 143-171). Springer, Cham. https://doi.org/10.1007/978-3-031-81966-7_6
35. Jahangiri, M., Rostamabadi, A., Hoboubi, N., Tadayon, N., & Soleimani, A. (2016). Needle stick injuries and their related safety measures among nurses in a university hospital, Shiraz, Iran. *Safety and Health at Work, 7*(1), 72–77.
36. Jangre, J., Prasad, K., & Patel, D. (2024). Management of healthcare waste collection and segregation for developing countries. *Waste Management & Research, 42*(11), 1079–1092.
37. Janik-Karpinska, E., Brancaleoni, R., Niemcewicz, M., Wojtas, W., Foco, M., Podogrocki, M., & Bijak, M. (2023). Healthcare waste—a serious problem for global health. *Healthcare, 11*(2), 242. https://doi.org/10.3390/healthcare11020242
38. Janik-Karpinska, E., Brancaleoni, R., Niemcewicz, M., Wojtas, W., Foco, M., Podogrocki, M., & Bijak, M. (2023, January). Healthcare waste—a serious problem for global health. In *Healthcare* (Vol. 11, No. 2, p. 242). MDPI.
39. Kanyal, D., Butola, L. K., & Ambad, R. (2021). Biomedical waste management in India—a review. *Indian Journal of Forensic Medicine & Toxicology, 15*(2), 108–113.
40. Kanyal, D., Butola, L. K., & Ambad, R. (2021). Biomedical waste management in India—a review. *Indian Journal of Forensic Medicine & Toxicology, 15*(2), 108–113.
41. Karim, N., Afroj, S., Lloyd, K., Oaten, L. C., Andreeva, D. V., Carr, C., Farmery, A. D., Kim, I. D., & Novoselov, K. S. (2020). Sustainable personal protective clothing for healthcare applications: A review. *ACS Nano, 14*(10), 12313–12340.
42. Kenny, C., & Priyadarshini, A. (2021, March). Review of current healthcare waste management methods and their effect on global health. In *Healthcare* (Vol. 9, No. 3, p. 284). MDPI.
43. Khalid, S., Haq, N., Sabiha, Z. U. A., Latif, A., Khan, M. A., Iqbal, J., & Yousaf, N. (2021). Current practices of waste management in teaching hospitals and presence of incinerators in densely populated areas. *BMC Public Health, 21*(1), 1340.
44. Khan, B. A., Cheng, L., Khan, A. A., & Ahmed, H. (2019). Healthcare waste management in Asian developing countries: A mini review. *Waste Management & Research, 37*(9), 863–875.
45. Khosla, R., Jha, A., Dua, S., Varmani, S. G., Rajput, N., & Pani, B. (2022). Upsurge in biomedical waste due to COVID-19 in India: A statistical correlation, challenges and recommendations. *Frontiers in Environmental Science, 10*, 1022098.
46. Kim, M. J., Park, Y. S., Kim, T., Choi, H. H., Yoon, Y. S., Jeon, T. W., & Um, N. (2024). An improved strategy to effectively manage healthcare waste after COVID-19 in Republic of Korea. *Sustainability, 16*(7), 2696.
47. Larsson, D. J., & Flach, C. F. (2022). Antibiotic resistance in the environment. *Nature Reviews Microbiology, 20*(5), 257–269.

48. Lee, S. M., & Lee, D. (2022). Developing green healthcare activities in the total quality management framework. *International Journal of Environmental Research and Public Health, 19*(11), 6504.
49. Leonard, C. M., Chunga, C. C., Nkaama, J. M., Banda, K., Mibenge, C., Chalwe, V., Biemba, G., Chilengi-Sakala, S., & Mwale, F. K. (2022). Knowledge, attitudes, and practices of health care waste management among Zambian health care workers. *PLOS Global Public Health, 2*(6), e0000655.
50. Liu, H., Whitehouse, C. A., & Li, B. (2018). Presence and persistence of Salmonella in water: The impact on microbial quality of water and food safety. *Frontiers in Public Health, 6*, 159.
51. Manupati, V. K., Ramkumar, M., Baba, V., & Agarwal, A. (2021). Selection of the best healthcare waste disposal techniques during and post COVID-19 pandemic era. *Journal of Cleaner Production, 281*, 125175.
52. Mekonnen, B., Solomon, N., & Wondimu, W. (2021). Healthcare waste status and handling practices during COVID-19 pandemic in Tepi General Hospital, Ethiopia. *Journal of Environmental and Public Health, 2021*(1), 6614565.
53. Mhaddolkar, N., Tischberger-Aldrian, A., Astrup, T. F., & Vollprecht, D. (2024). Consumers confused 'Where to dispose biodegradable plastics?': A study of three waste streams. *Waste Management & Research, 42*(9), 776–787.
54. Millanzi, W. C., Herman, P. Z., & Mtangi, S. A. (2023). Knowledge, attitude, and perceived practice of sanitary workers on healthcare waste management: A descriptive cross-sectional study in Dodoma region, Tanzania. *SAGE Open Medicine, 11*, 20503121231174735.
55. Moloisi, M. O., & Onwubu, S. C. (2024). An investigation into waste handler's knowledge of management of isolation waste: A case study of Dr George Mukhari Academic Hospital, Gauteng, South Africa. *PLOS ONE, 19*(6), e0305224.
56. Nelson, M., Green, S. B., Suchindran, S., & Witt, L. S. (2025). The hidden economic and environmental costs of antimicrobial therapies: A call to action. *Antimicrobial Stewardship & Healthcare Epidemiology, 5*(1), e24.
57. Nwosu, I. A., Ekpechu, J. O., Njemanze, V. C., Semidara, B., Eyisi, E. C., Ohuruogu, B., Nwazonobi, P. E., Umanah, U. N., Clement, W. C., Aleke, C. O., & Okoli, C. N. (2024). Assessment of awareness, attitude, and consequences of healthcare waste among health workers at health facilities in southeast Nigeria. *SAGE Open, 14*(1), 21582440241229598.
58. Olaifa, A., Govender, R. D., & Ross, A. J. (2018). Knowledge, attitudes and practices of healthcare workers about healthcare waste management at a district hospital in KwaZulu-Natal. *South African Family Practice, 60*(5), 137–145.
59. Oyekale, A. S., & Oyekale, T. O. (2017). Healthcare waste management practices and safety indicators in Nigeria. *BMC Public Health, 17*(1), 740.
60. Pandey, D., Verma, S., Verma, P., Mahanty, B., Dutta, K., Daverey, A., & Arunachalam, K. (2021). SARS-CoV-2 in wastewater: Challenges for developing countries. *International Journal of Hygiene and Environmental Health, 231*, 113634.
61. Paudel, P., Aryal, A., Joshi, Y. P., Thapa, B., Thapa, J., Yamuna, M., Shah, S. K., & Timilsina, B. (2023). Healthcare waste management practices in selected healthcare institutions within Kailali District of Nepal. *A Bi-annual South Asian Journal of Research & Innovation, 10*(2), 15–25.
62. Paudel, P., Thapa, J., Marasini, Y., Sha, S. K., & Timilsina, B. (2023, July). Healthcare waste management practices in selected healthcare facilities: A quantitative cross-sectional descriptive study. In *Proceedings of the Global Public Health Conference* (Vol. 6, No. 1, pp. 1–25).
63. Raubenheimer, K., & McIlgorm, A. (2018). Can the Basel and Stockholm Conventions provide a global framework to reduce the impact of marine plastic litter? *Marine Policy, 96*, 285–290.
64. Reda, S., Gebrehiwot, M., Lingerew, M., Keleb, A., Mekonnen, T. C., Wagaye, B., Atamo, A., Daba, C., Feleke, A., & Adane, M. (2021). Occupational blood exposure beyond needle stick injuries: Hospital-based cross-sectional study among healthcare workers in governmental hospitals of Northern Ethiopia. *BMC Health Services Research, 21*(1), 1136.
65. Saadat, S., Rawtani, D., & Hussain, C. M. (2020). Environmental perspective of COVID-19. *Science of the Total Environment, 728*, 138870.
66. Sami, N., Ahmad, R., Afzal, B., Naaz, H., & Fatma, T. (2022). SARS-CoV-2 in the environment: Its transmission, mitigation, and prospective strategies of safety and sustainability. *Reviews of Environmental Contamination and Toxicology, 260*(1), 8.
67. Sehlapelo, N. M., Rathebe, P. C., & Tlotleng, N. (2025). A pilot study exploring the risk of SARS-CoV-2 infection among employees handling healthcare waste in selected healthcare risk waste facilities in Johannesburg, South Africa. *International Journal of Environmental Research and Public Health, 22*(2), 243.
68. Shah, A. S., Wood, R., Gribben, C., Caldwell, D., Bishop, J., Weir, A., Kennedy, S., Reid, M., Smith-Palmer, A., Goldberg, D., & McMenamin, J. (2020). Risk of hospital admission with coronavirus disease 2019 in healthcare workers and their households: Nationwide linkage cohort study. *BMJ, 371*.
69. Sharma, M., Millner, P. D., Hashem, F., Vinyard, B. T., East, C. L., Handy, E. T., White, K., Stonebraker, R., & Cotton, C. P. (2019). Survival of Escherichia coli in manure-amended soils is affected by spatiotemporal, agricultural, and weather factors in the Mid-Atlantic United States. *Applied and Environmental Microbiology, 85*(5), e02392-18.
70. Singh, N., Tang, Y., Zhang, Z., & Zheng, C. (2020). COVID-19 waste management: Effective and successful measures in Wuhan, China. *Resources, Conservation, and Recycling, 163*, 105071.

71. Steadmon, M., Ngiraklang, K., Nagata, M., Masga, K., & Frank, K. L. (2023). Effects of water turbidity on the survival of Staphylococcus aureus in environmental fresh and brackish waters. *Water Environment Research, 95*(9), e10923.
72. Subramanian, G. C., Arip, M., & Subramaniam, T. S. (2017). Knowledge and risk perceptions of occupational infections among health-care workers in Malaysia. *Safety and Health at Work, 8*(3), 246–249.
73. Tesfahun, E., Kumie, A., & Beyene, A. (2016). Developing models for the prediction of hospital healthcare waste generation rate. *Waste Management & Research, 34*(1), 75–80.
74. Van Bijnen, E. M., Paget, J., de Lange-de Klerk, E. S., den Heijer, C. D., Versporten, A., Stobberingh, E. E., Goossens, H., Schellevis, F. G., & collaboration with the APRES Study Team. (2015). Antibiotic exposure and other risk factors for antimicrobial resistance in nasal commensal Staphylococcus aureus: An ecological study in 8 European countries. *PLOS ONE, 10*(8), e0135094.
75. Van Caneghem, J., Verstegen, A., Torremans, G., Hofman, J., Berghmans, P., Otten, G., Herremans, S., Van Meenen, E., De Ren, L., & Van Brecht, A. (2025). Polyfluoroalkyl substances in dedicated hazardous waste incinerators: Framework and industrial scale experimental estimation of destruction and removal efficiency. *Waste Management & Research*, 0734242X251345326.
76. Wafula, S. T., Musiime, J., & Oporia, F. (2019). Health care waste management among health workers and associated factors in primary health care facilities in Kampala City, Uganda: A cross-sectional study. *BMC Public Health, 19*(1), 203.
77. Wassie, B., Gintamo, B., Mekuria, Z. N., & Gizaw, Z. (2022). Healthcare waste management practices and associated factors in private clinics in Addis Ababa, Ethiopia. *Environmental Health Insights, 16*, 11786302211073383.
78. Windfeld, E. S., & Brooks, M. S. L. (2015). Medical waste management–A review. *Journal of Environmental Management, 163*, 98–108.
79. Xiao, F., Tang, M., Zheng, X., Liu, Y., Li, X., & Shan, H. (2020). Evidence for gastrointestinal infection of SARS-CoV-2. *Gastroenterology, 158*(6), 1831.
80. Yazie, T. D., Tebeje, M. G., & Chufa, K. A. (2019). Healthcare waste management current status and potential challenges in Ethiopia: A systematic review. *BMC Research Notes, 12*(1), 285.
81. Yoon, C. W., Kim, M. J., Park, Y. S., Jeon, T. W., & Lee, M. Y. (2022). A review of medical waste management systems in the Republic of Korea for hospital and medical waste generated from the COVID-19 pandemic. *Sustainability, 14*(6), 3678.