RESEARCH PAPER

Green Drug Delivery Technologies: Design, Development, and Applications

[1*]Dr Gajendra Singh, [2]Kirti B. Zare, [3]Dr. Pravat Ranjan Dixit, [4]Dr. Biswabandita Kar, [5]Dr Manokamana Ram, [6]Dr. Kabilan Annadurai

[1*]MSc (Disaster Mgt) Rashtriya Raksha University, Lucknow Campus, Email Id: talk2me@doctor.com, Orcid Id: 0000-0003-3945-5101

[2]Assistant professor, Department of Chemical Engineering, D Y Patil International University, Pune, Email Id: kirti.zare@dypiu.ac.in

[3]Lecturer in Chemistry, Chitalo Degree College,(Under Utkal University, Bhubaneswar) Jajpur, Odisha, India, Email Id: pravatdixit@gmail.com, Orcid Id: 0000-0001-5984-0117

[4]Professor of Chemistry, School of Applied Sciences, KIIT Deemed University, Bhubaneswar, Odisha, Pincode: 751004, India, Email id: bbkarfch@kiit.ac.in, Orcid Id: 0000-0002-9550-7335

[5]Assistant Professor in Economics, Department of Economics, Faculty of Social Sciences, Banaras Hindu University, Varanasi (UP, India)-221005, Email Id: manokamana@bhu.ac.in, Orcid Id: https://orcid.org/0000-0002-0689-4928

[6]Assistant Professor & Program Coordinator, Master of Public Health, Public Health, The Apollo University, Chittoor, Andhra Pradesh, Scopus Id: 57201278943, Orcid Id: 0000-0002-7338-0513

Abstract

Technologies of green drug delivery are rapidly poised as a viable path towards making therapeutic innovation in tandem with environmental responsibility. The review is a synthesis of advances in the areas of green design principles, sustainable materials, system architecture and manufacturing strategies that reduce solvent toxicity, material persistence and energy requirements without negatively affecting performance. Key green material classes discussed include biodegradable polymers, natural and bio-based excipients, and greener solvent/renewable feedstock approaches that support safer degradation and improved biocompatibility. Sustainable system designs spanning nanoparticles/nanocarriers, lipid–polymer platforms, and stimuli-responsive or targeted systems are highlighted for their ability to enhance bioavailability, improve site-specific delivery, and reduce dose burden across oral, topical/transdermal, and parenteral applications. The review also examines safety-by-design considerations, emphasizing integrated cytotoxicity testing, biocompatibility screening, and environmental hazard assessment supported by standardized in vitro, ex vivo, and in vivo methods. Some of the current challenges to translation consist of scale-up that can be reproduced, process control, cost limitation, and changing regulatory requirements of lifecycle and environmental safety evidence. The trends are emerging toward intelligent multi-capability green platforms and increased incorporation with the ability to personalize using nanotechnology. Altogether, the development of green drug delivery will demand scalable low-energy production, an effective safety framework, and clinically meaningful sustainability measures in order to help implement in pharmaceutics.

Keywords: drug delivery, green technology, biodegradable polymers, nanotechnology, sustainable pharmaceuticals

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1. Introduction

The technology of drug delivery systems has been facing a systematic revolutionizing process during the last seventy years, marked by the more traditional dosage delivery systems to the extremely advanced systems that have been created to further improve therapeutic efficiency, patient adherence, and safety. The initial work in the area was mainly on how to alter the drug release profiles so that they would be either long-acting or controlled. With time, developments in material science, biotechnology and nanotechnology have facilitated the development of purposeful and versatile delivery systems that can deal with the sophisticated pathologies of diseases. Such a gradual transformation is not just a manifestation of scientific and technological development but also a shift in the expectations of society and clinics in terms of the effectiveness of treatment, the focus on the interests of patients, and the safety of the pharmaceutical intervention over time[1]. Parallel to these technological improvements, the increasing environmental sustainability awareness has started to have a major effect on the pharmaceutical research and development. The conventional method of delivering drugs frequently relies on the use of non-renewable raw materials, energy-using production processes, and dangerous organic solvents, which pollute the environment and cause additional ecological pressure.

*Author for Correspondence: talk2me@doctor.com

Waste production, toxicity of solvents and low biodegradability of the material of a product are the issues that make researchers re-examine the traditional formulation strategies. Consequently, the concept of green drug delivery technologies has become an attractive paradigm that promises to incorporate the concepts of green chemistry and sustainable engineering into designing, developing, and processing pharmaceutical delivery systems[2]. These technologies are meant to have less impact on the environment but leave or enhance the therapeutic performance and patient safety. Ecotoxicity, biodegradability, and biocompatibility. Sustainable biomaterials have been of specific interest to research in green drug delivery, as they are less ecotoxic, biodegradable, and biocompatible. The substitution of synthetic components of the drug delivery formulations with natural polymers, bio-derived excipients, and renewable raw materials is gaining more and more supporters. These materials help enhance safer degradation routes and minimize the permanent build-up in the biological and environmental systems. Besides that, bio-based materials are in line with global strategies to ensure a secure production of pharmaceuticals and the principles of the circular economy in the healthcare system[3]. Material sustainability has therefore emerged as a major driving force in the creation of the next-generation drug delivery platforms. The new definition of drug delivery research is thus being re-framed as an important contributor to sustainable therapeutic innovation and not as a technical part of formulation science. The sustainable drug delivery systems will be able to help to enhance treatment efficiency, lower the dosing frequency, minimize adverse effects, and consequently minimize healthcare resource consumption, in general. Such an extended role emphasizes drug delivery as a strategic instrument to deal with clinical and environmental issues of contemporary medicine[4].

Recent viewpoints focus on the fact that sustainability in drug delivery is not limited to material choice but also includes system design efficiency, manufacturing scalability and translational feasibility. Implementing sustainable initiatives across all drug delivery lifecycle phases can drive innovation faster, besides mitigating regulatory, financial, and environmental limitations. This type of integration is becoming seen as very crucial to ensuring the next generation delivery systems are not only clinically viable, but also economically viable and environmentally friendly[5]. The idea of green pharmaceutics acts as an additional statement that necessitates the establishment of green pharmaceutical development ways that encompass the formulation design, processing methods, and lifecycle analysis. Green synthesis, reduction in solvents and minimal wastes have proved that sustainable approaches could be successfully adopted without diminishing the quality and performance of pharmaceuticals. Such developments highlight the viability of using drug delivery innovation as a way of balancing environmental stewardship and responsible manufacture[6]. In this regard, nanotechnology has been central in facilitating the creation of green nanomedicine platforms which incorporate high delivery efficiency, low environmental and biological risks. The green nanotechnology is supported by methods in which drugs can be targeted, released, and made more bioavailable while reducing the amount used and toxicity. These platforms are an intersection of technological complexity and sustainability-based design, which makes the delivery of green drugs a central force in the future of pharmaceutics[7].

This review is critical of green drug delivery technologies, and the emphasis was laid on their design philosophy, development strategies and their therapeutic use. Comprising the latest developments in the materials, delivery systems, and manufacturing methods, the review reveals the potential of sustainable drug delivery in the future of pharmaceutical science and green.

2. Principles of Green Drug Delivery Technologies

The application of green chemistry concepts to pharmaceutical design and development is the foundation of the principles of green drug delivery technologies. This has principles focusing on minimizing or completely avoiding any hazardous substances, utilizing renewable resources, and maximizing energy efficiency during the lifecycle of drug delivery systems. Green synthesis technology in nanotechnology-based delivery systems allows the production of functional nanocarriers that can be made with benign reagents, low-temperature conditions, and with minimal waste produced, making therapeutic innovation and environmental responsibility compatible[8]. In addition to chemistry, sustainability in the delivery of drugs involves the application of quantifiable measures when formulating and developing a drug. These measures are material renewability, biodegradability, solvent choice, process yield and lifecycle environmental impact. Sustainability-based performance metrics are used to evaluate drug delivery systems as they enable researchers to strike a balance between therapeutic efficacy and ecological safety. Research based on environmental biotechnology is applied in structured frameworks to determine the efficiency of resources and environmental compatibility in developing a drug, which strengthens the long-term sustainability aims[9].

Green drug delivery involves safety assessment, which is of vital importance not only for patient toxicity, but also for the environment and the workforce. The idea of green toxicology encourages the premature incorporation of predictive toxicity models, alternative testing plans and decreased dependence on harmful materials. This would allow the determination of safer materials and formulations at an early phase of development and reduce the downstream biological and environmental risks of drug delivery technologies[10]. The use of green principles in drug delivery research and translation is also influenced by regulatory and environmental factors. In order to promote sustainable pharmaceutical activities, regulatory bodies are advancing the policies that will facilitate the selection of materials harmoniously, responsible manufacturing, as well as minimizing the amount of waste. The alignment of drug delivery innovation with changing regulatory demands is crucial in the successful translation of drugs, market acceptance and sustainability in the use of medicines in healthcare systems[11]. Figure 1 provides the general scheme of green drug delivery technologies, starting with the selection of materials, then the safety, and regulatory alignment.

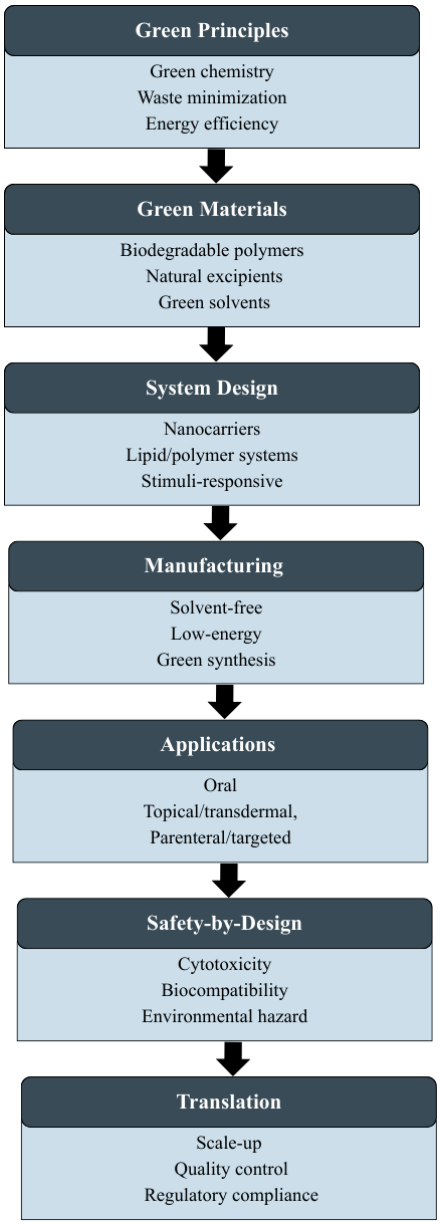

Figure 1. Conceptual framework of green drug delivery

3. Green Materials Used in Drug Delivery Systems

3.1 Biodegradable Polymers

Most of the green drug delivery systems are biodegradable polymers, which can be broken down to non-toxic and

biologically compatible byproducts. The recent developments in the field of polymeric drug delivery were directed at the creation of materials that could be used to deliver drugs at a controlled rate and reduce the accumulation of materials over time, both biologically and environmentally. These polymers provide adjustable mechanical strength, decomposition rate, and drug delivery efficiency so that they can be used in various therapeutic applications[12]. Biodegradable polymer-based delivery systems have also proven to be particularly promising in regenerative and site-specific therapies. Their regulated degradation behavior aids in localized release of drugs and integration with tissues, particularly in the bone and tissue regeneration systems. The versatility of the biodegradable polymers allows fine-tuning of carrier functionality and allows responsible pharmaceutical development in terms of the environment[13].

3.2 Natural and Bio-Based Excipients

Natural polymers and bio-based excipients have become more popular as an alternative to synthetic components of formulations with regard to sustainability. These materials are based on renewable biological sources and have inbuilt biocompatibility, lower toxicity and structural versatility. Nanoparticles made of natural polymers have been shown to perform well in drug loading and delivery, as well as reduce environmental and biological risks of synthetic carriers by a large margin[14]. Pharmaceutical excipients have been evolving with a better focus on safety, sustainability and multifunctional. Natural excipients are important in stabilization, solubilization, and controlled release, as well as enabling green formulation approaches via reduced chemical processing and sustainable sourcing. Incorporation into drug delivery systems makes formulation science consistent with the overall sustainability objectives in pharmaceutics[15].

3.3 Green Solvents and Renewable Raw Materials

The choice of solvents is the primary factor affecting the ecological impact of the drug delivery system production. Substitution of traditional organic solvents with green solvents has emerged as an effective approach in curbing toxicity, generation of wastes and use of energy in the formulation process. Green solvents allow the processing environment to be safer without affecting the stability of drugs or drug delivery performance. The fact that green solvents are combined with renewable raw materials also increases the sustainability profile of drug delivery systems. These strategies promote effective drug delivery and release and comply with the tenets of environmental responsibility. Ongoing progress in the selection of solvents and materials will become important in emerging technologies of green drug delivery[16]. Table 1 summarizes the most common classes of green materials used in drug delivery systems, highlights their main benefits, and main areas of application in drug delivery systems.

Table 1. Overview of green materials used in drug delivery systems

Green material class	Examples	Key advantages	Typical applications
Biodegradable polymers	PLA, PLGA, PCL, chitosan	Biocompatible, controlled degradation, reduced toxicity	Controlled release, tissue regeneration
Natural polymers	Alginate, gelatin, cellulose	Renewable, low immunogenicity, safe degradation	Nanoparticles, wound healing
Bio-based excipients	Plant-derived stabilizers, sugars	Improved safety, multifunctionality	Oral and topical formulations
Green solvents	Supercritical CO_2, ethanol, water	Reduced toxicity, low environmental impact	Nanoparticle fabrication

Renewable raw materials	Biomass-derived lipids, polysaccharides	Sustainable sourcing, low persistence	Lipid carriers, polymer matrices

4. Sustainable Drug Delivery System Design

4.1 Nanoparticles and Nanocarriers

Nanoparticles and nanocarriers can be considered as a foundation of sustainable drug delivery system design because of the high drug loading capacity, the controlled release pattern, and decreased dosage. These systems allow accurate control of the pharmacokinetics and biodistribution, which enhances therapeutic efficacy and minimizes the systemic exposure and waste. The development of nanocarriers has more often concentrated on greener synthesis paths and biodegradable carrier designs, which have aided in developing sustainable pharmaceuticals[17]. Nanoparticle-based drug delivery systems have been shown to be more effective in terms of targeting and less toxic (off-target) in oncology-related and other complex therapeutics. These carriers help to reduce the overall use of drugs and achieve better treatment results by allowing the accumulation of drugs at site-specific levels. This kind of efficiency-related design thinking can be used to combine sustainability with clinical outcomes, which supports the use of nanocarriers in green drug delivery initiatives[18].

4.2 Lipid-Based and Polymeric Systems

Polymer and lipid-based delivery systems continue to be at the forefront of designing sustainable drug delivery systems because they are versatile, scalable, and biocompatible. They enable accurate manipulation of drug encapsulation, release kinetics, and carrier degradation, and hence these systems are applicable to a very broad range of therapeutic protocols. Current studies focus on the application of biodegradable plastics and naturally occurring lipids to minimize environmental effects without compromising the formulation integrity[19]. The polymeric and lipid-based systems have the potential of providing engineering opportunities to make mate manufacturing efficient and optimize the use of materials. Controlled drug release designs achieve a lower dosing frequency and enhance patient adherence, which indirectly leads to sustainability due to the low resource consumption and healthcare burden. System design based on rationality is thus very important in the balancing of performance, safety and environmental responsibility[20].

4.3 Stimuli-Responsive and Targeted Green Systems

Stimulus-driven drug delivery systems are a future perspective of sustainable therapeutic design since it allows the release of drugs in response to certain internal or external stimuli. These systems increase treatment accuracy because therapeutic agents are only delivered under specific conditions (physiological or externally imposed) to reduce unwarranted exposure of drugs and wastage of material. Increasingly biodegradable carriers and low-toxicity components are used to develop targeted and stimuli-responsive systems of green delivery. The pH, temperature, enzyme, or external stimuli (e.g. light, magnetic fields) ensure highly controlled profiles of drug release. This smart system design can sustain and ensure therapeutic efficacies, and thus, the stimuli-responsive platform can be viewed as one of the primary contributors to the green drug delivery procedures in the future[21]. Table 2 summarizes the key designs of sustainable drug delivery systems and their therapeutic application.

Table 2. Sustainable drug delivery system designs and features

System type	Design features	Sustai
Nanoparticles	High surface area, tunable size	Reduc
Polymeric systems	Controlled degradation	Lower accum
Lipid-based systems	Biocompatible lipids	Green
Stimuli-responsive systems	Triggered drug release	Minim
Targeted delivery systems	Ligand-based targeting	Improv

5. Eco-Friendly Manufacturing and Processing Techniques

5.1 Solvent-Free and Low-Energy Fabrication Methods

The manufacturing strategies are decisive factors in issues of the environmental footprint of drug delivery systems. The traditional fabrication processes are usually expensive in terms of energy usage and include many organic solvents, which adds to the generation of waste and poses an environmental threat. Other sustainable methods that have come into existence to generate nanoparticles and delivery vehicles are solvent-free and low-energy fabrication methods, including melt processing, supercritical fluid technology and mechanical methods. This reduces the amount of chemicals used and the amount of energy needed, and yet there is control of the size of a particle and its functionality as well[22]. Scalability and reproducibility are other characteristics that are necessary in industrial translation in low-energy processing approaches. Such techniques promote pharmaceutical production that is environmentally friendly by minimizing manufacturing procedures and decreasing the use of reagents that are dangerous to the environment, and do not affect the delivery performance.

5.2 Green Synthesis of Nanocarriers

The green synthesis methods of developing nanocarriers are focused on benign reagents, renewable biological resources, and the mild conditions of the reaction. Functional nanomaterials have been fabricated using plant extracts, microorganisms, and bio-derived compounds to be used in drug delivery purposes. These techniques reduce toxic and stabilizers giving rise to nanocarriers that are much more biocompatible and less harmful to the environment. Nanocarriers synthesized using green chemistry have proven efficient in the loading of drugs, targeting, and therapeutic functions, especially when used in cancer drug delivery. The concept of green principles in the fabrication of nanocarriers is one of the main steps towards balancing nanomedicine and the sustainability goals[23].

5.3 Process Optimization for Reduced Environmental Impact

Optimization of processes is required to reduce the consumption and environmental impact of resources in the entire system of drug delivery. The best processing parameters are able to minimize material waste, energy consumption, and emissions, as well as enhance product consistency and performance. Nanoscale delivery research has provided a cross-disciplinary understanding of the significance of optimization at the system level, where manufacturing efficiency and ecological friendliness are taken into account alongside therapeutic activity[24]. Also, there can be formulation and process optimization to tackle the issues relating to drug stability, scalability, and performance, which is especially important in the case of complicated delivery systems. Lean processing approaches will help in lowering production expenses and enhanced sustainability that will help facilitate the wider use of environmentally friendly drug delivery technologies in medicinal research[25]. Table 3 summarizes eco-friendly manufacturing and processing strategies that are used in green drug delivery technologies.

Table 3. Eco-friendly manufacturing techniques for drug delivery systems

Technique	Principle	Environmental benefit	Application
Solvent-free processing	Eliminates organic solvents	Reduced waste and toxicity	Particle fabrication
Supercritical fluid technology	Low-temperature processing	Energy efficiency	Nanoparticle synthesis
Green synthesis	Bio-based reducing agents	Safer nanomaterials	Nanocarriers
Process optimization	Reduced steps and energy	Lower carbon footprint	Industrial scale-up

6. Applications of Green Drug Delivery Technologies

6.1 Oral Drug Delivery

Oral route of drug delivery is the most preferred mode of drug delivery by patients because it is convenient and compliant. The green drug delivery technologies have facilitated the invention of oral form that incorporates therapeutic effectiveness alongside environmentally friendly preparation processes. Nanostructured delivery systems that have been developed by adopting green chemistry have been shown to have superior stability of the drug, taste masking and controlled release, especially in use in children and chronic therapies[26]. Nanocarriers that are made of lipids have been useful in the development of sustainable oral drug delivery. Nanoparticles of solid lipids and nanostructured lipid carriers increase the aqueous solubility and bioavailability of drugs with low aqueous solubility and permit the utilization of biocompatible lipids and less solvent processing. These systems facilitate a more formulated philosophy that is green, with no oral delivery performance degrading[27].

6.2 Transdermal and Topical Delivery

Green drug delivery methods have become increasingly topical and transdermal, where topical and localized drug delivery is a desired characteristic, and low systemic exposure is preferable. Green excipients and biodegradable carriers enhance the compatibility with the skin and reduce irritation, as well as allow prolonged release of the drug. The scientific progress in formulations has led to the development of safer and more efficient topical and transdermal delivery systems with environmentally friendly materials[28]. Natural polymers and plant-derived bioactive compounds have also expanded the transdermal drug delivery scope of green. These materials have inherent biocompatibility and therapeutic properties, which aid in wound healing, transdermal delivery and minimize the use of artificial chemicals. The topical drug delivery is integrated with the ecological safety and sustainability goals through incorporating plant-based resources into the delivery platforms[29].

6.3 Parenteral and Targeted Delivery Applications

Green nanotechnology is highly advantageous to parenteral and targeted drug delivery systems because of the requirement of high purity, safety and accuracy of biodistribution. The targeting and controlled release of drugs through the green nanoparticulate systems based on biodegradable materials and benign methods of synthesis have proven effective and have reduced the toxicity risks. Such systems assist in the effective delivery of drugs with less environmental and biological impact[30]. Nanosuspensions and emulsions are two types of colloidal delivery systems that can be used extensively in parenteral formulation because of their versatility and flexibility. Green formulation approaches enhance the safety and stability of such systems and allow the provision of controlled delivery and improved therapeutic effects. Their use in parenteral drug delivery makes one see the potential of green technologies to facilitate high-level and sustainable therapeutic interventions[31].

7. Safety, Biocompatibility, and Performance Evaluation

7.1 Toxicological and Environmental Safety Assessment

Green drug delivery technology clinical translation requires a significant safety assessment as a condition. The green biomaterials are specifically geared towards being extremely biocompatible and reducing cytotoxic and inflammatory reactions. In-depth toxicological analysis is usually accompanied by cell viability, oxidative stress, immune response, and degradation byproducts, as a guarantee of safe interaction with biological systems. This kind of assessment ensures that therapeutic safety can be addressed using sustainable materials without affecting the biological performance[32]. Environmental risk assessment has become more relevant to drug delivery systems containing nanomaterials, besides biological safety. Polymeric and inorganic nano-biomaterials can be emitted to the environment during manufacturing, use, or disposal.

The analysis of environmental hazards, therefore, is based on the persistence, bioaccumulation and ecotoxicity to determine the overall effects of these materials, beyond clinical application[33]. The existence of regulatory focus on environmental, legal, and occupational safety has increased the necessity of an extensive risk assessment. Green nanomaterials have to meet the emerging safety requirements that include human health, environmental exposure, and regulatory requirements. These considerations should be integrated at an early stage of designing drug delivery systems to aid responsible innovation and help to gain regulatory approval[34].

7.2 In Vitro and In Vivo Performance Studies

The targeting performance and efficiency of green drug delivery systems require in vitro and in vivo research to assess the therapeutic efficacy of the delivery systems. Such studies will give a clue to drug release, cellular uptake, biodistribution, and pharmacological response. Biochemical engineering methods used on green nanomaterials have shown an increase in targeting ability and targeted drug release with good safety profiles to enable their use in advanced therapeutic techniques[35]. There is a growing interest in green drug delivery systems that are tested in combined in vitro, ex vivo and in vivo systems to produce comprehensive performance profiles. These kinds of multi-level evaluation strategies can enable the prediction of clinical behavior correctly, and enable ethical research practices by cutting down on extensive animal testing. Such methods also allow evaluating bio-adhesion, wound healing capacity, and local drug activity[36].

7.3 Comparison with Conventional Drug Delivery Systems

The benefits of green technologies need to be established by making a comparative evaluation with conventional drug delivery systems. The performance parameters are biocompatibility, release efficiency, stability, precision of targeting and safety outcomes. The green drug delivery systems often exhibit lower toxicity and better biological interaction with the traditional formulations. The standardized characterization techniques allow objective comparison of the green and conventional delivery platforms. In vitro, ex vivo and in vivo methods of assessing bio-adhesiveness, residence time, and therapeutic activity give robust data to demonstrate the clinical and environmental advantages of sustainable drug delivery systems[37]. Table 4 displays major applications of green drug delivery systems and safety considerations associated with their use. Figure 2 illustrates a systematic safety and performance evaluation route of delivery systems of green drugs.

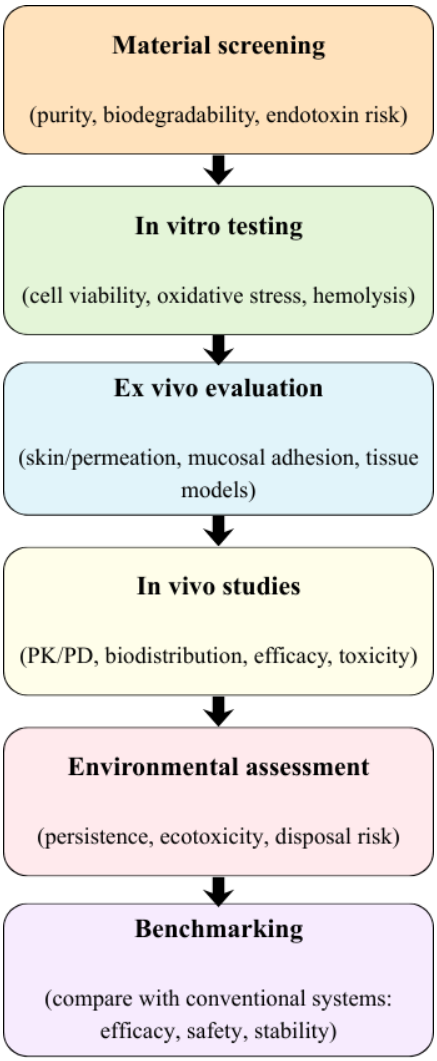

Figure 2. Safety and evaluation workflow for green drug delivery systems

Table 4. Applications and safety considerations of green drug delivery systems

Application route	Green delivery approach	Key benefit	Safety consideration
Oral delivery	Lipid nanoparticles	Improved bioavailability	Gastrointestinal compatibility
Topical/transdermal	Natural polymer carriers	Localized action	Skin irritation assessment
Parenteral delivery	Green nanocarriers	Targeted delivery	Sterility and toxicity
Targeted therapy	Stimuli-responsive systems	Reduced off-target effects	Long-term biocompatibility

8. Challenges and Limitations

Even though it has made a big leap, there are various technical and formulation challenges in the development of green drug delivery technologies. Numerous methods of green fabrication involve strict regulation of processing conditions in order to obtain homogeneous particle diameter, drug loading and release kinetics. Although certain technologies like supercritical fluid processing can provide environmentally friendly technologies in contrast to standard methods, they are not always viable because of complex equipment, restriction of formulation, and sensitivity to operating conditions that may cause a lack of reproducibility and scalability[38]. The important impediments to the widespread application of green drug delivery systems are scale-up and industrial implementation. The current approaches to green synthesis at the laboratory scale are often based on the use of batch reactions, biological materials, or low-throughput methods that are hard to convert into large-scale production. Moreover, scale-up of uniformity and quality control of products poses technical challenges that can constrain the industrial feasibility and commercialization opportunity[39].

The adoption of technologies of green drug delivery is also affected by economic and regulatory factors. Green materials and environmentally friendly process mechanisms can imply larger expenditures, special facilities, and longer time frames in development. The regulatory procedures in green nanotechnology-based drug delivery systems are in their early stages, and few standardized principles are available to deal with environmental safety, toxicity in the long-term and lifecycle assessment. It is a challenging issue to navigate these regulatory priorities and balance the innovation, cost-effectiveness and compliance to ensure the effective translation of green drug delivery technologies to clinical practice[40]. Figure 3 provides a comparative summary of the sustainability benefits of the green drug delivery technologies to the traditional systems.

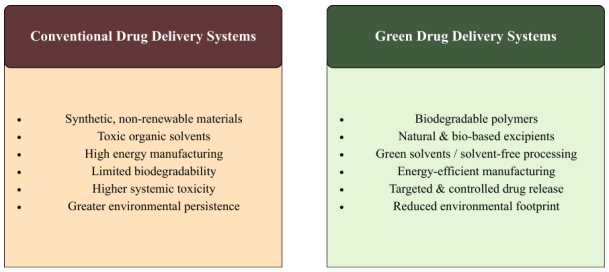

Figure 3. Sustainability advantages of green drug delivery technologies

9. Emerging Trends and Future Perspectives

New technologies in green delivery of drugs focus more on emerging trends of intelligent and multifunctional drug delivery systems that can be applied to solve intricate therapeutic needs. Recent progress shows the emergence of delivery platforms, which are able to deliver multiple targets in real-time, regulated release and therapeutic synergy. Such intelligent systems combine sensitivity to biological stimuli with multi-functionality, which allows the system to be more effective and less toxic. These trends indicate a shift in more precise-delivery-focused approaches to therapy maximizing therapeutic outcomes with minimal material consumption and minimal side effects[41]. The other emerging trend is another trend which is the growing amalgamation of the green drug delivery system with sophisticated nanotechnology. Multimodal

nanocarriers made of biodegradable materials are being developed to perform a range of tasks, such as to protect the drug and deliver it to the target, as well as to modify its performance. The cross-disciplinary studies demonstrate that multifunctional carrier systems can be made optimized in terms of functionality and sustainability, which supports the idea that nanotechnology is likely to be one of the key factors of innovation in designing green delivery systems[42]. Going forward, it is believed that personalized medicine will become central to determining the future of green drug delivery technology. The delivery systems enabled by nanotechnology provide the ability to customize the therapeutic approach according to the individual aspects of a patient, including genetic profile, disease condition and treatment response. A combination of sustainable nanocarriers with personalized medicine method could enhance precision in the delivery of therapeutic effects, minimization of drug waste, and increase patient safety[43]. Further avenues of research must aim at making the system design scalable, capable of predictive modeling, and harmonization of the regulatory framework to enable clinical translation of the personal and environmentally responsible drug delivery systems.

10. Conclusion

The pharmacology of delivering drugs by green technologies is transforming the drug-delivery system in terms of linking the effectiveness of the therapy with the ecological sustainability of the design. The sector is moving beyond individualized instances of green material replacements to carrier-to-carrier sustainability as well as lifecycle and fabrication. The polymers that are biodegradable, bio-based excipients and more environmentally friendly solvent systems facilitate safer degradation pathways without interfering with the formulation functionality. Sustainable system engineering, constituted of nanocarriers, lipid-polymer designs, and stimuli-responsive designs, is poised to enhance the accuracy of targeting, minimize dose load, and improve patient outcomes. More crucially, to credibly translate into human beings, stringent biocompatibility and environmental hazard testing, which is backed up by standardized in vitro, ex vivo, and in vivo testing, is critical. Nonetheless, scale-up reproducibility, control of quality, cost, and changing regulatory demands continue to be the major obstacles to broad adoption. The way forward needs to be focused on scalable low-energy production, resilient safety-by-design systems, and the presence of clinically relevant metrics of performance, combined with the consideration of smart multifunctional platforms and personalization. All these activities can empower clinically and sustainability-oriented innovations in drug delivery.

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