

Sustainable drug delivery systems: Building a greener future from design to disposal

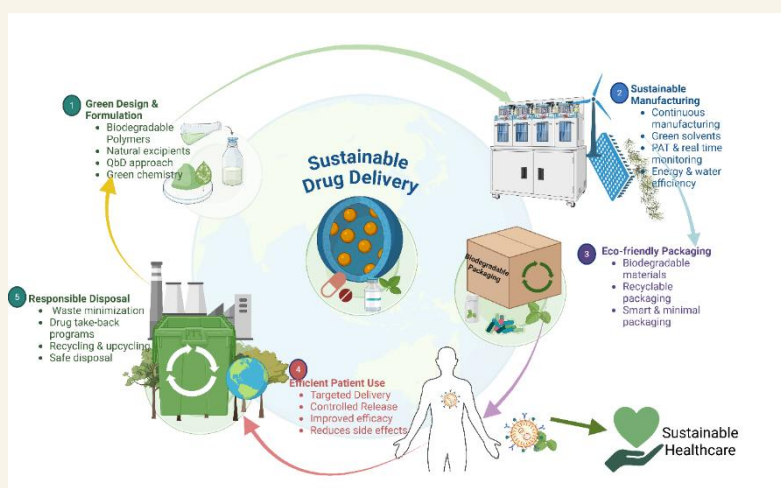


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Graphical Abstract



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Abstract

The increasing demand for pharmaceuticals has raised concerns regarding resource use, waste generation, environmental pollution, and sustainability of healthcare systems in the long run. To overcome these challenges and ensure the therapeutic efficacy and safety of patients, sustainable drug delivery systems (SDDS) have been proposed as a promising strategy. The present review deals with the use of biodegradable and renewable biomaterials such as chitosan, alginate, starch-based polymers, polylactic acid (PLA), cellulose nanofibers, silk fibroin, lignin nanoparticles, and bacterial cellulose for the preparation of green drug delivery systems. The article also discusses sustainable manufacturing techniques such as continuous

manufacturing, green solvents, Process Analytical Technology (PAT), and Quality by Design (QbD) that enhance resource efficiency and minimize waste. It also addresses the role of eco-friendly packaging, life-cycle assessment, waste management, and circular economy principles. Future drivers of sustainable pharmaceutical innovation were discussed including nanomedicine, artificial intelligence, digital twins and personalised medicine. In conclusion, SDDS is a revolutionary approach towards greener, smarter, and patient-centric healthcare.

Keywords: Sustainable Drug Delivery Systems, Green Pharmaceutical Manufacturing, Biodegradable Biomaterials, Nanomedicine, Life-Cycle Assessment (LCA)

1. Introduction

The pharmaceutical industry has been an important part of improving global health through the development of new drugs and advanced drug delivery systems. However, the rising consumption of pharmaceutical products has been accompanied by concerns related to resource consumption, waste generation, environmental contamination, and disposal of pharmaceutical residues. The growing emphasis on sustainable healthcare systems has made environmental considerations increasingly important throughout the pharmaceutical product lifecycle. The modernized therapeutics with improved efficacy, safety, and compliance of patients are achieved by the introduction of advanced drug delivery systems such as nanoparticles, liposomes, microspheres, and targeted delivery systems. Therefore, the development of sustainable pharmaceutical technologies, with a focus on innovation and environmental responsibility, is more relevant than ever (1). The present review discusses sustainable approaches to advanced drug delivery systems across the pharmaceutical product lifecycle, from formulation design and manufacturing to product use, waste management, and disposal.

2. Design of Sustainable Drug Delivery Systems

2.1 Sustainable Biomaterials

The choice of raw materials, excipients, drug carriers and manufacturing processes has a strong impact on the environmental footprint of a drug delivery system for its entire life cycle; therefore, sustainability considerations should be embedded at the earliest stages of pharmaceutical product design. However, contemporary formulation scientists are beginning to explore biodegradable and biocompatible polymers such as chitosan, alginate, gelatin, and polylactic acid (PLA) as alternatives to synthetic materials. These materials can support

effective drug delivery while reducing environmental persistence after disposal because of their biodegradable and, in many cases, renewable nature (2).

2.2 Green Manufacturing Technologies

The integration of sustainability principles into pharmaceutical product design, often referred to as ‘Green by Design,’ aims to minimize material consumption, streamline manufacturing processes, and enhance product stability, thereby reducing waste generation throughout the production cycle. Furthermore, Quality by Design (QbD) approaches aid in sustainability through the optimization of formulation variables and manufacturing parameters in the initial phases. By reducing trial-and-error experimentation, QbD can decrease the consumption of chemicals, solvents, energy, and laboratory resources (3). The most studied sustainable biomaterials for advanced drug delivery systems, their pharmaceutical applications, and environmental benefits are presented in **Table 1**.

Table 1. Sustainable Materials Utilized in Advanced Drug Delivery Systems

Material	Role in Drug Delivery Systems	Sustainability Benefit
Chitosan	Used in nanoparticles, hydrogels, and mucoadhesive formulations	Biodegradable, biocompatible, and derived from natural sources (4)
Alginate	Supports controlled and sustained drug release	Renewable, non-toxic, and environmentally friendly (5)
Gelatin	Used in microspheres, capsules, and drug carriers	Naturally degradable and safe for biomedical applications (6)
Polylactic Acid (PLA)	Applied in implants and nanoparticle formulations	Produced from renewable resources and is readily biodegradable (7)

Sustainable pharmaceutical manufacturing aims to improve process efficiency while reducing energy consumption, material use, waste generation, and environmental impact. Important advances include the use of green solvents and aqueous processing systems as safer alternatives to hazardous organic solvents. Real-time monitoring and process control maintains product quality uniformity and minimises material losses (8).

Techniques such as spray drying, supercritical fluid technology and solvent-free processing are being investigated for nanoparticle production to reduce the environmental impact. These

technologies support the production of quality pharmaceutical products while contributing to the goals of sustainable manufacturing. Additionally, the use of PAT (Process Analytical Technology) allows real-time monitoring of critical process parameters, leading to fewer batch failures and less waste of resources (9). **Figure 1** summarizes the key sustainable materials and technologies used to reduce resource consumption, minimize waste generation, and improve process efficiency. **Table 2** provides a comparative overview of these technologies.

Representative applications demonstrate how sustainable approaches can be incorporated into drug delivery systems. Chitosan has been used in biodegradable nanoparticles and mucoadhesive formulations for mucosal drug delivery, while alginate-based carriers have been investigated for controlled and sustained drug release. Gelatin-based nanoparticles and microspheres provide biodegradable platforms for controlled drug delivery, whereas PLA-based nanoparticles and implants enable sustained drug release followed by degradation of the polymeric matrix (4–6). Microfluidic technologies further support the resource-efficient preparation of nano formulations by reducing material and reagent requirements while enabling precise process control (10).

Table 2. Green manufacturing technologies for sustainable pharmaceutical production Technologies

Technology	Application in Pharmaceutical Manufacturing	Key Advantage
Continuous Manufacturing	Enables uninterrupted production of pharmaceutical products	Reduces waste, energy consumption, and production time (11)
Spray Drying	Produces dry powders and nanoparticulate formulations	Improves process efficiency and minimizes material loss (12)
Supercritical Fluid Technology	Used for particle engineering and drug encapsulation	Reduces dependence on organic solvents (13)
Microfluidics	Facilitates precise preparation of nano formulations	Requires smaller quantities of materials and reagents (10)

Process Analytical Technology (PAT)	Supports real-time monitoring and process control	Prevents batch failures and improves resource efficiency (14)
Solvent Recovery Systems	Reclaims and reuses process solvents	Reduces waste generation and operational costs (15)

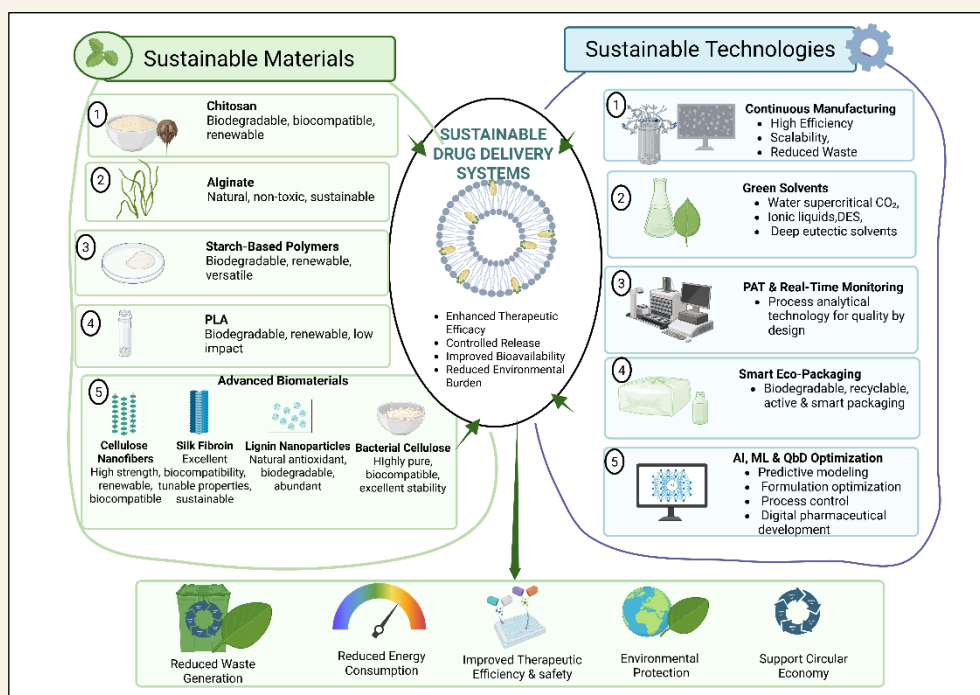


Figure 1. Key enablers of sustainable drug delivery systems: synergistic integration of sustainable biomaterials and innovative technologies.

(**Abbreviations:** PLA, Poly(lactic acid); PAT, Process Analytical Technology; QbD, Quality by Design; AI, Artificial Intelligence; ML, Machine Learning; DES, Deep Eutectic Solvents.)

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2.3 Sustainable Packaging

Packaging is an integral part of pharmaceutical products, providing stability, protection, and patient safety; however, conventional pharmaceutical packaging contributes substantially to plastic waste generation. The latest developments are based on packaging materials which are biodegradable and made from renewable resources. Scientists are searching for green alternatives to conventional plastics. These include plant-based polymers, paper-based composites and recyclable materials. There is also the attention to smart packaging technology.

Features such as temperature indicators, tamper-evident systems and digital tracking improve product management and reduce wastage due to improper storage or expired medicines. Designing sustainable packaging that is recyclable, responsibly sourced and reduces the amount of material can help support the circular economy principles in the pharmaceutical industry (16).

3. Environmental Aspects During the Use Phase

Sustainability of pharmaceutical products is not just the manufacturing process and packaging. Some of the drugs given to patients can enter the environment from excretion and improper disposal practices when patients take the drugs. Pharmaceuticals have been detected in surface waters, groundwaters, and in wastewater treatment systems. Some of these concerns could be solved by advanced drug delivery systems that could improve the drug targeting and reduce the needed doses. Targeted delivery methods improve therapeutic efficiency, minimise off target exposure and reduce environmental release. Research is also being conducted on biodegradable nanocarriers that degrade to non-toxic components after delivering their therapeutic payload (17).

4. Closing the Loop: Disposal and Waste Management

Public awareness programs and drug take-back initiatives can promote safer disposal practices and reduce the environmental release of unused medicines. Nanomaterials and polymeric carriers used in advanced drug delivery systems should be disposed of carefully. To minimise their environmental footprint, pharmaceutical manufacturers are adopting waste-minimization techniques, solvent-recovery systems, recycling procedures, and environmentally responsible disposal practices (18). **Table 3**, Comparison between conventional and sustainable approaches at different lifecycle stages.

Table 3. Moving to Sustainability Across the Pharmaceutical Product Lifecycle

Stage

Stage	Conventional Approach	Sustainable Approach
Product Design	Repeated trial-and-error formulation development	Systematic design using Quality by Design (QbD) principles (19)
Solvent Use	Dependence on organic solvents	Preference for safer and environmentally friendly solvents (20)

Manufacturing	Batch-wise production processes	Continuous and resource-efficient manufacturing (21)
Packaging	Conventional plastic-based materials	Biodegradable and recyclable packaging options (22)
Product Use	Limited focus on environmental impact	Improved targeting and optimized dosing to reduce waste (23)
Disposal	Medicines often discarded with general waste	Safe collection and responsible disposal practices (24)
Waste Management	Linear use-and-discard model	Recycling and circular economy approaches

5. Nanotechnology and the Future of Sustainable Drug Delivery

Nanotechnology is an emerging role of drug delivery towards sustainability. Nanotechnology plays an important role in modern drug delivery in the areas of targeted therapy, improved bioavailability and controlled release of drugs (25). Another emerging field of interest is the use of natural materials such as chitosan, alginate and gelatin in the development of nanocarriers. These methods reduce the need for hazardous solvents and enable cleaner manufacturing processes without sacrificing performance of the formulation. One less obvious way that nanotechnology may contribute to sustainability is in improving the efficiency of the treatment process itself. Targeted and controlled release systems usually lead to better therapeutic effects at lower drug doses and less frequent administrations (26). This can help reduce the total amount of pharmaceutical ingredients used, minimise waste in treatment and potentially reduce the amount of drug residues entering the environment. Another interesting development is the implementation of the Quality by Design (QbD) principles in nanomedicine development. QbD identifies the critical formulation and process variables systematically, thus reducing the unnecessary experimentation and making better use of laboratory resources (27). Meanwhile, breakthroughs in artificial intelligence and computational modelling are aiding researchers in predicting the behaviour of formulations and speeding up development to save time, materials and energy.

6. Limitations and Challenges

Despite their promising advantages, sustainable drug delivery systems face challenges related to the variability of biodegradable materials, the scalability of green manufacturing processes, and high upfront implementation costs. Limited knowledge of the environmental fate and ecotoxicity of nanocarriers, together with the lack of standardized methods for sustainability assessment and regulatory guidance, further limits their widespread adoption. Overcoming these challenges is essential for the successful translation of sustainable drug delivery systems from the laboratory to industrial and clinical applications.

7. Future Outlook: Circular Innovation in the Pharmaceutical Sector

Biodegradable nanocarriers and green manufacturing highlight the industry's commitment to innovation in sustainability.

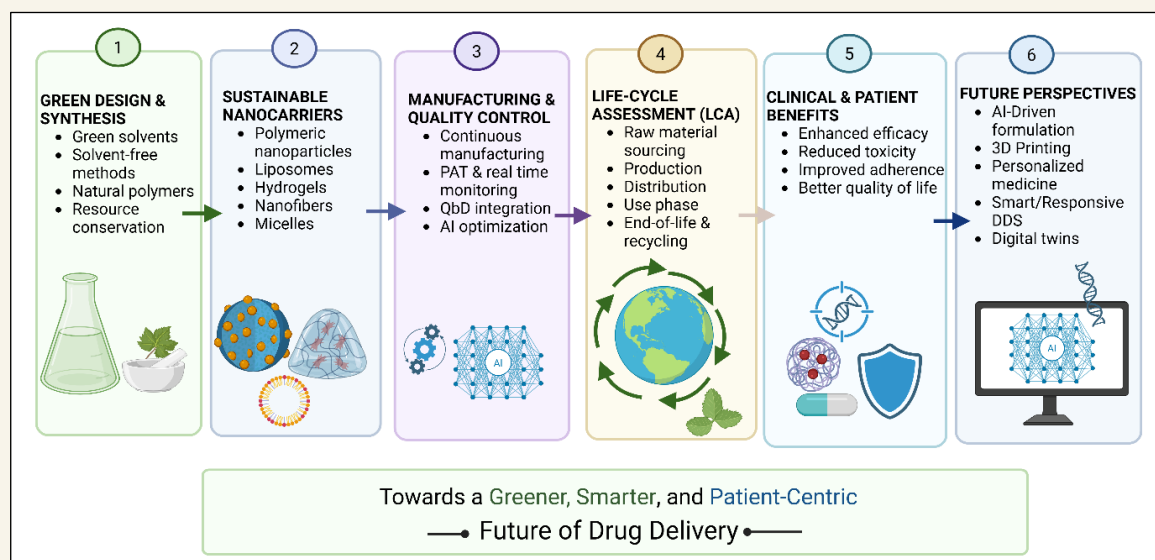


Figure 2. Sustainable drug delivery development pathway: from green design to clinical translation.

(**Abbreviations:** DDS, Drug Delivery Systems; LCA, Life-Cycle Assessment; PAT, Process Analytical Technology; QbD, Quality by Design; AI, Artificial Intelligence)

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8. Conclusion

In conclusion, sustainable pharmaceutical technologies are revolutionising the future of drug delivery systems. Opportunities exist at every stage of the product lifecycle, from formulation design and manufacturing to packaging and disposal, to reduce the environmental impact while

maintaining therapeutic usefulness. Advanced drug delivery systems, particularly using biodegradable materials and green manufacturing processes, could benefit patients' health and the sustainability of the environment. Lifecycle thinking and sustainable innovation can allow the pharmaceutical community to make a major contribution to global health goals and to protect the environment for future generations.

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