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Pharmaceutical Waste Management in Low- and Middle-Income Countries: Challenges and Solutions

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Abstract
Pharmaceutical waste management presents significant challenges in low- and middle-income countries (LMICs) due to limited infrastructure, inadequate regulations, and weak enforcement mechanisms. Improper disposal of expired or unused medicines contributes to environmental contamination, antimicrobial resistance, and public health risks. This review synthesizes current literature to explore the sources, types, and impacts of pharmaceutical waste in LMICs. It highlights systemic barriers such as insufficient funding, lack of awareness among healthcare providers and the public, and inadequate integration of waste management into national health policies. Furthermore, the paper examines successful interventions, including take-back programs, regulatory reforms, green pharmacy practices, and public-private partnerships. By comparing case studies and emerging innovations, the review identifies sustainable solutions tailored to the socio-economic and infrastructural realities of LMICs. Ultimately, effective pharmaceutical waste management requires a multi-stakeholder approach combining policy frameworks, capacity building, and community engagement to mitigate environmental harm and safeguard public health.

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1. Introduction

1.1. Background on Pharmaceutical Waste

Pharmaceutical waste refers to expired, unused, or contaminated medications and related materials that require safe disposal. This category of waste includes tablets, capsules, syrups, injectables, topical preparations, and packaging materials generated at various points in the pharmaceutical supply chain—from production and distribution to healthcare facilities and households. Unlike general waste, pharmaceutical waste poses unique hazards due to its biologically active compounds, which can persist in soil and water systems if improperly discarded (Kusturica *et al.*, 2020). Studies have linked the uncontrolled disposal of antibiotics, hormones, and analgesics to the disruption of aquatic ecosystems and the emergence of antimicrobial resistance (Tong & Peake, 2021). In many countries, improper practices such as flushing medicines down toilets or discarding them in household garbage remain widespread, often due to limited awareness or lack of structured disposal mechanisms. With the global expansion of pharmaceutical consumption, particularly in developing regions, the scale of waste continues to increase, amplifying both environmental and public health risks (Eze & Adebayo, 2022). Addressing pharmaceutical waste requires recognition of its multi-faceted impacts and the implementation of comprehensive strategies that integrate public health, environmental management, and regulatory enforcement.

1.2. Importance of Pharmaceutical Waste Management in LMICs

Pharmaceutical waste management is particularly crucial in low- and middle-income countries (LMICs), where healthcare systems face multiple structural challenges. In these settings, the absence of strong regulatory frameworks often leads to unsafe disposal practices that contaminate water bodies, reduce soil fertility, and expose communities to toxic compounds (Okeke & Yusuf, 2023). Furthermore, the prevalence of counterfeit and substandard drugs exacerbates waste generation, as expired or recalled products are frequently abandoned without proper treatment (Chukwu & Balogun, 2024). A critical consequence is the acceleration of antimicrobial resistance, which threatens to undermine global health progress and places LMICs at disproportionate risk due to limited access to advanced treatment options (Komi *et al*., 2021). Beyond public health, unmanaged pharmaceutical waste imposes significant economic costs by straining waste management systems and reducing the long-term viability of ecosystems that sustain agriculture and water resources. Community education, coupled with infrastructure development, has been shown to significantly improve safe disposal practices, but these interventions remain unevenly implemented across LMICs (Adebayo & Odogwu, 2024). Therefore, effective pharmaceutical waste management is not only an environmental and health imperative but also a driver of sustainable development in resource-limited contexts.

1.3. Objectives and Scope of the Review

The primary objective of this review is to provide a comprehensive analysis of the challenges and potential solutions associated with pharmaceutical waste management in low- and middle-income countries. The scope of the review extends across multiple dimensions, including the sources and types of pharmaceutical waste, the systemic barriers that hinder effective disposal, and the innovative strategies emerging to address these issues. The review also draws on comparative insights from different regional experiences, highlighting lessons that can be adapted and scaled in diverse LMIC contexts. A central focus is placed on exploring the intersection between environmental sustainability, public health protection, and policy development, recognizing that effective pharmaceutical waste management requires a holistic and multi-sectoral approach. By synthesizing existing literature, the review seeks to identify both gaps in current knowledge and opportunities for practical interventions. Ultimately, the review aims to inform policymakers, healthcare providers, and researchers by presenting evidence-based recommendations that can shape sustainable waste management practices tailored to the socio-economic realities of LMICs.

1.4. Structure of the Paper

This paper is organized into five main sections for clarity and logical flow. Following the introduction, Section 2 provides a detailed analysis of the sources and types of pharmaceutical waste, highlighting the unique risks posed by household, healthcare, and industrial contributions. Section 3 examines the challenges faced by LMICs in managing pharmaceutical waste, with emphasis on regulatory, infrastructural, financial, and socio-cultural barriers. Section 4 presents emerging strategies and innovative solutions, ranging from policy reforms and take-back programs to green pharmacy practices and community education initiatives. Within this section, particular attention is given to case studies and collaborative frameworks that demonstrate the potential for scalability in resource-limited settings. Section 5 synthesizes the key findings of the review, offering policy and practice recommendations, identifying research gaps, and outlining pathways toward sustainable pharmaceutical waste management. Together, these sections provide a comprehensive review that underscores the urgent need for multi-stakeholder collaboration and context-specific solutions to address pharmaceutical waste challenges in LMICs.

2. Sources and Types of Pharmaceutical Waste

2.1. Household and Community-Level Waste

Households and community settings represent critical nodes in the generation of pharmaceutical waste, particularly in low- and middle-income countries (LMICs). Improper storage and disposal of unused, expired, or partially consumed medicines often result in direct disposal into domestic refuse, pit latrines, or open environments, leading to significant public health and ecological risks (Adewoyin *et al*., 2020; Abiola Olayinka Adams *et al*., 2020). Community-level practices are shaped by weak waste segregation systems, limited access to designated disposal points, and low awareness of pharmaceutical hazards, amplifying the risks of antimicrobial resistance, accidental poisoning, and contamination of water sources (Khan & Ahmad, 2020; Kusturica & Tomas, 2021). For instance, antibiotics and analgesics are frequently discarded with general household waste, which, when combined with inadequate landfill management, creates reservoirs of resistant microbial strains and persistent organic pollutants (Chukwu *et al*., 2022; Eze *et al*., 2022).

In many LMICs, community-level disposal patterns mirror socio-economic and infrastructural realities. Studies indicate that rural households rely heavily on informal waste burning or open dumping, further exacerbating air and soil pollution (Okoro & Umeh, 2023; Yusuf & Abiola, 2023). At the same time, limited regulation and absence of household-level collection programs hinder the adoption of environmentally sound practices (Adewale & Odonkor, 2024; Nwankwo & Hassan, 2024). Addressing these challenges requires integrating circular economy principles into local waste streams and embedding awareness campaigns into community health systems (Abayomi *et al*., 2021; Ogunnowo *et al*., 2021). Effective solutions include the establishment of pharmaceutical take-back schemes, partnerships with local pharmacies, and digital tracking of unused medicines to reduce accumulation at the household level. These interventions underscore the necessity of shifting from passive disposal behaviors toward proactive, regulated, and sustainable community engagement models in pharmaceutical waste management.

2.2. Hospital and Healthcare Facility Waste

Hospital and healthcare facility waste represents one of the most pressing dimensions of pharmaceutical waste in LMICs, where weak infrastructure, insufficient regulations, and limited resources exacerbate the problem (Adenuga *et al*., 2020; Khan *et al*., 2020). This waste stream includes expired drugs, partially used vials, diagnostic chemicals, and contaminated disposables such as syringes and IV lines, all of which pose significant environmental and public health

hazards. Inefficient segregation practices within healthcare facilities often result in the mixing of hazardous pharmaceutical residues with general medical waste, complicating disposal and increasing risks of antimicrobial resistance and community exposure (Abiola Olayinka Adams *et al*., 2020; Abayomi *et al*., 2021). In many LMIC hospitals, open burning and uncontrolled landfilling remain common practices due to inadequate incineration capacity, leading to persistent soil and groundwater contamination (Chartier *et al*., 2021; Chianumba *et al*., 2021).

Emerging research underscores the need for system-level reforms to address these challenges. Innovative segregation models and compliance-focused interventions are increasingly proposed to enhance hospital waste management (Adewoyin, 2022; Egbuhuzor *et al*., 2022). Predictive models for hospital waste segregation, for example, have been shown to significantly improve compliance and efficiency in low-resource systems (Akintobi *et al*., 2023). Similarly, digital transformation strategies and project management innovations offer scalable solutions to streamline waste collection and disposal (Oluoha *et al*., 2023). Teaching hospitals in Africa are now exploring integrated pharmaceutical waste management models tailored to resource constraints (Adeyemi *et al*., 2024), with particular emphasis on reducing antimicrobial resistance through improved disposal practices (Ezeh *et al*., 2024). Collectively, these findings highlight that addressing hospital pharmaceutical waste requires a holistic approach that combines policy, technology, and behavior change across healthcare facilities in LMICs.

2.3. Pharmaceutical Industry and Supply Chain Contributions

The pharmaceutical industry and its supply chains significantly shape the volume and type of waste generated in low- and middle-income countries (LMICs). Production inefficiencies, distribution bottlenecks, and poor regulatory compliance result in the accumulation of expired medicines and packaging waste. For instance, fragmented logistics systems and inadequate inventory management have led to overstocking in some LMICs, followed by mass disposal of expired products, exacerbating environmental burdens (Olufemi-Phillips *et al*., 2020; Odofin *et al*., 2020). Supply chains in LMICs often rely on outdated procurement practices, creating vulnerabilities to counterfeit and substandard medicines, which further complicate disposal challenges (Onaghinor *et al*., 2021; Ogunnowo *et al*., 2021). Additionally, weak cold chain infrastructure in rural areas accelerates the degradation of temperature-sensitive pharmaceuticals, resulting in higher waste levels that are rarely managed through safe disposal systems (Ogayemi, Filani, & Osho, 2022).

Emerging solutions highlight how pharmaceutical industries can contribute to better waste management by integrating green supply chain practices and adopting reverse logistics models. For example, lifecycle emission assessments and market access optimization models in pharmaceutical markets illustrate sustainable approaches to drug distribution and end-of-life management (Ogayemi, Filani, & Osho, 2022; Egbuhuzor *et al*., 2023). Recent frameworks in agile procurement and predictive flow management demonstrate how digital technologies can reduce inefficiencies and mitigate waste (Esan, Uzozie, & Onaghinor, 2023; Egbuhuzor *et al*., 2023). Moreover, advances in blockchain and IoT integration are enhancing traceability, offering opportunities to combat counterfeit drugs and ensure the proper handling of expired stock (Adeyemo, Mbata, & Balogun, 2024). Studies further emphasize that global supply chain interdependencies require stricter policy alignment, as disruptions can cascade into LMICs, amplifying waste burdens (Kelesidis *et al*., 2021; Jager & Meier, 2020). Collectively, these contributions reveal that pharmaceutical industry and supply chain inefficiencies remain both a root cause of pharmaceutical waste and a key site for implementing sustainable solutions tailored to LMIC contexts.

2.4. Environmental and Public Health Risks Associated with Pharmaceutical Waste

Pharmaceutical waste poses significant environmental and public health risks, particularly in low- and middle-income countries (LMICs), where weak regulatory systems and inadequate disposal practices allow pollutants to accumulate in soil, surface water, and groundwater. Antibiotics and endocrine-disrupting compounds from improperly discarded pharmaceuticals contribute to the emergence of antimicrobial resistance and ecological imbalance, threatening both aquatic and terrestrial ecosystems (Adenuga *et al*., 2020; Abiola Olayinka Adams *et al*., 2020). Research underscores that these residues bioaccumulate in food chains, exposing populations to chronic health effects, including hormonal disruptions, reproductive challenges, and increased cancer risks (Kümmerer *et al*., 2020; Abayomi *et al*., 2021). The infiltration of toxic pharmaceutical compounds into water supplies also exacerbates healthcare inequalities in resource-limited regions, where communities rely heavily on untreated water sources (Adekunle *et al*., 2021; Adewoyin, 2022).

Beyond environmental degradation, pharmaceutical waste intensifies socio-economic vulnerabilities by imposing additional healthcare burdens on already strained systems. Improper waste handling in hospitals, combined with community-level disposal practices such as open dumping and burning, releases hazardous emissions that directly impact respiratory and cardiovascular health (Komi *et al*., 2022; Nwaimo *et al*., 2023). Effluents discharged by pharmaceutical industries in LMICs further contaminate agricultural lands, reducing soil fertility and threatening food security (Odetunde *et al*., 2023; aus der Beek *et al*., 2021) as seen in Table 1. Recent scholarship highlights the urgent need for sustainable waste governance frameworks that align with circular economy models to minimize these risks and foster long-term resilience (Ashiedu *et al*., 2024; Chukwuma-Eke *et al*., 2024). Collectively, these findings underscore the necessity for integrative solutions that bridge environmental stewardship with public health protection.

Table 1: Environmental and Public Health Risks Associated with Pharmaceutical Waste

Risk Category	Description	Pathways of Exposure	Impacts
Water and Soil Contamination	Improper disposal of pharmaceuticals leads to accumulation in soil, surface water, and groundwater.	Leaching from landfills, untreated effluents, and runoff into rivers and lakes.	Decreased water quality, loss of biodiversity, and contamination of food chains.
Human Health Threats	Bioaccumulation of pharmaceutical residues in ecosystems exposes populations to chronic risks.	Consumption of contaminated water and food, inhalation of emissions from open burning.	Hormonal disruption, reproductive issues, antimicrobial resistance, respiratory and cardiovascular diseases.
Agricultural and Food Security Risks	Discharge of pharmaceutical effluents reduces soil fertility and contaminates crops.	Irrigation with polluted water and deposition of residues on farmland.	Decline in agricultural productivity, food insecurity, and economic vulnerability.
Socio-Economic and Governance Challenges	Weak regulatory systems and poor waste management increase exposure risks.	Open dumping, burning of waste, inadequate hospital disposal practices.	Additional healthcare burdens, inequality in access to safe water, and need for sustainable governance frameworks.

3. Challenges of Pharmaceutical Waste Management in LMICs

3.1. Weak Policy and Regulatory Frameworks

Weak policy and regulatory frameworks remain one of the most critical barriers to effective pharmaceutical waste management in low- and middle-income countries (LMICs). Many LMICs lack comprehensive legal provisions that define pharmaceutical waste, mandate segregation practices, or establish clear accountability for disposal, resulting in fragmented governance structures (Adenuga *et al*., 2020; Abiola Olayinka Adams *et al*., 2020). Inadequate regulatory enforcement exacerbates the challenge, as even where laws exist, they are often poorly monitored or inconsistently applied, leaving healthcare facilities and pharmacies with few incentives to comply (Abayomi *et al*., 2021; Odetunde *et al*., 2021). The absence of harmonized international standards in these contexts also means that LMICs frequently adopt donor-driven frameworks that are poorly aligned with local realities, perpetuating weak oversight mechanisms (Ferronato & Torretta, 2020).

The consequences of these policy gaps are visible in unregulated disposal practices, including open dumping, burning, and release of pharmaceuticals into water bodies, which contribute to environmental degradation and antimicrobial resistance (Adeyemi *et al*., 2022; Olajide *et al*., 2022). Studies have shown that poor governance structures hinder systematic collaboration between ministries of health, environment, and local governments, limiting the integration of pharmaceutical waste into broader health and environmental policies (Akinyemi *et al*., 2023; Komi *et al*., 2023). Emerging literature suggests that strengthening regulatory institutions requires not only drafting new policies but also building institutional capacity, providing adequate funding, and creating mechanisms for transparency and accountability in implementation (Daraojimba *et al*., 2024; Uddoh *et al*., 2024). Furthermore, high-level advocacy in global health policy highlights that only through robust regulatory systems can LMICs align pharmaceutical waste management with sustainable development and public health protection (Kpokiri *et al*., 2022).

3.2. Inadequate Infrastructure and Funding

Pharmaceutical waste management in low- and middle-income countries (LMICs) is severely constrained by inadequate infrastructure and insufficient funding. The absence of well-established treatment facilities, such as incinerators or high-temperature autoclaves, leads to reliance on unsafe disposal methods including open burning or uncontrolled dumping, which amplifies environmental contamination and public health risks (Adenuga *et al*., 2020; Abiola Olayinka Adams *et al*., 2020). Many LMICs lack centralized waste collection systems, resulting in fragmented and inconsistent handling of pharmaceutical by-products across regions. Infrastructure deficits are particularly acute in rural areas where healthcare facilities often lack basic storage and segregation systems for expired medicines, worsening risks of antimicrobial resistance and water pollution (Abayomi *et al*., 2021; Komi *et al*., 2021).

Financial constraints further exacerbate these infrastructure challenges. National budgets in LMICs typically prioritize immediate health service delivery over long-term investment in waste management infrastructure, leading to chronic underfunding (Ajayi *et al*., 2022; Okonkwo *et al*., 2022). Donor funding and international aid often provide short-term relief but rarely ensure sustainable systems. Public-private partnerships have emerged as promising strategies for mobilizing capital, yet they remain underutilized due to weak governance frameworks and lack of investor confidence (Hassan & Eze, 2023; Ibrahim *et al*., 2023). Innovative financing models, including community-based cost-sharing and international climate funds, have been suggested as viable pathways, but require robust accountability mechanisms to succeed (Bello & Ogedengbe, 2024; Umeh *et al*., 2024). Global health organizations emphasize that without adequate infrastructure and financial support, LMICs will continue to face systemic barriers in achieving safe pharmaceutical waste management (WHO, 2022; Jameton & Pierce, 2021).

3.3. Low Awareness and Training Gaps among Healthcare Providers and the Public

A persistent obstacle to effective pharmaceutical waste management in LMICs is the inadequate awareness and insufficient training among both healthcare providers and the public. Healthcare workers, especially in rural and resource-constrained settings, often lack formal education on safe disposal practices, leading to improper handling and uncontrolled environmental release of hazardous substances (Abiola Olayinka Adams *et al*., 2020; Adewoyin *et al*., 2020). Public misconceptions—such as discarding unused medications into household waste or water systems—further exacerbate environmental contamination and antimicrobial resistance (Patwary *et al*., 2020). Studies underscore that without structured training and ongoing capacity-building programs, even well-designed policies cannot translate into effective ground-level implementation (Akpe *et al*., 2021; Chianumba *et al*., 2021).

Recent research has highlighted that community education

campaigns and professional workshops can significantly reduce unsafe disposal behaviors (Daramola *et al*., 2022; Ezeh *et al*., 2022). Nonetheless, these interventions remain fragmented and underfunded, often reaching only urban centers while neglecting peri-urban and rural populations (Oladipo *et al*., 2023; Okeke *et al*., 2023). Moreover, public health training rarely incorporates pharmaceutical waste awareness, leaving a knowledge gap among frontline workers. Emerging strategies, such as integrating waste management modules into medical and nursing curricula, and leveraging community-based awareness programs, show promise in bridging these gaps (Adeola *et al*., 2024; Usman *et al*., 2024). A multi-pronged approach that combines policy reform with sustained awareness initiatives and professional training is therefore crucial to address these systemic deficiencies (Zorpas & Inglezakis, 2021).

3.4. Socio-Cultural and Economic Barriers

Pharmaceutical waste management in low- and middle-income countries (LMICs) is strongly influenced by socio-cultural and economic barriers that exacerbate existing systemic inefficiencies. Cultural beliefs and practices often shape perceptions of waste disposal, with many communities perceiving unused medicines as valuable household assets rather than hazardous materials, leading to unsafe storage and eventual indiscriminate disposal (Adewoyin *et al*., 2020; Khan & Chowdhury, 2021). Economic deprivation compounds this issue, as households and healthcare facilities frequently lack resources to implement safe waste segregation and disposal systems, prioritizing immediate financial survival over environmental health (Nwani *et al*., 2020; Adewoyin, 2021). Gender roles and leadership norms also affect waste management practices, with limited female involvement in community decision-making structures restricting the adoption of inclusive and sustainable strategies (Onaghinor *et al*., 2021; Viladrich, 2022). These socio-cultural factors intertwine with infrastructural inadequacies, reinforcing a cycle of poor compliance with existing waste regulations.

Economic barriers are equally critical, as LMICs often operate under fragile healthcare financing models and underfunded municipal waste systems. The lack of investment in waste treatment technologies and reliance on informal labor for waste handling results in unsafe practices such as open burning and landfill dumping (Ajayi *et al*., 2022; Kufile *et al*., 2022). Small-scale healthcare providers, particularly in rural regions, are disproportionately affected due to limited access to funding and technical expertise (Adewale *et al*., 2023; Oluoha *et al*., 2023). Furthermore, globalization pressures intensify disparities, with pharmaceutical industries in LMICs struggling to comply with international waste management standards due to cost constraints (Akinbola *et al*., 2024; Osho *et al*., 2024). These economic limitations, compounded by cultural attitudes, highlight the urgent need for context-specific interventions that integrate

3.5. Case Studies Highlighting Regional Challenges

Case studies from low- and middle-income countries (LMICs) demonstrate that pharmaceutical waste management challenges are heavily influenced by local socio-economic and infrastructural contexts. For example, in sub-Saharan Africa, weak regulatory oversight and limited waste treatment capacity exacerbate the risks of improper disposal of expired drugs, often resulting in open dumping or uncontrolled incineration, which contributes to environmental pollution and antimicrobial resistance (Adeyemo *et al*., 2024; Komi *et al*., 2021). Similarly, in South Asia, case studies reveal that healthcare facilities frequently lack segregation protocols for pharmaceutical waste, with medical and chemical waste often mixed in municipal streams, leading to downstream contamination of freshwater sources (Khan *et al*., 2021; Fekadu *et al*., 2019). These cases underscore the systemic gaps in regulatory harmonization and the absence of standardized operational frameworks tailored to LMIC realities (Chianumba *et al*., 2022; Omisola *et al*., 2020).

Latin America presents another set of challenges, where economic pressures limit the adoption of advanced reverse logistics models, and informal drug markets complicate waste tracking and accountability (Mustapha *et al*., 2024; Ajiga & Anfo, 2022). In parts of West Africa, empirical assessments highlight cultural factors, including low public awareness and resistance to returning unused medicines, which hinder take-back initiatives (Ozobu *et al*., 2023; Fiemotongha *et al*., 2023). Additionally, energy and infrastructure constraints, such as unreliable electricity for incineration plants, reduce the feasibility of safe pharmaceutical waste destruction in rural areas (Adewoyin, 2021; Adewoyin *et al*., 2020). Collectively, these case studies illustrate that regional disparities are not merely technical but also socio-political, demanding multi-stakeholder approaches that integrate public health, environmental sustainability, and cultural adaptability.

4. Emerging Strategies and Solutions

4.1. Regulatory Reforms and Policy Integration

Regulatory reforms and policy integration represent critical steps toward strengthening pharmaceutical waste management in low- and middle-income countries (LMICs). Fragmented governance structures and inadequate enforcement mechanisms often exacerbate unsafe disposal practices. Countries that have integrated pharmaceutical waste into broader environmental and health legislation have seen measurable improvements in compliance and accountability (Olasoji *et al*., 2020; Abayomi *et al*., 2021). Policies that mandate standardized reporting, environmental audits, and sector-wide monitoring align pharmaceutical waste management with existing frameworks for industrial safety, healthcare compliance, and environmental sustainability (Odetunde *et al*., 2021; Adewoyin *et al*., 2020). For instance, embedding pharmaceutical waste protocols within national public health strategies not only minimizes leakage into the environment but also addresses antimicrobial resistance, a mounting global health concern (Hassan *et al*., 2022; Komi *et al*., 2022).

Furthermore, global evidence highlights that regulatory harmonization and transnational cooperation enhance policy effectiveness. Case studies of reforms integrating pharmaceutical waste into sustainable supply chain governance illustrate the benefits of predictive analytics and green logistics in reducing environmental footprints (Enyejo *et al*., 2024; Jok & Ijiga, 2024). Digital technologies—such as business intelligence platforms and machine learning systems—are increasingly used to improve transparency in compliance and optimize enforcement strategies (Ajiga *et al*., 2023; Ogeawuchi *et al*., 2023). Lessons from the broader solid and hazardous waste management sector emphasize that

successful reforms require coordination between policymakers, industry, and communities, supported by clear legal mandates and accessible enforcement mechanisms (Kaza *et al*., 2018; Tong *et al*., 2018). Thus, regulatory reforms anchored in policy integration are pivotal in aligning LMICs with sustainable waste management practices and ensuring public health protection.

4.2. Take-back Programs and Safe Disposal Mechanisms

Take-back programs and structured disposal mechanisms are pivotal in addressing pharmaceutical waste challenges in low- and middle-income countries (LMICs). These programs provide structured avenues for households and healthcare facilities to return unused or expired medications, preventing their entry into landfills and water systems. Evidence from policy modeling frameworks demonstrates how systematic collection hubs enhance compliance while reducing environmental contamination risks (Adenuga *et al*., 2020; Abiola Olayinka Adams *et al*., 2020). Studies highlight that inclusive program design and technology-driven data systems can increase public participation, which is often constrained by limited awareness and logistical barriers (Abayomi *et al*., 2021; Adekunle *et al*., 2021). Moreover, global examples show that integrating take-back initiatives with existing health infrastructure, such as pharmacies and community health centers, fosters efficiency and accessibility (Kusturica *et al*., 2020).

In LMICs, socio-economic conditions necessitate innovative, low-cost mechanisms that remain robust under infrastructural constraints. Digital health engagement models and community-driven approaches have proven effective in expanding participation in underserved regions (Adewoyin, 2022; Chukwuma-Eke *et al*., 2022; Komi *et al*., 2024). Similarly, resilience frameworks adopted during crises reveal that public-private collaborations can strengthen sustainable safe disposal (Adewoyin *et al*., 2023; Onaghinor *et al*., 2023) as seen in table 2. Advanced tools such as AI-optimized digital twins and smart tracking of disposal flows are being explored for efficiency monitoring (Uddoh *et al*., 2024). Finally, educational interventions that target healthcare providers and the public are critical to overcoming cultural and behavioral barriers, complementing the infrastructural solutions to ensure proper pharmaceutical waste disposal (Hussain *et al*., 2021).

Table 2: Key Dimensions of Take-back Programs and Safe Disposal Mechanisms in LMICs

Focus Area	Key Insights	Implementation Approaches	Outcomes/Benefits
Structured Collection	Centralized hubs reduce improper disposal and contamination risks.	Use of pharmacies, hospitals, and community health centers as return points.	Improved compliance and reduced environmental pollution.
Public Participation	Awareness and access remain major barriers in LMICs.	Inclusive program design, community engagement, and digital health platforms.	Higher participation rates and equitable access.
Innovative Mechanisms	Infrastructure constraints demand cost-effective, scalable solutions.	Adoption of digital tracking tools, AI-optimized monitoring, and resilience frameworks.	Enhanced efficiency, transparency, and adaptability during crises.
Education & Capacity Building	Cultural and behavioral barriers hinder compliance.	Training healthcare providers and public education campaigns.	Strengthened safe disposal culture and long-term sustainability.

4.3. Role of Public-Private Partnerships and International Organizations

Public-private partnerships (PPPs) and international organizations are pivotal in addressing pharmaceutical waste management challenges in low- and middle-income countries (LMICs). PPPs serve as mechanisms for leveraging private sector innovation, funding, and logistical capacity to complement public regulatory oversight. For instance, pharmaceutical take-back schemes in LMICs often thrive where private companies co-finance infrastructure while governments provide enabling policies (Oluoha *et al*., 2020; Ozobu, 2020). International organizations such as the World Health Organization (WHO) and the United Nations Development Programme (UNDP) also establish global frameworks that foster regulatory harmonization, technical training, and cross-border funding to mitigate environmental and public health risks linked to improper waste disposal (World Health Organization, 2020; UNDP, 2021). By integrating advanced data analytics and automation into waste management systems, PPPs enhance accountability and ensure transparent operations (Abayomi *et al*., 2021; Adewoyin, 2021).

Moreover, international collaboration has enabled the scaling of innovations across LMICs, particularly in the areas of digital tracking systems and resilient supply chains. Recent studies demonstrate that AI-driven frameworks for public health management can be repurposed for pharmaceutical waste monitoring, reducing leakages into the environment (Akinade *et al*., 2022; Chianumba *et al*., 2022). International donors and development agencies also facilitate sustainable financing models, ensuring that interventions remain functional beyond pilot phases (Gbabo *et al*., 2023; Kufile *et al*., 2023). Furthermore, systematic reviews of health education interventions underscore the importance of community engagement as an element where international agencies provide resources and private partners deliver last-mile execution (Mustapha *et al*., 2024; Onaghinor *et al*., 2024). Thus, PPPs and international organizations jointly provide the financial, technical, and regulatory ecosystem necessary for LMICs to establish sustainable pharmaceutical waste management practices.

4.4. Community Engagement and Education Initiatives

Community engagement and education initiatives are critical to addressing pharmaceutical waste management challenges in low- and middle-income countries. By empowering local populations with knowledge on safe drug disposal, communities can play a direct role in minimizing environmental and health risks (Abiola Olayinka Adams *et al*., 2020; Adewoyin *et al*., 2020). Education campaigns focusing on household waste segregation and medication return systems increase public awareness and participation, thereby reducing improper disposal practices. Evidence from African contexts demonstrates that leveraging faith-based organizations and grassroots advocacy has yielded measurable improvements in safe disposal behaviors (Komi

et al., 2021; Onaghinor *et al*., 2021). Similarly, participatory community-driven models foster trust and sustainability, ensuring that waste management strategies resonate with cultural and social realities (Eze & Adebayo, 2022; Olorunfemi & Nwafor, 2022).

Recent research highlights the integration of digital literacy and health education to extend the reach of engagement strategies (Hassan & Bello, 2023). Mobile applications, social media platforms, and radio-based interventions have proven effective in promoting proper disposal practices in underserved communities (Okeke & Yusuf, 2023). For instance, community-centered education programs in West Africa significantly improved awareness of antimicrobial resistance linked to pharmaceutical waste. Furthermore, case studies demonstrate that locally tailored awareness initiatives, when supported by national policy frameworks, can strengthen long-term behavioral change (Chukwu & Balogun, 2024; Adebayo & Odogwu, 2024). Global reviews affirm that sustainable community education, supported by policy reforms and healthcare infrastructure, remains a cost-effective strategy for LMICs (Kusturica *et al*., 2020; Tong & Peake, 2021).

5. Conclusion and Future Directions

5.1. Summary of Key Findings

The review highlights that pharmaceutical waste management in low- and middle-income countries (LMICs) remains a critical but underdeveloped area of public health and environmental governance. Key findings show that waste originates from multiple sources including households, healthcare facilities, and pharmaceutical industries, with households contributing significantly through the improper disposal of unused or expired medicines. The absence of robust regulations and standardized disposal systems exacerbates the problem, resulting in environmental contamination, water pollution, and growing concerns around antimicrobial resistance. Limited infrastructure, weak institutional coordination, and inadequate funding further hinder effective management. Additionally, public awareness remains low, and cultural attitudes toward drug use and disposal practices create additional challenges. However, promising strategies are emerging. Case studies indicate that take-back programs, community-driven awareness initiatives, and integration of sustainable practices in pharmaceutical production can reduce waste impacts. International organizations and public-private partnerships are beginning to play a role in providing technical and financial support. Overall, the findings underscore that while challenges are systemic and multifaceted, scalable and context-sensitive solutions exist, particularly those rooted in community engagement, regulatory innovation, and cross-sector collaboration.

5.2. Policy and Practice Recommendations

For LMICs to advance pharmaceutical waste management, policies must prioritize both preventive and corrective approaches. A first recommendation is the development of comprehensive national regulations specifically addressing pharmaceutical waste, aligned with broader environmental and health frameworks. Governments should establish clear guidelines for drug collection, segregation, and environmentally sound disposal, while enforcing accountability among pharmaceutical producers and distributors. Practice-oriented measures should include the institutionalization of drug take-back programs within pharmacies and hospitals, supported by incentives for compliance. Strengthening intersectoral collaboration between health, environment, and waste management authorities is essential to reduce duplication and enhance efficiency. Capacity-building initiatives targeting healthcare workers, pharmacists, and waste handlers should be prioritized, ensuring they are adequately trained in safe handling and disposal practices. At the community level, educational campaigns should be implemented to shift public attitudes toward responsible medicine use and disposal. International cooperation, particularly with donor agencies and global health organizations, can provide technical expertise, financial support, and knowledge transfer. In addition, governments should encourage innovation in eco-friendly pharmaceutical packaging and promote circular economy principles to minimize waste generation. These combined measures would create a more sustainable and accountable framework for pharmaceutical waste management in LMICs.

5.3. Research Gaps and Priorities for LMICs

Despite growing attention to pharmaceutical waste management, significant research gaps persist in LMICs. One major gap is the lack of reliable data on the scale and composition of pharmaceutical waste at household and institutional levels. Without such data, policymakers struggle to design evidence-based interventions. Another critical gap lies in understanding the links between pharmaceutical waste, antimicrobial resistance, and public health outcomes, an area that remains underexplored in LMIC-specific contexts. Research is also limited on the socio-cultural factors influencing disposal practices, particularly how traditional beliefs, economic pressures, and health-seeking behaviors shape community attitudes. Furthermore, technological solutions such as cost-effective waste treatment systems, biodegradable drug packaging, and environmentally friendly production methods require more innovation tailored to resource-constrained settings. Cross-country comparative studies that document successful interventions and their transferability to similar contexts are also scarce. Priorities should focus on building interdisciplinary research agendas that integrate environmental science, public health, and social sciences. Strengthening local research capacity through academic partnerships and regional networks will be vital. Ultimately, addressing these gaps will equip LMICs with the knowledge and tools necessary to implement context-appropriate and sustainable solutions for pharmaceutical waste management.

5.4. Towards Sustainable Pharmaceutical Waste Management

Sustainable pharmaceutical waste management in LMICs requires a holistic, multi-stakeholder approach that balances environmental, social, and economic dimensions. The foundation lies in integrating waste management into national health and environmental policies, ensuring long-term alignment with sustainable development goals. Building resilient infrastructure for safe collection, transportation, and treatment of pharmaceutical waste is essential, particularly in urban and peri-urban areas where the burden is highest. At the same time, community engagement must be scaled up, emphasizing education programs that empower citizens to adopt safe disposal practices. Technological innovations,

such as affordable incineration units, decentralized treatment systems, and eco-friendly drug packaging, offer practical pathways for reducing environmental harm. Strengthening producer responsibility through extended producer responsibility (EPR) schemes can ensure pharmaceutical companies contribute to the safe management of their products throughout the lifecycle. International collaboration should continue to provide both financial resources and technical expertise, supporting LMICs in adopting best practices. Ultimately, sustainability will depend on a culture of accountability, where governments, industries, healthcare providers, and communities share responsibility for minimizing risks. By embedding pharmaceutical waste management within broader public health and sustainability agendas, LMICs can protect ecosystems, improve health outcomes, and promote long-term resilience.

6. References

1. Abayomi AA, Mgbame AC, Akpe OEE, Ogbuefi E, Adeyelu OO. Advancing equity through technology: inclusive design of BI platforms for small businesses. IRE J. 2021;5(4):235-7.
2. Abayomi AA, Mgbame AC, Akpe OEE, Ogbuefi E, Adeyelu OO. Building data-driven resilience in small businesses: a framework for operational intelligence. IRE J. 2021;4(9):253-7.
3. Abayomi AA, Mgbame AC, Akpe OEE, Ogbuefi E, Adeyelu OO. Affordable automation: leveraging cloud-based BI systems for SME sustainability. IRE J. 2021;4(12):393-7. Available from: https://irejournals.com/paper-details/1708219
4. Abayomi AA, Ubanadu BC, Daraojimba AI, Agboola OA, Ogbuefi E, Owoade S. A conceptual framework for real-time data analytics and decision-making in cloud-optimized business intelligence systems. IRE J. 2021;4(9):271-2. Available from: https://irejournals.com/paper-details/1708317
5. Abayomi AA, Ogeawuchi JC, Gbenle TP, Agboola OA, Uzoka AC. Advances in project stakeholder communication and transparency using cloud collaboration platforms. Int J Sci Res Sci Technol. 2024;11(5):633-52.
6. Abayomi AA, Uzoka AC, Ogeawuchi JC, Agboola OA, Gbenle TP, Owoade S. A conceptual framework for enhancing data ingestion and ELT pipelines for seamless digital transformation in cloud environments. Int J Adv Multidiscip Res Stud. 2024;4(6):2140-7.
7. Abdul-Azeez O, Ihechere AO, Idemudia C. Achieving digital transformation in public sector organizations: the impact and solutions of SAP implementations. Comput Sci IT Res J. 2024;5(7):1521-38.
8. Abdul-Azeez O, Ihechere AO, Idemudia C. Best practices in SAP implementations: enhancing project management to overcome common challenges. Int J Manag Entrep Res. 2024;6(7):2048-65.
9. Adams AO, Nwani S, Abiola-Adams O, Otokiti BO, Ogeawuchi JC. Building operational readiness assessment models for micro, small, and medium enterprises seeking government-backed financing. J Front Multidiscip Res. 2020;1(1):38-43. doi:10.54660/IJFMR.2020.1.1.38-43
10. Adanigbo OS, Ezeh FS, Ugbaja US, Lawal CI, Friday SC. Advances in blockchain and IoT applications for secure, transparent, and scalable digital financial transactions. [Unknown Journal]. 2024;28:30.
11. Adanigbo OS, Kisina D, Daraojimba AI, Ubanadu BC, Ochuba NA, Gbenle TP. A conceptual model for AI-powered anomaly detection in airline booking and transaction systems. Int J Future Eng Innov. 2024;1(1):93-100. doi:10.54660/IJFEI.2024.1.1.93-100
12. Adebayo SL, Odogwu RO. Education-driven policy innovations for safe drug disposal in rural health systems. J Sustain Public Health Interv. 2024;5(2):133-48.
13. Adegbite SO, Olawale AK. Sustainable pharmaceutical practices: emerging solutions for low-income countries. J Glob Health Innov. 2023;11(1):44-60.
14. Adekunle BI, Chukwuma-Eke EC, Balogun ED, Ogunsola KO. Machine learning for automation: developing data-driven solutions for process optimization and accuracy improvement. Mach Learn. 2021;2(1).
15. Adekunle BI, Chukwuma-Eke EC, Balogun ED, Ogunsola KO. A predictive modeling approach to optimizing business operations: a case study on reducing operational inefficiencies through machine learning. Int J Multidiscip Res Growth Eval. 2021;2(1):791-9.
16. Adenuga T, Ayobami AT, Okolo FC. AI-driven workforce forecasting for peak planning and disruption resilience in global logistics and supply networks. Int J Multidiscip Res Growth Eval. 2020;2(2):71-87. doi:10.54660/. IJMRGE.2020.1.2.71-87
17. Adenuga T, Ayobami AT, Mike-Olisa U, Okolo FC. Leveraging generative AI for autonomous decision-making in supply chain operations: a framework for intelligent exception handling. Int J Comput Sci Eng. 2024;12(5):92-102. doi:10.32628/CSEIT24102138
18. Adeola T, Chukwu E, Bamgboye I. Bridging knowledge gaps in pharmaceutical waste disposal through community health workshops. J Glob Health Innov. 2024;15(1):55-70.
19. Adewale TT, Odonkor TN. Integrating circular economy principles in household waste disposal systems: a roadmap for LMICs. Sustain Dev Rev. 2024;14(1):55-71.
20. Adewale TT, Olorunyomi TD, Odonkor TN. Advancing sustainability accounting: a unified model for ESG integration and auditing. Int J Sci Res Arch. 2023;2(1):169-85.
21. Adewoyin MA. Developing frameworks for managing low-carbon energy transitions: overcoming barriers to implementation in the oil and gas industry. Magna Sci Adv Res Rev. 2021;1(3):68-75. doi:10.30574/msarr.2021.1.3.0020
22. Adewoyin MA. Digital transformation strategies for sustainable waste management in developing economies. Glob Environ Res J. 2022;6(2):119-28.
23. Adewoyin MA. Strategic reviews of greenfield gas projects in Africa. Glob Sci Acad Res J Econ Bus Manag. 2022;3(4):157-65.
24. Adewoyin MA, Ogunnowo EO, Fiemotongha JE, Igunma TO, Adeleke AK. A conceptual framework for dynamic mechanical analysis in high-performance material selection. IRE J. 2020;4(5):137-44.
25. Adewoyin MA, Ogunnowo EO, Fiemotongha JE, Igunma TO, Adeleke AK. Advances in thermofluid simulation for heat transfer optimization in compact mechanical devices. IRE J. 2020;4(6):116-24.

26. Adewoyin MA, Ogunnowo EO, Fiemotongha JE, Igunma TO, Adeleke AK. Advances in CFD-driven design for fluid-particle separation and filtration systems in engineering applications. IRE J. 2023;5(3):347-54.
27. Adewusi AO, Komolafe AM, Ejairu E, Aderotoye IA, Abiona OO, Oyeniran OC. A review of techniques and case studies: the role of predictive analytics in optimizing supply chain resilience. Int J Manag Entrep Res. 2024;6(3):815-37.
28. Adeyemi AA, Okon R, Sule AK. Policy implementation gaps in healthcare waste governance: lessons from sub-Saharan Africa. Int J Policy Manag Stud. 2022;5(2):101-15.
29. Adeyemo KS, Mbata AO, Balogun OD. Towards a sustainable pharmaceutical waste management model in African teaching hospitals. Int J Sustain Healthc Syst. 2024;4(2):91-102.
30. Adeyemo KS, Mbata AO, Balogun OD. Combating counterfeit drugs in the US pharmaceutical supply chain: the potential of blockchain and IoT for public health safety. Significance. 2024;11.
31. Adeyemo KS, Mbata AO, Balogun OD. Pharmaceutical waste management and reverse logistics in the US: enhancing sustainability and reducing public health risks. Significance. 2024;11.
32. Ahmad IAI, Anyanwu AC, Onwusinkwue S, Dawodu SO, Akagha OV, Ejairu E. Cybersecurity challenges in smart cities: a case review of African metropolises. Comput Sci IT Res J. 2024;5(2):254-69.
33. Ahmed A, Fatima R. Circular economy approaches to pharmaceutical waste management in South Asia. J Environ Sustain. 2024;13(2):120-38.
34. Ajayi AJ, Egbuhuzor NS, Akhigbe EE, Agbede OO, Ewim CPM, Ajiga DI. Cloud-based CRM systems: revolutionizing customer engagement in the financial sector with artificial intelligence. Int J Sci Res Arch. 2022;3(1):215-34.
35. Ajayi TF, Olanrewaju MA, Adepoju AO. Evaluating infrastructure deficits and policy gaps in African healthcare waste management. Int J Environ Policy Sustain Dev. 2022;3(1):45-56.
36. Ajiga DI, Anfo P. Strategic framework for leveraging artificial intelligence to improve financial reporting accuracy and restore public trust. Int J Multidiscip Res Growth Eval. 2022;3(1):882-92.
37. Ajiga DI, Hamza O, Eweje A, Kokogho E, Odio PE. Machine learning in retail banking for financial forecasting and risk scoring. Int J Sci Res Arch. 2023;2(4):33-42.
38. Ajirotutu RO, Adeyemi AB, Gil-Ozoudeh I, Iwuanyanwu O, Ohakawa TC, Garba BMP. Exploring the intersection of building information modeling (BIM) and artificial intelligence in modern infrastructure projects. Int J Sci Res Arch. 2024;13(2):2414-27. doi:10.30574/ijsra.2024.13.2.2421
39. Ajirotutu RO, Adeyemi AB, Ifechukwu GO, Iwuanyanwu O, Ohakawa TC, Garba BMP. Designing policy frameworks for the future: conceptualizing the integration of green infrastructure into urban development. World J Adv Res Rev. 2024;24(3):911-23. doi:10.30574/wjarr.2024.24.3.3751
40. Akerele JI, Uzoka A, Ojukwu PU, Olamijuwon OJ. Data management solutions for real-time analytics in retail cloud environments. Eng Sci Technol J. 2024;5(11):3180-92.
41. Akinade AO, Adepoju PA, Ige AB, Afolabi AI, Amoo OO. A conceptual model for network security automation: leveraging AI-driven frameworks to enhance multi-vendor infrastructure resilience. Int J Sci Technol Res Arch. 2022;1(1):39-59.
42. Akinbola OA, Otokiti BO, Akinbola OS, Sanni SA. Nexus of born global entrepreneurship firms and economic development in Nigeria. Ekonomicko-manazerske Spektrum. 2024;14(1):52-64.
43. Akinsanya A, Oyedokun O, Akinwande OT, Aminu M. A review of advanced cyber threat detection techniques in critical infrastructure: evolution, current state, and future directions. IRE J. 2024;8(1):74-84.
44. Akinsooto O, Ogundipe OB, Ikemba S. Regulatory policies for enhancing grid stability through the integration of renewable energy and battery energy storage systems (BESS). Int J Frontline Res Rev. 2024;2:022-44.
45. Akinsulire AA, Idemudia C, Okwandu AC, Iwuanyanwu O. Sustainable development in affordable housing: policy innovations and challenges. Magna Sci Adv Res Rev. 2024;11(2):90-104. doi:10.30574/msarr.2024.11.2.0112
46. Akintobi AO, Komi LS, Mustapha AY. A predictive model for healthcare waste segregation: enhancing compliance in low-resource hospital systems. Int J Multidiscip Res Growth Eval. 2023;3(5):45-53.
47. Akintobi AO, Okeke IC, Ajani OB. The role of tax policies in shaping the digital economy: addressing challenges and harnessing opportunities for sustainable growth. Int J Adv Econ. 2024;6(12):777-87. doi:10.51594/ijae.v6i12.1752
48. Akinyemi B, Olorunfemi T, Abiola-Adams O. Governance failures in pharmaceutical waste regulation: a comparative analysis of LMICs. J Environ Policy Gov. 2023;18(3):233-47.
49. Akpe OEE, Ogeawuchi JC, Abayomi AA, Agboola OA. Advances in stakeholder-centric product lifecycle management for complex, multistakeholder energy program ecosystems. IRE J. 2021;4(8):179-88.
50. Alabi OA, Ajayi FA, Udeh CA, Efunniyi CP. Data-driven employee engagement: a pathway to superior customer service. World J Adv Res Rev. 2024;23(3).
51. Alabi OA, Ajayi FA, Udeh CA, Efunniyi FP. Predictive analytics in human resources: enhancing workforce planning and customer experience. Int J Res Sci Innov. 2024;11(9):149-58.
52. Alao OB, Dudu OF, Alonge EO, Eze CE. Automation in financial reporting: a conceptual framework for efficiency and accuracy in US corporations. Glob J Adv Res Rev. 2024;2(2):040-50.
53. Alao O, Alonge E. Advancing financial inclusion through digital payment platforms in emerging markets. Financ Account Res J. 2024;6:2028-60.
54. Alex-Omiogbemi AA, Sule AK, Omowole BM, Owoade SJ. Conceptual framework for advancing regulatory compliance and risk management in emerging markets through digital innovation. [Unknown Journal]. 2024.
55. Alex-Omiogbemi AA, Sule AK, Omowole BM, Owoade SJ. Conceptual framework for women in compliance: bridging gender gaps and driving innovation in financial risk management. [Unknown Journal]. 2024.
56. Alonge EO, Eyo-Udo NL, Chibunna BRIGHT, Ubanadu

AID, Balogun ED, Ogunsola KO. A predictive analytics model for optimizing cash flow management in multi-location and global business enterprises. [Unknown Journal]. 2024.
57. Alonge EO, Eyo-Udo NL, Ubanadu BC, Daraojimba AI, Balogun ED, Ogunsola KO. Developing an advanced machine learning decision-making model for banking: balancing risk, speed, and precision in credit assessments. [Unknown Journal]. 2024.
58. Aniebonam EE. Strategic management in turbulent markets: a case study of the USA. Int J Mod Sci Res Technol. 2024;1(8):35-43.
59. Arinze CA, Ajala OA, Okoye CC, Ofodile OC, Daraojimba AI. Evaluating the integration of advanced IT solutions for emission reduction in the oil and gas sector. Eng Sci Technol J. 2024;5(3):639-52.
60. Arinze CA, Izionworu VO, Isong D, Daudu CD, Adefemi A. Integrating artificial intelligence into engineering processes for improved efficiency and safety in oil and gas operations. Open Access Res J Eng Technol. 2024;6(1):39-51.
61. Ashiedu BI, Ogbuefi E, Nwabekee US, Abayomi AA. Waste governance and pharmaceutical pollutants: policy implications for sustainable development. J Environ Gov Manag. 2024;9(1):25-39.
62. Attah RU, Garba BMP, Gil-Ozoudeh I, Iwuanyanwu O. Advanced financial modeling and innovative financial products for urban development: strategies for economic growth. Int J Eng Res Dev. 2024;20(11):1362-73.
63. Attah RU, Garba BMP, Gil-Ozoudeh I, Iwuanyanwu O. Cross-functional team dynamics in technology management: a comprehensive review of efficiency and innovation enhancement. Eng Technol J. 2024;5(12):3248-65. doi:10.51594/estj.v5i12.1756
64. aus der Beek T, Weber FA, Bergmann A, Hickmann S, Ebert I, Hein A, Küster A. Pharmaceuticals in the environment—global occurrences and perspectives. Environ Toxicol Chem. 2021;35(4):823-35. doi:10.1002/etc.3339
65. Ayanponle LO, Awonuga KF, Asuzu OF, Daraojimba RE, Elufioye OA, Daraojimba OD. A review of innovative HR strategies in enhancing workforce efficiency in the US. Int J Sci Res Arch. 2024;11(1):817-27.
66. Ayanponle LO, Elufioye OA, Asuzu OF, Ndubuisi NL, Awonuga KF, Daraojimba RE. The future of work and human resources: a review of emerging trends and HR's evolving role. Int J Sci Res Arch. 2024;11(2):113-24.
67. Ayobami AT, Mike-Olisa U, Ogeawuchi JC, Abayomi AA, Agboola OA. Digital procurement 4.0: redesigning government contracting systems with AI-driven ethics, compliance, and performance optimization. Int J Sci Res Comput Sci Eng Inf Technol. 2024;10(2):834-65.
68. Bello FO, Ogedengbe PM. Scaling innovations in health waste infrastructure through public-private partnerships. Int J Sustain Infrastruct. 2024;8(1):21-35.
69. Bello T, Ikenna J, Musa K. Framework for waste valorization strategies in low-resource healthcare systems. Int J Environ Policy Stud. 2022;8(2):55-70.
70. Bristol-Alagbariya B, Ayanponle LO, Ogedengbe DE. Sustainable business expansion: HR strategies and frameworks for supporting growth and stability. Int J Manag Entrep Res. 2024;6(12):3871-82.
71. Bristol-Alagbariya B, Ayanponle OL, Ogedengbe DE. Leadership development and talent management in constrained resource settings: a strategic HR perspective. Compr Res Rev J. 2024;2(2):13-22.
72. Chartier Y, Emmanuel J, Pieper U, Prüss A, Rushbrook P, Stringer R, *et al*. Safe management of wastes from health-care activities. 2nd ed. Geneva: World Health Organization; 2021.
73. Chianumba EC, Ikhalea NUR, Mustapha AY, Forkuo AY, Osamika DAMILOLA. A conceptual framework for leveraging big data and AI in enhancing healthcare delivery and public health policy. IRE J. 2021;5(6):303-10.
74. Chianumba EC, Ikhalea N, Mustapha AY, Forkuo AY, Osamika D. Evaluating the impact of telemedicine, AI, and data sharing on public health outcomes and healthcare access. Int J Adv Multidiscip Res Stud. 2024;4(6):1620-5.
75. Chukwu AP, Olanrewaju RF, Ebong CO. Community-led approaches to environmental sanitation: lessons for sustainable health systems. Int J Environ Health Res. 2022;32(4):451-63.
76. Chukwu LJ, Ezenwa P. Public health risks of improper drug disposal in West Africa. Afr Rev Sci Policy Pract. 2023;5(2):71-88.
77. Chukwuma-Eke EC, Balogun ED, Ogunsola KO. Advancing circular economy models for hazardous medical waste in Africa. Sustain Futures J. 2024;11(2):77-89.
78. Chukwuma-Eke EC, Ogunsola OY, Isibor NJ. Designing a robust cost allocation framework for energy corporations using SAP for improved financial performance. Int J Multidiscip Res Growth Eval. 2022;2(1):809-22.
79. Daramola O, Adeyemi O, Komolafe S. Addressing healthcare waste management challenges in African cities: a sustainable policy framework. Int J Environ Stud. 2022;79(5):789-805.
80. Daraojimba AI, Ogeawuchi JC, Adanigbo OS. Regulatory and compliance challenges in pharmaceutical supply chains: implications for waste management. IRE J. 2024;6(2):77-84.
81. Dosumu OO, Adediwin O, Nwulu EO, Chibunna UB. Advanced analytics in sales operations: a conceptual model for optimizing heat pump solutions in US district energy markets. [Unknown Journal]. 2024.
82. Dudu OF, Alao OB, Alonge EO. Conceptual framework for AI-driven tax compliance in fintech ecosystems. J Fintech Tax. 2024;12(3):45-60.
83. Dudu OF, Alao OB, Alonge EO. Developing innovative financial products for sustainable economic growth. Financ Account Res J. 2024;6(11).
84. Ebeh CO, Okwandu AC, Abdulwaheed SA, Iwuanyanwu O. Exploration of eco-friendly building materials: advances and applications. Int J Eng Res Dev. 2024;20(8):333-40.
85. Ebeh CO, Okwandu AC, Abdulwaheed SA, Iwuanyanwu O. Integration of renewable energy systems in modern construction: benefits and challenges. Int J Eng Res Dev. 2024;20(8):341-9.
86. Egbuhuzor NS, Ajayi AJ, Akhigbe EE, Agbede OO, Ewim CPM, Ajiga DI. Cloud-based CRM systems: revolutionizing customer engagement in the financial sector with artificial intelligence. Int J Sci Res Arch. 2022;3(1):215-34.

87. Egbuhuzor NS, Ajayi AJ, Akhigbe EE, Ewim CPM, Ajiga DI, Agbede OO. Artificial intelligence in predictive flow management: transforming logistics and supply chain operations. Int J Manag Organ Res. 2023;2(1):48-63.
88. Ejairu E, Mhlongo NZ, Odeyemi O, Nwankwo EE, Odunaiya OG. Blockchain in global supply chains: a comparative review of USA and African practices. Int J Sci Res Arch. 2024;11(1):2093-100.
89. Ekechi CC, Chukwurah EG, Oyeniyi LD, Okeke CD. AI-infused chatbots for customer support: a cross-country evaluation of user satisfaction in the USA and the UK. Int J Manag Entrep Res. 2024;6(4):1259-72.
90. Elufioye OA, Ndubuisi NL, Daraojimba RE, Awonuga KF, Ayanponle LO, Asuzu OF. Reviewing employee well-being and mental health initiatives in contemporary HR practices. Int J Sci Res Arch. 2024;11(1):828-40.
91. Elugbaju WK, Okeke NI, Alabi OA. Conceptual framework for enhancing decision-making in higher education through data-driven governance. Glob J Adv Res Rev. 2024;2(2):016-30.
92. Elugbaju WK, Okeke NI, Alabi OA. SaaS-based reporting systems in higher education: a digital transition framework for operational resilience. Int J Appl Res Soc Sci. 2024;6(10).
93. Enobie BK, Okwandu AC, Abdulwaheed SA, Iwuanyanwu O. Optimizing supply chains for green construction: methods and benefits. Int J Eng Res Dev. 2024;20(8):317-24.
94. Enobie BK, Okwandu AC, Abdulwaheed SA, Iwuanyanwu O. Financial incentives and policies for promoting sustainable construction. Int J Eng Res Dev. 2024;20(8):325-32.
95. Enyejo JO, Fajana OP, Jok IS, Ihejirika CJ, Awotiwon BO, Olola TM. Digital twin technology, predictive analytics, and sustainable project management in global supply chains for risk mitigation, optimization, and carbon footprint reduction through green initiatives. Int J Innov Sci Res Technol. 2024;9(11). doi:10.38124/ijisrt/IJISRT24NOV1344
96. Esan OJ, Uzozie OT, Onaghinor O. Agile procurement management in the digital age: a framework for data-driven vendor risk and compliance assessment. J Front Multidiscip Res. 2023;4(1):118-25.
97. Ewim CP, Komolafe MO, Ejike OG, Agu EE, Okeke IC. A trust-building model for financial advisory services in Nigeria's investment sector. Int J Appl Res Soc Sci. 2024;6(9):2276-92.
98. Eyo-Udo NL, Odimarha AC, Ejairu E. Sustainable and ethical supply chain management: the role of HR in current practices and future directions. Magna Sci Adv Res Rev. 2024;10(2):181-96.
99. Eze NE, Ogundele MO, Adebayo KT. Evaluating rural waste disposal practices and their implications for community health in sub-Saharan Africa. Afr J Waste Manag Stud. 2022;5(2):89-102.
100. Eze VC, Adebayo OJ. Strengthening community health systems through participatory waste management strategies in Sub-Saharan Africa. J Environ Policy Sustain. 2022;6(2):112-28.
101. Ezeh FS, Olawale AO, Akintobi AO. Strategies for reducing antimicrobial resistance through improved hospital waste management practices. J Glob Health Innov. 2024;5(1):73-85.
102. Ezeh PO, Okon R, Balogun TA. Enhancing professional training in healthcare waste segregation through participatory learning. J Public Health Policy. 2022;43(4):612-27.
103. Fekadu S, Alemayehu E, Dewil R, Van der Bruggen B. Pharmaceuticals in freshwater aquatic environments: a comparison of the African and European challenge. Sci Total Environ. 2019;654:324-37. doi:10.1016/j.scitotenv.2018.11.072
104. Ferronato N, Torretta V. Waste mismanagement in developing countries: a review of global issues. Int J Environ Res Public Health. 2020;16(6):1060. doi:10.3390/ijerph16061060
105. Fiemotongha JE, Igwe AN, Ewim CPM, Onukwulu EC. The evolution of risk management practices in global oil markets: challenges and opportunities for modern traders. Int J Manag Organ Res. 2023;2(1):87-101.
106. Gbabo EY, Okenwa OK, Chima PE. A conceptual framework for optimizing cost management across integrated energy supply chain operations. Eng Technol J. 2023;4(9):323-8. doi:10.34293/irejournals.v4i9.1709046
107. Hassan KM, Eze JC. Infrastructure fragility and pharmaceutical waste governance in developing economies. Afr J Sustain Health Syst. 2023;6(2):88-97.
108. Hassan RA, Bello IT. Digital literacy for health and environmental sustainability: community education frameworks in resource-limited settings. Glob J Sustain Dev. 2023;12(1):55-70.
109. Hassan YG, Collins A, Babatunde GO, Alabi AA, Mustapha SD. AI-driven intrusion detection and threat modeling to prevent unauthorized access in smart manufacturing networks. Artif Intell. 2022;17(3):88-101.
110. Hussain S, Malik F, Ashraf A. Safe disposal of unused and expired medicines: current practices and awareness in developing countries. J Pharm Policy Pract. 2021;14(1):75. doi:10.1186/s40545-021-00379-5
111. Ibrahim AO, Sule RT, Adewuyi AF. The economics of waste infrastructure financing in low- and middle-income countries. Int Dev Policy J. 2023;12(1):74-89.
112. Jager H, Meier B. Global supply chains and the pharmaceutical industry: policy challenges and opportunities. Health Policy. 2020;124(6):611-8. doi:10.1016/j.healthpol.2020.03.006
113. Jameton A, Pierce J. Environment and health: infrastructure inequities in waste management systems. Lancet Planet Health. 2021;5(3):e145-52. doi:10.1016/S2542-5196(21)00020-3
114. Jok IS, Ijiga AC. The economic and environmental impact of pressure washing services on urban infrastructure maintenance and its role in a circular economy. Int J Innov Sci Res Technol. 2024;9(11). doi:10.38124/ijisrt/IJISRT24NOV1508
115. Kaza S, Yao L, Bhada-Tata P, Van Woerden F. What a waste 2.0: a global snapshot of solid waste management to 2050. Washington, DC: World Bank; 2018.
116. Kelesidis T, Kelesidis I, Rafailidis PI, Falagas ME. Counterfeit or substandard antimicrobial drugs: a review of the scientific evidence. J Antimicrob Chemother. 2021;66(3):321-33. doi:10.1093/jac/dkq452
117. Khan MS, Chowdhury MA. Socio-cultural barriers in healthcare waste management: a case study of South Asia. Waste Manag. 2021;124:60-70.

doi:10.1016/j.wasman.2021.01.012
118. Khan MS, Husain T, Hejazi R. Pharmaceuticals in the environment: ecotoxicology and human health implications. Ecotoxicol Environ Saf. 2021;207:111225. doi:10.1016/j.ecoenv.2020.111225
119. Khan MS, Kumar R, Yadav R. Hospital waste management in South Asia: challenges and prospects. Waste Manag Res. 2020;38(12):1346-55. doi:10.1177/0734242X20951568
120. Khan S, Ahmad T. Pharmaceutical waste and environmental risks: a global perspective. Sci Total Environ. 2020;727:138761. doi:10.1016/j.scitotenv.2020.138761
121. Komi LS, Chianumba EC, Forkuo AY, Osamika D, Mustapha AY. Advances in public health outreach through mobile clinics and faith-based community engagement in Africa. IRE J. 2021;4(8):159-61.
122. Komi LS, Chianumba EC, Forkuo AY, Osamika D, Mustapha AY. Advances in community-led digital health strategies for expanding access in rural and underserved populations. IRE J. 2023;5(3):299-301.
123. Komi LS, Chianumba EC, Forkuo AY, Osamika D, Mustapha AY. Systematic review of digital maternal health education interventions in low-infrastructure environments. Int J Multidiscip Res Growth Eval. 2021;2(1):909-18. doi:10.54660/.IJMRGE.2021.2.1.909-918
124. Kpokiri EE, Taylor DG, Smith N, Taylor J. Strengthening regulatory systems for pharmaceuticals in low- and middle-income countries. BMJ Glob Health. 2022;7(5):e008043.
125. Kufile OT, Otokiti BO, Onifade AY, Ogunwale B, Okolo CH. Constructing cross-device ad attribution models for integrated performance measurement. IRE J. 2022;4(12):460-5.
126. Kümmerer K, Dionysiou DD, Olsson O, Fatta-Kassinos D. A path to clean water: pharmaceuticals in the environment. Nat Rev Chem. 2020;4(6):686-8. doi:10.1038/s41570-020-0210-2
127. Kusturica MP, Sabo A, Tomic Z. Disposal of unused drugs: knowledge and behavior among people around the world. Rev Environ Contam Toxicol. 2020;247:71-104. doi:10.1007/398_2019_32
128. Kusturica MP, Tomas A, Horvat O. Disposal of unused drugs: knowledge and behavior among people around the world. Rev Environ Health. 2020;35(3):195-204. doi:10.1515/reveh-2019-0030
129. Kusturica MP, Tomas A, Sabo A, Horvat O. Disposal of unused medicines in Serbia: practices, challenges and educational interventions. Waste Manag Res. 2020;38(12):1390-8.
130. Mustapha AY, Chianumba EC, Forkuo AY, Osamika D, Komi LS. Systematic review of digital maternal health education interventions in low-infrastructure environments. Int J Multidiscip Res Growth Eval. 2021;2(1):909-18. doi:10.54660/IJMRGE.2021.2.1.909-918
131. Mustapha AY, Tomoh BO, Soyege OS, Nwokedi CN, Mbata AO, Balogun OD, Iguma DR. Preventive health programs: collaboration between healthcare providers and public health agencies. Int J Pharma Growth Res Rev. 2024;1(6):41-7.
132. Nwaimo CS, Olaniyan FF, Adepoju AA. Pharmaceutical supply chain risks in low-income countries: a framework for resilience and transparency. Glob Public Health Innov. 2023;7(2):115-27.
133. Nwani S, Abiola-Adams O, Otokiti BO, Ogeawuchi JC. Designing inclusive and scalable credit delivery systems using AI-powered lending models for underserved markets. IRE J. 2020;4(1):212-4.
134. Nwankwo PC, Hassan YG. Household pharmaceutical waste and environmental pollution: a systematic review of LMIC evidence. Int J Environ Sci Technol. 2024;21(3):1189-204.
135. Nwankwo TC, Ejairu E, Awonuga KF, Usman FO, Nwankwo EE. Conceptualizing sustainable supply chain resilience: critical materials manufacturing in Africa as a catalyst for change. Int J Sci Res Arch. 2024;11(1):2427-37.
136. Odetunde A, Adekunle BI, Ogeawuchi JC. A systems approach to managing financial compliance and external auditor relationships in growing enterprises. IRE J. 2021;4(12):326-45.
137. Odetunde A, Adekunle BI, Ogeawuchi JC. Developing integrated internal control and audit systems for insurance and banking sector compliance assurance. IRE J. 2021;4(12):393-407.
138. Odetunde A, Adekunle BI, Ogeawuchi JC. Managing externalities of chemical and pharmaceutical effluents in emerging economies: regulatory gaps and responses. Int J Environ Policy Manag. 2023;12(1):44-59.
139. Odofin OT, Agboola OA, Ogbuefi E, Ogeawuchi JC, Adanigbo OS, Gbenle TP. Conceptual framework for unified payment integration in multi-bank financial ecosystems. IRE J. 2020;3(12):1-13.
140. Ogayemi C, Filani OM, Osho GO. A market access optimization model for new drug indications in emerging pharmaceutical markets. Shodhshauryam Int Sci Ref Res J. 2022;5(2):210-25.
141. Ogayemi C, Filani OM, Osho GO. Green supply chain design using lifecycle emissions assessment models. Int J Sci Res Eng Technol. 2022;9(9):68-85.
142. Ogeawuchi JC, Akpe OEE, Abayomi AA, Agboola OA. Systematic review of business process optimization techniques using data analytics in small and medium enterprises. IRE J. 2023;5(4):231-9.
143. Ogunnowo EO, Adewoyin MA, Fiemotongha JE, Igunma TO, Adeleke AK. A conceptual model for simulation-based optimization of HVAC systems using heat flow analytics. IRE J. 2021;5(2):206-13. doi:10.6084/m9.figshare.25730909.v1
144. Okafor BE, Yakubu H. The role of community-based initiatives in drug take-back programs. Glob Health Policy Rev. 2024;17(1):88-105.
145. Okeke I, Adegboye A, Yusuf R. Barriers to effective training on medical waste management among primary healthcare workers in sub-Saharan Africa. Health Policy Plan. 2023;38(7):856-68.
146. Okeke UP, Yusuf AA. Evaluating grassroots advocacy in pharmaceutical waste control initiatives: evidence from West Africa. Afr J Health Policy Stud. 2023;14(2):98-113.
147. Okonkwo BC, Yusuf AR, Abiodun OS. Financial bottlenecks in implementing environmental health interventions in Sub-Saharan Africa. J Glob Public Health. 2022;5(3):112-24.
148. Okoro IC, Umeh JO. Household-level waste disposal and its impact on antimicrobial resistance in low-income

settings. Glob Public Health Rev. 2023;8(1):15-27.
149. Okoye CC, Ofodile OC, Tula ST, Nifise AOA, Falaiye T, Ejairu E, Addy WA. Risk management in international supply chains: a review with USA and African cases. Magna Sci Adv Res Rev. 2024;10(1):256-64.
150. Oladipo M, Ogunbanwo A, Lawal K. Strengthening pharmaceutical waste awareness campaigns in low-income communities: lessons from Nigeria. Afr J Health Med Sci. 2023;22(2):145-60.
151. Olajide JO, Otokiti BO, Nwani S, Ogunmokun AS, Adekunle BI, Fiemotongha JE. Developing internal control and risk assurance frameworks for compliance in supply chain finance. IRE J. 2022;4(11):459-61.
152. Olasoji O, Iziduh EF, Adeyelu OO. A regulatory reporting framework for strengthening SOX compliance and audit transparency in global finance operations. IRE J. 2020;4(2):240-1. Available from: https://irejournals.com/paper-details/1709385
153. Olorunfemi TA, Nwafor CK. Public engagement and behavioral change in waste segregation practices: lessons from low-income urban communities. Int J Public Health Innov. 2022;7(3):202-17.
154. Olufemi-Phillips AQ, Ofodile OC, Toromade AS, Eyo-Udo NL, Adewale TT. Optimizing FMCG supply chain management with IoT and cloud computing integration. Int J Manag Entrep Res. 2020;6(11):1-15.
155. Oluoha OM, Odeshina A, Reis O, Okpeke F, Attipoe V, Orieno OH. Project management innovations for strengthening cybersecurity compliance across complex enterprises. Int J Multidiscip Res Growth Eval. 2023;2(1):871-81.
156. Omisola JO, Etukudoh EA, Okenwa OK, Tokunbo GI. Innovating project delivery and piping design for sustainability in the oil and gas industry: a conceptual framework. Perception. 2020;24:28-35.
157. Onaghinor O, Uzozie OT, Esan OJ. Gender-responsive leadership in supply chain management: a framework for advancing inclusive and sustainable growth. Eng Technol J. 2021;4(11):325-7. doi:10.47191/etj/v411.1702716
158. Onaghinor O, Uzozie OT, Esan OJ. Resilient supply chains in crisis situations: a framework for cross-sector strategy in healthcare, tech, and consumer goods. Eng Technol J. 2021;5(3):283-4.
159. Osho GO, Omisola JO, Shiyanbola JO. An integrated AI-Power BI model for real-time supply chain visibility and forecasting: a data-intelligence approach to operational excellence. [Unknown Journal]. 2024.
160. Ozobu CO. A predictive assessment model for occupational hazards in petrochemical maintenance and shutdown operations. Iconic Res Eng J. 2020;3(10):391-9.
161. Ozobu CO, Adikwu FE, Odujobi O, Onyekwe FO, Nwulu EO. Developing a national strategy for integrating wellness programs into occupational safety and health management systems in Nigeria: a conceptual framework. Int J Multidiscip Res Stud. 2023;3(4):214-28.
162. Patwary MA, O'Hare WT, Street G. Health risk from hospital waste in developing countries: a qualitative study. Waste Manag. 2020;102:531-8. doi:10.1016/j.wasman.2019.11.043
163. Tong AYC, Peake BM. Disposal practices of unused pharmaceuticals in New Zealand households. Environ Int. 2021;37(2):292-8. doi:10.1016/j.envint.2010.10.002
164. Tong X, Tao D, Lifset R. Varieties of regulation in e-waste management: insights from China and India. Environ Sci Technol. 2018;52(21):12001-9. doi:10.1021/acs.est.8b02302
165. Uche R, Mohammed A. Policy and regulatory challenges in sustainable waste management practices across Sub-Saharan Africa. Afr J Public Adm Policy. 2022;14(3):102-19.
166. Uddoh J, Ajiga D, Okare BP, Aduloju TD. Cross-border data compliance and sovereignty: a review of policy and technical frameworks. J Front Multidiscip Res. 2024;2(2):68-74.
167. Uddoh J, Ajiga D, Okare BP, Aduloju TD. Developing AI optimized digital twins for smart grid resource allocation and forecasting. J Front Multidiscip Res. 2024;2(2):55-60. doi:10.54660/.IJFMR.2021.2.2.55-60
168. Umeh IA, Chukwu JA, Lawal HM. Challenges of financial mobilization for waste management in resource-constrained settings. J Dev Environ Manag. 2024;9(2):101-17.
169. United Nations Development Programme. Public-private partnerships for sustainable development: policy perspectives. New York: UNDP; 2021.
170. Usman F, Bello H, Ibrahim A. Public engagement and awareness strategies for sustainable healthcare waste management in LMICs. Glob Environ Health Rev. 2024;12(3):199-214.
171. Viladrich A. Global inequalities and medical waste management: the role of culture, poverty, and governance in low-resource settings. J Environ Manag. 2022;313:114981. doi:10.1016/j.jenvman.2022.114981
172. World Health Organization. Global progress report on water, sanitation and hygiene in health care facilities: fundamentals first. Geneva: WHO Press; 2020.
173. World Health Organization. Global progress report on health care waste management: infrastructure, financing, and equity challenges. Geneva: WHO; 2022. Available from: https://www.who.int/publications/i/item/9789240065268