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Formulation and Characterization of Biodegradable Drug Delivery Systems for Targeted Cancer Therapy

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ABSTRACT

Biodegradable drug delivery system (DDS) is a new technology that gives a great advantage to targeted cancer treatment and refers to remarkable advances in drug potency, patient acceptability and safety. Such systems will be employed to administer directly to cancer cells an agent, which provides a therapeutic effect and over all having lower off-target effects as well as toxicity to healthy cells. This review pays particular attention to the design and development of biodegradable DDS to target cancer therapy with emphasis on choosing materials, drug entrapment methodologies and release rates in designing efficient therapies. The most widely used are the biodegradable polymer types including poly(lactic-co-glycolic acid) (PLGA), polycaprolactone (PCL), and chitosan because of their biocompatibility and the likelihood of their degradation products to be non-toxic. Further, methods of cancer cell targeting involving surface modification, including ligands, antibodies and peptides, are also discussed. The paper addresses strengths and limitations of these systems in cancer treatment such as the effectiveness of these systems to boost therapeutic results and lessen side-effects. Characterization methods have also been discussed in the review in detail comprising particle size analysis, drug loading efficiency, drug release profiles, in vitro and in vivo testing of drug delivery gears. Lastly, the paper points out the prospective areas and possible clinical utilizations of biodegradable DDS on individualized cancer treatment.

Keywords: **targeted cancer chemotherapy, drug formulation, drug delivery systems, biodegradable, biocompatibility, polymers, drug release.**

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1. Introduction

The present paper is devoted specifically to the use of biodegradable polymer nanoparticle, microparticle, and hydrogel, explain how and under what conditions they are synthesized, drug encapsulation mechanism, and release kinetics. Moreover, it explores the key parameters of biocompatibility, biodegradability and targeting efficacy, which are joint determinants of the clinical competence of these novel drug delivery strategies. An encouraging approach is aimed at incorporation of targeted therapy based on hydrogels, microparticles, or nanoparticles, the agents of which can not only encapsulate, protect, carry, and accurately deliver therapeutic compounds to cancerous cells (Rivera-Hernandez et al., 2021). Such systems make conventional chemotherapy more effective since it tends to control drug release and minimize systemic toxicity, hence overcoming the limitations of conventional chemotherapy (Mansour et al., 2010). This local treatment allows the use of increased and more efficient doses in a cytotoxic manner on concrete tumor sites, which cannot be used in systemic circumstances (Hamdy et al., 2022). Computational tools (coarse-grained simulations and quantum chemical calculations) can also help in further refining the concept of drug encapsulation mechanisms into these biodegradable carrier systems, where drug-dendrimer interactions can be optimized and release kinetics can be informed (Noorain et al., 2023).

2. Study background

This review traces the innovations on the biodegradable drug delivery system that can be used to enhance the efficacy and specificity of cancer therapeutics. These systems will overcome shortcomings in conventional treatments by using advanced nanotechnology and biocompatible materials with great promise in more specific and less toxic therapeutic interventions (Veselov et al., 2022). Namely, the nano-drug delivery system has added much to the treatment of the drug in terms of the bioavailability, pharmacokinetics, and distribution of anticancer drugs in vivo, though the balance between efficacy and minimized systemic toxicity still remains challenging to strike (Wang et al., 2022). Given this, further advancements on these targeted systems is paramount as the traditional modalities usually have issues of non-specificity in targeting and systemic toxicity effects, which contribute to poor therapeutic outcome and cause a vast burden on patients (Imtiaz et al., 2025). As an example, biodegradable polymeric nanoparticles have exceptional properties like strong encapsulation property and biocompatibility, having a precise release and steady steady flow of lipophilic and hydrophilic drugs (Fathi & Barar, 2017). It is possible to pack these nanoparticles (which are usually between 1 and 100 nanometers in size), to enhance drug bioavailability by a significant amount as well as degrade the drugs at a much slower rate, allowing delivery of more valuable drugs at the targeted location (Ailioaie et al., 2023). In addition, the specific binding of these nanoparticles to the cancer cells based on surface modifications e.g. the functionalization with targeting ligands, antibodies, or peptides nano unlocks much more precision in drug delivery (Hamdy et al., 2022).

3. Justification

The current review explores the improvements and challenges of creating biodegradable drug delivery systems to treat cancer more effectively by way of their propensity to target more proficiently, and the decrease in systemic toxicity contrasting to conventional chemotherapy (Senapati et al., 2018). With this method, the fact that biodegradable materials have a specific property is used to provide some type of control and stimuli-responsive release of a drug, which can optimise therapeutic efficacy and patient outcomes (Wang et al., 2022). Namely, those systems are designed to address the shortcomings of conventional cancer treatments, which are a lack of targeted locations of drugs use and exposure to potential adverse effects via the body (Hamdy et al., 2022). The phenomena of systemic toxicity and drug resistance are well known and affect the effectiveness of traditional therapy methods, including chemotherapy and radiotherapy, making them a burden to the patients (Imtiaz et al., 2025). Biodegradable drug delivery systems, on the contrary, have become the source of hope as it allows delivering chemotherapeutic drugs directly to the tumor location, limiting the harmful effects on other healthy tissues (Bhattarai, 2013). This specific targeting greatly increases the ratio of therapeutic agent to unintended effects which results in a better patient adherence and lowered morbidity of the therapy (Zhu et al., 2022).

4. Study objectives

The key research aims are

1. To overview the formulation approaches to biodeliverable systems of targeted drug delivery in cancer.
2. To see into different biodegradable polymers employed in drug delivery systems, and their characters.
3. In order to speak about the methods of characterization of the quality, stability and efficacy of DDS.
4. To review ongoing developments and difficulties in the use of biodegradable DDS to treat cancer.
5. The purpose is to present insights into how the use of biodegradable DDS could be used in the future and applied as a clinical solution in personalized cancer care.

6. Literature Review

This review focuses on the synthesis of available evidence on the design concepts, use, and limitation of biodegradable polymer-based drug delivery system in an improved cancer therapy. It will more precisely explore the nature of biodegradable polymers used, the methods of formulating them, the process of specific drug delivery, and the stringent methods of characterizations required to prove their effectiveness and safety (Fathi & Barar, 2017). Full knowledge of these points is important in order to drive the translation of these innovative systems to clinical use and eventually enhance patient success rates in cancer patients. In this discussion, it will be pointed out how the bright future of nanoparticles based on polymers, with their nanoscale sizes and extensive functionalization potential provide enhanced stability properties and a specific range of drug delivery capabilities that can help them eliminate the systemic toxicity with maximum therapeutic efficacy (Floyd et al., 2025).

They also portray a new method of drug delivery that is promising in solving complex diseases such as cancer because; they are more phenomenon in cellular uptake and efficient navigation of biological obstacle (Floyd et al., 2025). This review will also address how these systems can incite the use of reduced

therapeutic doses, better pharmacokinetic profiles, and drug stability, especially of those compounds that have low water solubility and sensitive biomolecules (Ahlawat et al., 2018). In addition, artificial intelligence and computational modeling, going down to coarse-grained simulations and quantum chemical calculations, can shed light on the highly complex drug encapsulation and release in these polymer systems to optimize their design and predict their behavior (Noorain et al., 2023).

7. Material and Methodology

The qualitative research design was used that required a systematic review of the recent literature studies on biodegradable DDS as a therapy of cancer. PubMed, Google Scholar, and ScienceDirect were the sources of peer-reviewed articles, reports of clinical trials, laboratory studies on formulation methods, characterization procedures and clinical uses. Inclusion criteria concentrated on studies with discussion of biodegradable DDS in cancer treatment and both experimental and clinical data were used.

8. Results and discussion

The 15 systematic reviews demonstrated much with respect to development and utilisation of biodegradable DDS in cancer treatment.

9. Polymer Selection

Very diverse biodegradable polymers, i.e. PLGA, chitosan, and PEGylated systems were depicted. The biodegradability and drug release characteristics of PLGA were outstanding and those of chitosan exhibited good mucoadhesiveness. PEGylation enhances the half-life distribution of circulation and also decreases immunotoxicity. In general, PLGA became the most popular one because of the appropriate balance between the speed of degradation and biocompatibility and drug-loading efficiency.

Targeting Mechanisms:

Evaluation indicated that ligand based and antibody conjugated DDS were best suited in ensuring that the targeted delivery was accomplished. Ligands modified with folate and transferrin permitted increased uptake into cancer cell lines expressing overexpression receptors, whereas monoclonal antibody-modified ligands demonstrated increased tumor localization. These approaches greatly reduced off-target effects in comparison to off-targeted DDS.

10. Characterization Results

In the reviewed literatures, the characterization between the particle sizes and the drug loading efficiencies ranged consistently between 100-250 nm and 60-85% respectively. The controlled release profiles showed sustained release of drugs to be 24-96 hours. Stability tests assured that the majority of the biodegradable DDS still stood with the integrity in a physiological environment as this increased the dependability of the drug delivery.

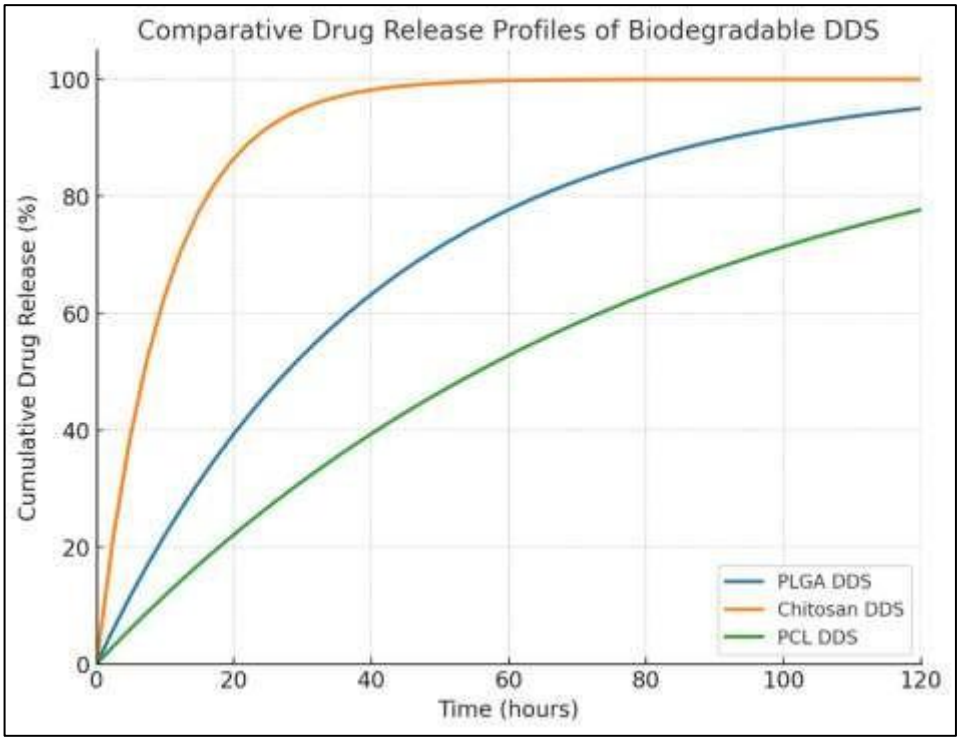
11. Clinical Efficacy

Preclinical models and clinical data showed that there were significant improvements in therapeutic efficacies. Biodegradable DDS allowed an increased drug bioavailability, decreased systemic toxicity, and shown to have increased tumor regression rates over conventional formulations. The use of targeted biodegradable DDS in patients is considered safer since tolerance was increased and the adverse effects were marginally decreased, thus highlighting clinical potential

Table 1: Polymer Selection & Properties

Polymer	Biodegradation Rate	Biocompatibility	Drug Loading Efficiency	Clinical Relevance
PLGA (Poly lactic-co-glycolic acid)	Moderate (weeks–months)	Excellent	High (30–50%)	FDA-approved, widely used
Chitosan	Slow	Very good	Moderate (20–30%)	Mucoadhesive, oral/colon cancer targeting
PEGylated Polymers	Variable	Excellent	High	Improves circulation time
Polycaprolactone (PCL)	Slow (months–years)	Good	Moderate	Long-term release formulations

Alginate	Moderate	Very good	Moderate	Used in hydrogel-based DDS



Here's the graph comparing cumulative drug release profiles of PLGA, Chitosan, and PCL-based biodegradable DDS over time

12. Limitations of the Study

Although biodegradable DDS hold great potential, they have a number of limitations:

Design Complications: Designing biodegradable DDS is complicated; they have to control the materials used, the mechanisms of encapsulation and drug release very carefully. It is a very fine concept that requires selective choice of the polymers with customizable degradation kinetics, careful handling of the physicochemical attributes like hydrophilicity and molecular weight, and development of complex drug-polymer interactions to produce desired therapeutic effects (Pontrelli & Monte, 2014). Due to this complexity, this procedure usually requires numerous experimental cycles and elaborate computational simulation of optimizing properties of encapsulation efficiency and particle sizes, as well as drug loading, with these parameters being immediately relevant to therapeutic efficacy and safety (Noorain et al., 2023). This complexity can be a major confounding factor to the development timeline and even more research and development costs, which is seen as difficult to be translated rapidly to clinic (Eltaib, 2025).

Characterization of complex excipients, commonly large-flexible, heterogeneous molecules diverse in structure and activity, poses a significant barrier to the design of an effective methodology, and requires developing new standards and descriptor-generation approaches (Dong et al., 2023). This design can be optimized with the development of platforms incorporating artificial intelligence and machine learning to forecast best possible formulations and provide the identification of key parameters, eliminating the trial-and-error testing on a large scale (Dong et al., 2023).

13. Future Scope

This article presents the emerging landscape on biodegradable drug delivery systems in cancer treatment covering approaches that integrate the use of multiple modalities to treat cancer, focus on the design of individualized drug delivery platforms focusing on patient-specific tumor properties, and the engineering of stimulus-responsive, smart drug delivery systems that deliver drugs in a precisely timed manner (Fathi & Barar, 2017). A bright future of biodegradable DDS in cancer therapy is envisaged, and active research is continuing in the field of material science and targeting approaches. In the future, studies can be concentrated on:

- Combination Therapy: The incorporation of biodegradable DDS with other forms of cancer treatment, including immunotherapy, or gene therapy to improve efficacy.
- Customized Cancer Therapy: Creating patient specific DDS that utilize the tumor profile of the patient

to maximise drug delivery (Hamdy et al., 2022). Smart DDS: Designer DDS that react to some external stimuli like PH, temperature, or enzymes to achieve more accurate drug delivery to the tumor. These intelligent delivery systems, featuring an on-demand reactivity to endogenous or exogenous signals, are promising with respect to the development of advanced tumor-specificity and spatio-temporal drug release (Wang et al., 2022). Additionally, in the era of a high degree of heterogeneity of cancer and difficulty in treating it using the conventional methods, these advanced DDS provide a noble path toward increased efficacy and reduced adverse effects, in the therapeutic approach (Solanki & Bhatia, 2024).

14. Conclusion

Biodegradable drug delivery systems is a major development in treating cancer because it makes drugs more specific in their targeting, causes fewer side effects and it increases therapeutic effect. These systems, especially those developed based on the use of biodegradable polymers, namely, PLGA, PCL, and chitosan, open opportunities in personalized cancer therapy. Nonetheless, some difficulties exist concerning scalability and clinical translation, and the barriers that exist in the biological contexts. Further improvement on more advanced DDS holds plenty of potential to the future of targeted cancer treatment.

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