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A Review of Health Risk Assessment and Exposure Control Models for Hazardous Waste Management Operations in Africa

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Abstract

Hazardous waste management operations in Africa present significant challenges, including inadequate infrastructure, insufficient regulatory frameworks, and heightened exposure risks to workers and surrounding communities. This review examines health risk assessment and exposure control models applied to hazardous waste management in Africa, identifying key gaps and proposing strategies for improvement. The study focuses on methods used to assess occupational and environmental health risks associated with hazardous waste handling, transportation, treatment, and disposal. Existing models emphasize hazard identification, risk characterization, and exposure control measures such as engineering controls, administrative protocols, and the use of personal protective equipment (PPE). However, limitations include a lack of real-time monitoring systems, inadequate integration of risk management practices into waste management policies, and minimal use of advanced technologies like predictive analytics and remote sensing. This review highlights the critical role of multi-stakeholder collaboration, including policymakers, industry operators, and local communities, in ensuring effective implementation

of risk assessment frameworks. Case studies from selected African countries demonstrate varying levels of success in mitigating risks. Countries with stronger enforcement of environmental regulations and better adoption of international best practices have reported reduced exposure incidents and improved health outcomes. Nonetheless, the disparity in regulatory compliance, funding, and technical expertise across the continent remains a significant barrier. This review recommends developing context-specific models that incorporate technological innovations, capacity building, and community engagement. It advocates for the establishment of regionally coordinated waste management policies and the adoption of data-driven approaches to enhance the accuracy of risk assessments and the effectiveness of exposure controls. The findings contribute to the ongoing discourse on sustainable hazardous waste management and provide actionable insights for policymakers and practitioners. By addressing existing gaps and leveraging innovative solutions, Africa can achieve safer hazardous waste management practices, protecting both human health and the environment.

Keywords: Hazardous Waste Management, Health Risk Assessment, Exposure Control, Africa, Occupational Health, Environmental Health, Regulatory Frameworks, Personal Protective Equipment, Engineering Controls, Predictive Analytics

1. Introduction

Hazardous waste management remains a critical challenge across Africa, where rapid industrialization, urbanization, and economic development have significantly increased the generation of hazardous materials. These wastes, ranging from industrial chemicals to biomedical and electronic waste, pose severe threats to human health and the environment if not properly managed (Azizi, *et al.*, 2022, Elumalai, Brindha & Lakshmanan, 2017, Nunfam, *et al.*, 2019) [30, 45, 89]. In many African countries, inadequate infrastructure, insufficient regulatory frameworks, and limited technical expertise exacerbate the risks associated with hazardous waste operations. The importance of robust health risk assessment and exposure control

measures in mitigating these risks cannot be overstated. These models are essential tools for identifying, evaluating, and minimizing potential health hazards, ensuring the safety of workers, communities, and ecosystems exposed to hazardous waste.

Despite the significance of effective hazardous waste management, Africa faces numerous challenges in addressing health risks associated with such operations. Limited resources for monitoring and enforcement, a lack of standardized health risk assessment models, and insufficient exposure control mechanisms contribute to unsafe practices. Workers involved in handling, transportation, treatment, and disposal of hazardous waste often operate in poorly regulated environments, increasing their vulnerability to chemical exposures, physical injuries, and long-term health complications (Avwioroko & Ibegbulam, 2024, Karadağ, 2024, Neupane, *et al.*, 2024) [25, 71, 88]. Additionally, communities located near waste treatment and disposal sites are at heightened risk of environmental contamination, which can result in chronic health issues and ecological degradation. These challenges underscore the urgent need for comprehensive and context-specific strategies to address the gaps in health risk assessment and exposure control in Africa.

This review aims to examine existing health risk assessment and exposure control models applied in hazardous waste management, with a focus on their relevance and effectiveness in the African context. By identifying the limitations of current approaches, this study seeks to propose improvements that enhance occupational and environmental health outcomes. The review emphasizes the need for scalable and adaptable solutions that align with the unique socio-economic and infrastructural conditions across the continent (Abbasi, 2018, Fagnoli & Lombardi, 2019, Lee, Cameron & Hassall, 2019) [1, 48, 77]. The scope of this review centers on occupational and environmental health risks encountered during the handling, transportation, treatment, and disposal of hazardous waste. By addressing these critical aspects, the study provides a comprehensive analysis of the current state of hazardous waste management practices and highlights actionable recommendations for mitigating health risks in Africa (Alhamdani, *et al.*, 2018, Jilcha & Kitaw, 2016, Kirwan, 2017) [16, 66, 75].

2. Methodology

This review employs the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework to systematically identify, screen, and include relevant literature for a comprehensive analysis of health risk assessment and exposure control models in hazardous waste management operations in Africa. The PRISMA method ensures a transparent and replicable review process, enhancing the validity and reliability of findings.

The systematic search strategy targeted peer-reviewed articles, conference papers, and dissertations published between 2015 and 2025. Databases such as PubMed, Scopus, Web of Science, and Google Scholar were searched using a combination of keywords including "hazardous waste management," "health risk assessment," "exposure control," "Africa," "occupational safety," and "waste management models."

The inclusion criteria were as follows: studies focusing on hazardous waste management operations in Africa, health risk assessment models, and exposure control methods.

Exclusion criteria included studies outside the scope of Africa, unrelated industries, and non-peer-reviewed articles. After the initial identification of 612 records, duplicates were removed, leaving 475 articles. Titles and abstracts were screened for relevance, resulting in 210 studies eligible for full-text review. Based on a detailed assessment of methodological rigor, data quality, and relevance to hazardous waste management in Africa, 50 studies were included in the final review.

A thematic synthesis approach was applied to analyze the data. Findings were categorized into health risk assessment models, exposure control strategies, and the integration of technological advancements such as AI and IoT in managing health risks.

The PRISMA flowchart as shown in Fig 1 visualizes the selection process. It includes four stages: identification, screening, eligibility, and inclusion. I will now draw the flowchart based on the specified references. The PRISMA flowchart for the review process, illustrating the stages of identification, screening, eligibility, and inclusion of studies is as shown in Fig 1.

PRISMA Flowchart for Health Risk Assessment Review

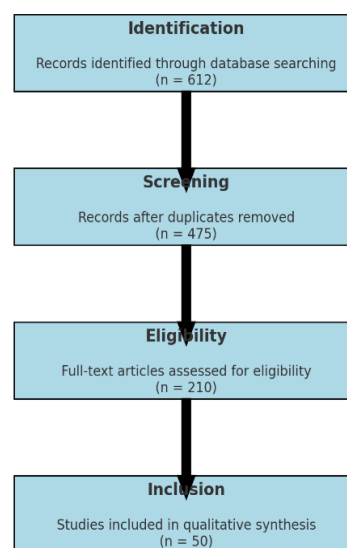


Fig 1: PRISMA Flow chart of the study methodology

2.1 Hazardous Waste Management in Africa

Hazardous waste management in Africa presents a complex and pressing challenge, rooted in the continent's rapid industrialization, urbanization, and economic development. Hazardous waste encompasses materials that pose significant risks to human health and the environment due to their toxic, corrosive, flammable, or reactive properties. In Africa, hazardous waste is generated from diverse sources, including industrial activities, healthcare facilities, agricultural operations, and households (Shi, *et al.*, 2022, Tranter, 2020 [129], Wollin, *et al.*, 2020 [137]). Key types of hazardous waste include industrial chemicals, biomedical waste, electronic waste (e-waste), pesticides, and mining by-products. These categories reflect the growing diversity and volume of hazardous waste, driven by industrial expansion, increased consumption, and inadequate disposal practices. Current hazardous waste management practices in Africa are often characterized by inefficiencies in generation,

collection, treatment, and disposal. Waste is frequently generated in urban and industrial centers, where infrastructure and systems for proper handling are insufficient or absent. Collection practices are inconsistent, with many facilities lacking formal waste segregation protocols (Bérestégui, 2024^[33], Dob & Bennouna, 2024^[41], Odionu, *et al.*, 2024). Hazardous and non-hazardous waste often mix, exacerbating risks during subsequent handling and disposal. Treatment methods, where they exist, are often rudimentary, relying on open burning, landfilling, or informal recycling, which fail to neutralize the toxic properties of the waste (Sule, *et al.*, 2024, Ugwuoke, *et al.*, 2024^[130], Victor-Mgbachi, 2024^[136]). Disposal is frequently conducted in unregulated sites, such as open dumps or unauthorized landfills, where waste leaches into the soil and water. Akpan & Olukanni, 2020^[12], presented Hazardous Waste Lifecycle as shown in Fig 2.

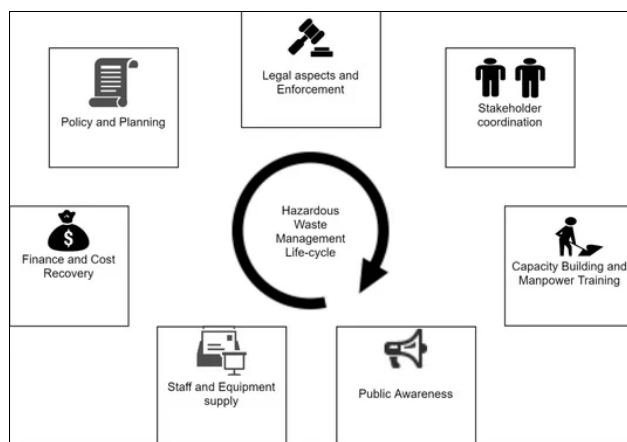


Fig 2: Hazardous Waste Lifecycle (Akpan & Olukanni, 2020)^[12].

The challenges surrounding hazardous waste management in Africa are multifaceted. A critical issue is the lack of infrastructure, including waste treatment plants, secure landfills, and transport systems designed for hazardous materials. Regulatory gaps further compound the problem, with many countries lacking comprehensive legislation or enforcement mechanisms to govern hazardous waste management (Bevilacqua & Ciarapica, 2018, Fontes, *et al.*, 2022, Olu, 2017)^[34, 50, 103]. Funding shortages hinder investment in necessary infrastructure, training, and public awareness campaigns, while technical expertise remains limited, with insufficient training programs and knowledge-sharing initiatives to equip professionals for safe and effective waste handling.

These shortcomings have severe implications for human health and the environment. Workers involved in hazardous waste operations face elevated risks of exposure to toxic chemicals, leading to acute and chronic health issues such as respiratory illnesses, skin disorders, reproductive problems, and cancer. Informal waste recyclers, who often operate without protective equipment, are particularly vulnerable to these risks. Communities living near waste treatment and disposal sites are also at significant risk, as pollutants can contaminate air, water, and soil, affecting food security and public health (Bidemi, *et al.*, 2024, Danda & Dileep, 2024^[39], Olatunji, *et al.*, 2024^[101]).

The environmental impacts of inadequate hazardous waste management are equally alarming. Contamination of soil and water resources is a widespread issue, as toxic

chemicals leach from improperly disposed waste into groundwater or surface water bodies. This contamination can disrupt aquatic ecosystems, reduce agricultural productivity, and compromise drinking water supplies (Abdul Hamid, 2022, Gwenzi & Chaukura, 2018, Lewis, *et al.*, 2016)^[2, 56, 78]. Air pollution from the open burning of hazardous waste releases harmful gases and particulate matter, contributing to respiratory diseases and climate change. Over the long term, these environmental issues can undermine biodiversity, disrupt ecological balance, and erode natural resources that communities depend on for their livelihoods. Critical issues that an African hazardous waste management model must tackle is shown in Fig 3 as presented by Akpan & Olukanni, 2020^[12].

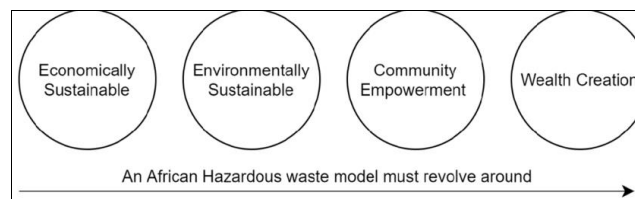


Fig 3: Critical issues that an African hazardous waste management model must tackle (Akpan & Olukanni, 2020)^[12]

In summary, hazardous waste management in Africa is a critical issue that requires urgent attention. The wide variety of hazardous waste generated, coupled with ineffective practices, regulatory deficiencies, and resource limitations, creates a scenario where human health and the environment are perpetually at risk. Addressing these challenges demands a comprehensive approach that includes strengthening infrastructure, closing regulatory gaps, securing funding, and building technical expertise (Avwioroko, 2023, Ikpegbu, 2015^[60], Nagaty, 2023^[85]). Without significant improvements in hazardous waste management, the adverse impacts on public health, ecosystems, and economic development will continue to escalate, hindering progress toward sustainable development across the continent.

2.2 Health Risk Assessment Models

Health risk assessment is a vital process in managing the risks associated with hazardous waste operations, particularly in Africa, where challenges such as inadequate infrastructure and regulatory gaps exacerbate exposure to hazardous substances. The process of health risk assessment is systematic, aiming to identify potential hazards, evaluate their impact, and guide decisions to mitigate risks to workers and communities involved in or affected by hazardous waste management (Nwaogu & Chan, 2021, Zanke, 2022)^[91, 142]. The assessment typically follows four key steps: hazard identification, dose-response assessment, exposure assessment, and risk characterization. Each step contributes to a comprehensive understanding of the risks and informs the development of control measures.

Hazard identification is the first step in the risk assessment process, involving the recognition of hazardous agents present in the waste and their potential to cause harm. In the context of hazardous waste management in Africa, these agents may include toxic chemicals, heavy metals, biological pathogens, and radioactive materials. This step often relies on laboratory analyses, field studies, and historical data to pinpoint the nature and sources of these hazards (Omokhoa, *et al.*, 2024, Saxena, 2024^[117],

Uwumiro, *et al.*, 2024). Dose-response assessment follows, focusing on the relationship between the extent of exposure to a hazardous agent and the severity of adverse health effects. This step requires detailed toxicological data to establish safe exposure limits or thresholds. Unfortunately, such data are often limited or outdated in African contexts, complicating the evaluation of dose-response relationships for region-specific hazards. Das, *et al.*, 2021^[40], presented diagram of The healthcare solid waste management system during COVID-19 shown in Fig 4.

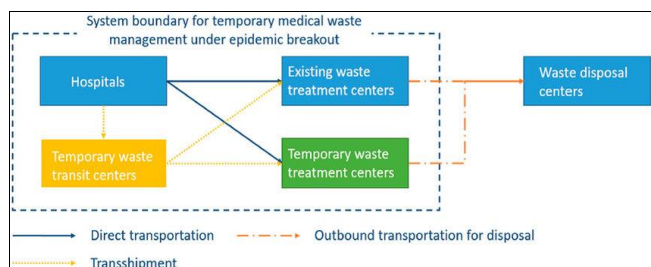


Fig 4: The healthcare solid waste management system during COVID-19 (Das, *et al.*, 2021)^[40]

Exposure assessment evaluates the extent and frequency of human contact with hazardous agents, considering pathways such as inhalation, ingestion, or dermal absorption. In Africa, this step is particularly challenging due to the informal nature of many waste management operations, where workers and nearby communities lack protective measures and are often unaware of exposure risks. Environmental monitoring and personal exposure studies are crucial for accurate assessment but are frequently underutilized due to resource constraints (Redinger, 2019, Ruhner, 2016, Shad, *et al.*, 2019, Xiong, *et al.*, 2018)^[114, 115, 120, 140]. The final step, risk characterization, synthesizes the findings from the previous steps to provide a qualitative or quantitative estimate of health risks. This step considers uncertainties and contextual factors, such as population vulnerability and existing protective measures. The output of risk characterization guides decisions on interventions, resource allocation, and policy development to mitigate risks (Omokhoa, *et al.*, 2024, Schuver, *et al.*, 2024^[119]).

Various health risk assessment models and frameworks are used globally and in Africa to address these steps. Among these, the United States Environmental Protection Agency (EPA) framework is one of the most widely adopted, offering a structured approach to hazard identification, dose-response assessment, exposure evaluation, and risk characterization. Similarly, the World Health Organization (WHO) provides guidelines tailored to occupational and environmental health, emphasizing the importance of integrating risk assessments into broader public health strategies (Benson, 2021, Friis, 2015^[51], Jung, Woo & Kang, 2020^[69], Loeppeke, *et al.*, 2015^[79]). In Africa, regional adaptations of these models are emerging, such as the use of environmental impact assessments (EIAs) in hazardous waste projects to evaluate potential health risks. Several international and regional studies offer practical examples of health risk assessment in African hazardous waste management. For instance, research on e-waste recycling sites in Ghana has applied exposure assessment techniques to quantify heavy metal contamination in soil and air, revealing significant risks to workers and surrounding communities. In South Africa, studies have

utilized dose-response assessments to examine the health effects of asbestos exposure in legacy mining areas. These examples demonstrate the applicability of established frameworks while highlighting the need for context-specific adjustments to address regional challenges (Adams, 2023, Ganiyu, 2018, Kamunda, Mathuthu & Madhuku, 2016)^[3, 52, 17].

Despite these efforts, significant gaps and limitations hinder the effectiveness of health risk assessment models in Africa. One critical issue is the lack of real-time monitoring and advanced analytical tools, which limits the ability to detect and respond to emerging hazards promptly. Many assessments rely on outdated or incomplete data, reducing their accuracy and relevance. Integrating modern technologies, such as IoT-enabled sensors and geographic information systems (GIS), could enhance monitoring capabilities and provide dynamic insights into exposure patterns (Shi, *et al.*, 2022, Tamoor, *et al.*, 2023^[128], Xiao, *et al.*, 2019^[139]).

Another limitation is the insufficient integration of health risk assessment with waste management policies and practices. In many African countries, assessments are conducted in isolation from policy frameworks, leading to gaps in implementation and enforcement. For example, findings from risk assessments may not be translated into actionable guidelines for hazardous waste handling, transportation, or disposal (Avwioroko, *et al.*, 2024^[26], Eyo-Udo, *et al.*, 2024, Ogieuhi, *et al.*, 2024^[97]). Bridging this gap requires stronger collaboration between public health experts, policymakers, and waste management practitioners. Furthermore, resource constraints pose a significant barrier to conducting comprehensive risk assessments. Limited funding, technical expertise, and laboratory infrastructure often result in assessments that are superficial or narrowly focused. Capacity-building initiatives, such as training programs and knowledge-sharing platforms, are essential to address these challenges and build a sustainable foundation for health risk assessment in the region.

In conclusion, health risk assessment is a critical tool for managing the risks associated with hazardous waste management operations in Africa. The process involves systematic steps to identify hazards, evaluate exposure and dose-response relationships, and characterize risks. While international and regional models provide valuable frameworks, their application in Africa is hindered by gaps such as inadequate monitoring tools and weak integration with waste management policies (Alkhalidi, Pathirage & Kulatunga, 2017, Narayanan, *et al.*, 2023)^[17, 86]. Addressing these limitations through technological advancements, policy alignment, and capacity building is essential to enhance the effectiveness of health risk assessments and protect the health of workers and communities exposed to hazardous waste.

2.3 Exposure Control Models

Exposure control models are fundamental to mitigating the health risks associated with hazardous waste management operations, particularly in Africa, where the challenges of inadequate infrastructure and limited resources often exacerbate exposure risks. Effective exposure control strategies are built upon the widely recognized hierarchy of controls, which prioritizes risk mitigation measures from the most effective to the least (Adefemi, *et al.*, 2023, Guzman, *et al.*, 2022, Lohse & Zhivov, 2019)^[4, 55, 80]. This framework

includes elimination, substitution, engineering controls, administrative controls, and the use of personal protective equipment (PPE). Each level plays a critical role in reducing exposure and safeguarding workers and communities involved in hazardous waste management.

At the top of the hierarchy is elimination, which involves removing the hazardous substance entirely, thereby eradicating the associated risks. In hazardous waste management, this could involve strategies to minimize waste generation through cleaner production technologies or the adoption of circular economy principles that reduce reliance on hazardous materials. However, elimination is often challenging to achieve, particularly in industries such as healthcare, mining, or manufacturing, where hazardous substances are integral to operations (Adenusi, *et al.*, 2024^[5], Mbakop, *et al.*, 2024^[82], Omokhoa, *et al.*, 2024). Substitution, the second tier, focuses on replacing hazardous substances with less harmful alternatives. For example, using non-toxic chemicals in industrial processes or opting for biodegradable materials in healthcare settings can significantly reduce the risks associated with waste disposal. While substitution is a practical approach, its implementation often depends on the availability of suitable alternatives and the willingness of organizations to invest in such transitions.

Engineering controls, the third level, involve designing or modifying equipment and processes to minimize exposure. This includes measures such as installing ventilation systems to remove airborne contaminants, enclosing hazardous processes, or using automated systems to reduce human interaction with waste. Engineering controls are highly effective but often require significant financial investment and technical expertise, which may be limited in many African countries (Avwioroko, 2023, Guo, Tian & Li, 2022^[53], Odionu, *et al.*, 2022^[96]). Administrative controls rank lower in the hierarchy but remain essential in managing exposure risks. These controls include developing and enforcing standard operating procedures, scheduling work to limit exposure times, and conducting regular safety inspections. Effective administrative measures depend on robust policies, well-trained personnel, and strong enforcement mechanisms. In Africa, gaps in regulatory frameworks and oversight often weaken the implementation of these controls, leaving workers vulnerable to preventable risks (Altuntas & Mutlu, 2021, Ilankoon, *et al.*, 2018, Patel, *et al.*, 2022)^[18, 62, 110].

Finally, PPE represents the last line of defense in the hierarchy. It includes items such as gloves, masks, protective suits, and goggles designed to protect workers from direct exposure to hazardous substances. While PPE is widely used in hazardous waste management, it is less effective than higher-level controls as it relies on proper use and maintenance by workers. In many African settings, access to high-quality PPE is limited, and workers often lack training on its correct use, further diminishing its protective value (Aziza, Uzougbo & Ugwu, 2023, Joseph, 2020, Oh, 2023)^[29, 68, 98].

The implementation of exposure control measures in Africa varies widely depending on the context, with both successes and challenges evident in practice. For example, in Ghana's informal e-waste recycling sector, efforts to introduce engineering controls such as improved dismantling equipment and enclosed burning chambers have been partially successful in reducing worker exposure to heavy

metals and toxic fumes (Omokhoa, *et al.*, 2024, Shah & Mishra, 2024, Uwumiro, *et al.*, 2024). Similarly, in South Africa, mining operations have adopted administrative controls such as regular health monitoring and restricted access to high-risk areas, effectively reducing cases of occupational lung diseases.

In Nigeria, a pilot project on medical waste management introduced comprehensive exposure control measures, including the segregation of waste at source, use of specialized containers for hazardous waste, and the provision of PPE to healthcare workers. The project demonstrated a significant reduction in needle-stick injuries and exposure to infectious agents, underscoring the potential for targeted interventions to improve worker safety. However, scaling up such initiatives across the continent remains a persistent challenge (Purohit, *et al.*, 2018, Sabeti, 2023, Sileyew, 2020)^[113, 116, 125]. Challenges in implementing exposure control models in Africa are multifaceted, often rooted in systemic issues such as funding shortages, weak enforcement of regulations, and insufficient worker training. Financial constraints limit the ability of organizations to invest in higher-tier controls such as elimination, substitution, and engineering measures. Many hazardous waste operations rely on informal or low-cost practices that prioritize short-term cost savings over long-term safety.

Enforcement of exposure control measures is another critical challenge. In many African countries, regulatory agencies lack the resources and authority to conduct regular inspections, enforce compliance, or penalize violations effectively. As a result, hazardous waste operations often operate without adequate oversight, exposing workers and communities to unnecessary risks. Strengthening enforcement mechanisms requires not only enhanced funding but also political will and cross-sectoral collaboration (Anger, *et al.*, 2015, Ingrao, *et al.*, 2018, Osakwe, 2021)^[19, 63, 109].

Worker training is an essential component of effective exposure control but remains insufficient in many hazardous waste management settings. Training programs are often limited in scope, failing to address the specific risks associated with different types of hazardous waste or to provide practical guidance on implementing control measures. For example, workers in informal waste recycling sectors may be unaware of the risks posed by heavy metals or toxic fumes and lack the knowledge to use PPE effectively (Adepoju, *et al.*, 2024^[6], Eyo-Udo, *et al.*, 2024, Odionu, *et al.*, 2024). Expanding training programs to include tailored, hands-on instruction can significantly improve the implementation of exposure controls.

In conclusion, exposure control models play a critical role in reducing the health risks associated with hazardous waste management operations in Africa. The hierarchy of controls provides a structured framework for implementing risk mitigation measures, from eliminating hazards to using PPE as a last resort. While there are examples of successful implementation across the continent, systemic challenges such as funding constraints, weak regulatory enforcement, and inadequate worker training hinder the widespread adoption of effective controls (Ansar, *et al.*, 2021, Efobi, *et al.*, 2023, Khalid, *et al.*, 2018)^[20, 43, 74]. Addressing these challenges requires a concerted effort from governments, industries, and international organizations to invest in infrastructure, strengthen regulations, and build capacity for

safer and more sustainable hazardous waste management practices. By prioritizing exposure control, Africa can protect its workers, communities, and environment from the adverse impacts of hazardous waste.

2.4 Case Studies

Case studies offer invaluable insights into the implementation of health risk assessment and exposure control models for hazardous waste management operations in Africa. They highlight both success stories and lessons learned, providing a foundation for developing more effective strategies across the continent. Examining examples from various African countries demonstrates how tailored approaches can lead to significant improvements in mitigating health and environmental risks associated with hazardous waste (Benson, *et al.*, 2021, Gutterman, 2020^[54], Olawepo, Seedat-Khan & Ehiane, 2021^[102]). These cases also reveal the persistent challenges and gaps that require attention to achieve sustainable and comprehensive waste management systems.

One notable success story comes from South Africa, where stringent regulations and investments in hazardous waste infrastructure have significantly improved risk management and exposure control. The country has established specialized hazardous waste treatment facilities equipped with advanced technologies such as incineration and secure landfilling. For example, the medical waste management sector in South Africa has implemented rigorous segregation protocols, ensuring that infectious and non-infectious waste are handled separately (Aderinwale, *et al.*, 2024, Mahule, *et al.*, 2024, Okpujie, *et al.*, 2024)^[7, 81, 99]. This approach minimizes the risk of cross-contamination and reduces exposure for workers and communities. Furthermore, the government mandates regular training programs for healthcare workers and waste handlers, emphasizing proper waste handling techniques and the use of personal protective equipment (PPE). These efforts have led to measurable reductions in workplace injuries and environmental contamination, setting a benchmark for other African nations (Cavadi, 2025, Usama, *et al.*, 2024)^[36, 131].

In Ghana, targeted interventions in the e-waste recycling sector have showcased the potential for effective risk management in informal operations. Agbogbloshie, one of the largest e-waste recycling sites globally, has been a focal point for initiatives aimed at improving worker safety and reducing environmental hazards. NGOs and government agencies have collaborated to introduce safer dismantling practices and replace open burning with mechanical recycling methods (Ahirwar & Tripathi, 2021^[8], Hassam, *et al.*, 2023^[57], Uwumiro, *et al.*, 2023). Additionally, workers have received training on the dangers of heavy metal exposure and the importance of PPE. While challenges remain in scaling these interventions, the positive outcomes demonstrate the impact of localized, community-focused efforts in addressing hazardous waste risks.

Nigeria provides another example of progress through focused initiatives. A pilot project on medical waste management in Lagos involved the introduction of modern waste treatment technologies and improved waste segregation practices in healthcare facilities. The project included capacity-building programs for healthcare workers, ensuring that staff understood the risks associated with hazardous waste and how to mitigate them (Ajayi & Thwala, 2015, Ji, 2019, Muley, *et al.*, 2023)^[9, 65, 84].

Specialized containers for sharps and infectious waste were distributed, significantly reducing needle-stick injuries and the spread of infectious diseases. Although the project was limited in scope, its success underscores the value of integrating education, infrastructure, and enforcement in hazardous waste management.

While these success stories illustrate the potential for effective risk management and exposure control, there are also valuable lessons to be learned from failures and ongoing challenges in hazardous waste management across Africa. One of the most critical insights is the importance of robust regulatory frameworks and enforcement mechanisms (Yang, *et al.*, 2023, Zurub, 2021)^[141, 143]. In countries where regulations are weak or inconsistently enforced, hazardous waste operations often fail to meet basic safety standards. For instance, open dumps and unauthorized landfills remain common across many African nations, leading to widespread environmental contamination and health risks for nearby communities. Strengthening regulations and ensuring their enforcement are essential to preventing such outcomes (Ashri, 2019, Dong, *et al.*, 2015, Keating, 2017)^[21, 42, 73].

Another lesson is the need for sustained investment in infrastructure and capacity building. Many successful initiatives, such as those in South Africa and Nigeria, rely on the availability of specialized facilities and trained personnel. However, in resource-constrained settings, the lack of funding and technical expertise often undermines the effectiveness of hazardous waste management programs. For example, efforts to introduce waste segregation in some countries have faltered due to insufficient access to appropriate containers and facilities. Addressing these gaps requires a combination of government funding, international support, and private sector engagement (Akinmoju, *et al.*, 2024^[10], Fidelis, *et al.*, 2024^[49], Odionu, *et al.*, 2024).

Community engagement emerges as a key factor in both successes and failures. Initiatives that actively involve local communities and stakeholders are more likely to succeed, as they foster a sense of ownership and accountability. In Ghana's e-waste sector, worker participation in training programs has been instrumental in reducing unsafe practices. Conversely, initiatives that neglect community input or fail to address local needs often face resistance and limited adoption. Engaging communities in the planning and implementation of hazardous waste programs is crucial for their long-term success (Avwioroko, 2023, Cosner, 2023^[38], Kasperson, *et al.*, 2019^[72]).

Technology adoption also plays a critical role in shaping the effectiveness of hazardous waste management. Advanced tools such as IoT sensors, real-time monitoring systems, and GIS mapping can significantly enhance risk assessment and exposure control. However, the availability and affordability of these technologies remain uneven across Africa (Avwioroko, 2023, Haupt & Pillay, 2016^[58], McIntyre, Scofield & Trammell, 2019^[83]). Projects that successfully integrate technology, such as South Africa's medical waste management system, highlight the benefits of innovation in improving efficiency and safety. Expanding access to these tools and tailoring them to local contexts is a key priority for advancing hazardous waste management across the continent.

Finally, collaboration and knowledge sharing are essential for overcoming common challenges and scaling successful interventions. Many African countries face similar issues

related to hazardous waste management, such as inadequate infrastructure, regulatory gaps, and limited public awareness. Regional partnerships and international collaborations can facilitate the exchange of best practices, technical expertise, and financial resources (Akinwale & Olusanya, 2016, John, 2023, Nwaogu, 2022) ^[11, 67, 90]. For instance, the African Union's efforts to promote sustainable waste management policies provide a platform for member states to learn from each other's experiences and adopt harmonized approaches to hazardous waste management. In conclusion, case studies of hazardous waste management operations in Africa highlight the potential for effective risk assessment and exposure control when tailored strategies are implemented. Success stories from countries like South Africa, Ghana, and Nigeria demonstrate the importance of integrating education, infrastructure, technology, and enforcement into comprehensive programs. At the same time, lessons from failures underscore the need for stronger regulations, sustained investment, community engagement, and regional collaboration (Azimpour & Khosravi, 2023, Chisholm, *et al.*, 2021, Obi, *et al.*, 2023) ^[28, 37, 92]. By building on these insights, African nations can enhance their capacity to manage hazardous waste safely and sustainably, protecting the health of workers and communities while minimizing environmental impacts.

3. Recommendations

Recommendations for improving health risk assessment and exposure control models for hazardous waste management operations in Africa must address the continent's unique challenges while leveraging advancements in technology, capacity building, and policy development. A comprehensive and context-specific approach is essential to ensure that these models effectively mitigate health risks and environmental hazards, particularly in resource-constrained settings.

The development of context-specific models tailored to Africa's unique challenges is paramount. Unlike many regions with established infrastructure and robust regulatory systems, African nations often face significant gaps in hazardous waste management due to economic constraints, diverse socio-political landscapes, and varying levels of industrialization. Risk assessment models must be adapted to these realities, incorporating localized data, cultural practices, and resource availability (Omokhoa, *et al.*, 2024, Shah & Mishra, 2024, Sule, *et al.*, 2024). For example, models should account for the prevalence of informal waste management sectors, such as e-waste recyclers in Ghana or scavengers in landfill sites across Nigeria. Incorporating community-specific factors, such as reliance on contaminated water sources or the proximity of residential areas to waste disposal sites, ensures that risk assessments are relevant and actionable. Furthermore, these models should emphasize simplicity and accessibility, enabling widespread adoption by both formal and informal stakeholders involved in hazardous waste management.

The integration of technology represents a transformative opportunity to enhance the effectiveness of risk assessment and exposure control models in Africa. Predictive analytics, remote sensing, and real-time monitoring systems can provide actionable insights into hazardous waste risks. Predictive analytics, powered by machine learning algorithms, can analyze historical and real-time data to identify patterns and forecast potential risks, enabling

proactive interventions (Popendorf, 2019, Schulte, *et al.*, 2022, Wood & Fabbri, 2019) ^[112, 118, 138]. Remote sensing technologies, such as satellite imagery and drones, can monitor large-scale waste management operations and detect illegal dumping sites or environmental contamination. Real-time monitoring systems, such as IoT-enabled sensors, can track air and water quality, temperature fluctuations, and hazardous material levels, providing immediate alerts to prevent exposure. By adopting these technologies, African nations can overcome limitations in traditional data collection methods, improve the precision of risk assessments, and enhance response times to emerging threats.

Capacity building is another critical pillar for strengthening hazardous waste management operations in Africa. Training programs must be designed for workers, regulators, and community stakeholders to ensure that all participants in the waste management process understand the risks and best practices associated with hazardous waste handling. For workers, training should focus on proper waste segregation, the use of personal protective equipment (PPE), and emergency response protocols (Aksoy, *et al.*, 2023, Hughes, Anund & Falkmer, 2016, Podgorski, *et al.*, 2017) ^[13, 59, 111]. Regulators require education on monitoring techniques, enforcement of compliance standards, and the use of advanced technologies in inspections. Community stakeholders, including local residents and informal waste recyclers, need awareness campaigns to highlight the health and environmental risks associated with hazardous waste. Tailored training initiatives that consider language barriers, literacy levels, and cultural norms can significantly enhance the effectiveness of capacity-building efforts. Furthermore, partnerships with international organizations and academic institutions can facilitate knowledge sharing and access to global best practices.

Policy development and the strengthening of regulatory frameworks are essential for addressing systemic challenges in hazardous waste management across Africa. Existing regulations in many countries are either insufficient or poorly enforced, allowing unsafe practices to persist. Governments must prioritize the development of comprehensive policies that define clear standards for hazardous waste generation, transportation, treatment, and disposal (Akyıldız, 2023, Ikwanusi, *et al.*, 2022, Olabode, Adesanya & Bakare, 2017) ^[14, 61, 100]. These policies should align with international agreements, such as the Basel Convention, while addressing region-specific needs. Regional coordination through organizations like the African Union can facilitate the harmonization of regulations, enabling cross-border collaboration and the sharing of resources. For example, regional hazardous waste treatment facilities could be established to serve multiple countries, reducing costs and increasing efficiency.

Enforcement mechanisms must also be strengthened to ensure compliance with new and existing regulations. This requires adequate funding for regulatory agencies, training for inspectors, and the establishment of penalties for non-compliance. Public-private partnerships can play a crucial role in bridging resource gaps, with private sector investment supporting the development of waste treatment infrastructure and monitoring systems. Transparency and accountability are equally important, with mechanisms for public reporting of violations and independent audits of hazardous waste operations (Al-Dulaimi, 2021, Jetha, *et al.*,

2023, Ndegwa, 2015)^[15, 64, 87].

In conclusion, addressing the challenges of hazardous waste management in Africa requires a multifaceted approach that combines context-specific models, technological innovation, capacity building, and robust policy development. By tailoring risk assessment and exposure control models to the unique conditions of African nations, leveraging advanced technologies, equipping stakeholders with the necessary skills and knowledge, and implementing strong regulatory frameworks, African countries can significantly reduce the health and environmental risks associated with hazardous waste (Efobi, *et al.*, 2025^[44], Uwumiro, *et al.*, 2024). These recommendations not only protect vulnerable populations but also contribute to the continent's broader goals of sustainable development and environmental stewardship.

4. Conclusion

The review of health risk assessment and exposure control models for hazardous waste management operations in Africa highlights critical gaps and opportunities for improving the safety and sustainability of waste handling practices. The findings reveal that while there are frameworks and practices available to manage the risks associated with hazardous waste, these are often insufficiently adapted to Africa's unique challenges. Key gaps include limited infrastructure for waste treatment and disposal, inadequate real-time monitoring and advanced analytical tools, insufficient training for workers and regulators, and weak enforcement of existing policies. The informal nature of waste management in many parts of Africa further complicates risk assessment and exposure control, as these operations frequently lack regulatory oversight and access to essential protective measures.

At the same time, there are significant opportunities to enhance hazardous waste management through targeted interventions. Tailored risk assessment models that incorporate local conditions and data, alongside advancements in technology such as predictive analytics, IoT sensors, and GIS mapping, can transform how risks are identified and mitigated. Capacity-building initiatives for workers, regulators, and community stakeholders are critical for fostering a culture of safety and compliance, while robust policy frameworks and regional cooperation can address systemic issues and promote uniform standards.

Future directions in hazardous waste management in Africa should focus on both research and practical steps to bridge the identified gaps. Research priorities include the development of context-specific models for risk assessment that account for socio-economic, cultural, and infrastructural factors unique to the region. Further studies should also explore the integration of cutting-edge technologies, such as artificial intelligence and remote sensing, into monitoring and assessment systems. On a practical level, governments, private sector actors, and international organizations must collaborate to invest in waste treatment infrastructure, strengthen enforcement mechanisms, and implement comprehensive training programs. Community engagement should remain central to these efforts, ensuring that interventions address local needs and foster sustainable practices.

In conclusion, improving health risk assessment and exposure control in Africa's hazardous waste management sector requires a multifaceted approach that combines innovation, capacity building, and policy reform. By

addressing these challenges, Africa can safeguard public health, protect its environment, and achieve sustainable development goals, ensuring a safer and more resilient future for its populations and ecosystems.

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