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PEGylated Fe_3O_4–β-Cyclodextrin Magnetic Nanocarriers for Controlled Drug Delivery

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Abstract

The advancement of controlled drug delivery systems is essential for improving therapeutic efficacy and minimizing adverse effects associated with conventional drug administration. Magnetic nanocarriers have emerged as promising candidates due to their responsiveness to external magnetic fields, enabling site-specific targeting and controlled localization. In this study, PEGylated Fe_3O_4–β-cyclodextrin magnetic nanocarriers were successfully synthesized through step-wise surface modification of magnetite nanoparticles. Polyethylene glycol was employed to enhance colloidal stability, biocompatibility, and aqueous dispersibility of the magnetic core, while β-cyclodextrin functionalization provided host–guest inclusion capability for hydrophobic drug molecules. The structural integrity, surface chemistry, optical properties, and morphology of the synthesized nanocarriers were systematically characterized using X-ray diffraction, Fourier-transform infrared spectroscopy, UV–Visible spectroscopy, and scanning electron microscopy. X-ray diffraction analysis confirmed that the inverse spinel crystalline structure of Fe_3O_4 was preserved after PEGylation and β-cyclodextrin functionalization, indicating that surface modification did not alter the magnetic core. Fourier-transform infrared spectra demonstrated the successful attachment of PEG and β-cyclodextrin through characteristic functional group vibrations. UV–Visible spectral analysis revealed surface modification–induced absorption changes and confirmed successful drug loading through the appearance of characteristic curcumin absorption bands. Scanning electron microscopy images showed near-spherical nanoparticles with reduced agglomeration and uniform nanoscale dimensions. The developed PEGylated Fe_3O_4–β-cyclodextrin nanocarriers exhibit enhanced stability, magnetic responsiveness, and drug inclusion capability, highlighting their potential as efficient platforms for controlled and magnetically guided drug delivery applications.

Keywords: Magnetic nanoparticles, PEGylation, β-cyclodextrin, Controlled drug delivery, Nanocarriers

Introduction

The efficient delivery of therapeutic agents to targeted sites within the body remains one of the most significant challenges in pharmaceutical and biomedical research. Conventional drug delivery systems often suffer from poor bioavailability, rapid degradation, non-specific distribution, and dose-dependent toxicity, which ultimately limit therapeutic outcomes. These limitations have driven extensive research into nanotechnology-based drug delivery systems, which offer enhanced control over drug release, improved pharmacokinetics, and the potential for targeted therapy.

Among the various nanomaterials investigated, magnetic nanoparticles have attracted considerable attention due to their unique ability to respond to external magnetic fields. This property enables spatial and temporal control over nanoparticle localization, making magnetic nanocarriers particularly suitable for targeted drug delivery and imaging applications. Magnetite (Fe_3O_4) nanoparticles are widely studied because of their favorable magnetic properties, chemical stability, relatively low toxicity, and ease of synthesis. However, unmodified Fe_3O_4 nanoparticles exhibit a strong tendency to aggregate owing to magnetic dipole–dipole interactions and high surface energy, which compromises their stability and limits their biomedical applicability.

Surface modification strategies are therefore essential to improve the stability, dispersibility, and biocompatibility of magnetic nanoparticles. Polyethylene glycol (PEG) is one of the most commonly employed surface modifiers in biomedical nanotechnology. PEGylation imparts hydrophilicity, reduces non-specific protein adsorption, and minimizes recognition by the

reticuloendothelial system, thereby prolonging circulation time in biological environments. PEG-coated nanoparticles exhibit improved colloidal stability and reduced aggregation, making them suitable for in vivo applications.

In addition to surface stabilization, efficient drug encapsulation remains a critical requirement for controlled drug delivery systems. β-Cyclodextrin (β-CD), a cyclic oligosaccharide composed of seven α-D-glucopyranose units, possesses a hydrophobic inner cavity and a hydrophilic outer surface. This unique molecular architecture allows β-cyclodextrin to form inclusion complexes with a wide range of hydrophobic drug molecules, thereby improving their aqueous solubility, stability, and bioavailability. Incorporating β-cyclodextrin onto PEGylated magnetic nanoparticles results in a multifunctional nanocarrier platform that combines magnetic guidance, surface stabilization, and drug inclusion capability.

The present study focuses on the synthesis and physicochemical characterization of PEGylated Fe_3O_4–β-cyclodextrin magnetic nanocarriers as a foundational platform for controlled drug delivery. The work aims to demonstrate the successful fabrication of a stable and multifunctional nanocarrier system while preserving the magnetic core structure essential for magnetically guided applications.

Materials and Methods

All chemicals used in this study were of analytical grade and employed without further purification. Iron salts required for magnetite synthesis, polyethylene glycol, and β-cyclodextrin were procured from standard chemical suppliers. Distilled water was used throughout the experimental procedures.

Magnetite nanoparticles were synthesized using a chemical co-precipitation method under alkaline conditions. Appropriate molar ratios of iron salts were dissolved in distilled water and stirred continuously to obtain a homogeneous solution. The pH of the solution was gradually adjusted using a base to induce precipitation of Fe_3O_4 nanoparticles. The reaction mixture was maintained under constant stirring to ensure uniform nucleation and growth. The resulting black precipitate was magnetically separated, washed repeatedly with distilled water to remove residual ions, and dried to obtain Fe_3O_4 nanoparticles.

PEGylation of Fe_3O_4 nanoparticles was carried out by dispersing the synthesized magnetite nanoparticles in an aqueous solution of polyethylene glycol. The mixture was stirred for an extended period to facilitate adsorption and surface coating of PEG onto the nanoparticle surface through hydrogen bonding and van der Waals interactions. PEGylated nanoparticles were magnetically separated, washed to remove unbound polymer, and dried.

β-Cyclodextrin functionalization was performed by introducing β-cyclodextrin into the PEGylated Fe_3O_4 nanoparticle suspension. The interaction between β-cyclodextrin and the PEGylated surface occurred primarily through intermolecular interactions and physical anchoring. The resulting PEGylated Fe_3O_4–β-cyclodextrin nanocarriers were separated, washed thoroughly, and dried prior to characterization.

Characterization Techniques

X-ray diffraction analysis was performed to examine the crystalline structure and phase purity of bare Fe_3O_4 nanoparticles and surface-modified nanocarriers. Fourier-transform infrared spectroscopy was used to identify functional groups and confirm successful surface modification with PEG and β-cyclodextrin. UV–Visible spectroscopy was employed to study optical properties, surface modification effects, and drug loading behavior. Scanning electron microscopy was used to analyze particle morphology, size distribution, and surface characteristics.

Results and Discussion

X-ray diffraction patterns of the synthesized Fe_3O_4 nanoparticles exhibited characteristic diffraction peaks corresponding to the inverse spinel structure of magnetite, confirming successful formation and high phase purity. After PEGylation and β-cyclodextrin functionalization, the diffraction peak positions remained unchanged, indicating that surface modification did not affect the crystalline structure of the magnetic core. A gradual reduction in peak intensity was observed, which can be attributed to the presence of amorphous organic

layers of PEG and β-cyclodextrin on the nanoparticle surface.

Fourier-transform infrared spectra of bare Fe_3O_4 nanoparticles showed a strong Fe–O stretching vibration around 580–600 cm^{-1}, confirming magnetite formation. PEGylated nanoparticles exhibited additional absorption bands corresponding to C–H and O–H stretching vibrations, indicating successful polymer coating. In PEGylated Fe_3O_4–β-cyclodextrin nanocarriers, characteristic C–O–C stretching vibrations associated with β-cyclodextrin were observed. The retention of the Fe–O band across all samples confirmed that surface modification occurred without altering the magnetic core.

UV–Visible spectra of Fe_3O_4 nanoparticles displayed a broad absorption band in the range of 300–350 nm, characteristic of charge transfer transitions in magnetite. PEGylation and β-cyclodextrin functionalization resulted in minor changes in absorption intensity, reflecting modifications in the surface environment. In drug-loaded nanocarriers, the appearance of a distinct absorption band around 420–430 nm corresponding to curcumin confirmed successful drug inclusion within the β-cyclodextrin cavity without disrupting the magnetic core.

Scanning electron microscopy images revealed near-spherical nanoparticles with nanoscale dimensions. Surface modification with PEG and β-cyclodextrin reduced particle agglomeration and improved dispersion, which is advantageous for biomedical applications. The observed morphology supports the suitability of the nanocarriers for drug delivery systems requiring uniform particle size and stability.

Potential Applications

The PEGylated Fe_3O_4–β-cyclodextrin nanocarriers integrate magnetic responsiveness, enhanced biocompatibility, and efficient drug inclusion capability. These combined features make the nanocarriers suitable for controlled and magnetically guided drug delivery applications. The system provides a versatile platform for future investigations involving targeted therapy, controlled release kinetics, and biomedical imaging.

Conclusion

PEGylated Fe_3O_4–β-cyclodextrin magnetic nanocarriers were successfully synthesized and characterized as a multifunctional platform for controlled drug delivery. Structural and spectroscopic analyses confirmed preservation of the magnetic core and effective surface functionalization. The developed nanocarrier system exhibits enhanced stability, improved dispersion, and efficient drug loading capability, highlighting its potential for advanced drug delivery and nanomedicine applications.

Future Scope

Future work may focus on quantitative drug loading efficiency, in vitro release kinetics, cytotoxicity studies, and in vivo targeting efficiency. The present study serves as a foundational platform for further development of magnetically guided drug delivery systems.

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