

Role Of Startups And Student Innovations In Pharmaceutical Waste Management: A Global Review Of Sustainable Practices

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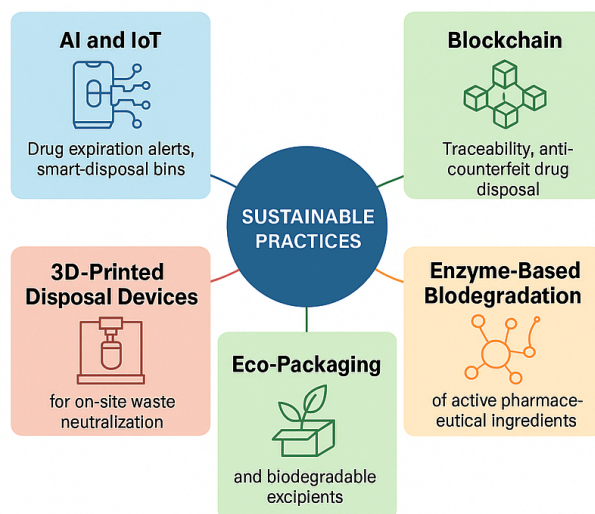
ABSTRACT

Background: Pharmaceutical waste presents a considerable risk to both environmental and human health due to inadequate disposal methods, resulting in problems like water pollution and the rise of antimicrobial resistance. **Methodology:** This review explores the significant contributions of startups and student-led initiatives in promoting sustainable management of pharmaceutical waste worldwide over the last decade (2015–2025). Various technological innovations, such as AI and IoT-enabled smart bins, blockchain systems for traceability, enzyme-driven biodegradation, and 3D-printed neutralization devices, are examined for their efficacy and practicality. **Results and Discussion:** The review underscores academic efforts like green pharmacy research, awareness initiatives on campuses, and innovation competitions such as the Smart India Hackathon. Despite these advancements, obstacles such as inconsistent regulations, financial challenges in under-resourced areas, and a lack of public involvement persist. **Conclusion:** This review calls for a unified global policy approach, the incorporation of environmental education into pharmacy programs, and enhanced collaboration among public, private, and academic sectors to expand sustainable strategies in the management of pharmaceutical waste.

KEYWORDS: Pharmaceutical waste management; Startups, Student innovation; Green pharmacy, AI in waste disposal, Sustainable healthcare

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Role of Startups and Student Innovations in Pharmaceutical Waste Management: A Global Review of Sustainable Practices and Case Studies



INTRODUCTION

Pharmaceuticals, essential for enhancing health outcomes worldwide, have become a significant yet frequently ignored source of environmental pollution. The rapid increase in pharmaceutical manufacturing, spurred by extended life expectancy, the prevalence of chronic illnesses, and greater global access to medicine, has led to an unparalleled production of waste. Expired medications, unused prescriptions, remnants from manufacturing, and the disposal of APIs all contribute to environmental contamination, bioaccumulation, and the rise of AMR [1]. In contrast to typical municipal waste, pharmaceutical waste poses distinct risks—its intricate chemical makeup, biological activity, and longevity in the environment necessitate specialized management approaches. Waste disposal methods today remain inconsistent, showing significant differences between developed and developing areas. In numerous low- and middle-income nations, practices such as open dumping and the release of wastewater from pharmaceutical companies are still prevalent, resulting in soil, surface water, and groundwater contamination [2]. Even in nations with stringent waste management laws, there are ongoing issues, such as improper disposal by households, inadequate take-back initiatives, and restricted traceability in international supply chains. The effects go further than just ecological harm—long-lasting traces of pharmaceuticals have been found in

drinking water, marine organisms, and crops, sparking concerns about public health and food safety [3]. In the past few years, the intersection of technological advancements, scholarly research, and entrepreneurial initiatives has started to transform the way pharmaceutical waste is managed. New companies are developing scalable solutions like AI-based predictive inventory systems, blockchain technology for supply chain transparency, and bioremediation methods for treating wastewater [4]. Educational institutions are enhancing these initiatives with awareness campaigns, community drug-return initiatives, and research focused on environmentally friendly drug synthesis. The application of green chemistry principles in pharmaceutical production—focusing on solvent-free processes, biocatalysis, and the use of renewable energy has the potential to minimize environmental impacts right from the source [5]. Nonetheless, the shift towards sustainable management of pharmaceutical waste is quite complex. There are considerable obstacles to overcome: the lack of internationally standardized eco-labeling, the high expenses associated with implementing clean technologies, strict regulatory requirements, and societal reluctance to return unused medications. Tackling these issues necessitates a coordinated, multi-sector strategy that unites industry, regulators, academia, and the general public. In addition, due to the fundamentally global character of pharmaceutical manufacturing and distribution, it is vital to

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engage in international cooperation to establish standardized protocols, ensure traceability systems, and develop capacity-building initiatives [6]. This review explores the various challenges and potential avenues for future progress in the sustainable management of pharmaceutical waste. By assessing the contributions of startups, academic projects, policy changes, and new technologies, it highlights that sustainable waste management has transcended being merely an environmental issue. It is now a critical matter of public health on a global scale. The necessary tools and knowledge are available; what is still needed is a unified determination to achieve systemic transformation.

PHARMACEUTICAL WASTE MANAGEMENT CURRENT PRACTICES AND GAPS

The conventional methods for disposing of pharmaceutical waste include incineration, landfilling, and flushing down the sewer. However, all of these techniques pose considerable risks to the environment and public health. Incineration is efficient in reducing waste volume, but it can emit harmful substances like dioxins and furans, particularly when not done correctly. Disposing of waste in landfills and through sewage systems frequently leads to the leaching of APIs into groundwater or surface waters, which adds to environmental pollution and fosters antimicrobial resistance [7]. For example, traces of Carbamazepine, a common antiepileptic medication, have been found in treated wastewater and even in drinking water sources because of its significant environmental durability and resistance to standard treatment methods [8]. A study conducted by The Bureau of Investigative Journalism in 2017 found elevated concentrations of ciprofloxacin and Sulfamethoxazole in water bodies close to pharmaceutical centers in India, particularly in Telangana and Andhra Pradesh, raising alarm about the increasing prevalence of antibiotic-resistant bacteria in aquatic environments [9]. In 2020, a case was brought before the National Green Tribunal against pharmaceutical firms in Baddi, Himachal Pradesh, for contaminating the Sirsa River by releasing untreated pharmaceutical waste [10]. A study published in *Infection* reported that lakes in Hyderabad exhibit significantly elevated concentrations of antibiotics, including β -lactamase and carbapenemase residues, with some measurements exceeding recommended environmental safety thresholds by up to three orders of magnitude [11].



Figure 1: Challenges and future directions in eco-labelling and sustainability in pharmaceuticals

Countries like Germany and the United Kingdom have implemented strict regulations requiring the disposal of hazardous pharmaceutical waste through high-temperature incineration plants that feature state-of-the-art emission control technologies. In comparison, countries with LMICs like India, Bangladesh, and Nigeria frequently face persistent issues such as weak regulatory enforcement, insufficient infrastructure, and a lack of financial resources, all of which impede the proper management of pharmaceutical waste (OECD, 2020). While certain major pharmaceutical companies e.g., Dr. Reddy's, Cipla, Sun Pharma have begun to implement green chemistry principles [12].

Key Gaps in Current Practices

• Lack of segregation Inadequate Segregation of Hazardous Waste

The lack of stringent separation protocols between hazardous and non-hazardous pharmaceutical waste plays a major role in increasing environmental and occupational risks. For instance, expired cytotoxic medications such as cyclophosphamide, methotrexate, and doxorubicin continue to exhibit carcinogenic, mutagenic, and teratogenic effects; if not adequately segregated and incinerated at high temperatures ($\geq 1200^{\circ}\text{C}$), their disposal as hazardous pharmaceutical waste poses serious threats to both human health and environmental safety [13].

• Low Public Awareness and Improper Disposal Behaviors

Research carried out in different cities across India indicates that many households either dispose of expired

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medications by flushing them down toilets or throwing them in municipal trash bins [14]. Particular concern is the NSAID diclofenac, which, when not disposed of correctly, has been found in surface water bodies. Its presence has been directly associated with kidney failure and significant declines in vulture populations in South Asia, highlighting a clear case of ecological crisis caused by pharmaceuticals [15].

• Insufficient Training of Healthcare Personnel and Waste Handlers

In many healthcare settings within LMIC, pharmacists, nurses, and sanitation workers often receive limited formal training regarding the protocols for handling pharmaceutical waste. As a result, there are frequent breaches of the Biomedical Waste Management Rules, which include neglecting to adhere to the color-coded segregation systems for sharps, expired medications, and contaminated materials. According to a study conducted by at tertiary care hospitals in India, more than 60% of staff members were not informed about the appropriate disposal methods for high-risk medications [16].

• **Limited Financial and Technological Infrastructure**
The implementation of sustainable technologies for treating pharmaceutical waste—such as high-temperature incineration equipped with emission scrubbers, bioreactors employing enzyme-driven degradation of APIs, and centralized systems for drug take-back—continues to be significantly constrained in developing nations. Financial limitations, insufficient enforcement of policies, and a lack of public-private collaboration impede their widespread utilization. Consequently, substantial amounts of pharmaceutical waste are released into the environment without treatment, leading to potential hazards for both human health and the ecosystem **Figure 1** [17].

ROLE OF STARTUPS IN PHARMACEUTICAL WASTE MANAGEMENT

In light of the increasing issues surrounding pharmaceutical waste, new startups are becoming significant creators of innovative solutions that are sustainable, efficient, and technology-based. These companies utilize AI, mobile applications, and unique business strategies to tackle the inefficiencies present in the pharmaceutical waste management system **Figure 2** [18].

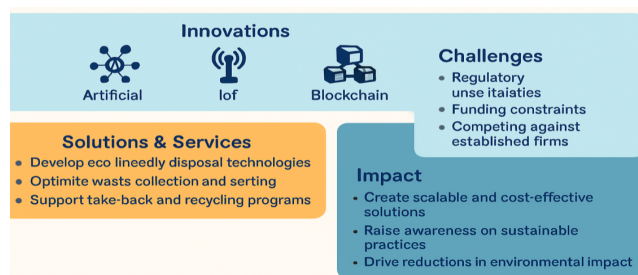


Figure 2: Role of startups in pharmaceutical waste management

• Smart Disposal Technologies

Emerging companies like Bin-E Pharma from Poland have developed AI-assisted smart bins that can independently recognize, categorize, and separate pharmaceutical waste. These units utilize machine learning algorithms and sensor technology to guarantee precise sorting according to biomedical waste regulations. Features such as real-time monitoring and cloud-based reporting reduce human mistakes, improve compliance, and optimize waste management processes [19].

• Drug Take-Back Programs

Organizations such as DisposeRx in the USA and MedTakeBack in the UK have established organized drug return programs in collaboration with community pharmacies, allowing individuals to safely dispose of unused, expired, or unnecessary medications. These initiatives help lower the chances of accidental poisoning and misuse, as well as reduce environmental pollution that can occur from inappropriate disposal methods like flushing or throwing away in landfills [20].

• Mobile Platforms for Waste Reduction

Digital health startups like RecycleMed, India and MyOldMeds, Canada provide mobile apps that allow users to monitor, donate, or responsibly dispose of unused medications. These platforms partner with NGOs and authorized healthcare institutions to guarantee that the gathering, storage, and redistribution of medications adhere to regulatory standards. By encouraging the reuse of medicines in a controlled manner, these platforms play a role in reducing waste and improving access to essential medications in underserved communities [21].

• Innovative Business Models

Startups are implementing tailored business models to address the varied needs of stakeholders within the pharmaceutical waste industry. For instance, B2B solutions are aimed at hospitals and clinics to facilitate the

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management of large volumes of waste, while SaaS platforms serve pharmacies by providing tools for inventory and expiration monitoring [22]. Furthermore, models driven by Corporate Social Responsibility involve communities and public sectors, promoting awareness and encouraging proper disposal methods for innovations from students and contributions from academia [23].

ACADEMIC AND CAMPUS-BASED CONTRIBUTIONS TO PHARMACEUTICAL WASTE MANAGEMENT

Higher education institutions are vital in advancing sustainable practices within pharmaceutical science via education, research, and innovation. Colleges of pharmacy and universities are progressively involving students in initiatives designed to enhance awareness, stimulate innovation, and help decrease pharmaceutical waste over the long term **Figure 3** [24].

• Campus Programs and Community Engagement

Many pharmacy institutions in India and the United States have launched campaigns to raise awareness, collect unused medicines, and host inter-college contests to reduce pharmaceutical waste. These initiatives focus on promoting responsible use of medications, caution against improper disposal methods like flushing or throwing away leftover drugs, and encourage student involvement in sustainability projects. Additionally, these grassroots movements help to educate future healthcare providers about the environmental and public health consequences of pharmaceutical pollution [25].

• Noteworthy Campus Programs & Community Engagement Initiatives

University of Mississippi School of Pharmacy (USA) Generation Rx – Medication Safety Education Campaign Program Students engage in Generation Rx, a nationwide program aimed at raising awareness about safe medication practices and the prevention of prescription drug abuse. This initiative encompasses visits to schools, community health fairs, and hands-on workshops. It highlights the importance of minimizing pharmaceutical waste by advising against the hoarding and improper disposal of leftover medications [26].

JSS College of Pharmacy Ooty, India Awareness Campaign on Safe Disposal of Medicines Program Pharmacy students initiated a community outreach effort focused on the safe disposal of unused medications. The

initiative included door-to-door education, the distribution of posters, and collection events in partnership with local health agencies. The campaign highlighted the importance of avoiding environmental contamination and preventing drug abuse [27].

Bombay College of Pharmacy Mumbai, India Green Pharmacy Initiatives Program Although it covers a wider range of topics, the college has organized workshops and research initiatives focused on eco-friendly drug formulation, biodegradable excipients, and waste from pharmaceutical packaging. It works together with environmental organizations and integrates these concepts into students' research and thesis projects.

Daniel K. Inouye College of Pharmacy (University of Hawai'i, USA) Medication Take-Back Initiative Program In partnership with the Hawai'i Narcotics Enforcement Division, the college frequently organizes community take-back events. More than 3.5 metric tons of unused and outdated medications have been gathered. These events help educate pharmacy students and the community about the safe disposal of medications and the prevention of opioid abuse [28].

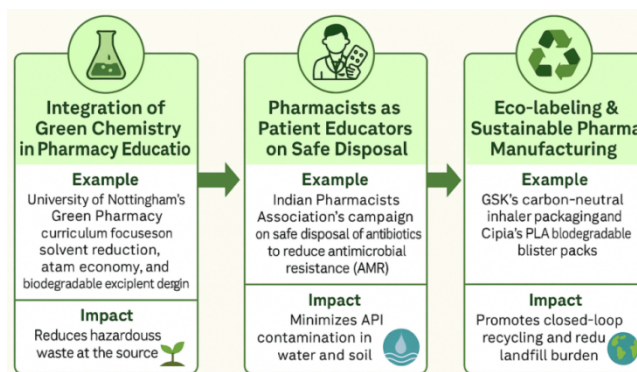


Figure 3: Campus-Based Innovations and Academic Efforts in Pharmaceutical Waste Management

• Hackathons and Innovation Challenges

Nationwide and state-level innovation competitions, like the Smart India Hackathon, have encouraged the creation of new, student-driven approaches to managing pharmaceutical waste. Suggested ideas encompass recyclable and biodegradable packaging for medications, AI-based solutions for monitoring drug expiry in hospital stock in real time, and mobile apps that facilitate community drug return initiatives. Competitions similarly arranged by pharmacy schools and professional

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organizations have produced concepts such as blockchain-based tracking systems for hazardous waste and cost-effective enzymatic degradation systems for expired antibiotics. These efforts not only promote technological advancement but also enhance cooperation between academia, industry, and policymakers, setting the stage for scalable and sustainable waste management solutions [29]. Two examples of these innovative technologies are as follows.

AI-Based Online Medicine Quality Testing Platform

At the Smart India Hackathon; 2024, a notable project was the creation of an online platform for testing and monitoring the quality of medicines, showcased during the finals at Sri Sairam Engineering College, Chennai. This development highlights the growing importance of student-driven digital solutions in improving pharmaceutical safety and monitoring systems [30].

Greywater Treatment Using Biochar and Solar UV

A notable highlight at SIH Hardware Edition 2024 was a project by students from DIAT Pune that integrated soya-based biochar with solar-enabled UV treatment for the purification of community greywater. This innovative approach illustrates how affordable, sustainable technology can address water pollutants, including pharmaceutical residues, in areas lacking reliable resources or off-grid environments [31].

EMERGING INNOVATIVE TECHNIQUES IN PHARMACEUTICAL WASTE MANAGEMENT

Recent Developments in technology are facilitating more efficient, traceable, and eco-friendly methods for managing pharmaceutical waste **Figure 4**.

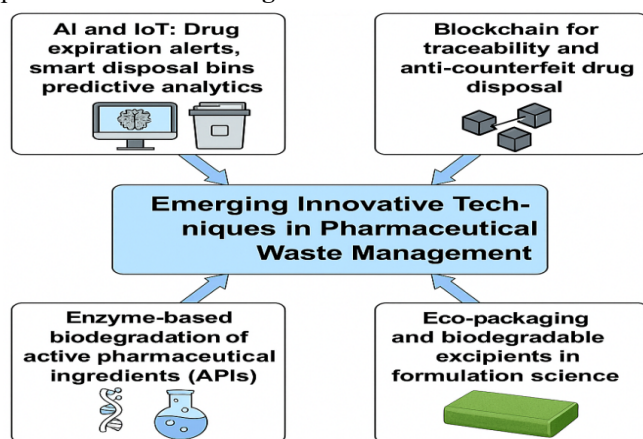


Figure 4: Cutting-Edge Techniques in Pharmaceutical Waste Management

- **AI and IoT Integration**

The integration of AI with Internet of Things (IoT) sensors is becoming more common for the real-time oversight of pharmaceutical waste. Examples of this include AI systems that identify medicines approaching their expiration dates in hospital stock and employ bin-level sensors to indicate when waste receptacles need to be emptied. Predictive analysis can anticipate high disposal times, helping to minimize overflow issues and enhance the efficiency of incineration operations [32].

- **Blockchain Technology**

Global pilot projects are underway for distributed ledger systems to ensure complete traceability of returned or discarded medications. Companies like Modum AG, Switzerland have experimented with blockchain technology to stop counterfeit drugs from entering pharmaceutical supply chains by securely documenting the drugs' origin, handling, and final disposal. In India, blockchain-based waste logs introduced in Jan Aushadhi Kendras track each process, from retail return to authorized destruction, establishing tamper-proof compliance trails for regulatory monitoring [33].

- **Biodegradation Using Enzymes**

Innovative methods utilizing microbial and enzymatic degradation are emerging as energy-efficient and environmentally friendly substitutes for traditional high-temperature incineration of hazardous APIs like antibiotics, hormones, and cytotoxic medications. Techniques such as enzyme-assisted hydrolysis and oxidative biotransformation can greatly decrease both environmental persistence and toxicity. For example, laccase enzymes derived from *Trametes versicolor* have achieved over 90% degradation efficiency of diclofenac and carbamazepine in just 24 hours under controlled laboratory conditions, while engineered strains of *Pseudomonas putida* have been able to metabolize β -lactam antibiotics, thereby reducing the likelihood of antimicrobial resistance in wastewater [34].

- **3D-Printed Portable Neutralizers**

Recent progress in additive manufacturing has made it possible to create compact and cost-effective devices for the on-site neutralization of small amounts of pharmaceutical waste. These systems are especially useful for rural healthcare facilities, community pharmacies, and field hospitals that do not have access to centralized hazardous waste disposal services. For instance, a pilot study conducted by researchers at the University of Nairobi

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designed a 3D-printed cartridge that utilizes layers of activated carbon and catalytic resins, which can detoxify chemotherapy waste fluids prior to disposal. Such decentralized approaches minimize transportation hazards, decrease disposal expenses, and allow for safe waste management in settings with limited resources [35].

• Eco-Packaging and Recycling Models in Pharmaceuticals

The transition toward sustainable pharmaceutical packaging is being driven by the urgent need to reduce post-consumer waste, mitigate microplastic pollution, and align with circular economy principles. Biopolymers such as polylactic acid and polyhydroxyalkanoates have emerged as promising alternatives to conventional PVC and aluminum-based blisters due to their biodegradability and tunable barrier properties [36]. While challenges remain in terms of scalability, cost, and maintaining stability standards set by ICH Q1A(R2), several commercial innovations are under development. For instance, Bilcare's EComply introduces biodegradable blister films designed to degrade more readily under landfill conditions [37]. Companies such as Novartis have pledged to eliminate PVC from secondary packaging and adopt molded fiber trays with water-based inks to reduce paperboard waste [38]. Similarly, Astellas Pharma has pioneered biomass-based blister packs derived from sugarcane, thereby reducing dependence on fossil-based polymers [39].

In parallel, emerging recycling models are reshaping pharmaceutical packaging sustainability. Schott Pharma has implemented a closed-loop recycling initiative for polypropylene transport trays, enabling tray-to-tray recycling and significantly reducing greenhouse gas emissions [40].

Independent LCA further support these transitions, showing that substituting traditional PVC-Alu and PET composites with recyclable PP or biopolymer-based systems can cut carbon emissions by 35–40%, depending on recycling efficiency and local waste management infrastructure [41]. Collectively, these advancements underscore that eco-packaging, when paired with robust collection and recycling strategies, represents a scalable pathway to reduce environmental burdens without compromising pharmaceutical safety or regulatory compliance.

ROLE OF GREEN PHARMACY AND ENVIRONMENTAL EDUCATION

Green pharmacy aims to minimize the environmental impact of pharmaceuticals throughout their life cycle from synthesis and production to usage and disposal by applying sustainable practices and green chemistry principles. Integrating environmental education into pharmacy curricula equips future pharmacists with the skills to perform eco-risk assessments, implement green practices in compounding and dispensing, and lead community initiatives for proper medication disposal. Programs like India's Pharma Clean initiative and the U.S. Dispose My Meds campaign have shown how pharmacist-led education can effectively enhance community practices regarding medication disposal **Figure 5** [42].

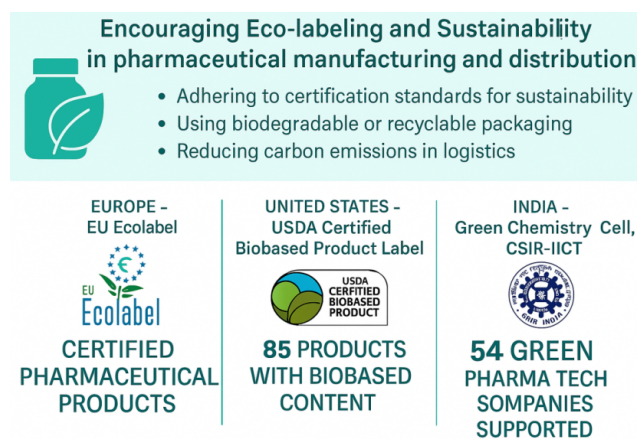


Figure 5: Integrating Green Pharmacy and Environmental Education for Sustainable Pharmaceutical Practices

Pharmacists act as crucial intermediaries between the healthcare system and the public, facilitating behavioral change that limits API contamination in water and soil. At the industry level, companies are adopting carbon footprint reduction strategies, optimizing energy use, and adopting recyclable and eco-labeled packaging to align production processes with sustainability goals. Firms such as Novartis and Cipla have implemented carbon reduction initiatives and recyclable packaging to support global environmental objectives [43]. By integrating science, education, and community engagement, green pharmacy fosters a sustainable pharmaceutical sector that protects both public health and the environment **Figure 6**.

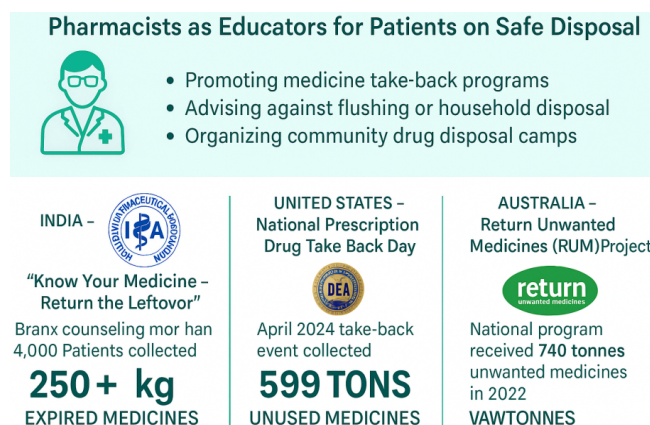


Figure 6: Educational Institutions Driving Change in Pharmaceutical Waste Management

• **Integration of Green Chemistry Principles in Pharmacy Education**

Embedding green chemistry principles into pharmacy education equips future pharmacists to design and produce environmentally sustainable medicines. Key strategies include minimizing solvent use, improving atom economy, employing renewable feedstocks, and selecting biodegradable excipients. Programs like NIPER, India use microwave-assisted and solvent-free synthesis workshops to reduce hazardous by-products and energy consumption [44]. University College London integrates life cycle assessment tools into medicinal chemistry, enabling students to evaluate environmental impacts from raw material extraction to disposal [45]. The University of Michigan’s Green Chemistry Program partners with industry to reformulate synthetic pathways, achieving waste reduction of up to 80% [46]. These initiatives demonstrate that early integration of green chemistry in pharmacy curricula fosters a workforce capable of harmonizing therapeutic innovation with environmental stewardship.

• **Pharmacists as Educators for Patients on Safe Disposal**

Pharmacists play a critical role in protecting environmental and public health by guiding patients on the safe disposal of unused, expired, or partially consumed medications. Their counseling helps prevent contamination of water systems, soil pollution, and accidental poisonings. Key strategies include promoting pharmacy-based medicine take-back programs, discouraging disposal via trash or toilets, coordinating community disposal events with local

health authorities, and providing clear disposal instructions through leaflets, QR codes, or digital messaging [47].

Examples of Successful Initiatives:

India – “Know Your Medicine – Return the Leftover” Campaign: Organized by the Indian Pharmaceutical Association’s Community Pharmacy Division, over 25 pharmacies counseled 4,000+ patients and collected 250 kg of medications for proper biomedical disposal [48].

United States – National Prescription Drug Take Back Day Conducted biannually by the DEA since 2010, with April 2024 alone was collecting 599 tons of unwanted medications, significantly reducing landfill and sewage contamination [49].

Australia – Return Unwanted Medicines (RUM) Project Government-funded, operating through community pharmacies, retrieving 740 tonnes of medications in 2022, with pharmacists trained to advise patients on storage, expiry, and eco-friendly disposal [50].

• **Encouraging Eco-Labeling and Sustainability in Pharmaceutical Manufacturing and Distribution**

Eco-labeling in pharmaceuticals certifies products based on their environmental performance, encompassing raw material sourcing, manufacturing efficiency, packaging, and distribution processes[51]. Sustainable manufacturing strategies include adopting renewable energy, optimizing water and energy efficiency, using biodegradable or recyclable packaging, and minimizing greenhouse gas emissions across supply chains. LCA methodologies have been applied by global companies, such as Johnson & Johnson and Novartis, to quantify environmental impacts from production through disposal, guiding process optimization. Cipla industry shifts towards recyclable polypropylene containers and FSC-certified cardboard secondary packaging illustrate tangible reductions in material consumption and waste generation. Regulatory and voluntary frameworks, including EU Ecolabel, Cradle to Cradle Certified™, and India’s Green Co-Rating System, incentivize environmentally responsible practices. Eco-labeling enables healthcare providers and patients to make informed choices and aligns pharmaceutical production with the UN sustainable development goals (SDG) fostering both ecological sustainability and public health protection [52].

CHALLENGES AND FUTURE DIRECTIONS

Despite its potential, eco-labeling in the pharmaceutical sector faces several challenges. These include the absence

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of globally harmonized certification systems, heterogeneous regulatory requirements across jurisdictions, substantial costs for implementation and compliance, limited consumer awareness, and resistance from manufacturers perceiving the market for sustainable products as marginal. Future strategies to overcome these barriers involve developing internationally standardized eco-labeling frameworks, leveraging blockchain technology to enhance supply chain transparency, promoting sustainable production via fiscal incentives and green procurement, and advancing innovations in biodegradable and low-carbon packaging [53]. Integration of green chemistry metrics into regulatory approvals, targeted public education campaigns, and multi-stakeholder collaborations among regulators, industry, academia, and NGOs are also critical to ensure effective implementation, monitor environmental impact, and support sustainable consumption in alignment with the UN SDG [54].

REGULATORY GAPS

The absence of globally harmonized policies on pharmaceutical waste management and eco-labeling generates uncertainty within multinational supply chains, impeding the adoption of sustainable practices [55]. Fragmented regulations result in variable compliance requirements, inconsistent classification of hazardous versus non-hazardous pharmaceutical waste, and disparate disposal protocols across jurisdictions. Such inconsistencies hinder innovation, complicate cross-border tracking of environmental impacts, and perpetuate unsafe disposal practices. In the absence of coordinated international frameworks such as a directive led by the WHO best practices remain localized, limiting scalability and reducing the effectiveness of global initiatives to mitigate pharmaceutical pollution. Harmonized regulatory guidance is therefore critical to facilitate uniform adoption of sustainable technologies, promote environmental accountability, and enhance global pharmaceutical stewardship [56].

• **Economic Barriers**

The implementation of advanced pharmaceutical waste management technologies presents significant financial challenges, particularly in LMICs. High capital and operational costs associated with technologies such as advanced incineration, plasma gasification, and on-site neutralization systems hinder their adoption. For instance, the establishment of efficient reverse-logistics systems to

collect and transport pharmaceutical waste back to recycling facilities can be a logistical challenge, especially when dealing with diverse and widespread sources.

Overcoming these challenges necessitates ongoing funding through international grants, government subsidies, low-interest green loans, and PPPs to ensure that advanced waste management solutions are financially feasible and available in various healthcare contexts [57]. Limited financial resources, the absence of targeted subsidies, and inadequate incentives for the private sector impede progress [58]. Even when pilot initiatives demonstrate positive outcomes, their scalability is often obstructed by maintenance expenses, import taxes on specialized equipment, and a shortage of trained personnel [59].

• **Public Behavior**

Limited awareness and cultural reluctance to return unused medications necessitate behavioral interventions, particularly in rural regions. A lack of knowledge regarding the environmental and health hazards associated with improper disposal of medicines, in addition to cultural aversion or stigma surrounding the return of unused or expired drugs, continues to obstruct effective management of pharmaceutical waste. In rural and underserved communities, this issue is further exacerbated by restricted access to formal take-back initiatives and a tendency to use traditional disposal options, like incineration or discarding in general waste. Behavioral interventions such as focused community outreach, incorporation of safe disposal information into public health initiatives, school-based environmental education programs, and incentives for returns have demonstrated effectiveness in enhancing participation. For instance, India's MedReturn pilot program in Himachal Pradesh correlated pharmacy-based take-back boxes with small reward vouchers, leading to a 42% increase in medicine returns over six months [60].

DISCUSSION

The convergence of technology, education, and entrepreneurship is transforming the management of pharmaceutical waste. New ventures are providing scalable solutions, while initiatives led by students foster community awareness and promote evidence-based sustainability. Innovative technologies like AI, IoT, and blockchain have the potential to revolutionize traceability, enhance efficiency, and decrease environmental impact; however, their implementation relies on supportive regulations, sufficient funding, and changes in public

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behavior. Considering the global nature of the pharmaceutical industry, it is crucial to have aligned international standards and cooperative efforts across borders to ensure effective and sustainable waste management.

CONCLUSION

This review emphasizes the essential contribution of startups and academic projects in transforming the management of pharmaceutical waste. The integration of sustainable technologies, changes in education, and encouraging regulations is vital for reducing pharmaceutical contamination. Realizing this vision requires a unified global initiative that brings together public, private, and academic sectors to protect environmental health and public well-being in light of increasing pharmaceutical use. Effective management of pharmaceutical waste in a sustainable manner is now essential for public health. By adopting eco-friendly manufacturing practices, implementing smart tracking systems, and fostering community engagement, we can shift from a linear, waste-heavy approach to a circular and robust system. Genuine transformation relies on courageous policy changes, internationally synchronized ecological standards, and steadfast cooperation among all stakeholders. The evidence is clear, the resources are prepared, and the need for action is critical what is left is to collaborate and move forward promptly.

ABBREVIATIONS

Active pharmaceutical ingredients (APIs), antimicrobial resistance (AMR), low- and middle-income levels (LMICs), Software-as-a-Service (SaaS), non-governmental organizations (NGOs), Public-Private Partnerships (PPPs), life cycle assessments (LCA).

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

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AUTHOR CONTRIBUTIONS

Mohini Patidar conceptualized the review, structured the content, and wrote the initial draft. Nitin Deshmukh contributed to literature collection, critical analysis, and manuscript revision. Ruchita Raghuvanshi assisted in compiling data, preparing tables and figures, and literature synthesis. Sunita Minz, Nilesh Mandloi and Prakhar Soni were provided critical feedback, edited the manuscript, and ensured clarity and coherence. All authors read and approved the final manuscript.

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