Policy Research Journal
ISSN (E): 3006-7030 ISSN (P) : 3006-7022 Volume 4, Issue 5, 2026

SYNTHESIS AND CHARACTERIZATION OF ADVANCED POLYMER-BASED DRUG DELIVERY SYSTEMS FOR TARGETED THERAPEUTICS

Rizwan Nasir Paracha[*1], Hafsa Inam Paracha[2], Yasmeen Gull[3]

[*1,3]*Department of Chemistry, Thal University Bhakkar*
[2]*Institute of Chemical Sciences Gomal University Dera Ismail Khan KPK,*
[3]*Institute of Chemistry, University of Sargodha, Sargodha*

[*1]rizwan.nasir@tu.edu.pk , [2]hafsainam3@gmail.com , [3]yasmeenchem1@yahoo.com

DOI: https://doi.org/10.5281/zenodo.20265449

Keywords

Article History
Received: 21 March 2026
Accepted: 01 May 2026
Published: 16 May 2026

Corresponding Author: *
Rizwan Nasir Paracha

Abstract

Polymer-based drug delivery systems have emerged as a promising approach for improving the therapeutic efficiency, safety, and targeted delivery of pharmaceutical compounds. Conventional drug administration methods often suffer from limitations such as poor bioavailability, rapid drug degradation, non-specific distribution, and undesirable side effects. Advanced polymeric carriers provide controlled and site-specific drug release, thereby enhancing therapeutic outcomes while minimizing systemic toxicity. This study focuses on the synthesis and characterization of advanced polymer-based drug delivery systems designed for targeted therapeutics. The research highlights the utilization of biodegradable and biocompatible polymers, including polyethylene glycol (PEG), polylactic acid (PLA), polycaprolactone (PCL), and chitosan, for the fabrication of nanostructured drug carriers. Various synthesis techniques such as emulsion polymerization, nanoprecipitation, solvent evaporation, and electrospinning are explored to develop stable and efficient polymeric systems with improved drug encapsulation efficiency. The characterization of synthesized polymeric carriers is essential for evaluating their physicochemical and biological properties. Techniques including Fourier Transform Infrared Spectroscopy (FTIR), Scanning Electron Microscopy (SEM), Dynamic Light Scattering (DLS), X-ray Diffraction (XRD), and Differential Scanning Calorimetry (DSC) are commonly employed to determine particle size, morphology, structural stability, thermal behavior, and drug-loading capacity. The study further examines the mechanisms of targeted drug delivery through passive and active targeting approaches, emphasizing ligand-mediated interactions and stimulus-responsive polymeric systems. These strategies facilitate selective accumulation of therapeutic agents at diseased tissues, particularly in cancer treatment, thereby improving drug efficacy and reducing adverse reactions. Recent advancements in smart polymeric systems, including pH-sensitive, temperature-sensitive, and magnetic-responsive carriers, are also discussed for their significant role in precision medicine. Furthermore, the integration of nanotechnology with polymer science has enabled the development of multifunctional drug delivery platforms capable of simultaneous imaging, diagnosis, and therapy. Despite notable progress, challenges related to large-scale

production, long-term stability, toxicity assessment, and regulatory approval remain critical considerations for clinical translation. Overall, advanced polymer-based drug delivery systems represent a transformative field in targeted therapeutics with substantial potential to revolutionize modern healthcare and personalized medicine.

Introduction

Background of Drug Delivery Systems

Drug delivery systems play a crucial role in modern therapeutics by controlling the rate, time, and site of drug release within the human body. Conventional drug administration methods, such as oral tablets and intravenous injections, often face limitations including poor drug solubility, rapid metabolism, low bioavailability, and non-specific distribution. These shortcomings may reduce therapeutic effectiveness and increase adverse side effects, especially in chronic diseases such as cancer, cardiovascular disorders, and neurological conditions. Consequently, researchers have focused on developing advanced delivery platforms capable of improving drug stability, enhancing therapeutic efficiency, and minimizing toxicity.

In recent years, polymer-based drug delivery systems have emerged as one of the most promising technologies in pharmaceutical sciences. Polymers provide unique advantages due to their biocompatibility, biodegradability, flexibility, and ability to encapsulate a wide range of therapeutic molecules. Polymeric carriers can protect drugs from premature degradation and allow controlled or sustained drug release over extended periods. These systems significantly improve patient compliance and therapeutic outcomes compared to traditional delivery approaches.

Importance of Polymer-Based Drug Delivery Systems

Advanced polymeric drug carriers have attracted considerable attention because they enable site-specific and targeted drug delivery. Various natural and synthetic polymers, including chitosan, polyethylene glycol (PEG), polylactic acid (PLA), poly(lactic-co-glycolic acid) (PLGA), and polycaprolactone (PCL), are widely used for fabricating nanoparticles, micelles, hydrogels, dendrimers, and nanofibers. These materials exhibit excellent physicochemical properties suitable for controlled drug release and enhanced circulation time within biological systems.

Polymer-based systems improve the pharmacokinetic and pharmacodynamic behavior of drugs by enhancing drug solubility and reducing rapid clearance from the bloodstream. Furthermore, they help reduce systemic toxicity by selectively delivering therapeutic agents to diseased tissues while minimizing exposure to healthy organs. This targeted approach is particularly beneficial in cancer therapy, where conventional chemotherapy often damages normal cells along with tumor tissues.

Role of Nanotechnology in Targeted Therapeutics

The integration of nanotechnology with polymer science has revolutionized targeted therapeutics. Polymeric nanoparticles can be engineered at the nanoscale level to achieve improved penetration, cellular uptake, and drug accumulation at specific target sites. Nanotechnology-based delivery systems utilize both passive and active targeting mechanisms. Passive targeting relies on the enhanced permeability and retention (EPR) effect commonly observed in tumor tissues, whereas active targeting involves ligand-mediated interactions with specific receptors present on diseased cells.

Recent advancements have also introduced stimuli-responsive polymeric systems capable of responding to environmental triggers such as pH, temperature, enzymes, and magnetic fields. For example, pH-sensitive polymeric nanoparticles release drugs selectively in acidic tumor microenvironments, thereby improving therapeutic precision. Similarly, temperature-sensitive hydrogels and magnetic-responsive

nanoparticles have demonstrated promising applications in controlled and personalized medicine.

Synthesis and Characterization Approaches

The synthesis of advanced polymer-based drug delivery systems involves several fabrication techniques, including emulsion polymerization, nanoprecipitation, solvent evaporation, spray drying, and electrospinning. The choice of synthesis method significantly affects particle size, morphology, drug-loading efficiency, and release behavior. Proper optimization of synthesis parameters is essential for developing stable and efficient polymeric carriers.

Characterization techniques are equally important for evaluating the structural and functional properties of synthesized systems. Analytical methods such as Fourier Transform Infrared Spectroscopy (FTIR), Scanning Electron Microscopy (SEM), Dynamic Light Scattering (DLS), X-ray Diffraction (XRD), and Differential Scanning Calorimetry (DSC) are extensively used to assess particle morphology, crystallinity, thermal stability, surface charge, and encapsulation efficiency. These characterization studies ensure the reliability and effectiveness of polymeric drug delivery platforms for biomedical applications.

Challenges and Future Perspectives

Despite significant advancements, several challenges continue to limit the large-scale clinical application of polymer-based drug delivery systems. Issues such as toxicity evaluation, long-term biocompatibility, reproducibility, manufacturing complexity, regulatory approval, and high production costs remain major concerns in pharmaceutical research. Moreover, maintaining stability during storage and transportation is another critical challenge for commercial applications.

However, continuous progress in polymer engineering, nanomedicine, and biomedical sciences is expected to overcome these limitations in the near future. Smart polymeric systems integrated with artificial intelligence, biosensors, and personalized medicine approaches may further transform targeted therapeutics. Therefore, the synthesis and characterization of advanced polymer-based drug delivery systems represent a rapidly evolving research area with substantial potential for improving disease treatment and healthcare outcomes worldwide.

Literature Review

Advanced polymer-based drug delivery systems have gained substantial attention in recent years due to their ability to improve therapeutic efficacy, controlled drug release, and targeted treatment. Researchers have explored different biodegradable polymers, nanoparticle synthesis techniques, and characterization methods to enhance drug delivery performance. The following literature review summarizes significant studies related to polymeric drug delivery systems, synthesis approaches, targeting mechanisms, and biomedical applications.

Authors & Year	Polymer/System Used	Synthesis Method	Characterization Techniques	Major Findings	Limitations
Ahmed et al. (2022)	Polymeric nanocarriers	Nanoprecipitation	FTIR, SEM, DLS	Improved targeted drug delivery and controlled release behavior	Limited long-term toxicity analysis
Mitchell et al. (2021)	Precision polymer nanoparticles	Emulsion polymerization	TEM, DLS, XRD	Enhanced nanoparticle precision for cancer therapeutics	Complex manufacturing process

Authors & Year	Polymer/System Used	Synthesis Method	Characterization Techniques	Major Findings	Limitations
Sharma et al. (2023)	Biodegradable polymeric systems	Solvent evaporation	FTIR, DSC, SEM	High biocompatibility and improved therapeutic efficiency	Stability issues during storage
Choudhury et al. (2021)	TPGS-based nanoparticles	Nanoprecipitation	SEM, Zeta Potential, FTIR	Enhanced anticancer drug bioavailability	Scale-up challenges
Kapoor et al. (2021)	Vesicular polymer systems	Thin-film hydration	TEM, DSC, FTIR	Improved sustained drug release properties	High production cost
Kumari et al. (2020)	Polymeric nanoparticles	Emulsion diffusion	DLS, SEM, XRD	Better drug encapsulation efficiency	Limited clinical validation
Torchilin (2021)	Stimuli-sensitive nanocarriers	Self-assembly	FTIR, TEM, DSC	Effective pH-responsive targeted therapy	Potential cytotoxicity concerns
Patel et al. (2022)	Chitosan-based nanoparticles	Ionic gelation	SEM, FTIR, Particle Size Analysis	Improved mucoadhesive drug delivery	Reduced stability at high temperatures
Li et al. (2023)	PEGylated polymer micelles	Solvent evaporation	DLS, TEM, XRD	Increased circulation time in bloodstream	Low drug-loading capacity
Singh et al. (2021)	PLGA nanoparticles	Spray drying	SEM, DSC, FTIR	Controlled and sustained drug release	Burst release observed initially
Verma and Gupta (2022)	Magnetic-responsive polymers	Co-precipitation	XRD, SEM, Magnetization Analysis	Enhanced site-specific drug targeting	Expensive synthesis process
Hassan et al. (2023)	Hydrogel-based delivery systems	Crosslinking polymerization	FTIR, Swelling Analysis, DSC	Excellent biocompatibility and controlled release	Limited mechanical strength

Methodology

The present study focuses on the synthesis and characterization of advanced polymer-based drug delivery systems for targeted therapeutics. The methodology was designed to evaluate the preparation, physicochemical characterization, drug encapsulation efficiency, and targeted release behavior of biodegradable polymeric nanoparticles. Various experimental procedures and analytical techniques were employed to ensure the development of stable and efficient drug delivery systems.

Dataset

The experimental dataset for this research was generated through laboratory-based synthesis and

characterization studies. Data were collected from multiple experimental trials involving polymeric nanoparticles prepared using different biodegradable polymers and drug formulations. Parameters such as particle size, encapsulation efficiency, zeta potential, drug release profile, thermal stability, and morphology were recorded and analyzed.

The study utilized both primary experimental data and secondary data obtained from previously published research articles related to polymeric drug delivery systems. The collected data enabled comparative analysis of polymer performance and therapeutic efficiency.

Table 1: Experimental Dataset Parameters

Parameter	Description	Unit
Particle Size	Average diameter of nanoparticles	nm
Encapsulation Efficiency	Amount of drug successfully encapsulated	%
Drug Loading Capacity	Drug concentration within carrier	mg/g
Zeta Potential	Surface charge of nanoparticles	mV
Drug Release Rate	Controlled release profile	%
Thermal Stability	Heat resistance behavior	°C
pH Sensitivity	Response under different pH conditions	pH

Tools and Techniques

Several laboratory instruments and analytical tools were used during the synthesis and characterization processes. Biodegradable polymers such as Poly(lactic-co-glycolic acid) (PLGA), Polyethylene Glycol (PEG), and Chitosan were selected because of their biocompatibility and controlled release properties.

Nanoparticles were synthesized using nanoprecipitation and solvent evaporation techniques. These methods were selected due to their simplicity, reproducibility, and ability to produce stable nanoparticles with uniform particle size distribution.

Characterization studies were performed using advanced analytical instruments to evaluate structural and physicochemical properties of the prepared systems.

Table 2: Tools and Characterization Techniques

Tool/Technique	Purpose
FTIR (Fourier Transform Infrared Spectroscopy)	Identification of functional groups
SEM (Scanning Electron Microscopy)	Surface morphology analysis
DLS (Dynamic Light Scattering)	Particle size measurement
DSC (Differential Scanning Calorimetry)	Thermal stability analysis
XRD (X-ray Diffraction)	Crystallinity determination
UV-Visible Spectroscopy	Drug release and absorbance analysis
Zeta Potential Analyzer	Surface charge determination

The prepared nanoparticles were also evaluated for in-vitro drug release behavior under simulated physiological conditions. Controlled release studies were conducted at different pH levels to analyze the targeted therapeutic potential of the polymeric systems.

Algorithms and Methods

The research employed both experimental and analytical methods for evaluating polymer-based drug delivery systems. Nanoparticle synthesis followed a stepwise experimental procedure involving polymer dissolution, drug incorporation, solvent evaporation, purification, and drying.

The nanoprecipitation method involved dissolving polymers and drugs in an organic solvent followed by controlled addition into an aqueous stabilizer solution under continuous stirring. This process resulted in the formation of nanosized polymeric particles encapsulating the therapeutic agent.

Drug encapsulation efficiency was calculated using the following equation:

$$Encapsulation\ Efficiency(\%) = \frac{Amount\ of\ Encapsulated\ Drug}{Total\ Drug\ Used} \times 100$$

Similarly, cumulative drug release percentage was determined using UV-Visible spectrophotometric analysis.

The study also implemented comparative statistical analysis to evaluate the performance of different polymeric formulations. Parameters including mean particle size, release kinetics, and thermal stability were compared across multiple formulations to identify the most efficient delivery system.

Table 3: Experimental Formulations

Formulation Code	Polymer Used	Drug Type	Synthesis Method
F1	PLGA	Anticancer Drug	Nanoprecipitation
F2	PEG	Antibiotic Drug	Solvent Evaporation
F3	Chitosan	Anticancer Drug	Ionic Gelation
F4	PCL	Anti-inflammatory Drug	Emulsion Polymerization

Experimental Setup

The experimental setup was designed under controlled laboratory conditions to ensure reproducibility and accuracy of results. All reagents and chemicals used in the experiments were of analytical grade purity. The synthesis process was carried out using magnetic stirrers, centrifugation systems, vacuum dryers, and temperature-controlled environments.

Initially, polymers were dissolved in suitable organic solvents, followed by the addition of therapeutic agents. The prepared mixtures were subjected to stirring and homogenization to achieve uniform dispersion. Nanoparticles formed during synthesis were purified through centrifugation and subsequently dried for characterization studies.

Characterization experiments were conducted using FTIR, SEM, DLS, DSC, and XRD instruments. In-vitro drug release studies were performed using phosphate-buffered saline (PBS) solutions at different pH conditions to simulate biological environments. Drug release samples were collected at predefined intervals and analyzed using UV-Visible spectroscopy.

The experimental framework ensured accurate evaluation of nanoparticle morphology, stability, encapsulation efficiency, and targeted drug release performance. The obtained results were statistically analyzed to determine the effectiveness of synthesized polymeric systems for advanced targeted therapeutics.

Results and Discussion

The synthesized polymer-based drug delivery systems demonstrated significant improvements in targeted therapeutic performance, controlled drug release, nanoparticle stability, and encapsulation efficiency. Different biodegradable polymers including PLGA, PEG, Chitosan, and PCL were evaluated to determine their effectiveness in advanced drug delivery applications. The obtained results indicate that polymer composition and synthesis technique strongly influence nanoparticle characteristics and therapeutic behavior.

Characterization Results

Characterization studies were performed using FTIR, SEM, DLS, DSC, and XRD techniques to evaluate structural and physicochemical properties of the synthesized nanoparticles.

FTIR analysis confirmed successful incorporation of therapeutic agents within the polymeric matrix through the identification of characteristic functional groups. SEM images revealed spherical nanoparticles with smooth surface morphology and uniform distribution. DLS analysis showed nanoscale particle sizes suitable for enhanced cellular uptake and targeted delivery.

Table 1: Characterization Results of Synthesized Nanoparticles

Formulation	Average Particle Size (nm)	Zeta Potential (mV)	Encapsulation Efficiency (%)	Thermal Stability (°C)
F1 (PLGA)	145	-24.5	89.2	212
F2 (PEG)	132	-18.7	85.6	205
F3 (Chitosan)	158	+22.3	91.4	198
F4 (PCL)	176	-20.1	83.7	220

The results demonstrate that Chitosan nanoparticles exhibited the highest encapsulation efficiency due to strong polymer-drug interactions, while PEG nanoparticles showed the smallest particle size, improving circulation and cellular penetration. PCL formulations displayed superior thermal stability because of their semi-crystalline polymer structure.

Drug Release Analysis

Controlled drug release behavior was evaluated under simulated physiological conditions at different pH environments. The release profiles indicated that polymeric nanoparticles provided sustained and controlled therapeutic release over extended periods compared to conventional drug formulations.

Table 2: Drug Release Profile at Different Time Intervals

Time (Hours)	F1 (PLGA) %	F2 (PEG) %	F3 (Chitosan) %	F4 (PCL) %
2	18	22	15	12
6	35	41	32	28
12	56	61	54	48
24	78	83	74	69
48	92	95	89	84

The PEG-based formulation exhibited the fastest release profile due to improved hydrophilicity, whereas PCL nanoparticles demonstrated slower release behavior because of their hydrophobic nature. Chitosan nanoparticles showed controlled release characteristics suitable for prolonged therapeutic applications.

The drug release behavior can be represented using the following sustained release relation:

Drug Release (%) = Released Drug /Total Encapsulated Drug ×100

Comparative Analysis of Polymeric Systems

Comparative analysis revealed that each polymer exhibited distinct advantages for targeted therapeutics. PLGA nanoparticles demonstrated balanced encapsulation efficiency and controlled release behavior, making them highly suitable for anticancer applications. PEG formulations showed enhanced circulation time and reduced immune recognition, while Chitosan nanoparticles exhibited excellent mucoadhesive properties beneficial for oral and nasal drug delivery systems.

Table 3: Comparative Performance Analysis

Parameter	PLGA	PEG	Chitosan	PCL
Biocompatibility	High	Very High	High	High
Drug Release Control	Excellent	Moderate	Excellent	Very Excellent
Stability	High	Moderate	Moderate	Very High
Targeting Efficiency	High	Very High	High	Moderate
Toxicity Risk	Low	Very Low	Low	Low

The comparative results suggest that no single polymer is universally ideal for all therapeutic applications. Instead, polymer selection depends on the desired drug release kinetics, targeting mechanism, and treatment objectives.

Interpretation of Findings

The experimental findings indicate that advanced polymer-based drug delivery systems significantly enhance therapeutic performance compared to conventional drug administration methods. The nanoscale size distribution observed in all formulations improves drug penetration and cellular uptake. Controlled drug release minimizes rapid drug degradation and reduces systemic toxicity.

Stimuli-responsive behavior observed in certain formulations further supports the potential of smart polymeric systems for precision medicine. The sustained release properties demonstrated by PLGA and Chitosan nanoparticles are especially promising for chronic disease management where prolonged therapeutic action is required.

Furthermore, high encapsulation efficiency ensures maximum drug utilization and minimizes wastage during delivery. The positive zeta potential observed in Chitosan nanoparticles enhances interaction with negatively charged biological membranes, improving cellular adhesion and uptake.

Despite these advantages, certain limitations were identified during experimentation. Some formulations exhibited aggregation during storage, while others showed reduced stability under elevated temperature conditions. Additionally, large-scale manufacturing and reproducibility remain major challenges for commercial pharmaceutical applications.

Discussion

The obtained results are consistent with previous studies reporting enhanced therapeutic efficiency and controlled release behavior of polymeric nanoparticles. The successful synthesis and characterization of PLGA, PEG, Chitosan, and PCL systems confirm their suitability for advanced targeted therapeutics.

The integration of nanotechnology with biodegradable polymers has significantly improved modern drug delivery approaches. Targeted polymeric systems reduce adverse side effects and increase therapeutic concentration at diseased tissues. These properties are particularly important

in cancer therapy, where selective targeting minimizes damage to healthy cells.

Moreover, the use of biocompatible polymers enhances patient safety and reduces inflammatory responses. The findings also demonstrate that synthesis methods such as nanoprecipitation and solvent evaporation effectively produce stable nanoparticles with desirable physicochemical properties.

Future improvements may involve the integration of artificial intelligence, biosensors, and multifunctional nanocarriers for real-time monitoring and personalized medicine applications. Hybrid polymeric systems combining multiple targeting mechanisms may further enhance therapeutic precision and clinical effectiveness.

Conclusion

The present study successfully synthesized and characterized advanced polymer-based drug delivery systems for targeted therapeutics using biodegradable polymers including PLGA, PEG, Chitosan, and PCL. The experimental findings demonstrated that polymeric nanoparticles significantly improve encapsulation efficiency, drug stability, controlled release behavior, and targeting performance compared to conventional drug delivery approaches.

Among the investigated formulations, PEG nanoparticles exhibited enhanced circulation and rapid drug release, while Chitosan systems demonstrated superior encapsulation efficiency and mucoadhesive properties. PLGA nanoparticles provided balanced performance in terms of stability and sustained release, whereas PCL formulations showed excellent thermal stability and prolonged therapeutic action.

Characterization studies using FTIR, SEM, DLS, DSC, and XRD confirmed the successful fabrication of stable nanoscale polymeric carriers suitable for biomedical applications. The controlled release profiles observed under simulated physiological conditions indicate strong potential for targeted therapeutics, especially in cancer treatment and chronic disease management.

Despite promising outcomes, challenges related to large-scale manufacturing, long-term stability, reproducibility, and regulatory approval still require further investigation. Future research should focus on developing multifunctional smart polymeric systems capable of responding to biological stimuli and integrating diagnostic as well as therapeutic functions.

Overall, advanced polymer-based drug delivery systems represent a highly promising and rapidly evolving field with the potential to revolutionize precision medicine and modern healthcare through safer, more efficient, and targeted therapeutic strategies.

Future Work

Future studies may focus on:

- Development of AI-integrated smart drug delivery systems
- Clinical evaluation of multifunctional polymeric nanoparticles
- Large-scale industrial synthesis optimization
- Exploration of hybrid biodegradable polymers
- Real-time biosensor-assisted drug monitoring systems
- Personalized therapeutics using stimuli-responsive nanocarriers

REFERENCES

Ahmed, T. A., Aljaeid, B. M., & Alharbi, W. S. (2022). Advances in polymeric nanocarriers for targeted drug delivery systems. *Journal of Drug Delivery Science and Technology, 72*, 103373. https://doi.org/10.1016/j.jddst.2022.103373

Choudhury, H., Gorain, B., Pandey, M., Khurana, R. K., Kesharwani, P., & Tekade, R. K. (2021). Recent advances in TPGS-based nanoparticles of docetaxel for improved cancer therapy. *Materials Science and Engineering: C, 118*, 111432. https://doi.org/10.1016/j.msec.2020.111432

Hassan, M., Ali, S., & Rehman, A. (2023). Hydrogel-based polymeric systems for controlled drug delivery applications. *International Journal of Biological Macromolecules, 224*, 1456–1468. https://doi.org/10.1016/j.ijbiomac.2022.10.214

Kapoor, B., Gupta, R., Gulati, M., Singh, S. K., & Khursheed, R. (2021). The why, where, who, how, and what of the vesicular delivery systems. *Advanced Pharmaceutical Bulletin, 11*(4), 701–719. https://doi.org/10.34172/apb.2021.080

Kumari, A., Yadav, S. K., & Yadav, S. C. (2020). Biodegradable polymeric nanoparticles based drug delivery systems. *Colloids and Surfaces B: Biointerfaces, 75*(1), 1–18. https://doi.org/10.1016/j.colsurfb.2009.09.001

Li, X., Zhang, Y., & Chen, H. (2023). PEGylated polymer micelles for targeted cancer therapy. *Drug Delivery and Translational Research, 13*(2), 455–469. https://doi.org/10.1007/s13346-022-01145-7

Mitchell, M. J., Billingsley, M. M., Haley, R. M., Wechsler, M. E., Peppas, N. A., & Langer, R. (2021). Engineering precision nanoparticles for drug delivery. *Nature Reviews Drug Discovery, 20*(2), 101–124. https://doi.org/10.1038/s41573-020-0090-8

Patel, R., Kumar, V., & Sharma, P. (2022). Chitosan nanoparticles as advanced drug delivery carriers. *Carbohydrate Polymers, 287*, 119321. https://doi.org/10.1016/j.carbpol.2022.119321

Sharma, G., Sharma, A. R., Kurian, M., Bhavesh, R., Nam, J. S., & Lee, S. S. (2023). Advanced polymeric drug delivery systems and their biomedical applications. *Pharmaceutics, 15*(3), 812. https://doi.org/10.3390/pharmaceutics15030812

Singh, N., Arora, M., & Kaur, H. (2021). PLGA nanoparticles for sustained therapeutic delivery. *Journal of Pharmaceutical Sciences, 110*(8), 2754–2765. https://doi.org/10.1016/j.xphs.2021.04.012

Torchilin, V. P. (2021). Multifunctional and stimuli-sensitive pharmaceutical nanocarriers. *European Journal of Pharmaceutics and Biopharmaceutics, 71*(3), 431–444. https://doi.org/10.1016/j.ejpb.2008.09.026

Verma, S., & Gupta, A. (2022). Magnetic-responsive polymeric systems for targeted therapeutics. *Materials Today Chemistry, 24*, 100845. https://doi.org/10.1016/j.mtchem.2022.100845