

From protection to sustainability: Transforming packaging for oral solid dosage forms



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Abstract

Sustainability has become a key emphasis in the pharmaceutical industry, with packaging playing a vital role in product protection, patient safety, and environmental impact. This review examines sustainable packaging technologies for oral solid dosage forms (OSDs), including tablets, capsules, powders, and granules, by comparing conventional materials such as PVC/PVDC blisters, aluminium foils, glass bottles, HDPE containers, and paperboard cartons with eco-friendly alternatives like paper-based blisters, cellulose materials, starch-derived polymers, polylactic acid (PLA), and polyhydroxyalkanoates (PHAs). Sustainable design strategies, including lightweight packaging, material reduction, recyclable mono-material systems, and life-cycle assessment, are discussed for minimizing environmental burden while maintaining product quality. The review also highlights pharmaceutical waste management approaches, including recycling, solvent recovery, wastewater treatment, and medicine take-back programs. Review addresses challenges including regulatory requirements, high costs, limited recycling infrastructure, and biodegradable material limitations, while exploring future opportunities through artificial intelligence, continuous manufacturing, renewable energy, circular economy principles, and evolving environmental regulations.

Keywords: Sustainability, Biodegradable packaging, pharmaceutical disposal

1 Introduction

The pharmaceutical industry is essential to global healthcare, contributing to the prevention, diagnosis, and treatment of various diseases through the development of safe and effective medicinal products. Growing environmental concerns, pollution and resource limits are encouraging industries to adopt eco-friendly packaging while maintaining safety and quality standards (1-3).

Sustainability in the pharmaceutical industry mainly focuses to reduce environmental impact at every stage of a medicine's life cycle, from development and manufacturing to packaging, transport, use and disposal. It supports circular economy practices through resource reuse and responsible handling, while reducing waste and costs, improving efficiency, and protecting the environment (4).

Global initiatives such as the United Nations Sustainable Development Goals (SDGs), encourage pharmaceutical companies to reduce environmental impact (3). Green manufacturing, renewable energy, modern technologies, and sustainable packaging help reduce waste and pollution while maintaining medicine quality and safety.

The objective of this review is to discuss primary and secondary packaging material used for oral solid dosage forms in pharmacy, its design specification with appropriate features and disposal procedure for sustainable technology.

2 Sustainable Packaging Solutions in the Pharmaceutical Industry

Pharmaceutical packaging plays an important role in protecting medicine quality, ensuring patient safety, and meeting regulatory requirements. Conventional packaging materials, including petroleum-based plastics, aluminum foils, laminates, and multilayer materials, provide effective protection against moisture, light, and contamination(5). However, many of these materials are difficult to recycle and degrade slowly, which contributes to environmental concerns. As a result, the pharmaceutical industries are focusing on sustainable packaging approaches to reduce its environmental impact.

The main goal of sustainable pharmaceutical packaging is to protect medicines while reducing environmental burden. This involves choosing safer materials, improving packaging design, and considering the entire life cycle of packaging, from production to disposal.

2.1 Overview of Pharmaceutical Packaging Materials for Oral Solid Dosage Forms

Table 1 summarizes the packaging materials mainly used for oral solid dosage forms (OSD) including tablets, capsules, powders and granules. These materials are important for maintaining product quality, stability, safety and therapeutic efficacy. Primary packaging materials, including strip and blister packs, HDPE container, glass bottles and sachets come into direct contact with the product and protect it from moisture, oxygen, light, and contamination. Secondary packaging, including paperboard cartons and cardboard boxes(6), provides mechanical protection during handling, transportation and storage and may also offer opportunities for recycling and biodegradation.

Table 1: Key Features, Disposal Strategies and Challenges of Different Pharmaceutical Packaging Materials for Oral Solid Dosage Forms

Source of packaging	Name of packaing material	Name of formulation to be packed	Recommended Storage condition	Protection/features	Primary/secondary	Disposal	Challenges
Cartonbox	Paper-board/card board	ORS/Glucose powder pack-ets Blister pack cartons	Room temperature	Mechanical protection	Secondary	Recyclable through paper pulping; biodegradable	Residue after burning, reduced strength with moisture
Blister pack	PVC/PVDC-Aluminium foil	Tablet/Capsules	Room temperature	Excellent moisture, oxygen, and light barrier; tamper evidence	Primary	Difficult to recycle due to plastic-aluminium layers	Layers seperation is challanging
Plastic bottle	HDPE	Tablets Capsules	Room temperature	Temper-proof Moisture protection, lightweight, easy dispensing	Primary	Mechanical recycling	Plastic waste can cause pollution
Glass bottles	Amber/Transparent glass	Effervescent Tablets, Capsules	Room temperature	Excellent moisture, chemical and light protection, inert	Primary	100% recyclable and reusable	Heavy weight
Plastic sachets	Plastic laminate (Multilayer)	Powders, Granules, ORS	Cool and dry place	Moisture barrier, single-dose convenience, lightweight and portable	Primary	Multilayer structure	Difficult recycling
Strip pack	Aluminium	Tablets, Capsules	Room temperature	Moisture proof	Primary	Recyclable when properly collected	Aluminium production requires higher energy
Paper based blister	Cellulose/Fiber based materials	Tablets	Room temperature	Reduced plastic content	Primary	Recyclable and biodegradable (depending on coating)	Modification is required to due to barrier
Bio based packing	Starch based/Cellulose	Tablets, Capsules	Controlled temperature	biodegradable, reduced carbon footprint	Primary	Compostable or biodegradable under suitable conditions	High Cost

Sustainable alternatives, including paper-based blister packs and bio-based materials derived from cellulose or starch, are gaining attention due to their reduced environmental impact and improved biodegradability. However, high production costs, reduced barrier performance, and limited large-scale recycling remain significant challenges. Conventional materials like glass and aluminum offer excellent recyclability and product protection but may involve higher energy during manufacturing and transportation. Therefore, pharmaceutical packaging selection must balance product stability, protection, cost-effectiveness and end-of-life disposal considerations(5).

2.2 Eco-Friendly Packaging Materials

Advances in material science have enabled the use of more environmentally friendly pharmaceutical packaging. Materials like polylactic acid (PLA), cellulose, starch-based materials and polyhydroxyalkanoates (PHAs) use fewer fossil resources and may create less pollution after disposal. Recycled paper and responsibly sourced paper help conserve natural resources and reduce waste(7). Glass and aluminium remain sustainable options due to their strong protection and high recyclability. Single-material recyclable packaging, lightweight containers, thinner films, and intelligent design can further reduce material use and transportation-related carbon emissions(8).

Sustainable packaging depends not only on using sustainable materials but also on how the package is designed. Important strategies include reducing packaging components, minimizing package weight, improving recyclability, and making packaging more efficient for transport and storage (Figure 1). Life-cycle assessment helps manufacturers evaluate environmental impacts from raw material selection, production, transportation, use, and disposal(9). This supports sustainable packaging choices while maintaining medicine safety, product quality, patient convenience, and regulatory requirements.

2.3 Pharmaceutical Waste Management and Safe Disposal

Despite progress in pharmaceutical sustainability, pharmaceutical waste remains an environmental issue. Waste is generated throughout the medicine life cycle, including research labs, manufacturing plants, hospitals, pharmacies, and homes. Proper disposal is essential to prevent hazardous substances from entering soil, groundwater, rivers, and wastewater(10). They can be detrimental to aquatic life and contribute to antibiotic resistance.

Pharmaceutical industries generate solid and chemical waste, leftover solvents, wastewater, and damaged/rejected product. Effective waste management begins by minimizing waste during production through optimized processes. Waste sorting enables safe treatment of harmful waste and reuse of recyclable materials, reducing environmental harm and simplifying disposal.

One of the significant methods used in the manufacture of pharmaceuticals is solvent recovery. Solvents can be recovered and reused with technologies such as distillation and purification to decrease pollution, conserve resources, and decrease production costs. Wastewater treatments, such as filtration, activated carbon, oxidation, and biological processes, remove harmful pharmaceutical chemicals before discharge.

2.4 Safe Disposal of Unused Medicines by Consumers

Unused or expired medicines should not be thrown in household waste or flushed. Medicine residue may be released to water and impact microbial flora. Public awareness is crucial, as

many people are unaware of proper medicine disposal. Encouraging them to return unused medicines can help protect the environment(11).



Figure 1: Overview of Sustainable Pharmaceutical technologies for packaging of OSD (19)

2.5 Challenges to Sustainable Pharmaceutical Technologies

Sustainable technologies offer environmental and economic benefits, but high investment costs and strict regulations can limit its adoption. Some eco-friendly packaging materials also have lower strength, protection, and shelf life(12). Further R&D is needed to improve their performance. Collaboration among industry, researchers, regulators, healthcare professionals, and consumers is essential for lasting environmental benefits(13).

2.6 Carbon Border Adjustment Mechanism (CBAM) Risk in Pharmaceutical Packaging for Export: An Emerging Challenge for Sustainable Packaging

Pharmaceutical companies are moving toward greener packaging as environmental concerns and global regulations increase. Materials such as aluminium foil, plastics, blister packs, glass, and paper cartons protect and stabilize tablets and capsules(14). However, their production and disposal can be carbon intensive, creating challenges for global trade. The CBAM is a carbon-based policy that the European Union has enacted to lower carbon emissions and promote the use of low-carbon products. Although, the CBAM does not currently target pharmaceuticals, packaging may face future attention due to its carbon footprint. Therefore, future packaging should balance emissions, sustainability and safety performance(15).

2.7 Future Perspectives of Sustainable Pharmaceutical Industry

New technologies and environmental goals are shaping a greener pharmaceutical industry. AI, digital tools, and smart systems can improve production, reduce waste, and save energy(16). Continuous manufacturing may grow due to lower material loss. Future packaging will focus on biodegradable and recyclable materials, renewable energy and better water management(17). Life-cycle assessment, circular economy practices, and reuse and recovery of solvents and medicines will further reduce waste. Strong coordination among industry, researchers, government, and healthcare professionals will support sustainable development(18).

3 Conclusion

Sustainability has become an integral component of the pharmaceutical manufacturing and packaging, with greater focus on reducing their impact on the environment. Greener production methods, sustainable packaging, renewable energy, and proper waste management can help reduce waste, energy use, and harmful emissions while protecting water, wildlife, and human health. Although some challenges remain, continued research, innovation, and collaboration can help the pharmaceutical industry move towards a safer and more sustainable future.

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