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Pharmaceutical waste management: sources, environmental Impacts, and sustainable solutions

Ima Uzni Baroka*
Master Program of Public Health, Faculty of Medicine, Universitas Lampung, Bandar Lampung, Indonesia
*Corresponding author: Jl. Prof. Dr. Sumantri Brojonegoro No. 1 Bandar Lampung, 35145, Lampung, Indonesia.
Email: imauzni@gmail.com

Abstract: Pharmaceutical waste represents a growing global environmental and public health challenge requiring urgent attention across healthcare systems worldwide. This review examines the sources, environmental impacts, and management strategies for pharmaceutical waste based recent studies across six continents. Healthcare facilities generate the largest volumes of pharmaceutical waste, with hospitals producing 1,150-5,967 grams daily and specialized units contributing disproportionately high amounts. Community and household sources add significant distributed waste through improper disposal practices, with up to 95% of households maintaining unused medication inventories. Environmental impacts include widespread contamination affecting 96% of disposal pathways inappropriately, creating multiple exposure routes through terrestrial (49%), drainage (21%), and aquatic systems (25%). Antimicrobial resistance development represents a critical consequence, with 60% of environmental bacterial isolates demonstrating extended-spectrum β-lactamase production. Effective management strategies encompass source reduction achieving 1.9 kg CO_2-equivalent climate benefits annually, hospital recycling programs generating $415,000 net value while diverting 461,000 medication units from incineration, and advanced treatment technologies reducing antibiotic concentrations to 0.002-0.68 mg/kg in recovered materials. Implementation success requires integrated approaches combining prevention, technology solutions, stakeholder engagement, and regulatory frameworks. Urgent action is needed to establish comprehensive pharmaceutical waste management systems that protect environmental and public health while achieving economic sustainability.

Keywords: pharmaceutical waste management, environmental contamination, antimicrobial resistance, waste reduction strategies, healthcare sustainability

Introduction

The exponential growth in global pharmaceutical consumption has created a major challenge in managing pharmaceutical waste across diverse healthcare settings and communities worldwide. Healthcare facilities generate substantial daily volumes, with hospitals producing 1,150-5,967 grams daily depending on size and specialization [1], while approximately 95% of households maintain unused medication inventories contributing to distributed waste streams [2]. This waste encompasses expired medications, unused prescriptions, contaminated materials, and manufacturing residues that collectively pose serious threats to environmental integrity and public health security, with annual economic losses reaching hundreds of millions of dollars globally [3,4].

Healthcare systems generate pharmaceutical waste through multiple interconnected pathways that reflect diverse operational contexts and resource constraints. Hospital operations demonstrate remarkable complexity, with specialized units like operating rooms contributing disproportionately high amounts—propofol alone accounting for one-third of surgical pharmaceutical waste [1]. Public health facilities in resource-limited settings face additional challenges, with Ethiopian facilities experiencing overall wastage rates of 3.68% annually, valued at approximately $159,762, predominantly due to medication expiration (92.05%) rather than clinical factors [5]. Community sources add significant distributed waste, with up to 82.1% of households disposing unused medications through household garbage, reflecting widespread gaps in disposal awareness and infrastructure [2,6].

Environmental contamination from pharmaceutical waste creates cascading effects extending far beyond immediate disposal sites to encompass entire ecosystems and public health systems. Systematic assessments reveal that up to 96% of pharmaceuticals are disposed through environmentally harmful pathways, with 49% contaminating terrestrial environments, 21% entering drainage systems, and 25% discharged directly into receiving waters [7]. This widespread contamination facilitates antimicrobial resistance development in environmental microbiomes, with 60% of bacterial isolates from pharmaceutical-polluted environments demonstrating extended-spectrum β-lactamase production and 16.9% exhibiting extensively drug-resistant phenotypes [8]. The COVID-19 pandemic has further exacerbated these challenges, with healthcare facilities experiencing doubled waste generation rates and altered medication utilization patterns that created significant shifts in environmental risk profiles [9,10].

Current pharmaceutical waste management approaches demonstrate both considerable potential and persistent gaps that limit their effectiveness and scalability. Successful interventions achieve notable results, including 1.9 kg CO_2-equivalent climate benefits annually through medication redispensing programs [11], weekly savings of $865.63 through targeted operating room waste reduction [12], and potential net value of $415,000 through comprehensive hospital recycling initiatives that divert 461,000 medication units from incineration [13]. However, implementation remains fragmented across healthcare systems, with considerable variations in waste management practices, limited stakeholder engagement, and insufficient integration of prevention, recycling, and disposal strategies. Knowledge gaps persist regarding optimal intervention design, long-term environmental outcomes, and cost-effectiveness across diverse operational and economic contexts.

This review synthesizes current evidence regarding pharmaceutical waste sources, environmental and health impacts, and management strategies based on analysis of recent studies from healthcare systems across six continents spanning 2020-2025. The specific objectives are to: (1) characterize the sources and volumes of pharmaceutical waste generation across healthcare facilities and community settings; (2) evaluate environmental contamination pathways and health impacts, particularly antimicrobial resistance development; (3) assess the effectiveness of current management strategies including source reduction, recycling programs, and disposal technologies; and (4) identify critical success factors and implementation barriers for comprehensive pharmaceutical waste management systems. The ultimate goal is to provide evidence-based recommendations for developing sustainable pharmaceutical waste management approaches that protect environmental and public health while achieving economic viability and operational feasibility across diverse healthcare contexts.

Sources and generation of pharmaceutical waste

Hospital and healthcare facilities

Healthcare institutions represent the largest and most concentrated sources of pharmaceutical waste globally, demonstrating consistent patterns across diverse healthcare systems while reflecting unique operational characteristics and resource constraints. Hospital pharmaceutical waste generation demonstrates consistent composition while varying substantially in volume based on facility size, specialization, and operational intensity. Danish hospitals exemplify typical patterns, with urban facilities producing 1,150 grams daily and regional centers generating 5,967 grams daily, reflecting the correlation between patient acuity and waste generation [1]. Therapeutic composition consistently prioritizes nervous system medications, cardiovascular drugs, and alimentary tract therapeutics as primary waste categories, while antibiotics for systemic use constitute both the most diverse and volumetrically significant category across different healthcare systems [14,15] (Table 1).

Per capita waste generation rates provide standardized metrics for comparing institutional performance and identifying improvement opportunities. Iranian hospitals demonstrate generation rates of 181.81 grams per patient daily and 264.7 grams per hospital bed daily for pharmaceutical waste, with drug residues adding an additional 54.22 and 88.21 grams respectively [15]. Emergency departments and operating rooms consistently emerge as major waste-generating units, reflecting the high-intensity, time-critical nature of clinical care that prioritizes immediate patient needs over waste minimization considerations.

Specialized clinical units

Operating rooms represent particularly challenging environments for pharmaceutical waste management due to sterility requirements, diverse procedural needs, and medication preparation protocols. Propofol accounts for approximately one-third of operating

Table 1. Global pharmaceutical waste generation by source and setting

Source category	Location/ setting	Daily generation rate	Per capita/ bed rate	Major waste categories	Key characteristics	Reference
Hospital operations						
Urban hospital	Denmark (Odense)	1,150 g/day	-	Nervous system, cardiovascular, alimentary tract medications	Consistent therapeutic composition	[1]
Regional hospital	Denmark (Svendborg)	5,967 g/day	-	Operating rooms: 3,143 g/day	Propofol = 1/3 of OR waste	[1]
General hospital	Iran (Tehran)	153.82 kg/ day total pharmaceutical waste	181.81 g/patient/ day, 264.7 g/ bed/day	Antibiotics (highest weight %), emergency and OR units major contributors	Drug residue: 45.87 kg/day additional	[15]
Specialized units						
Emergency department	US Hospitals	-	-	Opioids: 21,767 mg morphine waste, 11,689 mg hydromorphone waste	35% morphine orders, 85% hydromorphone orders create waste	[16]
Medical imaging	Norwegian Hospitals	-	-	Iodinated contrast media	26% recycled, 38% reused, 17.1% inappropriately disposed	[18]
Palliative care	Canadian outpatient clinics	-	-	Opioid medications	52.3% of patients don't routinely dispose opioids	[17]
Resource-limited settings						
Public health facilities	Ethiopia (Dessie)	-	-	Supplies (37.1% wastage), tablets (20.78%), injectables (16.49%)	3.68% overall wastage rate, 92.05% due to expiration	[5]
Supply chain	Ethiopia (Western)	-	-	Tetanus antitoxin (20% of single drug value loss)	5% expiration rate, 20 million ETB loss over 2 years	[4]
Pandemic response	Ethiopia (Dire-Dawa)	-	-	Anti-infectives (58.3% of waste value)	3.07% wastage rate during COVID-19	[20]
Community sources						
Household accumulation	Indonesia	-	-	NSAIDs, vitamins, antibiotics	95% households maintain unused inventories	[2]
Household disposal	South Africa (Johannesburg)	-	-	Analgesics (73%), cold/flu medications (52%)	77% have waste knowledge, poor disposal practices	[6]
Parental storage	Saudi Arabia	-	-	Analgesics (92.2%), antihistamines (62.1%)	88.6% refrigerator storage, 80% household garbage disposal	[21]

Source category	Location/ setting	Daily generation rate	Per capita/ bed rate	Major waste categories	Key characteristics	Reference
Community pharmacy						
Client returns	Ghana	280 medications assessed	-	Analgesics (36.4%), antibiotics (17.9%), antacids (7.9%)	77% dispose via general waste bin	[22]
Pharmacy operations	UAE	-	-	Skin/hair products, antibiotics, analgesics most expired	>1/3 use licensed contractors, concerning unauthorized disposal	[23]
Pandemic impact						
COVID-19 facilities	Morocco (Rabat-Sale-Kenitra)	4 kg/bed/day (COVID beds) vs. 2 kg/bed/day (normal)	-	Medical and pharmaceutical waste combined	100% increase during pandemic peaks	[9]

OR: operating room, ETB: Ethiopian Birr (Ethiopia currency), US: United States, UAE: United Arab Emirates, NSAIDs: Nonsteroidal anti-inflammatory drugs, COVID-19: Coronavirus Disease 2019

room pharmaceutical waste due to single-use protocols and standard vial sizes that exceed typical dosing requirements [1]. Emergency departments demonstrate different waste patterns, with opioid medications creating considerable disposal challenges—35% of morphine orders and 85% of hydromorphone orders generating waste totaling 21,767 mg and 11,689 mg respectively across 34,465 intravenous orders [16].

Specialized clinical settings introduce unique waste management considerations that require tailored approaches. Palliative care environments demonstrate notable patterns, with 52.3% of patients with life-limiting cancers failing to routinely dispose of opioid medications, creating potential diversion risks and environmental contamination [17]. Medical imaging departments generate specialized waste streams dominated by contrast media, with 26% collecting materials for recycling and 38% repurposing for alternative applications, yet 17.1% inappropriately disposing materials through drainage systems [18,19].

Resource-limited healthcare settings

Public healthcare facilities in resource-constrained environments face systematic pharmaceutical waste challenges that interweave supply chain inefficiencies, limited infrastructure, and economic pressures. Ethiopian public facilities demonstrate overall pharmaceutical wastage rates of 3.68% with expired medications accounting for 92.05% of total waste, indicating fundamental failures in inventory management rather than clinical decision-making [5]. Health centers consistently demonstrate nearly twofold higher wastage rates compared to hospitals, suggesting that smaller facilities with limited pharmaceutical management expertise face greater challenges in maintaining efficient inventory systems.

Supply chain disruptions and inventory management deficiencies create predictable waste patterns in resource-limited settings. Western Ethiopian supply chains experienced 5% expiration rates over two financial years, representing losses of 20 million Ethiopian Birr, with tetanus antitoxin alone accounting for 20% of single drug value losses [4]. Anti-infectives constitute 58.3% of total waste value, reflecting both increased therapeutic utilization and supply chain failures that result in medication expiration before clinical use [20].

Community and household sources

Household pharmaceutical accumulation demonstrates consistent global patterns, with approximately 95% of households maintaining unused medication inventories dominated by nonsteroidal anti-inflammatory drugs, vitamins, and antibiotics [2]. South African households show that 77% acknowledge pharmaceutical waste awareness yet demonstrate limited understanding of proper disposal methods, with analgesics (73%) and cold/flu medications (52%) representing the most common accumulated categories [6]. Parental medication management introduces additional complexity, with 88.6% storing medications in refrigerators and 69.9%

maintaining medications above adult eye level, yet only 28% utilizing secure storage locations [21].

Disposal practices reveal notable gaps between awareness and behavior across diverse cultural contexts. Indonesian households predominantly dispose of unused medications through household garbage (82.1%), with 53.1% remaining unaware of environmental impacts despite widespread medication accumulation [2]. Educational attainment significantly influences disposal willingness, yet actual practices remain consistently inappropriate across socioeconomic groups, indicating that knowledge alone proves insufficient for behavior change without supportive infrastructure and regulatory frameworks.

Community pharmacy operations

Community pharmacies occupy dual roles as both waste generators through expired inventory and potential collection points for consumer disposal programs. Ghanaian community pharmacies demonstrate this complexity, receiving 280 returned medications including analgesics (36.4%), antibiotics (17.9%), and antacids (7.9%), while simultaneously disposing of their own expired inventory primarily through general waste bins (77.0%) and down sinks (14.3%) [22]. United Arab Emirates pharmacies show more sophisticated approaches, with over one-third utilizing licensed contractors for various dosage forms, yet considerable proportions still employ unauthorized disposal methods including general garbage, sinks, and toilets [23].

Professional experience and regulatory enforcement emerge as critical factors influencing pharmacy waste management practices. Years of practice experience correlate significantly with support for specialized disposal centers ($p<0.05$), while 68.4% of pharmacists advocate for improved disposal infrastructure, indicating professional recognition of current system inadequacies [23]. Skin and hair products, antibiotics, and analgesics consistently represent the most frequently expired categories, suggesting predictable patterns that could inform targeted inventory management strategies.

Emergency and pandemic-related sources

The COVID-19 pandemic altered pharmaceutical waste generation patterns, creating increased volumes and introducing new waste categories requiring specialized management approaches. Moroccan healthcare facilities experienced doubled pharmaceutical waste generation during pandemic peaks, with COVID-19 designated beds producing 4 kg per bed daily compared to 2 kg during normal operations, representing a 100% increase in waste generation intensity [9]. Brazilian primary healthcare systems demonstrated significant pharmaceutical utilization pattern changes that translated directly into altered environmental risk profiles, with azithromycin and ivermectin showing increased environmental loads between 2019 and 2020, followed by supply-related decreases in 2021 [10].

Pandemic-related waste generation patterns reveal systematic vulnerabilities in healthcare supply chain management and clinical decision-making processes. Ethiopian public health facilities during pandemic periods experienced anti-infectives accounting for 58.3% of total pharmaceutical waste value, reflecting both increased therapeutic use and supply chain disruptions that resulted in medication expiration before utilization [20]. These findings indicate that emergency preparedness planning must incorporate pharmaceutical waste management considerations from the outset, including surge capacity for waste handling and adaptive supply chain management protocols.

Synthesis of global waste generation patterns

Cross-study analysis reveals consistent patterns in pharmaceutical waste generation that transcend geographical and economic boundaries while highlighting specific intervention opportunities. Healthcare facilities consistently generate 2-6 kg of pharmaceutical waste per day per facility, with specialized units contributing disproportionately high amounts relative to their size. Anti-infectives, analgesics, and cardiovascular medications consistently dominate waste streams across diverse settings, indicating universal challenges in inventory management and therapeutic decision-making. Community sources contribute substantial distributed waste through widespread household accumulation, with 80-95% of households maintaining unused medications and 70-80% utilizing inappropriate disposal methods.

Economic implications demonstrate considerable financial burdens, with individual healthcare systems experiencing annual losses ranging from hundreds of thousands to millions of dollars through pharmaceutical waste generation. The concentration of waste in specific high-value therapeutic categories suggests that targeted interventions focusing on particular medication classes could achieve disproportionate economic and environmental benefits. Emergency situations consistently exacerbate baseline waste generation patterns, emphasizing the need for resilient management systems capable of adapting to extraordinary circumstances while maintaining environmental protection and public health objectives.

Environmental and health impacts

Environmental contamination pathways and distribution

Pharmaceutical waste creates systematic environmental contamination through multiple interconnected pathways that persist in environmental systems and resist conventional remediation approaches, establishing long-term pollution legacies with cascading ecosystem effects. Environmental risk assessments reveal widespread contamination patterns originating from inadequate disposal practices across healthcare and community settings. Ghanaian municipalities demonstrate that 96% of pharmaceuticals are disposed through environmentally harmful pathways, with only 4% managed through appropriate methods, creating widespread contamination across multiple environmental media [7]. Systematic distribution analysis shows 49% of pharmaceutical waste contaminating terrestrial environments, 21% entering drainage systems, and 25% discharged directly into receiving waters, establishing multiple exposure pathways for wildlife and human populations (Table 2).

Environmental fate analysis during public health emergencies reveals how extraordinary circumstances exacerbate baseline contamination levels through altered consumption patterns and disposal practices. Brazilian primary healthcare systems during COVID-19 demonstrated notable fluctuations in predicted environmental concentrations, with azithromycin and ivermectin showing increased environmental loads between 2019 and 2020 [10]. Risk quotient assessments consistently identify fluoxetine, ethinylestradiol, and azithromycin as presenting the highest environmental risks, indicating that environmental impact assessment requires consideration of inherent toxicity profiles rather than focusing solely on consumption volumes.

Environmental persistence of pharmaceutical compounds creates long-term contamination challenges that extend beyond immediate disposal events to encompass sustained ecosystem exposure and potential bioaccumulation effects. The identification of multiple contamination routes including terrestrial dispersal, surface water contamination, and groundwater infiltration demonstrates how pharmaceutical waste management failures create persistent environmental legacies [7]. Environmental transport mechanisms facilitate widespread distribution of pharmaceutical contaminants throughout interconnected environmental systems, creating complex exposure scenarios that affect multiple ecosystem components and trophic levels.

Aquatic ecosystem effects

Aquatic environments represent particularly vulnerable receptors for pharmaceutical contamination due to their limited degradation capacity and role as ultimate sinks for waterborne contaminants, creating complex exposure scenarios with documented physiological effects on aquatic organisms. Sewage effluent containing pharmaceutical residues demonstrates measurable capacity to induce biochemical alterations in aquatic organisms at environmentally relevant concentrations. Brazilian studies utilizing Astyanax bimaculatus reveal that treated sewage containing pharmaceuticals including caffeine, ciprofloxacin, ofloxacin, paracetamol, and various sulfonamides produces oxidative stress responses and enzymatic alterations [24]. Thiobarbituric acid reactive substances (TBARS) levels increased in brain tissues, while acetylcholinesterase (AChE) activity decreased in muscle tissues, indicating disruption of fundamental neurological and muscular functions.

Pharmaceutical mixture effects demonstrate complexity beyond individual compound toxicity, with integrated biomarker response values indicating greater physiological disruption in organisms exposed to higher pharmaceutical concentrations [24]. Advanced treatment approaches using ozone, hydrogen peroxide, and ultraviolet radiation reduce TBARS levels in multiple tissues, yet continued measurable effects indicate that complete elimination requires source reduction rather than relying solely on end-of-pipe treatment solutions.

The demonstrated capacity of pharmaceutical mixtures to alter fundamental physiological processes suggests potential for bioaccumulation and biomagnification effects that could concentrate compounds in higher trophic levels, including species consumed by humans [24]. This possibility emphasizes the need for

Table 2. Environmental contamination pathways and distribution

Contamination route	Distribution percentage	Geographic location	Pharmaceutical categories	Environmental impact	Resistance development	Reference
Disposal pathway analysis						
Environmentally harmful disposal	96%	Ghana (Krowor Municipality)	General pharmaceutical waste	Multiple contamination pathways	Not specified	[7]
Environmentally appropriate disposal	4%	Ghana (Krowor Municipality)	General pharmaceutical waste	Proper waste management	Not specified	[7]
Environmental distribution						
Terrestrial contamination	49%	Ghana (Krowor Municipality)	Local and surrounding area contamination	Soil and land contamination	Not specified	[7]
Drainage System contamination	21%	Ghana (Krowor Municipality)	Pharmaceutical waste in drainage	Water system contamination	Not specified	[7]
Receiving waters discharge	25%	Ghana (Krowor Municipality)	Direct water body contamination	Aquatic ecosystem impact	Not specified	[7]
Aquatic system effects						
Sewage effluent contamination	-	Brazil	Caffeine, ciprofloxacin, clindamycin, ofloxacin, oxytetracycline, paracetamol, sulfonamides	TBARS increase in brain, AChE decrease in muscle	Not specified	[24]
Environmental risk assessment						
High risk compounds	-	Brazil (Rio de Janeiro)	Fluoxetine, ethinylestradiol, azithromycin	Highest risk quotients regardless of consumption volume	Not specified	[10]
Pandemic-altered patterns	-	Brazil (Rio de Janeiro)	Azithromycin, ivermectin (increased 2019-2020)	Changed environmental load patterns	Not specified	[10]
Antimicrobial resistance development						
ESBL-positive bacteria	60% of isolates	India (Delhi, Yamuna River)	Pharmaceutical effluent exposure	Environmental resistance reservoir	Extended-spectrum β-lactamase production	[8]
Multiple antibiotic resistance (MAR)	68% of ESBL+, 24% of ESBL- (MAR ≥0.5)	India (Delhi, Yamuna River)	Multiple antibiotic classes	Broad resistance patterns	Multi-drug resistance	[8]
Extensively drug resistant (XDR)	16.9% of ESBL+ isolates	India (Delhi, Yamuna River)	Multiple antibiotic exposure	Treatment limitation	Extremely limited therapeutic options	[8]
Pandrug resistant (PDR)	0.7% of ESBL+ isolates	India (Delhi, Yamuna River)	Multiple antibiotic exposure	Clinical treatment failure risk	No effective therapeutic options	[8]
Biofilm enhancement						
Enhanced biofilm formation	-	India (Delhi, Yamuna River)	Mercuric chloride + antibiotics	Increased resistance gene stability	Horizontal gene transfer facilitation	[8]
Treatment efficacy						
Advanced oxidation treatment	Partial reduction	Brazil	Pharmaceutical mixture in sewage	Reduced but not eliminated toxicity	Continued environmental effects	[24]
Bio-fertilizer conversion	0.002-0.68 mg/kg final concentration	China	Antibiotic fermentation residue	Resource recovery with reduced contamination	233 ARGs and 43 MGEs detected	[25]

TBARS: Thiobarbituric acid reactive substances, AChE: Acetylcholinesterase, ESBL: Extended-spectrum β-lactamase, ARGs: Antibiotic resistance genes, MGEs: Mobile genetic elements comprehensive environmental monitoring programs that track pharmaceutical contamination throughout aquatic food webs and assess human exposure risks through dietary pathways.

Antimicrobial resistance development

Environmental pharmaceutical contamination creates selective pressure favoring antimicrobial-resistant bacterial populations while facilitating horizontal gene transfer and resistance evolution, representing one of the most serious long-term consequences of inadequate waste management. Environmental pharmaceutical contamination demonstrates systematic capacity to promote antimicrobial resistance development across diverse bacterial populations and geographical contexts. Indian river systems receiving pharmaceutical effluent show 60% of bacterial isolates exhibiting extended-spectrum β-lactamase (ESBL) production capabilities, with 68% of ESBL-positive isolates demonstrating multiple antibiotic resistance indices ≥0.5 [8]. The emergence of extensively drug-resistant (XDR) phenotypes in 16.9% of ESBL-positive bacteria and pandrug-resistant (PDR) phenotypes in 0.7% of isolates indicates evolution of resistance mechanisms compromising virtually all available therapeutic options.

Horizontal gene transfer mechanisms demonstrate how pharmaceutical contamination facilitates resistance dissemination beyond immediate contamination sources. Conjugation experiments reveal optimal resistance gene transfer under environmental conditions including neutral pH (7-7.5) and temperatures of 35-40°C, with transconjugant bacteria demonstrating tolerance to mercuric chloride concentrations ranging from 0.0002-0.2 mg/L, indicating co-selection for multiple resistance mechanisms [8].

Environmental biofilm formation enhancement under pharmaceutical contamination conditions represents an additional mechanism contributing to resistance persistence and dissemination. Biofilm formation increases significantly when growth media is supplemented with mercuric chloride alone or combined with antibiotics, creating environmental conditions favoring resistance gene maintenance and transfer through biofilm-mediated protection [8]. These findings indicate that pharmaceutical waste management strategies must consider both direct resistance selection and indirect effects on bacterial community structure that perpetuate contamination impacts beyond initial disposal events.

Human health exposure and clinical implications

Direct and indirect human health impacts from pharmaceutical waste occur through multiple exposure pathways including environmental contamination, accidental ingestion, and resistance gene acquisition that collectively threaten public health security. Human exposure to pharmaceutical waste occurs through contaminated drinking water sources, agricultural products grown in contaminated soil, and direct contact with improperly disposed medications. The widespread environmental distribution of pharmaceutical contaminants through terrestrial (49%), aquatic (25%), and drainage (21%) pathways creates multiple potential exposure routes for human populations [7]. Household storage and disposal practices introduce additional direct exposure risks, particularly for children and vulnerable populations who may encounter improperly stored or disposed medications.

Environmental development of antimicrobial resistance creates clinical threats through acquisition of resistant pathogens from environmental sources and horizontal transfer of resistance genes to clinical isolates. The identification of extensively drug-resistant and pandrug-resistant bacterial phenotypes in pharmaceutical-contaminated environments indicates potential for untreatable infections emerging through environmental exposure pathways [8]. These resistance patterns compromise therapeutic effectiveness and increase healthcare costs while threatening patient outcomes across diverse clinical contexts, emphasizing the critical connection between environmental pharmaceutical contamination and clinical treatment failures.

Management strategies and solutions

Prevention and source reduction

Source reduction represents the most effective approach to pharmaceutical waste management by addressing fundamental causes of waste generation through improved clinical practices, inventory optimization, and systematic process improvements. Innovative dispensing and utilization approaches demonstrate significant waste reduction potential while maintaining therapeutic efficacy and patient safety standards. Dutch hospitals pioneered redispensing programs for unused oral anticancer drugs using quality assurance protocols including seal bags and time-temperature indicators, achieving environmental benefits of 1.9 kg CO_2-equivalent per patient annually through strategic focus on temperature-sensitive medications [11]. Emergency department opioid management optimization demonstrates potential for substantial waste reduction through dosing standardization and vial size matching, with waste optimization scenarios reducing total waste by 97% while maintaining cost-effectiveness [16] (Table 3).

Collaborative clinical interventions targeting specific waste-generating processes achieve success through targeted infrastructure improvements. American cardiovascular operating rooms achieved weekly savings of $865.63 through strategic medication placement in existing refrigeration systems and automated dispensing cabinet optimization, demonstrating how process improvements simultaneously reduce waste, save costs, and improve operational efficiency without requiring major capital investments [12]. Systematic inventory management improvements address fundamental drivers of pharmaceutical waste generation, particularly in resource-limited settings where procurement and distribution inefficiencies create systematic expiration patterns. Poor inventory management practices correlate with medication expiration rates, with facilities demonstrating inadequate storage management showing higher waste generation [4].

Recovery and reuse programs

Pharmaceutical recycling and reuse programs recover economic value while reducing environmental impact through established quality assurance and redistribution systems that ensure patient safety while achieving waste reduction objectives. Hospital medication recycling programs demonstrate potential for environmental protection and cost recovery through systematic collection and redistribution protocols. Canadian hospital systems implemented comprehensive programs collecting unused oral solid medications from nursing units, achieving potential diversion of 461,000 medication units from incineration across 21 hospitals while generating estimated net value of $415,000 annually after accounting for operational expenses [13]. Economic viability depends on systematic approaches to medication collection, quality verification, and redistribution that ensure patient safety while minimizing operational costs through coordinated management across healthcare systems.

Community take-back programs represent critical infrastructure for household pharmaceutical waste management through centralized collection and safe disposal systems. American experience demonstrates take-back programs as the most common disposal method utilized by 22% of respondents, with effectiveness depending heavily on public awareness and accessibility factors [26]. Healthcare provider communication emerges as important for program success, yet 78% of patients never receive disposal guidance from physicians, 76% from pharmacists, and 53% from veterinarians, representing opportunities for enhancing program effectiveness through professional engagement. Community pharmacy participation demonstrates variable engagement reflecting regulatory frameworks and operational considerations, with expanding participation offering potential to improve household pharmaceutical waste management while building upon existing consumer relationships [22].

Technology solutions and infrastructure

Technological innovations encompass both hardware solutions for improved storage and handling and information systems for enhanced inventory management and waste tracking, offering systematic improvements in waste reduction and disposal efficiency. Advanced storage technologies reduce pharmaceutical waste through improved environmental control and inventory management addressing fundamental causes of medication degradation and expiration. Automated dispensing systems and specialized refrigeration solutions represent proven approaches for high-volume clinical settings where temperature excursions and inventory mismanagement frequently contribute to disposal requirements. Strategic medication placement based on stability requirements demonstrates how technological solutions address specific waste generation mechanisms while integrating with existing clinical workflows [12].

Quality assurance technologies including time-temperature indicators and seal bags provide essential capabilities for medication reuse and redispensing programs requiring verification of pharmaceutical integrity and storage conditions. Experience with oral anticancer drug redispensing demonstrates both potential and limitations of quality assurance technologies, showing that selective application based on medication characteristics optimizes environmental benefits while maintaining patient safety standards [11]. Advanced treatment technologies convert pharmaceutical waste into useful products while reducing environmental

Table 3. Management strategy effectiveness and economic impact

Strategy type	Setting/ location	Intervention description	Key outcomes	Economic impact	Environmental benefits	Reference
Source reduction						
Redispensing program	Dutch Hospitals	Quality assurance with seal bags and time-temperature indicators for oral anticancer drugs	Maintained therapeutic efficacy with optimized disposal	Cost reduction through waste minimization	1.9 kg CO_2-equivalent climate benefits per patient annually	[11]
Operating room optimization	US Cardiovascular ORs	Strategic medication placement in refrigeration systems and automated dispensing cabinets	Process improvement without capital investment	$865.63 weekly savings (~$45,000 annually)	Reduced refrigerated medication waste	[12]
Opioid waste optimization	US Emergency Departments	Dosing standardization and vial size matching	35% morphine orders and 85% hydromorphone orders created waste	97% waste reduction in optimization scenario	Reduced diversion opportunities and waste volume	[16]
Recycling programs						
Hospital recycling	Canadian Hospital Systems	Collection of unused oral solid medications from nursing units	Quality-assured redistribution protocols	$415,000 net annual value across 21 hospitals	461,000 medication units diverted from incineration	[13]
Community take-back	US Community Programs	Centralized collection and safe disposal systems	22% of respondents use take-back as primary disposal method	Cost offset through proper disposal	Reduced environmental contamination from household disposal	[26]
Technology solutions						
Advanced treatment	Chinese Facilities	Hydrothermal spray-drying and multi-plate dryer for antibiotic residues	Bio-organic fertilizer production with reduced contamination	Resource recovery with agricultural utility	Antibiotic concentrations reduced to 0.002-0.68 mg/kg	[25]
Advanced oxidation	Brazilian Treatment Systems	Ozone, hydrogen peroxide, and UV radiation for pharmaceutical effluent	Reduced oxidative stress in aquatic organisms	Treatment cost vs. environmental protection	Measurable reduction in environmental toxicity	[24]
Education and training						
Healthcare provider training	Ethiopian Hospitals and Pharmacies	Regular pharmaceutical waste management training programs	Improved knowledge and practices correlation	Reduced waste through better practices	Enhanced compliance with environmental protocols	[27]

OR: operating room, US: United States, UV: Ultraviolet

impact through innovative processing methods. Hydrothermal spray-drying and multi-plate dryer technologies demonstrate potential for converting antibiotic fermentation residues into bio-organic fertilizers with substantially reduced antibiotic concentrations (0.002-0.68 mg/kg) while maintaining agricultural utility [25].

Stakeholder engagement and education

Successful pharmaceutical waste management requires comprehensive stakeholder engagement encompassing healthcare providers, patients, communities, and regulatory agencies through targeted education and capacity building initiatives. Healthcare provider education emerges as an important success factor for pharmaceutical waste management implementation, with experience and training correlating with improved knowledge and practices. Ethiopian healthcare professionals demonstrate that regular pharmaceutical waste management training and experience associate with good knowledge, while hospital-based practice correlates with improved waste management practices [27]. Professional development programs must address both technical knowledge and behavioral change management to achieve sustainable improvements in waste management practices.

Community education initiatives demonstrate potential for improving household pharmaceutical waste management through targeted awareness campaigns and accessible disposal guidance. Awareness of pharmaceutical environmental pollution and receipt of proper disposal information both correlate with take-back program participation, indicating that targeted education efforts improve program utilization [26]. Educational interventions must address cultural contexts and socioeconomic factors while providing practical guidance that accommodates diverse community needs and infrastructure limitations.

Policy and regulatory frameworks

Effective pharmaceutical waste management requires supportive policy environments that establish clear responsibilities, provide economic incentives, and ensure regulatory enforcement while promoting innovation and adaptation to emerging challenges. Regulatory frameworks must address gaps in current legislation while supporting implementation of comprehensive waste management systems. Ethiopian experience demonstrates that lack of enforcement represents a primary barrier to proper pharmaceutical waste disposal, with regulatory compliance depending on clear standards, adequate enforcement mechanisms, and stakeholder capacity building [22,27]. International guidelines and standardized disposal protocols could facilitate knowledge transfer and best practice implementation across diverse healthcare systems and regulatory environments.

Economic incentives and extended producer responsibility programs represent policy tools for accelerating progress toward sustainable pharmaceutical waste management through market-based mechanisms and industry accountability. The development of cost-recovery systems, disposal infrastructure funding, and producer responsibility frameworks could address current economic barriers while creating sustainable financing mechanisms for comprehensive waste management systems.

Conclusions

This review demonstrates that pharmaceutical waste management represents a major global challenge requiring urgent, coordinated action across healthcare systems, communities, and regulatory frameworks. The evidence reveals consistent patterns of considerable waste generation, with healthcare facilities producing thousands of grams daily while households contribute distributed waste through widespread medication accumulation and improper disposal practices. Environmental impacts create persistent contamination affecting 96% of disposal pathways inappropriately, facilitating antimicrobial resistance development in 60% of environmental bacterial isolates and threatening ecosystem integrity through multiple contamination routes.

Successful management strategies demonstrate considerable potential for achieving environmental, economic, and public health benefits through integrated approaches combining source reduction, recycling programs, and stakeholder engagement. Evidence-based interventions achieve annual climate benefits of 1.9 kg CO_2-equivalent per patient, weekly cost savings of $865.63 through process optimization, and potential net value of $415,000 through systematic recycling programs. However, implementation remains fragmented, with notable variations in practices and limited integration of comprehensive management systems.

Important success factors include stakeholder engagement, technological innovation, regulatory support, and economic sustainability that enable systematic rather than fragmented approaches to waste reduction and environmental protection. Future priorities must focus on developing standardized measurement systems, evaluating long-term outcomes, and establishing policy frameworks that support innovation while ensuring environmental protection and public health security. The pathway forward requires recognition of pharmaceutical waste management as a shared responsibility demanding coordinated action, sustained commitment, and evidence-based approaches capable of protecting both current and future generations while supporting sustainable healthcare delivery systems.

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Author contribution

IUB: Conceptualization, Methodology, Investigation, Writing – Original Draft, Writing – Review & Editing.

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