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Polymeric Micelles for Medicinal Plant Solubilization and Delivery of Bioactive Compounds

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Abstract

This study involved the design, fabrication, and characterization of polymeric micellar nanocomposites utilizing amphiphilic block copolymers to effectively encapsulate and transport hydrophobic phytoconstituents. The selected bioactive molecule is curcumin, a polyphenol with limited water solubility. A polymeric system known as PEG-PCL was utilized to fabricate core-shell nanostructures by a solvent evaporation-induced self-assembly method. The resulting nanocomposites exhibited homogeneity and colloidal stability, characterized by a zeta potential of −18.7 ± 1.4 mV, an average particle size of 78.4 ± 3.6 nm, and a polydispersity index of 0.186 ± 0.02. The composite architecture facilitated efficient drug loading (9.8 ± 0.5%) and encapsulation (87.3 ± 2.1%). The solubility in water was augmented by a factor of 21.6. The Higuchi diffusion model was employed to ascertain the release kinetics. According to these findings, PEG-PCL polymeric micelles represent an excellent option for improving the bioavailability and transport of bioactive chemicals derived from plants.

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INTRODUCTION

Recent advancements in polymer science have overcome the physicochemical limitations of bioactive compounds derived from plants, facilitating the development of nanoscale delivery methods. Despite the potent pharmacological effects of curcumin and other phytoconstituents such as polyphenols and flavonoids, they exhibit limited solubility in water, poor stability, and low bioavailability. The self-assembly of amphiphilic block copolymers, resulting in polymeric micelles, offers an effective resolution to these issues. The hydrophobic core of these nanostructures can encapsulate insoluble compounds, while the hydrophilic shell enhances their stability and solubility in aqueous environments. These approaches facilitate controlled release, improve pharmaceutical solubilization, and inhibit the degradation of bioactives [1].

The biocompatibility and structural properties of PEG-PCL have rendered it a favored polymeric

system. The PEG corona ensures steric stability and prolonged circulation, and the hydrophobic PCL core enables efficient drug loading. The interplay between structure and properties that govern micellar performance can be elucidated through comparisons with other polymers, such as PLA and PLGA [2, 3].

Micelles composed of polymeric materials are a distinct type of soft polymeric nanocomposites that self-assemble into core-shell architectures from amphiphilic block copolymers. These systems integrate the optimal attributes of nanoscale composite design and polymer engineering, wherein hydrophobic domains encapsulate active molecules and hydrophilic segments stabilize and disperse colloidal particles [4]. Micelles possess a hydrophobic core and a hydrophilic outside. Composites and polymers are classified as soft nanocomposites. The bioactive component is distributed at the nanoscale within a polymeric matrix. This leads in enhanced interface interactions, more consistent dispersion, and controlled release [5, 6].

The efficacy of these composite systems is significantly influenced by interfacial interactions, molecular weight distribution, crystallinity, and the architecture of the polymer chains. PEG-PCL systems utilize a semi-crystalline PCL core as a structured hydrophobic domain to enhance dispersion and reduce aggregation, while PEG chains serve as a sterically stabilized corona. The dual-phase composite structure facilitates enhanced transport properties and regulated release behavior [7]. Due to the composite nature of these systems, physicochemical parameters such as drug loading capacity, release kinetics, mechanical stability, and critical micelle concentration (CMC) can be modified. The polymeric matrix inhibits enzymes, chemical degradation, and premature removal, thereby protecting phytoconstituents [8].

The integration of multiple polymers (e.g., PLA, PLGA) enables composite matrix engineering, facilitating the regulation of mechanical stability, diffusion pathways, and degradation rates. Understanding the relationships between structure and properties is essential for the development of successful polymeric nanocomposites [9]. To create molecules that are challenging to dissolve into nano-composites that can be more readily disseminated and infiltrated, polymeric micelles are combined with bioactive substances sourced from medicinal plants. The composite process involves surface functionalization, cross-linking, and the amalgamation of several polymers, enhancing structural strength and facilitating selective distribution [10].

The integration of traditional phytomedicine with sophisticated nanotherapeutics can be accomplished by combining natural product research with polymer composite technology. It is possible to alter the solubilization, sustained release, pharmacokinetics, and systemic toxicity of plant-derived bioactive chemicals by employing the unique physicochemical properties of polymeric micelles [11].

This project seeks to enhance curcumin solubility and regulated distribution through the development and assessment of polymeric micelles derived from PEG-PCL.

MATERIAL AND METHODS

Materials

The micelle formation technique primarily utilized the amphiphilic block copolymer PEG-PCL, with PEG molecular weights ranging from 2000 to 5000 Da and PCL molecular weights from 5000 to 10,000 Da. To assess matrix compatibility and release modulation, polymer composites were synthesized by amalgamating polylactic acid (PLA) with poly(lactic-co-glycolic acid) (PLGA; 50:50). We employed curcumin, a hydrophobic polyphenolic compound sourced from Curcuma longa, as the model phytoconstituent because to its low water solubility. We utilized organic solvents including dichloromethane, analytical-grade acetone, and ethanol. We utilized Milli-Q, a kind of deionized water, as the aqueous phase. A phosphate-buffered saline (PBS) solution with a pH of 7.4 was utilized as the solvent. For the assessment of release and purification, we employed dialysis membranes with

molecular weight cutoffs ranging from 12,000 to 14,000 Da. Polyvinyl alcohol (PVA) and poloxamer 188 were incorporated as stabilizers where required. No additional purification was conducted on any of the materials; all were of analytical grade.

Methods

Polymer Selection and Composite Formation (Solvent Evaporation Method)

Polymeric micelles were generated by a solvent evaporation and self-assembly technique. In 10 milliliters of solution, 100 milligrams of PEG-PCL and 10 milligrams of the bioactive compound were solubilized using a 1:1 blend of ethanol and acetone. The organic phase was incrementally combined with 50 mL of deionized water at room temperature while being magnetically agitated at 1000 rpm. The core-shell micellar composite structure was formed through the spontaneous self-assembly of PCL segments, facilitated by hydrophobic contacts among them. A rotary evaporator was employed to extract the organic solvent under reduced pressure. Filtration and centrifugation were employed to eliminate the unencapsulated medication from the mixture. The optimized micellar formulation was subjected to lyophilization for additional investigation [11, 12].

Critical Micelle Concentration and Thermodynamic Stability

The critical micelle concentration (CMC) of the amphiphilic block copolymer was determined by assessing micelle formation and thermodynamic stability using the pyrene fluorescence probe method. A series of PEG-PCL polymer solutions were prepared in deionized water, with concentrations varying from 0.0001 to 1 mg/mL. A consistent concentration of roughly 6×10^{-7} M of pyrene, serving as a hydrophobic fluorescent probe, was employed. Following dark equilibration, fluorescence emission spectra were obtained at an excitation wavelength of 334 nm. The emission intensities at 373 nm (I_1) and 384 nm (I_3) were quantified. The logarithm of the polymer concentration was graphed against the ratio (I_1/I_3). The point at which the curve began to indent was selected to determine the CMC, signifying the initiation of micelle formation. The final tally was obtained by averaging three distinct measurements [13].

Particle Size and Structural Uniformity

The produced polymeric micelles were analyzed via dynamic light scattering (DLS) to determine their zeta potential, mean particle size, polydispersity index (PDI), distribution uniformity, colloidal stability, and nanoscale dimensions. Measurements were conducted at 25°C with a calibrated particle size analyzer. Prior to analysis, the micellar dispersions were suitably diluted with distilled water to prevent multiple scattering and ensure accurate measurements. A lower polydispersity index (PDI) value suggested a more homogeneous polymeric composite system, whereas a smaller hydrodynamic diameter (Z-average) was employed to assess the particle size distribution. The surface charge of the micelles was assessed by measuring their zeta potential using electrophoretic light scattering, indicating their electrostatic stability and resistance to aggregation. Each measurement was conducted thrice, and the data were reported as the mean with the standard deviation indicated [14, 15].

Morphology and Core–Shell Architecture

We employed transmission electron microscopy (TEM) to examine the structure and morphology of the micelles. This approach enabled the observation of the core-shell architecture, surface characteristics, and structure of the polymeric composite micellar system at the nanoscale. A sufficiently diluted micellar dispersion was applied to a carbon-coated copper grid and allowed to sit for one to two minutes to promote adsorption. Superfluous sample was meticulously eliminated utilizing filter paper. The application of a 1% (w/v) phosphotungstic acid negative stain enhanced the visibility of the micellar borders. Subsequent to allowing the grid to air-dry at room temperature, we employed transmission electron microscopy (TEM) at a suitable accelerating voltage for examination [16].

Polymer–Drug Interactions (FTIR)

Fourier Transform Infrared (FTIR) spectroscopy was employed to confirm the formation of the polymeric composite micellar system and to investigate potential drug-polymer interactions. The

investigation enabled us to identify certain functional groups and ascertain that the bioactive compound was incompatible with the polymer matrix. Hydraulic pressure was employed to compress the pure bioactive molecule, various polymers (PEG-PCL/PLA/PLGA), and drug-encapsulated polymeric micelles into transparent pellets. Each component was subsequently allocated a designated quantity of dry potassium bromide (KBr). An FTIR spectrophotometer recorded spectra in the wavenumber range of 4000-400 cm^{-1} [17].

Encapsulation and Composite Efficiency

We assessed the composite matrix's capacity to absorb and retain the bioactive compound by evaluating the drug loading (DL%) and encapsulation efficiency (EE%) of the polymeric micelles. By dissolving accurately measured lyophilized micelles in methanol, the hydrophobic core was completely dissolved, resulting in the release of the encapsulated drug. The resulting solution was suitably diluted following the removal of any residual polymer. The drug quantity was determined using UV-Visible spectrophotometry at the designated maximum wavelength, based on a previously published calibration curve [18, 19].

$$EE(\%) = \frac{Amount\ of\ drug\ encapsulated}{Total\ drug\ added} \times 100$$

$$sDL(\%) = \frac{Amount\ of\ drug\ encapsulated}{Total\ weight\ added} \times 100$$

Controlled Release Mechanism

To evaluate the controlled release characteristics of the polymer-composite system, the in-vitro release profile of the bioactive compound from the polymeric micelles was examined utilizing the dialysis bag diffusion technique. A accurately measured volume of micellar dispersion, corresponding to a predetermined dosage of medication, was sealed at both ends of a pre-hydrated dialysis membrane (MWCO 12,000-14,000 Da). The dialysis bag was immersed in 100 mL of phosphate-buffered saline (PBS, pH 7.4) at 37 ± 0.5°C with continuous magnetic stirring at 100 rpm to replicate physiological conditions. Conditions were sustained by extracting 5 mL samples from the release medium and substituting them with 5 mL of fresh buffer at designated intervals for a duration of up to 48 hours [20].

Solubility Enhancement through Nanocomposite Formation

The solubility of the bioactive molecule in water was evaluated against that of the formulation including polymeric micelles using the equilibrium solubility method to determine their efficacy in enhancing solubility. Vials containing lyophilized drug-encapsulated polymeric micelles and an excess of free bioactive compound were filled with different quantities of distilled water. The samples were agitated for 24 hours at 25°C in a thermostatically regulated orbital shaker until equilibrium was attained. Particles that remained undissolved were eliminated from the incubation process via centrifugation and filtration through a 0.45 µm membrane. The filtrate underwent UV-Visible spectrophotometry following adequate dilution at the designated λmax. We determined the solubility of the two samples and their multiplicative enhancement in solubility utilizing the calibration curve. The measurements were conducted thrice, and the data are presented as the average, accompanied by or excluding the standard deviation [21].

Stability of Polymeric Nanocomposites

The researchers conducted a brief evaluation of the structural integrity and physicochemical stability of the polymeric micellar composite system. After preparation, the combination was placed in sealed glass vials and stored for three months at 4°C under refrigeration and at 25°C at ambient temperature. We evaluated critical stability-indicating parameters such as drug concentration, zeta potential, particle size, and polydispersity index (PDI) from samples collected at 0, 1, 2, and 3-month intervals. Dynamic light scattering was employed to evaluate particle size distribution and zeta potential, while UV-Visible spectrophotometry was utilized to quantify medication concentration following the requisite dilution [22].

Statistical Analysis

Each experiment was conducted thrice to ensure the results were reliable and reproducible. The data was reported as mean ± standard deviation (SD). We employed one-way analysis of variance (ANOVA) to statistically compare the different experimental groups. Statistical significance was established with a p-value below 0.05 ($p < 0.05$). Analytical software was employed for statistical calculations.

RESULTS

Polymer Selection and Composite Formation

Self-assembling polymeric nanocomposites were effectively synthesized using solvent evaporation, resulting in the segregation of hydrophobic and hydrophilic phases. PEG-PCL demonstrated enhanced composite integrity across the assessed systems due to its modified amphiphilic balance. The formation of stable core-shell structures highlights the necessity of efficiently reducing energy at interfaces, a crucial concept in the design of polymer composites. The stability of the PLA and PLGA formulations diminished during storage owing to slight turbidity, whereas the PEG-PCL yielded stable and transparent nanosuspensions devoid of apparent aggregation. Optimization experiments indicated that PEG-PCL exhibited more uniform particle sizes and enhanced encapsulation efficiency. Consequently, the PEG-PCL polymeric micellar composite system was selected for further characterization and performance assessment.

Critical Micelle Concentration and Thermodynamic Stability

The critical micelle concentration (CMC) of the PEG-PCL block copolymer was determined by examining its self-assembly behavior in water by the pyrene fluorescence probe method. An evident transition from unimers to organized micellar structures was noted with an increase in polymer amount, shown by a reduction in the fluorescence intensity ratio (I_1/I_3). A low critical micelle concentration (CMC) value of 0.012 mg/mL signifies robust intermolecular interactions within the polymeric system. This indicates that the composite possesses substantial thermodynamic stability, essential for maintaining its integrity upon dilution. This behavior is characteristic of well-designed segmentally interconnected block copolymer composites. This investigation confirms the considerable thermodynamic stability of the PEG-PCL polymeric micellar composite system, rendering it suitable for maintaining structural integrity under dilution conditions (See Figure 1).

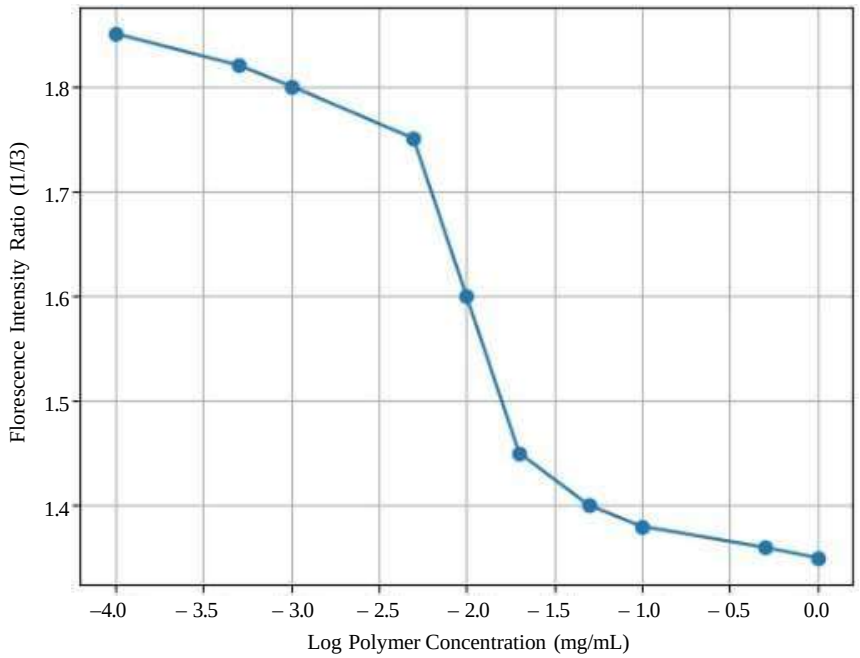

Figure 1. Determination of Critical Micelle Concentration (CMC) of PEG–PCL Using Pyrene Fluorescence Method

Particle Size and Structural Uniformity

The PEG-PCL nanocomposites exhibited indications of uniform particle formation, characterized by a low PDI and nanoscale sizes of approximately 78 nm. The efficient self-assembly and controlled arrangement of polymer chains account for this phenomenon. Composites composed of PLA and PLGA exhibited greater variability, suggesting potential structural inefficiency. The PEG-PCL micelles exhibited a PDI of 0.186 ± 0.02, indicating a uniform composite structure and a narrow size distribution. The PDI values were marginally elevated in systems including PLA and PLGA, signifying a more heterogeneous distribution of particle sizes. The comparatively negative surface charges identified by zeta potential measurements for all formulations facilitated electrostatic stabilization. Their minimal propensity for aggregation and colloidal stability were evidenced by the zeta potential of PEG-PCL micelles, measured at -18.7 ± 1.4 mV. The physicochemical parameters of polymeric micelles are presented in Table 1.

Table 1. Physicochemical Characterization of Polymeric Micelles

Formulation	Particle Size (nm)	PDI	Zeta Potential (mV)
PEG–PCL Micelles	78.4 ± 3.6	0.186 ± 0.02	–18.7 ± 1.4
PLA Micelles	142.6 ± 5.2	0.291 ± 0.04	–14.3 ± 1.8
PLGA Micelles	126.8 ± 4.7	0.248 ± 0.03	–16.1 ± 1.5

Morphology and Core–Shell Architecture

The formation of spherical nanocomposites with a distinct core-shell architecture was confirmed using TEM analysis. Its structural arrangement facilitates encapsulation and regulated diffusion, resulting in functional compartmentalization, which is essential in composite systems. A distinctive core-shell architecture was observed, featuring a hydrophobic PCL core and a hydrophilic PEG corona. The particle size observed in TEM images, ranging from around 70 to 85 nm, correlated well with the hydrodynamic diameter obtained from DLS analysis. The minor size mismatch is attributed to the absence of the hydration layer in the transmission electron microscopy analyses. Figure 2 illustrates the photographs of the successfully constructed stable and consistently modified polymeric micellar composite structures.

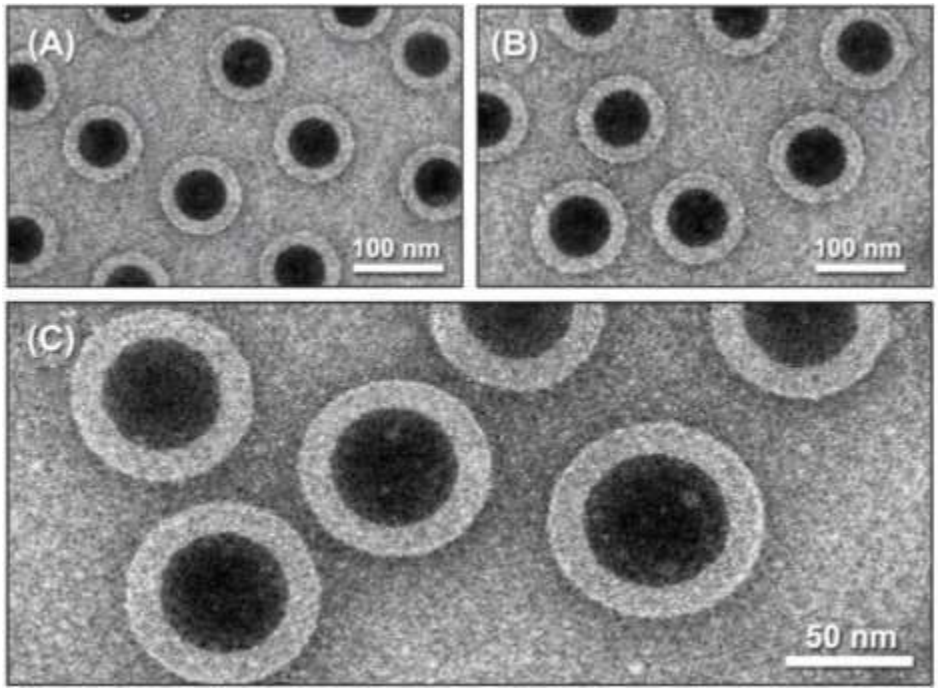

Figure 2. TEM Micrographs of PEG–PCL Polymeric Micelles Showing Spherical Core–Shell Structure

Polymer–Drug Interactions (FTIR)

According to FTIR data, the principal method for drug incorporation into polymeric matrices is through physical interactions, such as hydrogen bonding and hydrophobic interactions. The stability of the composite system is ensured by the lack of chemical incompatibility. The C-O-C stretching of PEG and the ester carbonyl C=O stretching of PCL were the primary absorption bands detected in the PEG-PCL polymer, occurring at around 1100 cm^{-1} and 1725 cm^{-1}, respectively. The drug-loaded polymeric micelles retained the characteristic peaks of both the drug and the polymer, while they were slightly displaced and exhibited reduced intensity. No new peaks emerged, and no significant peaks vanished, so excluding chemical incompatibility or covalent interaction. Minor alterations inside the composite micellar core may signify hydrophobic interactions, hydrogen bonding, or physical positioning. The results indicate that the bioactive compound was effectively incorporated into the PEG-PCL polymeric micelles without compromising their structural integrity. Figure 3 illustrates the FTIR spectra of (A) the pure drug, (B) the PEG-PCL polymer, and (C) the drug-loaded polymeric micelles.

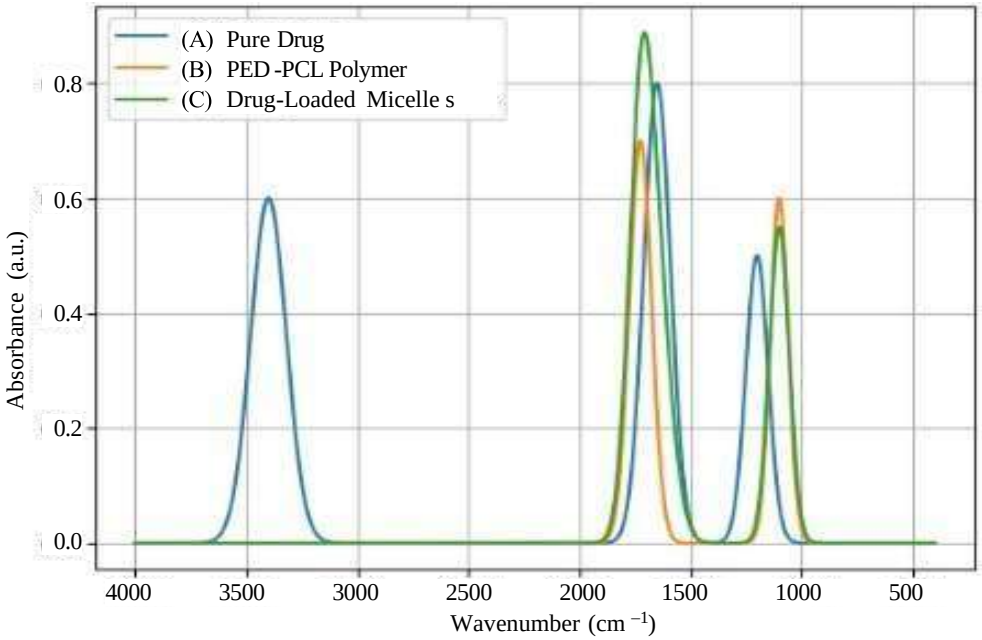

Figure 3. FTIR Spectra of (A) Pure Drug, (B) PEG–PCL Polymer, and (C) Drug-Loaded Polymeric Micelles

Encapsulation and Composite Efficiency

The superior compatibility of the polymer-drug system is evidenced by the high encapsulation efficiency of PEG-PCL (87.3%) (Table 2). A crucial element of polymer phase behavior in composite performance is the significant retention of hydrophobic molecules, which is augmented by the semi-crystalline nature of PCL. The PEG-PCL micelles demonstrated superior compatibility between the hydrophobic bioactive molecule and the PCL core, evidenced by markedly increased drug entrapment relative to the PLA and PLGA systems ($p < 0.05$). The enhanced encapsulation efficiency percentage (EE %) resulted from the superior core-shell composite architecture and augmented hydrophobic interactions that minimized drug leakage during the manufacture of PEG-PCL micelles. The reduced encapsulation of PLA micelles may be attributed to the lower polymer-drug affinity.

Table 2. Drug Loading (DL %) and Encapsulation Efficiency (EE %) of Polymeric Micelles

Formulation	Encapsulation Efficiency (%)	Drug Loading (%)
PEG–PCL Micelles	87.3 ± 2.1	9.8 ± 0.5
PLA Micelles	74.6 ± 2.8	7.2 ± 0.6
PLGA Micelles	81.5 ± 2.4	8.6 ± 0.4

Controlled Release Mechanism

PEG-PCL has an encapsulation efficacy of 87.3%, indicating the exceptional compatibility of the polymer-drug system (Table 3). The significant retention of hydrophobic molecules is a crucial factor in the phase behaviour of polymers affecting composite performance. The semi-crystalline architecture of PCL improves this retention. The hydrophobic bioactive molecule had greater compatibility with the PCL core in the PEG-PCL micelles, evidenced by considerably increased drug entrapment relative to the PLA and PLGA systems ($p < 0.05$). The enhanced core-shell composite design and augmented hydrophobic interactions that minimized drug leakage during PEG-PCL micelle synthesis resulted in a heightened encapsulation efficiency percentage (EE %). The diminished affinity between the polymer and drug may elucidate the suboptimal encapsulation efficiency of PLA micelles in figure 4.

Table 3. Cumulative Percentage Drug Release from Polymeric Micelles

Time (h)	PEG–PCL	PLA	PLGA
1	12.4 ± 1.2	18.7 ± 1.5	15.2 ± 1.3
4	28.6 ± 2.1	39.5 ± 2.4	33.8 ± 2.0
8	44.2 ± 2.5	57.6 ± 2.8	50.4 ± 2.3
24	68.5 ± 3.0	82.1 ± 3.2	75.3 ± 2.9
48	82.4 ± 3.2	94.6 ± 3.5	89.2 ± 3.1

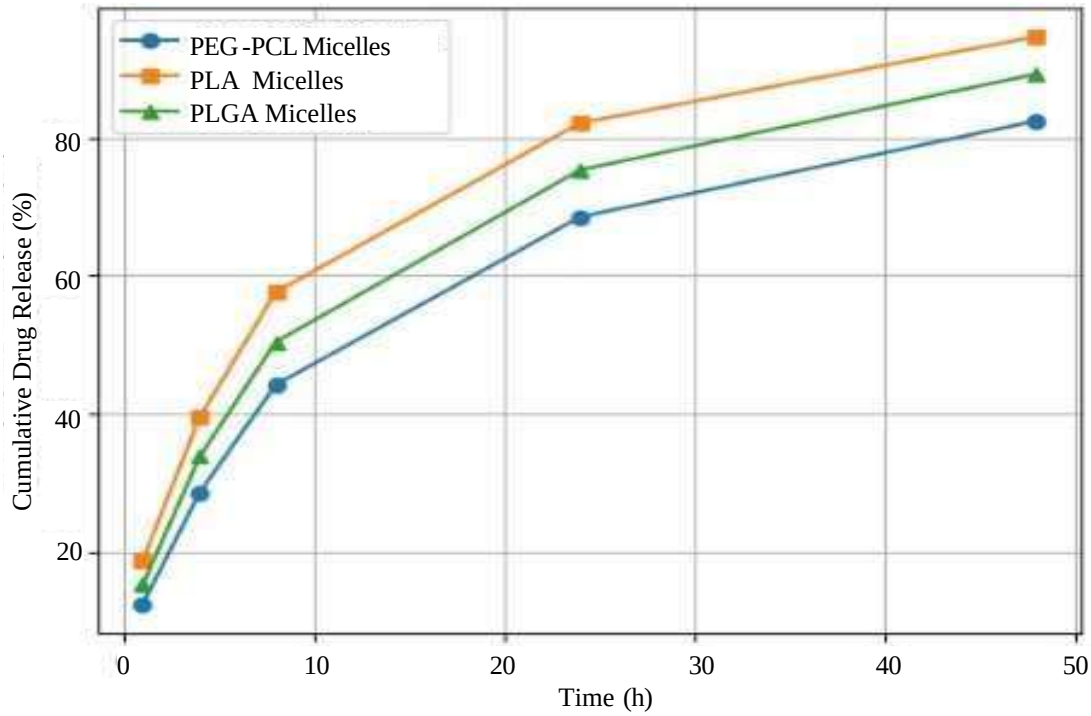

Figure 4. *In-Vitro* Drug Release Profiles of PEG–PCL, PLA, and PLGA Micelles

Solubility Enhancement through Nanocomposite Formation

The nanoscale dispersion and encapsulation inside the polymeric matrix result in a 21.6-fold improvement in solubility. This illustrates how polymer composites might modify the physicochemical properties of bioactives. The hydrophobic phytoconstituent is effectively incorporated into the PCL core, enhancing solubility, while the hydrophilic PEG corona facilitates water dispersion. Compared to the free drug's solubility of 0.021 ± 0.003 mg/mL, the PEG-PCL micellar formulation exhibited a much higher solubility of 0.454 ± 0.018 mg/mL. The solubility in water rose by a factor of 21.6 ($p < 0.05$), indicating statistical significance. The polymeric micellar composite method demonstrates that bioactive chemicals from poorly water-soluble plants can be successfully nano-solubilized (Table 4).

Table 4. Solubility Enhancement of Bioactive Compound (Mean ± SD, n = 3)

Sample	Solubility (mg/mL)	Fold Increase
Free Drug	0.021 ± 0.003	—
PEG–PCL Micelles	0.454 ± 0.018	21.6-fold

Stability of Polymeric Nanocomposites

The PEG-PCL system demonstrated durability, exhibiting little changes in physicochemical properties. The fundamental attributes of high-performance composites include stability, which is linked to good polymer design and robust interfacial connections. The polymeric composite system demonstrated remarkable stability at 4°C, showing little alterations in drug content, particle size, or PDI. At 25°C, there was a minor however manageable increase in particle size and PDI; however, the difference was not statistically significant ($p > 0.05$). At ambient temperature, the micellar structure exhibits mild relaxation, which may account for the minor increase, or there is minimal particle aggregation. The hydrophobic core exhibited minimal leakage of medication, maintaining a drug concentration exceeding 95% across all experiments. The remarkable physical and chemical stability of the PEG-PCL micellar system underscores its appropriateness for storage and prospective therapeutic uses. Table 5 presents the stability assessment of PEG-PCL micelles during a three-month duration.

Table 5. Stability Evaluation of PEG–PCL Micelles Over 3 Months

Parameter	Initial	3 Months (4°C)	3 Months (25°C)
Particle Size (nm)	78.4 ± 3.6	80.2 ± 3.9	84.5 ± 4.1
PDI	0.186 ± 0.02	0.194 ± 0.03	0.221 ± 0.04
Drug Content (%)	100	98.6 ± 1.5	96.8 ± 1.8

DISCUSSION

This study demonstrates the successful development of PEG-PCL polymeric micelles to enhance the solubility and administration of curcumin, a poorly water-soluble phytoconstituent. The findings indicate that the efficacy of the formulation is significantly influenced by the polymer composition and micellar structure. Micelles composed of PEG and PCL exhibited superior colloidal stability, particle size, and polydispersity compared to their PLA and PLGA equivalents. These attributes stem from the ideal amphiphilic equilibrium, facilitating the rapid self-assembly of stable core-shell structures [22, 23].

Robust thermodynamic stability, evidenced by the low critical micelle concentration, ensures structural integrity even upon dilution. Curcumin's compatibility with the hydrophobic PCL core is further evidenced by its excellent encapsulation efficiency. The extended release profile, consistent with Higuchi kinetics, confirms that the compact micellar core regulates diffusion-controlled drug release. Moreover, the significant enhancement in water solubility demonstrates that nanoscale encapsulation is advantageous for improving dissolution behavior [24, 25].

The thermodynamic stability and robust hydrophobic interactions within the polymeric core enabled PEG-PCL to attain a low critical micelle concentration (CMC) of 0.012 mg/mL. The micellar structure persists under the diluted circumstances of systemic circulation, hence enhancing drug delivery applications due to a low critical micelle concentration (CMC). This feature demonstrates that the PEG-PCL composite system possesses structural integrity [26].

Particle size analyses validated the consistent fabrication of nano-composites, indicating that PEG-PCL micelles exhibited a low polydispersity index of 0.186 and an average diameter of approximately 78 nm. Nanoscale dimensions under 100 nm can enhance bioavailability and cellular uptake. The anti-aggregation and electrostatic stabilization characteristics are corroborated by the significantly negative zeta potential of -18.7 mV. The TEM analysis verified the spherical morphology and distinctive core-

shell architecture, corroborating the formation of nanoscale micelles and affirming the DLS findings [27].

The preservation of distinct peaks for the polymer and drug in the FTIR analysis demonstrated the absence of chemical incompatibility. Peak shifts smaller than those resulting from covalent modification suggested physical entrapment and possible molecular interactions, such as hydrogen bonding and hydrophobic connections. Consequently, the medicine was successfully integrated into the polymeric composite matrix without inflicting any structural harm [28].

PEG-PCL micelles significantly enhanced drug loading and encapsulation efficiency relative to PLGA and PLA systems. The hydrophobic medication exhibits a great affinity for the PCL core, evidenced by an EE% of 87.3%, indicating minimal drug loss during manufacturing. In the development of composite nanocarriers for drug incorporation, it is essential to consider polymer-drug compatibility [29].

Pharmaceutical release tests indicated that PEG-PCL micelles sustained drug release for 48 hours, whereas PLA formulations exhibited rapid release. The release profile aligned well with the Higuchi diffusion model, indicating that diffusion through the polymeric matrix was the principal factor influencing drug release. PEG-PCL's diminutive hydrophobic core likely facilitated prolonged release as a diffusion barrier, hence enhancing its therapeutic potential [30].

The significant enhancement in water solubility, measured at 21.6 times greater than the unencapsulated medication, was a remarkable result of the study. The superior performance of micelles is attributed to their nanoscale dispersion, augmented surface area, and hydrophobic core, which effectively encapsulates the substance. Higher water solubility may enhance the bioavailability and dissolution of phytoconstituents compared to those with lower solubility [31].

The stability assessments indicated that the physicochemical characteristics of the PEG-PCL system remained unchanged throughout storage, implying its robustness. The findings indicate that PEG-PCL micelles may serve as an effective carrier for hydrophobic phytoconstituents, representing a viable research avenue [32, 33].

Further validation of the PEG-PCL composite system's durability was obtained from stability assessments. After three months, particularly when refrigerated, there are negligible alterations in particle size, PDI, or drug content, demonstrating the medicine's exceptional physicochemical stability and low leakage. Due to their stability, medicines can be preserved for prolonged durations and utilized in practical applications [34].

CONCLUSION

This study demonstrated enhanced structural stability, solubilization capacity, and controlled release capabilities in the PEG-PCL-based polymeric micellar nanocomposites. Findings indicate that interfacial engineering, molecular architecture, and polymer composition significantly influence composite performance. The importance of selecting the appropriate polymer in nanocomposite design is demonstrated by PEG-PCL's enhanced performance compared to PLA and PLGA. The new versatile polymer composite demonstrates significant potential for advanced medicine delivery systems. This work facilitates the development of future nanocomposite systems by illustrating the significance of polymer structure in relation to functional performance.

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None

Conflict of Interest

None

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