Review

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Sustainable Drug Delivery Systems with Biodegradable Innovations for Targeted and Efficient Therapy

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Sustainable Drug Delivery Systems with Biodegradable Innovations for Targeted and Efficient Therapy

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Abstract: Development of drug delivery systems has introduced environmentally friendly and degradable technology due to the advent of targeted, effective, and sustainable therapies. Recent advances on biodegradable polymers, nanotechnology-based smart carriers, and AI-based personalized medicine are being presented here and are all setting the platform for the next-generation drug delivery system. Use of biodegradable material reduces environmental burden but increases drug stability, bioavailability, and controlled release. Nanotechnology has revolutionized site-specific drug delivery with responsive drug delivery systems delivering drugs at desired locations, reducing toxicity and maximizing therapeutic efficacy. Natural and plant molecules are becoming more commonly used as green drug excipients and also improving biocompatibility and less synthetic waste. In addition, advances in AI-based drug design and precision medicine are allowing therapy to be personalized to the patient, improving treatment efficacy with reduced side effects. In antibiotic resistance management, novel nanotechnology-based drugs and drug delivery systems offer enhanced bacterial targeting and enhanced drug retention to overcome the top clinical challenges. Green and biodegradable drug delivery will be at the forefront of future pharmaceutical science with AI, nanotechnology, and green excipients being the pioneers. In this review, emphasis is placed on the future of such novel technologies to re-define drug delivery with patient safety and environmental sustainability at its core.

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1. Introduction

The discipline of drug delivery has grown to enormous size in the last ten years due to the necessity of more potent, target-directed, and patient-individualized therapy [1],[2]. The traditional drug delivery systems are plagued with issues of poor bioavailability, systemic toxicity, and inefficient target, which results in poor therapeutic efficacy and augmented side effects [3]. In order to overcome such adversity, more sophisticated drug delivery systems like biodegradable carriers, nanotechnology-based drug delivery systems, and vesicular drug transport systems have been of considerable interest [4].

Likely among these are biodegradable drug delivery systems capable of offering drug stabilization, controlled release, and minimizing side effects [5]. They utilize new biomaterials which are broken down biologically by the body with lower risk of long-term build-up and toxicity. Site-specific drug delivery strategies such as nanoparticles and liposomal carriers also give targeted action with increased therapeutic response at the cost of diminished systemic exposure [2],[3].

In this section, we will talk about novel and green drug delivery systems in the form of biodegradable drug carriers, targeted therapy, and their application in contemporary medicine. Some of the recipes such as nanoparticles, vesicular systems, oral films, and effervescent tablets are what will be discussed here, and their application to increase bioavailability of the drug, patient compliance, and therapeutic activity. We would like to know how this is done with the help of nanotechnology, personal medicine, and phytomedicines [4],[5].

2. Biodegradable Polymers and Their Role in Drug Delivery

Biodegradable polymers are today the backbone of modern drug delivery systems that are characterized by prolonged release, reduced toxicity, and improved therapeutic efficiency [6],[7]. These polymers biodegrade into harmless metabolites in the body, eliminating any possibility of long-term accumulation and improving patient safety. Polylactic acid (PLA), polyglycolic acid (PGA), poly(lactic-co-glycolic) acid (PLGA), and chitosan are extensively employed biodegradable polymers applied in drug delivery and can release drugs in a controlled fashion and maintain stability [8].

Table 1. Biodegradable Polymers in Drug Delivery.

Polymer Type	Examples	Key Benefits	Applications
Synthetic Polymers	PLA, PGA, PLGA [6],[7]	Controlled release, biocompatibility	Chronic disease management [9]
Natural Biopolymers	Chitosan, Alginate, Gelatin [7]	Low toxicity, minimal immune response	Injectable hydrogels, nanoparticles [7]
Nanocarriers	Biodegradable nanoparticles, micelles [6]	Enhanced solubility, protection from degradation	Cancer therapy, targeted delivery [6]
Stimuli-Responsive Polymers	pH-sensitive, temperature-sensitive [8],[9]	Site-specific degradation for precision medicine	Personalized treatments [8]

One of the most important advantages of biodegradable polymers is their ability to prolong drug action by offering sustained release at the site of action. This is particularly beneficial in the management of chronic disease, where frequent dosing is linked with patient non-compliance and systemic toxicity [9]. Furthermore, biodegradable micelles and nanoparticles have been engineered to encapsulate drugs, improving solubility and bioavailability and reducing premature degradation [6].

Besides synthetic polymers, biodegradable natural polymers such as alginate, gelatin, and dextran have been leading the field with their biocompatibility and lack or minimal immunogenicity [7]. They have broad applications in nanoparticles, hydrogel preparations, and injectable depots that release drugs in a sustained and targeted fashion for extended periods of time.

Appearance of novel pH-, temperature-, or enzymatically degradable stimulus-sensitive biodegradable polymers has also augmented the potential of such systems for controlled drug delivery [8],[9]. These developments will unlock the future of patient-specific and personalized therapy with minimum systemic toxicity and maximum therapeutic effects.

3. Nanotechnology and Smart Carriers for Targeted Drug Delivery

Nanotechnology has overcome the deficit in drug delivery by targeted delivery, increased bioavailability, and drug release [10],[11]. Intelligent nanocarriers like liposomes, dendrimers, micelles, and polymeric nanoparticles have been designed to deliver the drug site specifically with no or fewer systemic side effects [12].

The nanocarriers are designed for delivery through barriers of the biology for site-specific deposition of the drug and therapeutic effect [13].

Targeted drug delivery with nanocarriers involves active and passive targeting mechanisms. Passive targeting makes use of the EPR effect to enable passive accumulation of nanocarriers in tumor tissue via permeable vasculature [10]. Active targeting, on the other hand, involves surface functionalization of nanocarriers with ligands, antibodies, or peptides with selective affinity to

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overexpressed receptors on pathologic cells [11]. The technique significantly enhances the selectivity of drugs and minimization of off-target toxicity.

The recent advance in stimulus-sensitive smart nanocarriers has stimulated the concept of "on-demand drug delivery" based on specific physiological conditions such as pH, temperature, or enzyme level [12]. These responsive systems offer the release of the drug at the desired site to the lowest degree of premature degradation and the highest therapeutic response.

Furthermore, nanotechnology has enabled the development of multi-functional nanocarriers to deliver imaging agents for real-time monitoring of drug delivery and therapeutic response [13]. All these come under personalized medicine and patient-specific therapy, a new paradigm in modern therapeutics.

4. Herbal and Natural Compounds in Sustainable Drug Formulations

Plant and herbal products have been highlighted as green alternatives in new drug formulations based on their biocompatibility, low toxicity, and effectiveness [14]. Curcuma longa (curcumin), Withania somnifera (ashwagandha), and Centella asiatica medicinal plants were found to exhibit robust pharmacological activity and hence are potential candidates for drug delivery [15]. These drugs possess anti-inflammatory, antimicrobial, and antioxidant properties, which result in holistic therapeutic effects.

Recent advances have incorporated herbal bioactives in nanocarrier systems such as liposomes, nanoparticles, and phytosomes to improve their stability and bioavailability [16]. Classical herbal medicines are poorly soluble, unstable, and quickly metabolized, hence reducing their effectiveness. Formulations derived from nanotechnology circumvent such constraints by conferring sustained release, targeting, and improved pharmacokinetics.

Also, naturally occurring biodegradable polymers like chitosan, alginate, and starch are increasingly utilized in herbal drug release systems with prolonged release and improved absorption [14]. They offer a green pathway of drug manufacture with fewer synthetic excipients but high curative efficiency.

Introduction of the herbal ingredients into contemporary drug delivery systems fills the gap between ancient medication and newer drugs in a sustainable patient-focused strategy for disease control [15].

5. Overcoming Antibiotic Resistance with Advanced Drug Delivery

The global challenge of antibiotic resistance has enhanced the requirement for upgraded drug delivery technology for increasing treatment efficiency [17]. Conventional antibiotic therapies are prone to releasing subtherapeutic drug concentrations, bacterial drug resistance, and toxic effects at a systemic level, decreasing the level of therapeutic action. New-generation nanocarrier-based systems of drug delivery for antibiotics like liposomes, polymeric nanocarriers, and dendrimers exhibit prospective opportunities in upgrading the drugs' stability, site specificity, and release properties [18].

Table 2. Innovations in Antibiotic Drug Delivery.

Category	Challenges	Innovative Solutions
Conventional Antibiotics	Suboptimal drug concentrations, systemic toxicity [17]	Nanocarrier-based delivery for targeted action [18]
Bacterial Resistance	Development of resistance due to prolonged exposure [19]	Stimuli-responsive nanocarriers triggered by pH, enzymes [19]
Biofilm Penetration	Poor antibiotic penetration into bacterial biofilms [17]	Advanced nanocarriers improving site-specific drug release [18]
Combination Therapies	Need for alternative approaches to combat resistance [19]	Herbal-antibiotic synergy using curcumin, allicin [17]

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Toxicity & Biocompatibility	High toxicity affecting patient safety [18]	Biodegradable polymers ensuring controlled release [18]

pH, enzyme, or biofilm environment stimulus-sensitive nanocarriers, releasing antibiotics, are engineered to allow drug penetration and efficacy [19]. These formulations ensure the disruption of bacterial resistance systems to obtain controlled action of the drug at the infection site.

Furthermore, combination of antibiotics with herbal antimicrobials such as curcumin, allicin, and berberine has been identified as a synergistic strategy against resistance. The plant products contain antibacterial compounds and supplement the traditional antibiotics in making bacteria more susceptible and preventing drug resistance [17].

The use of biodegradable polymers for delivering antibiotics also maximizes drug efficiency and minimizes toxicity, laying the groundwork for the next generation of antimicrobial therapy [18]. Such developments have the promise to revolutionize infectious disease treatment with ecologically friendly, efficient, and patient-compatible antibiotic therapy [19].

6. Personalized Medicine and AI in Drug Formulation

Personalized medicine has transformed drug discovery from one-size-fits-all to patient-individualized drugs. Personalized medicine employs genetic, environmental, and lifestyle factors to engineer targeted therapy with enhanced efficacy and lesser side effects [20]. It is of tremendous value in cancer, metabolic disease, and neurodegenerative disease therapy, where drug response is very heterogeneous among patients.

Artificial intelligence (AI) is also quickly becoming a key propelling force for personalized drug development. AI algorithms screen vast biological data, anticipate drug-drug interaction, and create formulation optimization, accelerating the process of drug discovery [21]. Machine learning algorithms can identify best combination of drugs, bioavailability optimization, and patient-diversity-based release profile customization. AI-created nanocarrier systems also provide targeted delivery of drugs with minimized systemic toxicity and enhanced therapeutic action [20].

Moreover, AI has also improved the efficacy of the choice of biodegradable polymers in controlled release drug formulation with biocompatibility. AI has also enabled in silico screening of drugs, reducing the consumption of traditional clinical trials and hastening regulatory approval [21].

With the technological progress with AI, its combination with pharmacogenomics, 3D printing of tailored medicine, and real-time patient monitoring will determine the future of precision therapeutics that will make the therapy more sustainable, effective, and patient-focused [20].

7. Future Trends in Biodegradable and Eco-Friendly Drug Delivery

The drug delivery industry is moving towards green and biodegradable drug delivery systems to deliver maximum therapeutic activity at the cost of reducing environmental footprint. Polylactic acid (PLA), polycaprolactone (PCL), and chitosan are some biodegradable polymers that have become the green substitutes for traditional synthetic excipients [22]. They are broken down into non-toxic units that reduce long-term environmental waste.

The second newly evolving direction is the creation of biodegradable, stimulus-sensitive smart carriers responsive to physiological stimuli, including pH, temperature, and enzyme, to deliver the drug in a predetermined and controlled manner at the site of action [23]. This technology ensures optimal efficacy of the drug with decreased systemic toxicity and side effects.

Furthermore, plant and bioinspired nanocarrier-based drug delivery systems have also been more popular, employing lipids, proteins, and polysaccharides in environmentally benign and biocompatible systems. Not only do they enhance the solubility and stability of drugs but they also enable green pharmaceutical processes focusing on chemical waste reduction and ecotoxicity footprint [24].

The days ahead will see 3D-printed biodegradable implants, AI-optimized formulation design, and biodegradable drug delivery carriers to order, which will characterize the next-generation green therapeutics [22]. Biodegradable material-nanotechnology-AI hybrids will re-shape the equation of drug delivery as ever more environment friendly, patient friendly, and ultra-potent [23,24].

8. Conclusions

Green and biodegradable drug delivery systems are the aspiration of novel drugs. With the combination of blended biodegradable polymers, nanotechnology, plant extracts, and AI-based drugs, scientists today have to handle efficacy, safety, and environmental issues together. Smart nanocarriers improve the specificity of the medicine, and biodegradable polymers ensure slow release and lesser waste.

Targeted therapy through very effective artificial intelligence-based big data mining is lowering drug design to the patient's individual need for greater therapeutic benefit and lesser side effects. Herbal drug carriermers-based natural drug carriers also provide a greener, more natural route to conventional synthetic excipients. The need for warfare against antibiotic resistance by new nano-formulations and new drug carriers arises out of the current search for research in that area.

Future that lies ahead: green drug delivery is the next era's future and future which is multidisciplinary innovation that has the thread of biotechnology holding them all together, material science, and precision medicine through AI. Pharmainnovation interfused with sustainability will push the biodegradable technologies to take center stage in order to secure the greatest planned cures using the smallest possible ecological footprints. The following review focuses on increasing relevance of intelligent and biodegradable drug delivery systems in leading us to the future where drug formulation is customized according to the patient and environment.

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