



SUSTAINABLE PHARMACEUTICAL PACKAGING: INNOVATIONS, CHALLENGES AND FUTURE PERSPECTIVE

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ABSTRACT

Packaging plays an important role in pharmaceuticals by maintaining drug stability, shelf life, and effectiveness. It provides physical and biological barrier to the drug and protects it from the external environment and contamination. Depending upon the level of safety, packaging is of three major types – primary packaging, secondary packaging, and tertiary packaging. However conventional packaging systems use glass, plastic, aluminum, cardboard and other non-biodegradable material which in turn generates a lot of plastic waste, increases landfill, pollutes the ecosystem, and raises greenhouse gas production. To tackle these challenges sustainable packaging materials such as starch, chitosan, xylan, chitin, and proteins are emerging as alternatives. Recent innovations including sustainable blister packaging, smart intelligent packaging system, intelligent indicator system, nano coatings providing support biodegradable packaging systems. Despite the benefits of environmental, economic, regulatory compliance, and drug safety and quality there are some major challenges such as high cost, limited availability of raw material, and performance and durability issues, due to which the use of sustainable packaging is limited. These limitations can be overcome through advanced manufacturing techniques, multifunctional active packaging, integration of nanotechnology which are the future trends and new technologies emerging in packaging.

INTRODUCTION

Pharmaceutical packaging is a science and technology that protects medications from the external environment. It is essential to keep medications protected, but it also ensures drug stability, clear labeling, and provide instructions to the patient.^[3, 9, 11]

A pharmaceutical package is generally used for packaging and includes various materials for safety, such as glass materials (ampoules, vials), plastic containers, blisters, Aluminum-based foils (sachets), inhalers, syringes, and cartridges. Sustainability is an important concern for balancing human needs and environmental safety. As nature has limited resources, it has become important to conserve environmental resources.^[12] The increasing use of non-biodegradable plastic in pharmaceutical packaging generates substantial waste, degrades nature and increases environmental concern.^[1]

It is important to decrease and gradually eliminate carbon footprint and greenhouse gas emissions.^[6]

The recycling or reuse of biodegradable materials should be promoted, even as consumers shift toward eco-friendly products. Sustainable packaging not only helps protect nature but also ensures consumer health. If sustainable packaging is followed in the long term, it will help build a better brand image for any pharmaceutical company.^[7] The main objective of this review is to provide an overview of sustainable packaging. This highlights the problems and challenges associated with the use of conventional packaging and shows the importance of switching to sustainable packaging. This article briefly discusses the eco-friendly materials that can be used in pharmaceutical packaging and their benefits. It shows the recent innovations, future trends and new technologies emerging in the field of sustainable packaging.

CONVENTIONAL PACKAGING

Conventional packaging also known as “TRADITIONAL PACKAGING SYSTEM” it includes materials like aluminum, plastic, cardboard, glass to protect the drug from any physical and chemical damage during storage or while transportation. Although this packaging system provides excellent stability, this plays significant role in damaging the environment due to its non-biodegradable nature. There are several types of packaging listed below.

1. Primary packaging: The material that is directly in contact with the drug or many other medications, for example – blister packs, vials, ampoules, bottles, and tubes. As it directly touches the medicine, it is essential that they are safe to use.

PHARMACEUTICAL PACKAGING

2. Secondary packaging: Packaging that encloses the primary packaging is known as secondary packaging for example, cardboard boxes, cartons, sleeves.
3. Tertiary packaging: This is the final step in packaging, which is used for bulk transport. This ensures that the drug reaches the destination safely during transportation. For example - large shipping boxes, pallets, and shrink wraps.^[3,9]

MATERIAL USED IN PACKAGING

1. Glass: It is a rigid, transparent packaging material used for storing injections, ampoules, vials without losing its quality. It is made up of natural raw material such as silica, soda ash and limestone. It is classified into four types based on chemical composition and resistance.

● **Table 1: Types of glass use in packaging.**

TYPE I GLASS (borosilicate)	Parenteral preparations, injectables, ampoules, vials, lyophilized products, holding strong acids and alkalis.
TYPE II GLASS (treated soda lime)	Aqueous injections and buffers
TYPE III GLASS (soda lime)	Oral solids, topical products, powders and tablets.
TYPE IV GLASS (general purpose glass)	Ointments and liquids for external/topical or oral use

2. Plastic: It is widely used because it is lightweight, strong, flexible and cost effective. Traditional plastic causes environmental pollution but new innovations focus on recyclable plastic.

a. Polyethylene terephthalate (PET): it is highly recyclable and commonly used for syrup and vitamin bottles. However, as it is recyclable, it does not cause environmental pollution.

b. High-density polyethylene (HDPE): It is strong, durable, and highly recyclable. Many

Tablet, powder containers are prepared using HDPE,

c. Polypropylene (PP): It is lightweight heat resistance in nature it is used for syringes pill organizers.^[9]

d. Polylactic acid (PLA): It is a bio-based, degradable polymer that helps reduce plastic waste it helps to make blister packs disposable medical packaging.^[12]

CORE FUNCTIONS OF PHARMACEUTICAL PACKAGING

Packaging plays an important role in each department as it is important to keep medications safe. It also reduces the risk of damaging medications. Different types of materials are used for different types of medications. Here are some important functions of packaging.

- Barrier protection: This is meant for protection against the conditions that can alter the properties of the medicine, such as moisture, light, and temperature. Blister packaging.

Can provide this type of protection.

- Biological protection: This protection is provided against biological contaminants.
- Physical protection: This provides pharmaceutical dosage protection against physical damage.

- Provide information: In the pharmaceutical context, it should provide all the information related to the correct use of dosage forms, their contents, side effects, and warnings.

- Identification: This is meant for the identification of the product.

- Security: Pharmaceutical packaging possesses features that prevent counterfeiting. It also prevents small children from accessing the contents of the formulations.

- Convenience: Packaging must be convenient to increase consumer access to products, improve distribution, handling, and selling of such products.

NEED FOR SUSTAINABLE PACKAGING

Conventional packaging creates a lot of pollution as it is difficult to degrade and remain in the environment for hundreds of years, to minimize this issue sustainable materials should be used. Pharmaceutical companies generate a large volume of packaging to maintain the safety of drug which results in significant pollution and increased landfill.

Environmental degradation and microplastics: Plastic breaks down into microplastics which contaminate soil, water, food chain, ecosystem and human health. The production of traditional packaging material consumes a large amount of fossil fuel, energy and natural resources which may directly affect climate change. The growing population increases the demand for healthcare which directly results in more use of packaging material and disturbing the environment by using conventional packaging. Many conventional packaging materials are difficult to recycle because they are made up of multiple layers of different packaging materials. Improper disposal contributes to environmental pollution.

Growing environmental awareness among consumers, health care professionals and government has increased demand for sustainable packaging and eco-friendly materials contributing to the protection of environment from degradation.

Regulatory and global drives: Governments across the world are implementing stricter rules and regulations that help in supporting sustainable alternatives. Sustainable packaging helps to reduce greenhouse gas emissions by using renewable resources, recyclable, biodegradable, and compostable materials and energy-efficient manufacturing processes. Light weight sustainable packaging material helps reduce the transportation cost, fuel consumption and reduce greenhouse gas emissions. Using renewable resources such as plant-based material has reduced the dependence on non-renewable resources. Sustainable packaging helps manufacturers to adopt cleaner production technologies and energy-efficient manufacturing processes.

Economic and brand advantages: The healthcare sector is under increasing pressure to reduce environmental footprint making sustainable packaging an important strategy. It promotes circular economy by promoting 3Rs - reduce, reuse, and recycle. Resource scarcity and rising raw material costs make efficient use of packaging material economically beneficial in the long term. Eco-friendly material helps to conserve natural resources by reducing dependence on virgin raw material and encouraging the use of renewable resources. Sustainable packaging can lower waste management and disposal cost in long term. Pharmaceutical companies adopting sustainable packaging can improve their corporate social responsibility [CSR] image and strengthen consumer trust. It supports global sustainability goals by reducing pollution, conserving biodiversity, reducing resource utilization, and mitigating climate change. Advances in material science and packaging industry have now made it possible to use eco-friendly materials for packaging while maintaining the stability, quality and sterility. Sustainable packaging balances environmental production with essential requirements of pharmaceutical

packaging and ensuring patient safety while minimizing environmental impact. Continuous innovation in sustainable materials helps maintain pharmaceutical product quality while reducing environmental impact.

ECO FRIENDLY PACKAGING MATERIAL

Eco-friendly packaging is also known as environment-friendly packaging as it does not cause any harm to the environment. It is also known as nature friendly packaging. Materials used in this packaging are renewable and biodegradable. They degrade easily and can also be recycled. They ensure the safety of the material as well as the environment. Eco labels are used widely which helps consumers to identify environmentally friendly materials easily. Research and development [R&D] is continuously developing new eco-friendly and Biodegradable material which helps reduce the environmental pollution. Biodegradable and eco-friendly materials have now emerged as viable alternative to conventional packaging and can either replace or complement the existing pharmaceutical packaging. Materials such as cardboard, agricultural waste, and other renewable resources are used in pharmaceutical packaging.

Starch-based biopolymers such as Corn starch; offer a biodegradable alternative for packaging products such as trays, pouches. Environmental sustainability should be considered during the initial steps to minimize economic impact.

Optimized packaging design aims to reduce material consumption, decrease waste generation, and improve efficiency. Sustainable packaging should facilitate recyclability, reusability, biodegradability and energy recovery supporting efficient waste management.^[13] Ideal eco-friendly packaging should possess characteristics such as lightweight construction, environmental compatibility, recyclability and functional performance. Eco-friendly pharmaceutical packaging has become an important global trend reflecting the growing emphasis on sustainable healthcare practice. [4, 7, and 11]

● **Table 2: Natural eco-friendly based materials.**

MATERIAL CLASS	SOURCE	KEY CHARACTERISTICS
Starch	Plant sources such as corn, legumes, tubers and cereals.	Renewable, biodegradable, inexpensive and brittle. Modified with plasticizer (glycerol ,urea) and biopolymers (PLA,PA,PHBV,PVA)
Cellulose	Plant biomass (plentiful organic polymer)	Natural, renewable, offers excellent biodegradability and stability.
Xylan	Plant biomass and agricultural-by-products(hemi cellulose)	Biodegradable, substitute for petroleum-derived packaging.
Chitin and Chitosan	Crustacean shells and invertebrates	Produced by deacetylation of chitin. Shows antimicrobial activity and heavy metal ion exchange adsorption
Protein-based	Plant (soy, gluten, pea, potato) and animal (whey, collagen)	Amino acid polymers. Structural properties are improved by modification, grafting, cross-linking techniques.

RECENT INNOVATIONS

The field of sustainable development is changing now and improving the recyclability, biodegradability of the materials by maintaining the stability, quality, safety of the drug. Recent innovations include structural changes which improve the recyclability, smart system and nanotechnology for providing barrier protection.^[12] These innovations help to shift from traditional packaging system to new and eco-friendly solutions which are not harmful for environment.

1. Sustainable blister packaging: Traditional blister packaging is the most

Common in packaging. Generally it is multilayer and consists of PVC and aluminum foil. However, as it is multilayered, it is difficult to recycle which causes environmental pollution. This is the reason why, new recyclable blister packs are being developed.

a. Recyclable blister packs - Blister packs are now designed in a simple form by using single material which makes the recycling process easy and reduce environmental waste contributing in circular economy.

b. Mono-material blister system - This is made by using only one material [PP OR PET] which reduces the work of separating different materials which directly improves recycling, reduce the environmental impact simultaneously providing protection to the drug.

2. Smart active and intelligent packaging: This is a unique technique in which digital technology and advanced materials are used. This type of packaging not only provides safety and protection to the drug, additionally, it provides information related to the medicine.

3. Smart tracking infrastructure: This is a more advanced technique in which QR, RFID tags or electronic leaflets are used. Medicine can easily be tracked in supply chain as well as fake medicine can be identified with less effort. Temperature and storage conditions can be monitored with ease with the help of technology. Paper leaflets are not required, so waste will also be reduced and environmental pollution can be controlled.

4. Active packaging system: This system helps to reduce the need of using secondary packaging, special functional materials are added, which help to save medicine from degradation, inhibits the microbial growth, oxygen scavengers prevent oxidation, decrease moisture absorption which ultimately increases the shelf life of the medicine.^[12]

5. Intelligent indicator system: Sensors and indicators are inserted in the medicine packaging which helps to monitor the moisture, temperature, humidity and provide real-time information. If the storage condition is not appropriate, it will indicate a warning. It also ensures quality and safety of drug.

6. Nanotechnology based packaging: This is significantly used for sensitive medicines and helps to prevent the entry of moisture and oxygen. Barrier properties are Improved by using nanotechnology and improve the overall performance of the drug.

7. Nano cellulose and nanocomposites: This is a biodegradable material which is formed with a mixture of Nano cellulose and biopolymer. It inhibits the entry of water vapor and moisture and helps to keep the moisture-sensitive medicine safe. It supports the sustainable packaging and reduces the chances of environmental pollution.

8. Nano coatings: An ultra-thin eco-friendly coating is applied on the surface of packaging which helps to block gas and moisture. It is a biodegradable packaging material and hence helps in fulfilling the need to protect the environment from pollution and keep the drug stable and maintain shelf life.

BENEFITS OF SUSTAINABLE PACKAGING

Sustainable packaging is a type of packaging which helps to reduce the harm to the environment and protect the drug from the external environment like moisture, temperature, and storage conditions.^[6, 9, 11, 12]

Pharmaceutical Industry is now moving towards the sustainable packaging however it not only provides safety to the drug but also.

Provide benefit to the economy and society.

1. Environmental benefits: By using recyclable materials carbon emission is also reduced additionally; biodegradable packaging helps in natural decomposition of the material reducing the plastic waste and landfill. Lightweight packaging helps to reduce transport fuel consumption. It also reduces the greenhouse gas emissions.
2. Economic benefits: It helps to reduce transportation and shipping cost which makes the supply chain stable. Companies save the cost in the long term of using Sustainable packaging. Sustainable packaging helps in regulatory compliance.
3. Social benefits: Reputation of company improves by using recyclable packaging as customers nowadays trust in eco-friendly materials which helps to protect the public health at the same time waste reduction benefits the society.
4. Drug Safety and quality benefits: It helps to protect packaging materials from oxygen light and other parameters it promotes the drug stability, effectiveness as well as shelf life is also increase by using sustainable materials. Medicine reaches to the patient in safe condition.
5. Regulatory and compliance benefits: Companies can follow the environmental regulations easily as they are using eco-friendly materials. Most of the international companies demand for the recyclable material conditions which can easily be accepted by the companies which are already using reusable materials for packaging. Using sustainable packaging reduces the risk of penalties and other charges.
6. Technological benefits: Smart technologies are used to track real-time process, storage conditions by using QR, RFID, sensors which improves supply chain transparency.

7. Future sustainability benefits: The sustainable packaging encourages innovation, promotes renewable resources as they do not cause any harm to the environment and can be reused. It provides support to the Sustainable Development Goals [SDGs] and ensures a cleaner environment for future generations.

CHALLENGES

Sustainable packaging has many benefits but it also faces several challenges.

1. High cost: Sustainable materials are often expensive compared with the conventional materials, which increases its production cost. Small pharmaceutical industries may find this cost difficult to afford. In addition to high cost, companies often need to Invest in research, new machinery, production and technologies. Small- and medium-sized companies may find it difficult to afford the investments, making it difficult for them to adopt sustainable packaging. Biopolymers like Lignocelluloses fibers and polyhydroxyalkanoates are complex and costly.
2. Limited availability of raw material: The demand for sustainable packaging is growing but still limited. Renewable materials such as bamboo, sugarcane fiber and fibroblastic are not available in all regions. Seasonal variation, agricultural limitations and Supply chain disruption can further reduce availability. This creates uncertainty for manufacturers and may increase production cost.
3. Performance and durability issues: Traditional packaging system is valued for its strength, flexibility, water resistance and longer shelf life, whereas biodegradable materials still struggle to match these properties because of their sensitive nature, making them less suitable for packaging products such as food, beverages, pharmaceuticals, electronics. Poor durability can also cause damage of material while transporting.
4. Lack of recycling and composting infrastructure: Many countries do not have proper composting facilities to handle sustainable materials. Compostable packaging materials require specific industrial Composting conditions that are not available in many areas.^[13] As a result, eco-friendly packaging material still end up in land filling whereas environmental benefits are still unlocked.
5. Consumer awareness and Disposal practices: Consumers play an important role in sustainable development, some consumers are confused between recyclable, biodegradable and compostable materials. Improper disposal, throwing the recyclable material into general waste bin, which reduces recycling efficiency. Lack of knowledge and awareness prevents sustainable packaging from achieving its intended environmental benefits.
6. Supply chain and transportation challenges: There are fewer sustainable packaging suppliers so if there is a shortage of material it will cause problem in transportation and production will decrease.
7. Regulatory and compliance issues: Every country has its own rules and regulations, so if any company plans to sell their product in different countries they have to follow their protocols which is complicated and costly for the company however, their standards are high and to meet them a good investment is required. Regulatory agencies like FDA and EMA require testing for bio based materials.
8. Green washing: Some companies advertise their packaging as “eco-friendly “or “green “however they are not sustainable and consumers lose their interest and build a misconception that sustainable packaging is “myth “.
9. Product safety and quality: The main purpose of packaging is to keep the medicine safe from the external environment. However some natural material like starch, cellulose, and gelatin are unable to provide protection from the moisture, temperature hence degrading the medicine.
10. Technological limitations: Sustainable packaging technologies are not fully developed yet. Scientists are still researching new technologies that can make packaging better and easier to use.

FUTURE TRENDS AND EMERGING TECHNOLOGIES

1. AI-driven material innovation: With the help of AI and machine learning novel eco-friendly materials are developing. AI suggests the best combination by comparing different biopolymers such as starch, cellulose or PLA and this helps speed up the research by reducing trial and error. As a result better quality of biodegradable Environment-friendly packaging materials are innovated.
2. Advanced manufacturing techniques: New technologies such as 3D printing are helpful in building packaging. It also promotes customized shape and size of Packaging as well as special features such as antimicrobial coating and controlled release.
3. Self-healing and fully edible packaging: Smart polymers are used which automatically repair the cracks or any damage which reduces the waste of material and Increases the shelf life of the material. Edible packaging is made up of food-grade materials such as starch, gelatin or chitosan, as these materials are edible so there is no problem in their disposal.
4. Next generation traceability and circularity: Prediction indicates that in future block chain technology and smart labels will be used. Packaging origin and recycling status will be tracked with the help of this technology. Fake products will be minimized by Using this technique and recycling process will improve.
5. Multifunctional and active packaging: This type of packaging not only protects the product but also maintains its quality. Antimicrobial agents and moisture control features are offered by this packaging it increases the shelf life of the product and reduces the wastage of food. In future sensors will help in the monitoring of freshness, temperature and microbial growth.

6. Integration of nanotechnology: Nanotechnology is used to make the packaging more lightweight and strong. Nanomaterials increase the barrier properties and antimicrobial protection against moisture and gases. Biocomposites made of nanomaterials perform as well as, or better than the conventional packaging.

CONCLUSION

This review demonstrated that, transition from traditional to a sustainable packaging system is not an optional choice but an essential requirement for pharmaceutical companies. Though conventional packaging provides drug security it simultaneously results in continuous plastic waste, microplastics, and high carbon footprint. This disturbs the ecosystem and increases environmental concern.

Highlighted biopolymer materials in article such as starch, chitosan, chitin, proteins and advanced systems such as sustainable blister packaging and active packaging prove that eco-friendly materials maintain drug stability, sterility, and barrier protection without causing harm to the environment.

The execution of these green materials in the real world is constrained by key bottlenecks such as high costs, seasonal raw material shortages, green washing and complex regulatory guidelines. The ultimate takeaway is that, overcoming these challenges requires pharmaceutical companies to adopt Circular Economy 3Rs (Reduce, Reuse, Recycle), AI-driven biopolymer, 3D printing, self-healing polymers or block chain traceability. Only through these future technological solutions pharmaceutical sector can maintain a balance between patient safety and environmental sustainability.

REFERENCES

1. Tayade VV, Surwase KP, Syed Asif. Biodegradable Packaging for Pharmaceuticals: A Step Towards Sustainability. *International Journal of Advanced Research in Science, Communication and Technology*, 2025; 5(2). DOI:10.48175/IJARSCT-27410.
2. Shinde AA, Umale AN, Deshmukh SP. Biodegradable Polymer-Based Pharmaceutical Packaging and Digital Technology for Waste Circularity: An Integrative Review. *International Journal of Creative Research Thoughts*, 2025; 13(11): j359-j376.
3. Singh A, Sharma PK, Malviya R. Eco Friendly Pharmaceutical Packaging Material. *World Applied Sciences Journal*, 2011; 14(11): 1703-1716.
4. Ashiwaju BI, Orikipte OF, Fawole AA, Alade EY, Odogwu C. A Step toward Sustainability: A Review of Biodegradable Packaging in the Pharmaceutical Industry. *Matrix Science Pharma*, 2023; 7(3): 73-84.
5. Sauhta S. Sustainable Pharmaceutical Packaging Market, till 2035. Master's dissertation, Jaypee University of Information Technology, 2024.
6. Helanto K, Matikainen L, Talja R, Rojas OJ. Bio-based Polymers for Sustainable Packaging and Biobarriers: A Critical Review. *BioResources*, 2019; 14(2): 4902-4951.
7. Bansal K, Narayanankutty R, Roy A, Singh K. Redefining Pharmaceutical Packaging: From Protective Layers to Sustainable Supply Chain Solutions. EY-Parthenon and Associated Capsules Group (ACG), 2025.
8. Vediya P, Mehta D. Ecofriendly and Sustainable Pharmaceutical Primary Packaging Materials of Solid Dosage Form. *International Journal of Plant and Environment*, 2025; 11(2): 418-427.
9. Lv Y, Liu N, Chen C, Cai Z, Li J. Pharmaceutical Packaging Materials and Medication Safety: A Mini-Review. *Safety*, 2025; 11(3): 69.
10. Wang J. Sustainable Pharmaceutical Packaging: Integrating Eco-Service Design and Circular Economy for Patient-Centered Innovation. In: *Proceedings of the 2025 3rd International Conference on Digital Economy and Management Science*, 2025; 295-310.
11. Jackman S, Mc Guinness P, Brennan L, Pereira R, Tyrrell A, Barry AM, Brennan C, Naughton BD. Global Innovations in Sustainable Pharmaceutical Packaging in the Last 25 Years: A Scoping Review. *Sustainability*, 2025; 17: 10716.
12. Aguilar GJ, de Oliveira AM, Augusto PED, Tapia-Blácido DR. Advances in Eco-friendly Materials for Sustainable Packaging and Single-Use Utensils: A Decade of Innovation in Preparation, Characterization, and Applications. *ACS Applied Materials & Interfaces*, 2025; 17: 59032-59050.
13. Perkola N, Äystö L, Hagström M, Kauppi S, Fjäder P. Pharmaceutical residues in plastic tablet containers, Impacts on recycling and the environment. *Waste Management*, 2024; 189: 159-165.