



Original Article

Eco-friendly strategies for pharmaceutical waste: Integrating green chemistry into management

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Abstract

The management of pharmaceutical waste is an escalating global issue that intersects with environmental protection and public health. Increased pharmaceutical production and use have led to significant waste accumulation from healthcare facilities, households, and industry. When improperly handled, substances such as expired medicines and contaminated materials pose dangers like pollution of water and soil, growth in antimicrobial resistance, and potential long-term health concerns such as cancer. In particular, the release of active pharmaceutical ingredients (APIs) into ecosystems has disrupted aquatic life and is more severe in low-resource regions due to inadequate waste regulation and disposal infrastructure. While disposal strategies like incineration, landfilling, and drug return programs are in place, many face challenges due to outdated technology and weak enforcement. Sustainable alternatives, including green pharmacy practices, advanced treatment systems, and increased community involvement, are now essential. This article examines global and local approaches to pharmaceutical waste management and advocates for a multi-stakeholder effort to ensure eco-friendly and safe practices are integrated into healthcare systems. Pharmaceutical waste management has become a pressing global issue, closely linked to environmental sustainability and public health. The rapid growth in pharmaceutical production and consumption has led to a rise in waste generation from sources such as hospitals, households, pharmacies, and manufacturing units. Improper disposal of expired drugs, manufacturing residues, and contaminated medical supplies poses severe risks, including water and soil pollution, antimicrobial resistance, and long-term health hazards like cancer.

Active pharmaceutical ingredients (APIs) released into the environment can disrupt ecosystems, particularly aquatic life. This problem is more acute in developing regions, where weak healthcare infrastructure and limited regulatory oversight exacerbate the challenge. While disposal methods such as incineration, landfilling, and drug take-back programs are in use, their effectiveness is often compromised by inadequate technology and enforcement. To address these concerns, the adoption of sustainable strategies—such as green pharmacy, reverse logistics, public awareness initiatives, and advanced waste treatment technologies like high-temperature incineration and oxidation processes—is essential. A collaborative approach involving regulatory bodies, healthcare professionals, pharmaceutical companies, and the public is critical for ensuring safe, effective, and environmentally responsible pharmaceutical waste management.

Keywords: Pharmaceutical Waste, Waste Management, Environmental Pollution, Drug Disposal, Active Pharmaceutical Ingredients (APIs), Expired Medications, Healthcare Waste.

Introduction

Pharmaceutical waste, generated from diverse healthcare activities such as compounding, medication administration, and handling of medical supplies, presents significant management challenges. This waste includes expired, unused, and contaminated drugs, as well as associated materials like gloves and IV equipment. Historically, improper disposal practices—such as flushing drugs down the drain—have led to environmental contamination, particularly in aquatic ecosystems. While small quantities from households may be discarded with precautions, large-scale waste from facilities requires strict handling to prevent exposure and environmental harm. Although solid waste is easier to manage, liquid waste poses greater containment difficulties. The return of unused medications to suppliers offers a more sustainable solution. Growing awareness of these impacts calls for improved regulatory policies, stakeholder education, and responsible disposal strategies to ensure effective pharmaceutical management of waste.

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Pharmaceutical waste, if not managed responsibly, can introduce harmful chemicals into the environment. Hospitals and clinics regularly dispose of large quantities of pharmaceuticals—some of which enter the sewage system untreated. Improper disposal allows active ingredients to infiltrate ecosystems and affect aquatic organisms and potentially humans through bioaccumulation in food chains. Several studies have reported water contamination due to long-term pharmaceutical disposal, leading to serious public health issues. Furthermore, environmental exposure to these substances may interfere with wildlife reproduction and development. These environmental threats reinforce the importance of implementing and following strict pharmaceutical waste disposal procedures.

- At some point in their life, almost everyone has visited a hospital or clinic. Hundreds or perhaps thousands of medications are used daily at these clinics or hospitals, even the tiniest ones. Have you ever pondered the fate of a large portion of this pharmaceutical waste?
- Waste from pharmaceuticals can be quite harmful. To properly dispose of it, extra steps are needed because it is completely different from ordinary waste. It is a conglomeration of many waste processes produced in healthcare facilities. This waste is often drained in hospitals, with the exception of some agents that need to be placed in a waste incinerator. Because of the need of properly disposing of pharmaceutical waste, stringent laws have been implemented.
- Because of the hazardous nature of the trash, several techniques are employed to dispose of it. Furthermore, new techniques are always being developed to replace outdated ones in order to guarantee safety and lower the risk associated with disposal. Let's review some more of the reasons why appropriate disposal of pharmaceutical waste is so crucial.
- The presence of substances that are deemed hazardous to a healthy environment is one of the primary reasons that this type of garbage needs to be disposed of appropriately. Furthermore, pharmaceutical compounds often find their way into aquatic habitats through the sewage system because the majority of them are not eliminated from the waste water. Through food chains, this can occasionally have an adverse effect on marine life and endanger humans.
- Contaminated water sources are among the most serious outcomes of poor pharmaceutical waste disposal practices (Verma, 2017). Over the years, several water sources have been affected, raising concerns about the health implications for communities relying on these supplies for daily use.
- Among the greatest issues of not disposing of the waste-water from pharmaceutical waste properly is the affect it is having on wildlife. Studies suggest that pharmaceutical pollutants in aquatic environments may disrupt reproductive cycles in fish and other marine species, potentially contributing to declining populations or even species extinction in some regions.
- The improper handling of pharmaceutical waste is a mounting concern that demands immediate attention

(Smith et al., 2021). These substances can infiltrate ecosystems via various channels such as leaking landfills, untreated wastewater, and damaged sewage systems. This not only pollutes the environment but also increases the risk of long-term exposure to harmful chemicals for both wildlife and humans. This is why it is completely important to make sure they are disposed of and in the safest way possible

Pharmaceutical waste is generated from various stages of medical and pharmaceutical activities, including manufacturing, prescription, and disposal. It can be broadly categorized as solid waste—such as expired pills, syringes, and packaging—and liquid waste, including drug residues and solvents. Waste sources include healthcare facilities, pharmacies, households, and production plants. Based on composition and risk, pharmaceutical waste is classified into several categories: hazardous waste (e.g., flammable or toxic chemicals), non-hazardous waste (e.g., slightly contaminated packaging), and specialized chemo waste from cancer treatments. Biomedical waste, often associated with pharmaceutical waste, includes infectious materials, pathological waste, and genotoxic substances, all of which require special handling to prevent harm to humans and the environment.

1. Types of Waste from Pharmaceuticals Unused or expired medications, contaminated objects (gloves, IV bags), sharps (needles, scalpels), and empty medicine containers are all considered solid waste. Unused liquid pharmaceuticals and byproducts of manufacturing processes, such as chemical sludge and tainted solvents, are examples of liquid waste. Biomedical Waste: This category includes waste products like infectious or chemical waste that are produced during diagnosis, treatment, or research.

2. Sources of Pharmaceutical Waste

Healthcare facilities (hospitals, clinics, pharmacies)

Patient-discarded medications

Pharmaceutical manufacturing and compounding operations

3. Classification of Waste

Hazardous Waste: Includes listed (commercial chemical products) and characteristic (ignitable, corrosive, reactive, toxic) wastes.

Non-Hazardous Waste: Poses no significant risk but may contain minimal hazardous components; requires careful management.

Chemo Waste: Contains cytotoxic drugs used in cancer treatment, highly hazardous due to genotoxic properties.

4. Biomedical Waste Subcategories

Infectious Waste: Contains pathogens (e.g., contaminated materials from surgeries).

Pathological Waste: Includes human tissues, blood, body parts.

Genotoxic Waste: Contains substances like chemotherapy drugs that can cause genetic damage.

Chemical Waste: Includes toxic, flammable, or reactive laboratory chemicals.

Other types: Heavy metal waste, radioactive waste.

Pharmaceutical waste disposal in India follows a structured framework guided by national biomedical waste regulations. Several treatment techniques are used:

- **Incineration:** A high-temperature combustion process that reduces pharmaceutical waste volume and neutralizes harmful components. Though effective, it emits pollutants and requires secure ash disposal.
- **Autoclaving:** Waste is sterilized using pressurized steam, often used for microbial decontamination. It is environmentally safer but limited in scope for chemical waste.
- **Microwaving:** Electromagnetic waves heat and neutralize infectious materials; it is energy-efficient and suitable for specific waste types.
- **Chemical Disinfection:** Suitable for liquid waste and contaminated instruments. The process depends on chemical concentration and exposure time but requires caution due to potential toxicity.
- **Deep Burial:** Used in rural or low-population areas, where waste is placed in deep trenches lined with lime and covered with soil.
- **Secure Landfilling:** Waste is sealed in secure sites to prevent leaching. Effective but requires environmental safeguards.
- **Encapsulation & Inertisation:** Waste is immobilized in drums using cement or lime mixtures. This reduces the mobility of hazardous compounds and is cost-effective for stable disposal.
- **Sewer Disposal:** Allowed for only limited non-toxic liquid waste. Regulatory oversight is required to ensure public safety and environmental protection.

These methods vary in complexity and environmental impact, highlighting the need for technology selection based on local capacity and risk level.

1. Incineration:

One form of disposal is incineration, which involves burning solid garbage to produce residue and gaseous products. Solid waste management and waste water management, which includes solid waste, can benefit from this technique. During this phase, the volume decreases by about 20 to 30 percent. Thermal treatment is another name for it. Incinerators transform waste materials into thermal energy, gas, steam, and ash. Industry uses incineration on both a small and large scale. Waste that is solid, liquid, or gaseous is disposed of with it. It is acknowledged as a feasible way to get rid of hazardous trash. Because it releases gaseous contaminants, it is a controversial technique of garbage disposal.

Pressurised gas containers, significant quantities of chemical waste, garbage processed with halogenated chemicals, plastic materials containing halogens like polyvinyl chloride, waste containing mercury and cadmium, and radiographic waste are among the items that incineration is not appropriate for. Incinerator ash needs to be dumped in safe landfills. This approach is connected with a highly skilled operator.

2. **Autoclaving:** To eradicate microorganisms, biomedical waste is directly exposed to saturated steam in a pressure vessel at a certain temperature and time. BMW has established guidelines for safe disinfection, including minimum autoclave temperature, pressure, and residence duration. Autoclaving generates garbage

that can end up in landfills along with other municipal rubbish. There is a wastewater treat that must be disposed of with the proper controls. Operating a medium-investment, medium-operating autoclave requires a skilled technician.

3. **Microwaving:** Microwave treatment offers a low-energy, cost-effective solution for neutralizing infectious waste using electromagnetic radiation (NIH, 2021). While it is energy-efficient and cost-effective, the method does require trained personnel and may be limited by equipment reliability, such as frequent malfunctioning of shredders.
4. **Chemical disinfection:** This technique destroys or inactivates microorganisms and is mostly used to treat liquid waste, such as blood, faeces, urine, and strong antioxidants like aldehyde and phenol chemicals. Chemical disinfection is a common practice for treating biohazardous materials like used sharps and lab cultures (Tiwari & Kadu, 2013). The effectiveness of chemical disinfection depends on several factors including the type of chemical used, its concentration, and the duration of exposure to the waste. Because chemical disinfection is harmful, it cannot be released into surface water and is not permitted in significant quantities in sewers. The user should exercise caution when performing the disinfection process because it can have dangerous consequences.
5. **Deep burial:** For less urbanized regions, deep burial remains a practical method for pharmaceutical waste disposal, following safety guidelines (Bio-Medical Waste Rules, 1998). This involves digging a trench approximately two meters deep, filling it halfway with biomedical waste, covering it with lime, and then sealing it with soil to prevent contamination.
6. **Secure land filling:** Typically, deposited garbage is covered to keep rodents (such mice or rats) away and compacted to boost its density and stability. According to the biomedical waste rule, incinerator ash, solid chemical waste, and leftover medications and cytotoxic chemicals must be disposed of in secure landfills. Secure land filling is the process of using land filling to dispose of hazardous materials and solid waste. The majority of nations use secure property for landfills, which are located on undeveloped terrain outside of cities. Effective, hygienic, and cost-effective land filling is achieved by careful planning and management. The environment may be negatively impacted by improper management. The byproduct of this process, which is primarily carbon dioxide or methane, is one of its drawbacks. Organic waste breaks decomposed aerobically to produce gas. Because it is a greenhouse gas, gas can cause smell issues. Modern land filling techniques include leach materials like clay and plastic liner. Gas extraction from landfills is one of the methods. In order to produce power, gas is pumped out of the ground via perforated pipes.
7. **Waste immobilisation:** encapsulation: This technique immobilises pharmaceutical solid waste in a steel or plastic drum. Drums should be completely cleaned and free of any explosive or dangerous materials. Drums

are 75% full of solid or semi-solid material. The remaining 25% is made up of media, such as sand, cement, plastic foam, or cement/lime mixture. Once drums are 75% full, add a combination of cement, lime, and water in a weight ratio of 15:15:5. Then, fill the drums to the top. Sometimes more water is added to modify the consistency of mixture. Spot or seam welding is used to seal steel drums. Fresh municipal solid garbage is spread over sealed drums that are positioned at the landfill's base.

8. **Waste immobilisation:** Inertisation: Inertisation is a type of encapsulation in which the pharmaceuticals' paper, cardboard, and plastic packaging are removed. Pills must be taken out of their blister packaging. After that, the medicinal ingredients are pulverised and combined with cement, lime, and water to create a uniform paste. Workers must be protected by masks and protective clothes since dust might be a threat.

The paste is then decanted into the regular urban rubbish after being delivered in its liquid state by a concrete mixer truck to a landfill. In the municipal solid waste, the paste then solidifies into a bulk. Simple equipment can be used for the procedure, which is reasonably priced. The primary necessities are a concrete mixer, cement, lime, and water sources, as well as a grinder or road roller to smash the medications.

9. **Sewer:** A limited number of certain medications, such as liquids like syrups and intravenous fluids, are diluted with water and subsequently flushed into sewers without having a significant negative impact on the environment or public health. Small amounts of antiseptics or diluted liquid medications are discharged in swift-moving waterways. In cases where sewers are in poor condition or have been destroyed by conflict, the help of a hydro geologist or sanitary engineer may be necessary. **Biomedical Waste:** A Classification System Biomedical waste is the term for the solid or liquid waste produced during the manufacture or testing of biological material, as well as during the diagnosis, treatment, and immunisation of humans or animals.

The World Health Organization (WHO) indicates that around 85% of waste generated by hospitals is non-hazardous, though the remaining waste poses significant risks (WHO, 2019). However, the remaining waste includes about 10% that is infectious and around 5% that may contain toxic substances such as formaldehyde or methyl chloride, necessitating careful disposal. HIV and Hepatitis B or C viral transmission are the primary issues with infectious trash in this case. Consequently, illness is spread by syringes and needles. A hospital's wards, delivery rooms, emergency and outpatient departments, operating rooms, labs, and chemical and pharmaceutical shops are the primary contributors of biomedical waste. Patients and their guests, waste management facility staff and scavengers, and healthcare facility employees (physicians, nurses, health care assistants, maintenance staff, and support staff for waste handling, transportation, and laundry) are among the people who could be exposed to BMWs. Eco-Friendly Removal To prevent drugs from harming the environment, it's critical to

properly dispose of any unused or expired medications. Antimicrobial resistance (AMR) could be exacerbated by the environmental presence of antibiotics. Resistance genes may emerge in the environment and perhaps spread to dangerous bacteria when antibiotic residues are present. Furthermore, there is concern that antibiotic residues in the environment may facilitate the exchange of resistance genes between environmental and pathogenic microbes, potentially weakening the effectiveness of essential antimicrobial therapies (Gyesi et al., 2022). Moreover, improper drug disposal can contaminate soil and water supplies, endangering ecosystems and public health. This section covers key tactics for disposing of medications in an environmentally responsible manner.

5.1 Programs for Refunding Unused Medicines Several neighbourhood pharmacies and medical facilities provide medicine take-back through neighborhood-based programs. Evidence from the U.S. shows that pharmacy-based kiosks can significantly boost proper medication returns, improving environmental safety (Ehrhart et al., 2020). National collection events, like the U.S. Drug Enforcement Administration's National Prescription Drug Take Back Day, helped prevent environmental pollution by collecting over 745,000 pounds of unneeded pharmaceuticals in April 2023 alone (DEA, 2023). According to a SafeMed pilot program, mail-back initiatives provide a practical option for places with limited access to collection stations, increasing correct disposal rates by 30% in rural towns (Ehrhart et al., 2020).

5.2 Appropriate Consumer Disposal Guidelines Educating customers on appropriate disposal techniques is crucial. Public awareness initiatives can, in fact, significantly impact disposal behaviour, and proper labelling of pharmaceutical packaging improves disposal behaviour (Kinrys et al., 2018). Additionally, it has been demonstrated that using readily accessible internet resources with disposal information to guide customers towards appropriate disposal procedures works well.

Formulations for Biodegradable Pharmaceuticals Photodegradable formulations and naturally disintegrating medications, often known as enzymatically degradable medications, are new study areas. Drugs that breakdown when exposed to sunlight are being developed by some scientists, while others are studying medications that degrade quickly once evaluated in the presence of specific environmental enzymes (Leder et al., 2021). Although there has been a lot of progress in the area of green pharmaceutical disposal, there are still obstacles to be addressed. These include making sure that take-back programs are accessible to a large number of people, dealing with the disposal of liquid medications, and creating sophisticated, affordable wastewater treatment technologies for smaller communities. In order to better safeguard the environment, pharmaceutical disposal procedures must be maintained by additional study, policy creation, and public education.

Conclusion:

Pharmaceutical waste presents a growing threat to environmental integrity and public health due to the



increasing presence of active pharmaceutical ingredients (APIs) in soil and water systems. Current waste management practices remain insufficient, largely due to regulatory gaps, limited public awareness, and inadequate treatment infrastructure. The persistence of these pollutants, even at low concentrations, underscores the urgency of implementing effective and coordinated strategies. While advancements in green chemistry, sustainable packaging, and responsible disposal methods are promising, their widespread adoption is hindered by economic, technological, and regulatory barriers. A comprehensive, multi-stakeholder approach is essential—requiring collaboration among governments, industry, healthcare professionals, NGOs, and the general public. To safeguard both human and environmental health, pharmaceutical waste management must become an integral component of sustainable healthcare systems. This transition demands clear policy directives, robust enforcement mechanisms, public engagement, and continued investment in research and innovation. Without decisive and unified action, the environmental and health risks posed by pharmaceutical pollution will continue to escalate.

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