

Review Article

ENVIRONMENTAL AND HEALTH IMPACTS OF IMPROPER DISPOSAL OF PHARMACEUTICAL WASTE: A COMPREHENSIVE REVIEW

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ABSTRACT

Aim: This review aims to examine the major sources, improper disposal practices, and subsequent environmental and public health impacts of pharmaceutical waste, while evaluating current management strategies and regulatory frameworks.

Methodology: A comprehensive literature search was conducted to identify relevant peer-reviewed articles, government guidelines, and reports concerning pharmaceutical waste management. Institutional guidelines from WHO, FDA, EPA, and CPCB were analyzed to synthesize current practices and environmental consequences.

Results: Pharmaceutical waste originates from households, healthcare facilities, pharmacies, industry, and veterinary services. Improper disposal via household bins, flushing, and open burning leads to soil, water, and air contamination. While ecological impacts like aquatic toxicity are well-documented, direct human health effects (e.g., endocrine disruption, cancer risk) at environmental concentrations remain potential risks requiring further localized studies. Management regulations vary, with WHO emphasizing controlled incineration, the FDA prioritizing take-back programs, and India's CPCB focusing on biomedical waste segregation.

Conclusion: Effective pharmaceutical waste management requires sustainable disposal technologies, accessible take-back systems, strict regulatory enforcement, and increased public awareness to mitigate environmental and health risks.

Keywords: Pharmaceutical waste; Improper disposal; Environmental contamination; Pharmaceutical residues; Water pollution; Soil pollution; Antimicrobial resistance; Pharmaceutical waste management; Drug take-back programs; Environmental health.

1. Introduction

1.1 Background

Pharmaceuticals are essential to modern healthcare, but their production, distribution, use and disposal create a waste stream with consequences beyond the healthcare system. Pharmaceutical waste broadly includes unused, expired, damaged or unwanted medicines and materials containing active pharmaceutical ingredients. It may include prescription medicines, over-the-counter products, veterinary medicines and pharmaceutical products discarded by households, healthcare facilities, farms, pharmacies and manufacturing operations.⁽¹⁾ Unlike ordinary municipal waste, pharmaceutical waste may retain biologically active compounds after it is discarded. If it is poured into drains, placed in household rubbish, buried, burned under uncontrolled conditions or released through inadequately managed waste streams, these compounds can reach soil, surface water, groundwater and wastewater systems.⁽¹⁾

The problem is not limited to the quantity of waste generated. Pharmaceutical residues can remain active at low concentrations, and the environmental effects of many active pharmaceutical ingredients and their transformation products are still incompletely understood. Reviews have associated inappropriate disposal with water and soil contamination, toxicity to aquatic and terrestrial organisms, accidental

human exposure, and the selection or spread of antimicrobial resistance. Pharmaceutical-waste disposal therefore sits at the intersection of environmental protection, public health, medicines governance and antimicrobial-resistance prevention.⁽²⁾

Definition of pharmaceutical waste

Pharmaceutical waste can be understood as any medicine or pharmaceutical material that is no longer wanted, usable or suitable for its intended purpose and therefore enters a disposal or recovery pathway. This includes expired medicines, products damaged during storage or transport, excess stock, recalled products, partially used medicines, medicines returned by patients and materials contaminated with pharmaceutical ingredients.⁽¹⁾ The definition also covers waste generated before a medicine reaches a patient, such as manufacturing residues and discarded products from pharmacies, hospitals, clinics, veterinary facilities and other healthcare settings.⁽²⁾ A useful distinction is between pharmaceutical waste generated during production and service delivery and post-consumer or household pharmaceutical waste. Production and healthcare waste can be managed through institutional procedures, whereas post-consumer waste depends heavily on patient knowledge, convenient collection systems and regulatory enforcement. When these systems are absent or poorly understood, people may store unwanted

medicines at home, share them with relatives or friends, or discard them with household waste or wastewater. This distinction is important because a safe pharmaceutical-waste strategy must address the entire medicine life cycle rather than focusing only on hospitals or manufacturing plants.(3)

Global increase in pharmaceutical consumption

The volume and diversity of pharmaceutical waste are closely linked to the expanding use of medicines. Pharmaceutical companies continue to introduce new products while large numbers of existing medicines remain in circulation, increasing the amount of pharmaceutical material moving through households, healthcare facilities, farms and industry.(2) A recent scoping review similarly links the global rise in pharmaceutical production and consumption with increasing pharmaceutical waste and associated environmental and public-health risks.(4)

Increased consumption does not translate into waste through a single pathway. Medicines may become waste because they are prescribed in excess, purchased but never used, replaced by another treatment, discontinued when symptoms improve, damaged during storage or left to expire. The resulting waste may be dispersed across millions of households and healthcare sites, making it difficult to collect and treat through centralized systems.(5) As pharmaceutical consumption grows, preventing unnecessary procurement and ensuring that unwanted medicines can be returned become as important as treating waste after it has already been generated.(6)

Increasing healthcare facilities

Healthcare facilities are important sources of pharmaceutical waste because they use medicines continuously and handle products across procurement, storage, preparation, administration and disposal. Hospitals, clinics, pharmacies, laboratories and other service points may generate unused medicines, expired stock, damaged packaging, contaminated materials and partially used preparations. Pharmaceutical waste is also generated beyond formal healthcare facilities, including at community pharmacies, markets, households and animal-husbandry settings.(7)(8)(9)

The expansion and decentralization of healthcare services can make pharmaceutical-waste management more difficult. Waste is produced at many locations, while treatment and disposal infrastructure may be concentrated in urban centers or unavailable altogether. In settings with limited resources, pharmaceutical products and associated materials may be placed in open dumps or mixed with general waste, increasing the likelihood of environmental release and occupational or community exposure. Waste-management planning should therefore be integrated into healthcare expansion, procurement systems and facility accreditation rather than treated as an afterthought.(10)

Increasing use of antibiotics

Antibiotics deserve particular attention because their improper disposal may add to the broader problem of antimicrobial resistance. Pharmaceutical-waste reviews identify antibiotic residues and inappropriate disposal as environmental concerns, while newer syntheses specifically connect antibiotic overconsumption and pharmaceutical-waste management with antimicrobial-resistance risks.(1)(11) Antibiotics can enter the environment through discarded medicines, pharmaceutical and healthcare waste, excretion after use, and wastewater streams that do not fully remove biologically active compounds.(7)

The concern is not simply that antibiotics are present in water or soil. Environmental exposure can create conditions in which susceptible microorganisms are inhibited while more tolerant organisms survive, potentially contributing to the maintenance and dissemination of resistance. The available literature supports treating antibiotic waste as both a pollution issue and a medicines-governance issue: reducing unnecessary antibiotic use, preventing disposal into general waste or drains, improving wastewater treatment and ensuring appropriate collection are complementary interventions.(11)

COVID-19 impact on medicine consumption

The COVID-19 pandemic intensified several pathways that generate pharmaceutical waste. Demand for medicines and pharmaceutical supplies increased as countries responded to rising infection rates and expanded testing, treatment and protective measures. In developing-country settings, pandemic-related supplies included materials described as toxic or non-degradable, and inadequate disposal could add to existing environmental-health risks.(10)

At the household level, the pandemic was associated with excess prescribing, panic buying, stockpiling and the accumulation of medicines that were never used or later expired. These products may include medicines left by recovered or deceased patients, excess supplies and medicines made unnecessary by changes in treatment.(5)(6) Lockdowns and competing demands on health systems also disrupted routine community take-back programs, leaving unwanted medicines in households for longer periods.(5)

The pandemic therefore created a delayed disposal problem in addition to the immediate increase in healthcare waste. Medicines purchased during a period of uncertainty could remain potent long after they passed their expiry dates, and their eventual release into household or municipal waste may occur without adequate oversight. COVID-19 demonstrated that pharmaceutical-waste systems need continuity plans for emergencies, including reliable collection routes, public guidance and capacity to manage sudden changes in medicine demand.(5)

Review Methodology

This review synthesized existing literature on pharmaceutical waste generation, environmental pathways, health impacts, and regulatory frameworks. A literature search was conducted to identify peer-reviewed articles, scoping reviews, and environmental assessments published up to 2026. Search terms focused on "pharmaceutical waste," "improper disposal," "environmental contamination," "antimicrobial resistance," and "drug take-back programs." Additionally, institutional guidelines and regulatory documents from the World Health Organization (WHO), the US Food and Drug Administration (FDA), the US Environmental Protection Agency (EPA), and India's Central Pollution Control Board (CPCB) were analyzed to compare global waste management frameworks. Selection criteria prioritized publications detailing disposal pathways, ecological and human health impacts, and waste management technologies across household and institutional settings.

2. Pharmaceutical Waste: Definition and Classification

2.1 Definitions of pharmaceutical waste

Pharmaceutical waste includes expired, unused, unwanted, damaged, rejected or contaminated medicines, active pharmaceutical ingredients, medicine containers and materials contaminated with pharmaceutical products. It may be generated during manufacture, storage, distribution, dispensing, administration, use and disposal. It

includes tablets, capsules, syrups, creams, injectables, vaccines, aerosols and eye drops from households, health-care facilities, pharmacies, industries, veterinary institutions and laboratories.(7)(8)(12)

WHO perspective

WHO places pharmaceutical waste within the broader category of health-care waste. It identifies pharmaceutical waste as expired or unnecessary medicines and materials containing or contaminated by medicines. Cytotoxic waste is treated separately because it contains Genotoxic substances, such as some cancer medicines.(12)

US EPA perspective

The US EPA uses a regulatory definition. Waste is hazardous when it is listed by regulation or shows one or more characteristics: ignitability, corrosivity, reactivity or toxicity. Therefore, not every discarded medicine is automatically hazardous under US law. EPA rules cover hazardous pharmaceutical waste from hospitals, clinics, pharmacies, retail facilities and veterinary settings and prohibit sewerage of hazardous pharmaceutical waste.(13)

US FDA perspective

The FDA focuses mainly on the safe disposal of unused and expired medicines. Take-back and mail-back programs are preferred. If these are unavailable, disposal depends on the product: some medicines are on the FDA Flush List, while others should follow household-trash instructions. This is a disposal-guidance system rather than a complete hazardous-waste classification.(14)

Biomedical Waste Management Rules, 2016 and CPCB perspective in India

India's Biomedical Waste Management Rules, 2016 apply to institutions that generate, collect, store, transport, treat or dispose of biomedical waste. The scope includes hospitals, clinics, veterinary institutions, vaccination centres, laboratories, research institutions and educational establishments. CPCB and the relevant State Pollution Control Boards oversee authorization and compliance. Household pharmaceutical waste may require separate municipal, take-back or local arrangements.

2.2 Classification of pharmaceutical waste

Pharmaceutical waste can be classified by source, hazard and dosage form. These categories overlap. For example, a hospital-generated cytotoxic injection is simultaneously hospital waste, hazardous waste, cytotoxic waste and injectable waste.(12)(13)

A. Classification Based on Source

- **Household:** Unused, expired, or unwanted medicines discarded by patients, often mixed with municipal rubbish or flushed into wastewater when take-back services are unavailable. (3,14)
- **Healthcare Facilities (Hospitals & Clinics):** Expired stock, unused ward medicines, contaminated packaging, and residual medicines in vials. This includes antibiotics, cytotoxic drugs, hormones, and infectious waste. (12,15)
- **Pharmacies:** Expired, recalled, or returned stock, and products collected through take-back programs. (15)
- **Pharmaceutical Industry:** Active ingredients, rejected batches, manufacturing residues, and pharmaceutical-containing wastewater. (14,15)
- **Veterinary & Research:** Expired veterinary antibiotics, vaccines, experimental medicines, and contaminated laboratory materials. (7,12)

B. Classification Based on Hazard

- **Hazardous & Cytotoxic:** Waste with toxic, corrosive, reactive, or ignitable properties, including antineoplastic medicines that pose genotoxic threats. (13)
- **Infectious:** Medicines or containers contaminated with blood, pathogens, or infectious materials (often overlapping with sharps waste). (12)
- **Ecologically Disruptive (Antibiotics & Hormones):** Residues that contribute to antimicrobial resistance or interfere with endocrine-regulated biological systems in the environment. (12)
- **Non-Hazardous:** Waste not meeting hazardous criteria and lacking specific biological, chemical, or physical dangers. (12)

C. Classification Based on Dosage Form

- **Solids (Tablets & Capsules):** Oral medicines that must remain contained to prevent accidental access. (16)
- **Liquids & Creams:** Syrups, ointments, and lotions that easily leak and contaminate drains or soil; disposal depends on the active ingredient rather than assuming all liquids can be flushed. (12)
- **Injectables & Vaccines:** Ampoules, vials, and prefilled syringes presenting overlapping pharmaceutical, infectious, and sharps hazards. (14)
- **Aerosols:** Pressurized canisters requiring special handling due to explosion hazards alongside chemical risks.(14)

3. Sources and Improper Disposal Practices of Pharmaceutical Waste

3.1 Sources

Pharmaceutical waste is produced when medicines are manufactured, supplied, prescribed, dispensed, used, stored, or discarded. The major sources are households, hospitals, pharmacies, pharmaceutical industries, and the veterinary sector. Unused, expired, damaged, contaminated, and rejected medicines can enter ordinary waste, sewage, soil, or air when they are not segregated and treated correctly.(7,17)

Household: Households produce pharmaceutical waste mainly from unused, expired, leftover, or damaged medicines. Common disposal routes include throwing medicines into household bins and flushing them into toilets or drains. A global review identified household waste and sewage as the most frequently reported disposal routes for unwanted medicines.(18)

Hospitals: Hospitals generate waste from expired stock, damaged products, unused medicines, returned medicines, and medicines prepared but not administered. They may also produce hazardous pharmaceutical waste and contaminated packaging. In a study of healthcare facilities in Lagos, open burning was reported for 85% of pharmaceutical-waste disposal, while fewer than 10% of facilities had a disposal programme.

Pharmacies: Pharmacies generate waste from expired stock, damaged packages, recalled products, dispensing errors, and medicines that are

not collected. They also play an important role in advising patients about take-back and safe disposal. In Nkubu Town, burning was the common disposal method among community pharmacies.

Pharmaceutical industries: Pharmaceutical industries produce rejected batches, expired raw materials, off-specification products, manufacturing residues, laboratory waste, packaging, and contaminated wastewater. These wastes may be hazardous or non-hazardous, depending on their composition. Industrial waste must therefore be segregated, treated, and disposed of through authorized systems rather than mixed with municipal waste.

Veterinary sector: The veterinary sector produces waste from unused or expired medicines, vaccines, antimicrobials, antiparasitic products, and their packaging. Disposal on farms or in households may involve general waste, burial, burning, drains, or open land. A survey of human and veterinary medication use found that leftover medicines were common and that trash and flushing remained reported disposal routes.(19)

Major sources and pathways of pharmaceutical waste:

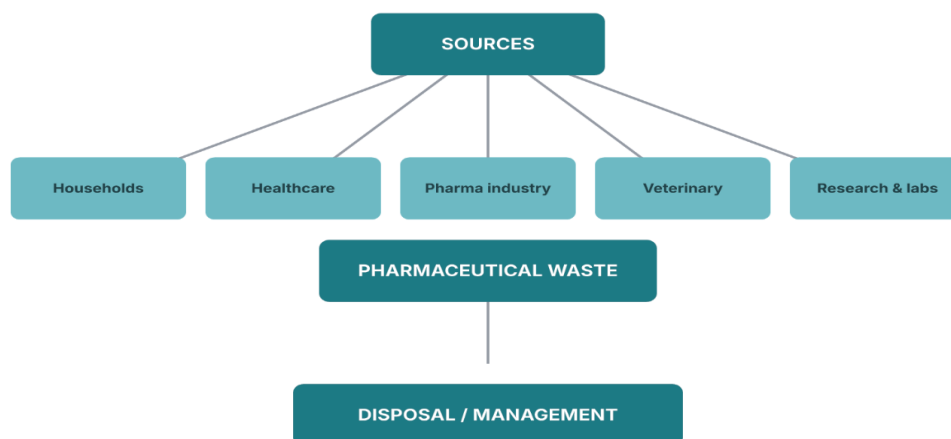


Figure 1. *Pharmaceutical waste from households, hospitals, pharmacies, pharmaceutical industries, and veterinary practice can enter municipal waste, sewage, air, and soil or groundwater, producing landfill, water, air, and soil contamination.*

Pharmaceutical waste arises from households, healthcare facilities, pharmaceutical industry, veterinary services, and research laboratories before entering disposal or management systems.(7,17)

3.2 Improper disposal practices

Improper disposal occurs when pharmaceutical waste is discarded without segregation, collection, treatment, or controlled destruction. The most common practices are throwing medicines into household bins, flushing them into toilets, open burning, mixing them with municipal waste, and illegal dumping or burial. These practices can release active pharmaceutical ingredients into landfills, sewage, air, soil, and groundwater.(7,18)

Throwing into household bins: Medicines placed in household bins are transported with ordinary refuse to landfills or dump sites. Pharmaceutical residues may leach into soil and groundwater, while discarded medicines may be accessed by children, animals, scavengers, or waste workers.(7,20)

Flushing into toilets: Flushing sends medicines directly into sewage and wastewater. Treatment systems may not completely remove all pharmaceutical compounds, allowing residues to reach surface water, groundwater, or public water systems.(7,18)

Open burning: Open burning releases smoke and pharmaceutical residues into the atmosphere and may leave contaminated ash. It is an uncontrolled method that can cause air pollution, particularly when medicines are burned with other waste.

Mixing with municipal waste: Mixing pharmaceutical waste with municipal waste prevents proper identification, segregation, recovery, and treatment. It increases the risk of landfill contamination, scavenging, accidental exposure, and uncontrolled burning.(18)

Illegal dumping: Dumping medicines in open land, drains, pits, or latrines allows pharmaceutical residues to enter soil and groundwater. It can also expose humans and animals to active medicines and makes environmental cleanup difficult.(7)

Disposal method	Environmental impact
Household bin	Landfill and soil contamination; possible leaching and scavenger exposure.(20)
Toilet flushing	Water pollution through sewage, surface-water, groundwater, and public-water contamination.(7)
Open burning	Air pollution caused by smoke and uncontrolled release of pharmaceutical residues.
Mixing with municipal waste	Soil and landfill contamination, scavenging, accidental exposure, and uncontrolled burning.(18)
Illegal dumping	Soil and groundwater contamination with possible exposure of people and animals.(7)

Table 1. *Common improper disposal practices and their consequences*

4. Environmental Pathways and Fate of Pharmaceutical Waste

Pharmaceutical waste can move from disposal sites into soil, groundwater, wastewater, rivers, lakes, and air. Its fate depends on the disposal route, chemical properties, persistence, and treatment efficiency.(21)

4.1 Movement of Pharmaceutical Waste

Improper disposal mainly creates three pathways: landfill, sewage, and open burning. Landfill waste produces leachate; flushed medicines enter sewage; and burning releases smoke, particles, and residues. These contaminants may later reach soil, groundwater, surface water, or air.(22)

4.2 Environmental Fate: After release, a pharmaceutical may be diluted, degraded, transformed, attached to soil or sediment, transported downstream, or taken up by organisms. The outcome varies with solubility, persistence, sorption, and environmental conditions.(22)

4.2.1 Soil and groundwater contamination: Pharmaceutical residues can enter soil through landfill leakage, contaminated ash, wastewater sludge, agricultural runoff, and veterinary waste. Rainwater may carry residues through soil into groundwater or into nearby streams and lakes. Landfill leachate is an important concern because pharmaceuticals may remain in treated leachate and reach surface waters.

4.2.2 Water contamination: Flushed medicines and wastewater discharges can transport pharmaceutical residues to rivers and lakes. Some compounds remain in water, while others attach to sediment or change into metabolites. Continuous sewage inputs can make pharmaceutical residues persist in receiving waters.(21)

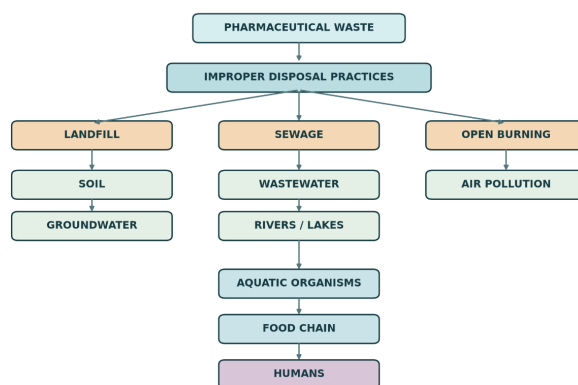
4.2.3 Wastewater-treatment plants: Wastewater-treatment plants remove some pharmaceutical residues, but not all compounds are eliminated. Some substances are degraded or transformed, some remain in sludge, and others pass through in treated effluent to rivers or lakes.(21) Preventing disposal at source is therefore more reliable than depending only on treatment.

4.2.4 Bioaccumulation and aquatic organisms: Aquatic organisms may absorb pharmaceutical residues from water, sediment, or food. Long-term exposure can affect growth, reproduction, development, and behaviour, particularly for biologically active or endocrine-disrupting compounds. Bioaccumulation varies among substances and organisms, so it should be assessed rather than assumed. Antibiotic residues may also contribute to antimicrobial resistance in environmental bacteria.(23)

4.3 Integrated Pathway

The overall pathway is: **pharmaceutical waste → landfill, sewage, or open burning → soil, groundwater, wastewater, rivers/lakes, or air → aquatic organisms → food chain → possible human exposure.** Human exposure is a potential risk, not proof that every detected pharmaceutical causes harm; it depends on concentration, duration, toxicity, and exposure route.(21)

Figure 2. Environmental Pathway and Fate of Improper Pharmaceutical Waste Disposal



5. Environmental and Human Health Impacts of Pharmaceutical Waste

Pharmaceutical waste can affect ecosystems and human health when medicines, residues, or contaminated wastewater enter soil, surface water, groundwater, or air. The severity of the impact depends on the drug, concentration, persistence, exposure duration, and the sensitivity of the exposed organism. Reviews consistently identify ecological effects as better documented than direct human-health effects at environmental concentrations.(24,25)

5.1 Environmental Effects

Water pollution: Pharmaceutical residues may reach rivers, lakes, groundwater, and drinking-water sources through sewage, landfill leachate, industrial effluent, and poorly treated wastewater. Wastewater-treatment plants reduce some compounds but do not remove all pharmaceutical residues, allowing treated effluent to remain an important route into aquatic environments.(26)

Soil pollution: Disposal in landfills, application of contaminated sludge, and industrial releases can introduce pharmaceutical residues into soil. These compounds may remain in the soil, move with water toward groundwater, or affect soil microorganisms and plants. Soil contamination is therefore connected to both terrestrial exposure and later contamination of water resources.(25)

Air pollution: Air pollution may occur when pharmaceutical waste is openly burned or when industrial activities release contaminated dust or vapors. Burning can also produce additional hazardous substances, depending on the drug and combustion conditions. Airborne contaminants may later return to land or water through atmospheric deposition.(27)

Aquatic toxicity: Aquatic organisms can be exposed continuously to low concentrations of pharmaceuticals in water and sediments. Reported effects include altered behavior, growth, development, reproduction, and normal biological function. Endocrine-active compounds are of particular concern because even small exposures may interfere with hormone-regulated processes.(27)

Biodiversity loss: Long-term pharmaceutical exposure can place stress on sensitive species and disturb ecological relationships. Changes in reproduction, development, or behavior may reduce the ability of some populations to survive and reproduce, contributing to wider ecosystem imbalance. Evidence for population-level biodiversity loss is less direct than evidence for toxicity in individual organisms, so this effect should be described as a possible ecological consequence rather than a universal outcome.(26,28)

5.2 Human Health Effects

Direct human health impacts resulting from environmental exposure to pharmaceutical residues remain less certain than ecological effects,

primarily because exposure levels, chemical mixtures, and long-term continuous effects are difficult to measure in human populations.

- **Kidney, Liver, and Cancer Risks:** While the kidneys and liver metabolize medicines, current environmental studies do not establish that typical environmental exposure to pharmaceutical residues causes kidney or liver disease in the general population. Similarly, a direct increase in cancer risk from typical environmental exposure has not been conclusively established, though the presence of genotoxic and cytotoxic compounds in wastewater justifies ongoing risk assessment. (25)
- **Endocrine and Reproductive Disruption:** Endocrine effects are well-documented in aquatic organisms, particularly

concerning compounds that alter reproductive development. However, direct reproductive and endocrine effects in humans from environmental exposure remain a concern but are not yet demonstrated with the same strength as laboratory and ecological findings. (27)

- **Antimicrobial Resistance:** Antibiotic residues in wastewater treatment systems may provide conditions where resistance is maintained or selected, creating concern that environmental resistance could contribute to harder-to-treat infections, though the magnitude of this contribution varies by setting. (28)

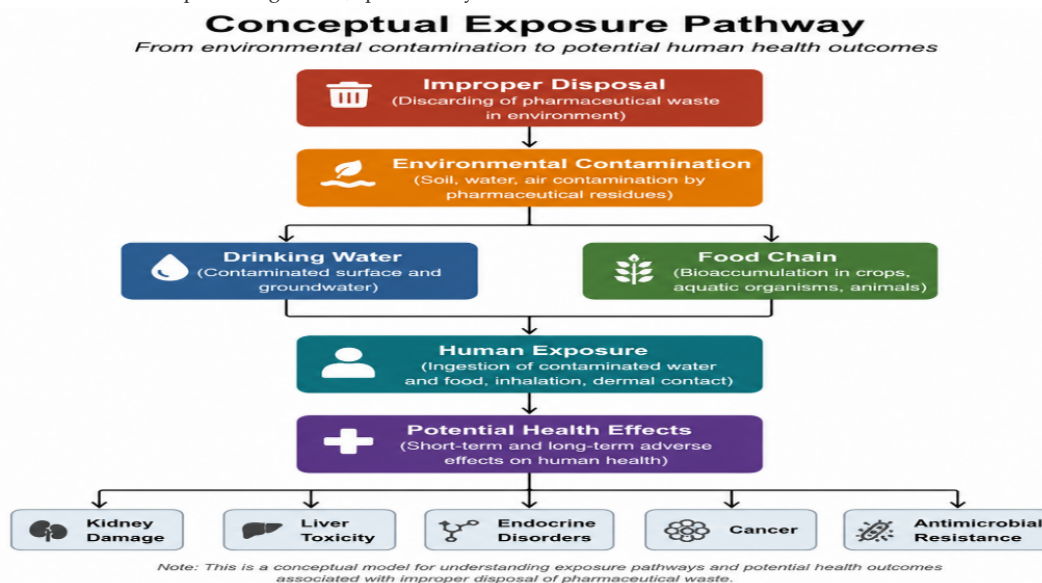


Figure 3. Human Exposure Pathway

6. Waste Management and Regulations for Pharmaceutical Waste

Pharmaceutical waste is not limited to medicines that have passed their expiry date. It also includes unused or damaged products, contaminated materials, drug residues, and waste produced by hospitals, laboratories, pharmacies, and pharmaceutical industries. The way this waste is handled matters because medicines discarded in sinks, toilets, open areas, or ordinary landfills can enter water and soil. Unused medicines may also be taken from waste containers and misused. Antibiotic residues are a further concern because they may contribute to antimicrobial resistance. (7,31)

6.1 Proper Disposal Methods

The first step is segregation. Pharmaceutical waste should be separated from general waste as soon as it is generated. Hospitals and other facilities should identify hazardous medicines, cytotoxic products, contaminated materials, liquids, and sharps, and keep them in secure, leak-proof, labelled containers. Records should be maintained until the waste is handed over to an authorised treatment facility. India's biomedical-waste system specifically emphasizes segregation, colour-coded containers, labelling, transport, and treatment standards. (32)

Incineration uses controlled high temperatures to destroy many solid and semi-solid medicines while reducing their volume. It can be a suitable option when the facility is properly operated and has effective controls for emissions and ash. Open burning is not an acceptable alternative because it can release hazardous substances into the air. A review of pharmaceutical-waste technologies considered incineration a comparatively sustainable method for many solid and semi-solid

wastes, although the final choice should depend on the waste's form and hazard. (33)

Encapsulation means enclosing pharmaceutical waste in a stable material, often a cement-based matrix, before it is placed in an engineered disposal site. This reduces direct contact with the waste and makes scavenging or leakage less likely. It does not destroy the active drug, however, so the encapsulated material must remain stable over time. For this reason, encapsulation is better viewed as a controlled containment method than as a complete destruction process. The review literature generally considers it less sustainable than incineration for many solid and semi-solid wastes. (33)

Inertization is a related approach in which tablets, powders, or other solid medicines are mixed with binding materials to form a stable mass with lower leachability. It can be useful where incineration is unavailable or unsuitable. The process still requires secure handling, quality checks, documentation, and disposal in an engineered landfill. Since inertization immobilizes the medicine rather than removing it, it should be chosen only after considering the waste composition and local disposal conditions. (33,34)

Drug take-back programs give households and healthcare workers a safe way to return unwanted medicines through pharmacies, authorised collection points, mail-back services, or community collection events. They reduce flushing and ordinary household disposal and also limit the amount of medicine available for accidental poisoning or misuse. These programs work best when collection points are convenient, the public is informed, transport is secure, and the collected material has a clearly defined treatment route. Evidence from one community program suggested public- and environmental-

health benefits, but it could not prove that the take-back events alone caused those improvements.(35)

6.2 Regulations and Institutional Responsibilities

Different regulatory bodies prioritize varying aspects of pharmaceutical waste management:

- **WHO:** Focuses on safe disposal in humanitarian and healthcare settings, heavily supporting risk-based classification and controlled, high-temperature incineration for solid/semi-solid wastes. (36)
- **US FDA:** Primarily targets household waste, emphasizing drug take-back locations and mail-back programs. It utilizes a specific "Flush List" for high-risk medicines when take-

back is unavailable, advising that non-listed medicines be mixed with unappealing substances and trashed. (14)

- **US EPA:** Regulates institutional hazardous waste from healthcare and pharmacies, strictly prohibiting the sewerage (flushing) of hazardous pharmaceuticals to protect water systems. (37)
- **India (Biomedical Waste Management Rules, 2016 & CPCB):** Mandates strict color-coded segregation, specific container labeling, and authorized transport for institutional biomedical waste, relying on common biomedical-waste treatment facilities (incinerators and autoclaves). (32,38)

Regulatory Body	Primary Focus Area	Main Disposal/Management Recommendation
WHO	Global healthcare & emergency settings	Risk-based segregation; controlled high-temperature incineration
US FDA	Post-consumer/Household waste	Drug take-back programs; specific "Flush List" guidance (14)
US EPA	Institutional hazardous waste	Strict hazardous-waste segregation; prohibition of sewerage (37)
India (CPCB)	Healthcare, research, & veterinary facilities	Strict color-coded segregation, labeling, and authorized facility treatment (32,38)

Table 2. Comparison of Pharmaceutical Waste Management Guidelines

7. Research Gaps and Future Perspectives

7.1 Research Gaps

Although pharmaceutical waste is increasingly recognised as an environmental and public-health issue, important gaps remain in both knowledge and implementation.

Poor public awareness. Many people still do not know how to dispose of unused or expired medicines. As a result, medicines may be flushed, thrown into ordinary household waste, or stored for long periods at home. These practices can allow pharmaceutical residues to enter water systems and can leave medicines available for accidental poisoning or misuse. Public awareness is also important because take-back programs cannot work effectively if people do not know where collection points are located or what materials they accept.(7,35,39)

Lack of monitoring. Monitoring is often insufficient across the pharmaceutical-waste chain. In many settings, there is limited information on how much waste is generated, where it is transported, which treatment method is used, and whether residues remain after treatment. Environmental monitoring is also uneven, particularly for pharmaceutical compounds in wastewater and surface water. Without reliable data, it is difficult to compare treatment technologies, identify high-risk waste streams, or measure the success of take-back programs. One assessment of a community take-back program reported possible public- and environmental-health benefits but could not show that the program alone caused those improvements, illustrating the need for stronger monitoring designs.(35)

Weak implementation. Regulations may be available, but their practical implementation is often limited by inadequate infrastructure, insufficient training, poor segregation, and weak coordination

between healthcare facilities and treatment providers. In India, reviews of biomedical-waste management identify lack of awareness and inadequate infrastructure as continuing challenges. Effective rules therefore require inspections, staff training, clear responsibility, proper record keeping, and reliable access to authorised treatment facilities.(32,38)

Limited research in developing countries. Much of the available evidence focuses on selected countries, facilities, or compounds. There is less information from low- and middle-income settings about household disposal behaviour, pharmaceutical-waste quantities, treatment performance, costs, and long-term environmental effects. This makes it difficult to know whether guidance developed in countries with advanced waste infrastructure can be applied directly elsewhere. Research in developing countries should include local waste pathways, informal waste activity, rural and urban differences, and the capacity of pharmacies, hospitals, municipalities, and common treatment facilities. Existing reviews also describe data gaps in take-back participation and call for more objective evidence on treatment sustainability.(33,35)

7.2 Future Perspectives

Green pharmacy. Future pharmaceutical practice should aim to reduce waste throughout the medicine life cycle. This includes better inventory control, smaller or more appropriate purchasing quantities, prevention of unnecessary expiry, environmentally responsible packaging, and safe opportunities for reuse or re-dispensing where legally and clinically appropriate. Extended producer responsibility and life-cycle assessment can help manufacturers and policymakers consider environmental impacts from production through disposal.(33)

Sustainable disposal technologies. No single treatment method is suitable for every pharmaceutical waste stream. Future systems should match treatment to the medicine's dosage form, chemical properties, and hazard. Controlled incineration may remain useful for selected solid and semi-solid wastes, while encapsulation and inertization can provide containment when destruction is not practical. Their long-term performance should be assessed using measurable indicators such as emissions, leachability, energy use, cost, and residual toxicity. Current review evidence calls for more objective comparisons rather than relying mainly on subjective judgments of sustainability.(33,34)

Public awareness campaigns. Governments, pharmacists, hospitals, schools, and community organisations should provide simple and repeated information about safe disposal. Campaigns should explain what should never be poured into a sink or toilet, where medicines can be returned, and how to handle products for which no take-back option is immediately available. Collection points must be convenient and trusted. Evidence from take-back research suggests that participation is influenced by practical factors such as the distance people are willing to travel, so local access should be considered when programs are designed.(14,35)

AI-based waste tracking. As a future practical option, digital systems could improve traceability from the point where pharmaceutical waste is generated to its final treatment. Barcode or QR-code records, electronic manifests, geographic information systems, and artificial-intelligence tools could help predict waste volumes, verify collection, and identify gaps in transport or treatment records. These systems should be designed with clear data standards, privacy protections, human oversight, and access for smaller healthcare facilities. AI should support regulatory monitoring, not replace professional responsibility or physical verification. This proposal follows the existing emphasis on records, monitoring, infrastructure, and awareness in biomedical-waste implementation.(32,38)

8. Conclusion

Pharmaceutical waste originates from several connected sources, including households, hospitals, pharmacies, laboratories, veterinary services, pharmaceutical manufacturing, and healthcare research. It includes expired, unused, damaged, contaminated, or rejected medicines, as well as residues and materials produced during handling and treatment. The problem becomes more serious when these waste streams are mixed with ordinary municipal waste, flushed into drains, dumped in landfills, burned in uncontrolled conditions, or recovered from waste by unauthorised persons.(7,31)

Improper disposal allows active pharmaceutical ingredients to move into wastewater, surface water, groundwater, soil, and air. Even when concentrations are low, repeated release can create continuing environmental exposure. Reported concerns include effects on aquatic organisms, changes in wildlife physiology or behaviour, and the possible contribution of antibiotic residues to antimicrobial resistance. Unused medicines also create direct human-health risks through accidental ingestion, intentional misuse, poisoning, and diversion. The full long-term effects of pharmaceutical mixtures and chronic low-level exposure are not yet fully understood, which makes prevention and responsible disposal preferable to relying on environmental dilution.(7,31)

Effective management begins with reducing avoidable waste and segregating pharmaceutical materials at the point of generation. Secure storage, clear labelling, authorised transport, accurate records, and trained staff are essential controls. Take-back programs are especially valuable for household medicines, while treatment technologies should be selected according to the waste's form and

hazard. Controlled incineration can be appropriate for selected solid and semi-solid wastes; encapsulation and inertization can reduce contact and leaching when the waste is immobilised and placed in an engineered disposal system. These methods must be supported by emission controls, leachability testing, monitoring, and enforcement.(32,33)

Regulatory systems provide the structure for these measures. WHO guidance supports safe, risk-based disposal; FDA guidance prioritises take-back and mail-back options for most household medicines; EPA requirements address hazardous pharmaceutical waste from regulated facilities; and India's Biomedical Waste Management Rules, 2016, together with CPCB guidance, establish requirements for segregation, colour coding, transport, treatment, and monitoring. Regulations are effective only when facilities have the infrastructure, training, funding, and oversight needed to follow them.(14,32,37,38)

Future progress will depend on combining green-pharmacy principles with sustainable treatment technologies, accessible public-awareness campaigns, stronger environmental monitoring, and digital systems for tracking waste. Research should give greater attention to developing countries and should evaluate not only whether a method destroys or contains pharmaceutical waste, but also its cost, energy use, emissions, leachability, and suitability for local conditions. A coordinated approach across manufacturers, healthcare professionals, regulators, waste-treatment operators, and the public is necessary to reduce the risk of continuing environmental contamination and human-health impacts.(7,33)

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