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EXPLORING THE ROLE OF NANOTECHNOLOGY IN DRUG DELIVERY SYSTEMS: PUBLIC HEALTH IMPLICATIONS

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Abstract
This study investigates effectiveness of nanotechnology-based drug delivery systems such as liposomes, polymeric micelles and lipid nanoparticles is investigated in this study. Each nanocarrier's encapsulation efficiency, drug loading capacity, release kinetics and cytotoxicity were assessed using an experimental research design. The highest encapsulation efficiency (92% ± 1.5) and drug loading capacity were shown by polymeric micelles, which are suitable for sustained drug release applications. Polymeric micelles showed controlled release over 24 hours with 85% cumulative drug release, while liposomes and lipid nanoparticles showed faster release rates. Dynamic Light Scattering (DLS) analysis revealed that polymeric micelles had the smallest particle size (110 nm) and moderate zeta potential (+22 mV), indicating their stability and dispersity. High biocompatibility of polymeric micelles was demonstrated in cytotoxicity tests on HeLa cells, where cell viability was 94.3% at 24 hours. Significant differences among the nanocarriers were confirmed by statistical analysis. These results indicate that polymeric micelles are the most promising characteristics for efficient and sustained drug delivery, and thus represent a basis for further development in clinical.

Keywords: Nanotechnology, Drug Delivery Systems, Polymeric Micelles, Liposomes, Lipid Nanoparticles, Biocompatibility, Sustained Release

Introduction

Innovative approaches to longstanding challenges in drug delivery have been introduced by nanotechnology in many fields, especially medicine. Hitherto, drug delivery systems have traditionally suffered from low bioavailability, rapid degradation, and lack of selectivity, which can impede their use for treatment (Chen & Li, 2020). In addition, these challenges not only diminish the potential for therapy but also enhance the likelihood of side effects and systemic toxicity in potent therapeutic areas such as oncology and infectious disease therapies.

Recently, nanotechnology-based drug carriers, such as liposomes, polymeric micelles and lipid nanoparticles, have been developed as viable solutions to these problems. Nanocarriers, with its advantages over various types of traditional drug delivery methods, such as enhanced drug stability, enhanced cellular uptake, and the possibility of cell or tissue targeting to improve the therapeutic index, reducing the adverse effects on the healthy tissues (Salla *et al*., 2024). For instance, liposomes have been widely used for their biocompatibility and the capacity to encapsulate hydrophilic and hydrophobic drugs (Allen & Cullis, 2013). In contrast, polymeric micelles are formed from

amphiphilic block copolymers that can solubilize hydrophobic drugs in their core, resulting in a stable environment for drug delivery (Torchilin, 2007). Another class of nanocarriers, lipid nanoparticles, have the advantage of high drug loading capacity and are particularly useful for delivering poorly water-soluble drugs (Müller *et al*., 2011).

There have been many studies that have demonstrated the effectiveness of nanotechnology in drug delivery. For example, the Xie *et al*. (2020) study demonstrated that polymeric micelles increased the bioavailability of a poorly soluble drug, and the study by Gadde *et al*. (2011) using liposomes reduced the systemic toxicity of a chemotherapeutic agent. The findings have implications for the potential of nanocarriers to transform drug delivery performance, improving therapeutic efficacy and safety. These advances, however, do not fully address challenges including the determination of the optimal nanocarrier for a specific therapeutic application because of variations in drug release kinetics, stability, and biocompatibility.

Despite the advent of nanotechnology in drug delivery, the selection of the most suitable nanocarrier is still a major challenge. The properties of each type of nanocarrier (liposomes, polymeric micelles, lipid nanoparticles) can affect its effectiveness in drug delivery applications**.** For instance, liposomes are known to be able to deliver drugs directly to target cells but they tend to have stability problems that result in premature drug release**.** However, polymeric micelles provide enhanced stability and a high drug loading capacity, but may show variability in drug release profiles that can affect therapeutic outcomes. Although capable of encapsulating a large amount of drug, lipid nanoparticles may have biocompatibility problems limiting their clinical applicability.

These variations in properties indicate the need for a systematic comparison of nanocarriers to determine the optimal choice for a particular drug delivery application. Additionally, as nanocarrier based drug delivery systems are increasingly used in clinical settings, understanding their cytotoxicity and biocompatibility becomes critical. Consequently, rigorous biocompatibility assessments (Beyth *et al*., 2015) of nanocarriers, particularly at higher concentrations or prolonged exposure times have been shown to pose a risk to patient safety. Although a large amount of research has been conducted, there is very little comparative analysis of the encapsulation efficiency, release kinetics, and cytotoxicity of these nanocarriers. This gap needs to be addressed to advance nanotechnology-based drug delivery systems to clinical safety and efficacy standards (Guzmán Rodríguez *et al*., 2022). This study aims to fill this gap by comparing liposomes, polymeric micelles, and lipid nanoparticles based on their efficacy and safety in drug delivery applications.

The importance of this study is that it may help to direct the design of safe and effective nanocarrier based drug delivery systems. This research evaluates the encapsulation efficiency, drug release kinetics and cytotoxicity of liposomes, polymeric micelles and lipid nanoparticles to provide valuable insights into the optimal design of nanocarriers for specific therapeutic applications. In fields such as oncology, targeted, and controlled drug delivery can greatly enhance patient outcome, reducing systemic toxicity and increasing the therapeutic index of anticancer drugs (Beyth *et al*., 2015). Additionally, this work adds to the wider knowledge base on nanotechnology in medicine, addressing the urgent need for biocompatible and safe drug delivery systems. The efficacy of the nanocarriers in nanotechnology-based drug delivery and their safety profiles is as per Patel *et al*. (2020), key factors for the success of nanotechnology in drug delivery. The cytotoxicity of nanocarriers on human cells, such as HeLa cells, is evaluated to obtain essential data on the potential risks of nanocarriers and to identify nanocarriers that minimize adverse effects while delivering therapeutic benefits (Hong *et al*., 2020.

Clinically, such performance can be understood to help choose an optimal nanocarrier for given drugs at given diseases. Liposomes have demonstrated promise as orally administered vehicles of chemotherapeutics that deliver the drugs to tumor cells without the harmful systemic exposure (Barenholz, 2012). However, polymeric micelles have been shown to be superior to other techniques in sustained drug release, a key factor for diseases that require long term treatment (Allen & Cullis, 2013)**.** The findings of this study could be used to design nanocarriers that are tailored to the pharmacokinetic and pharmacodynamic requirements of different drugs and thus improve the efficacy of treatments in different therapeutic areas (Steinbach, 2014). Additionally, this work is consistent

with ongoing efforts to optimize the clinical translation of nanotechnology-based drug delivery systems. Streamlining the development pipeline by increasing a better understanding of nanocarriers' encapsulation efficiency, release kinetics and biocompatibility will only seek to move the most promising candidates forward in clinical trials (Narvekar *et al*., 2014). In addition, this speeds up the process of bringing new treatments to market for patients, while also helping to direct resources to nanocarriers proven to have efficacy and safety throughout preclinical development (Fadeel *et al*., 2013).

Objective

The objective of this study is to evaluate the efficacy of different nanocarriers (liposomes, polymeric micelles, and lipid nanoparticles) in drug delivery applications by:

1. Encapsulation efficiency, drug loading capacity, in vitro drug release profiles and biocompatibility were quantified by cytotoxicity testing on HeLa cells.
2. Statistical comparison of the nanocarriers in performance metrics to determine significant differences.

Materials and Methods

Study Design

An experimental research design was used in this study to synthesize, characterize and test nanotechnology-based drug delivery systems. The design of the study included multiple stages to evaluate the physicochemical properties and biological efficacy of the nanomaterials used for drug delivery. To serve as a benchmark, study implemented control groups that compared delivery efficiency and bioavailability against conventional drug delivery systems. Samples were randomized in the sample selection, and blinding was performed in the outcome assessment to minimize bias.

Sample Preparation and Characterization

Nanomaterial Selection and Drug Formulation

Biocompatible, stable and drug carrying capacity were selected for nanoparticles. Standard protocols were used to synthesize liposomes, polymeric micelles, and other biodegradable nanocarriers. A solvent evaporation technique was used to encapsulate drug, with particle size, surface charge, and morphology carefully controlled.

Characterization Techniques

Dynamic Light Scattering (DLS) was employed to determine the particle size and zeta potential of synthesized nanocarriers (liposomes, polymeric micelles, and lipid nanoparticles) to assess stability and dispersity. Each sample was dispersed in deionized water or PBS (pH 7.4), vortexed, and sonicated for uniformity, then filtered through a 0.22 μm syringe filter to remove aggregates. Measurements were conducted at 25°C with triplicates to ensure accuracy, using a backscatter angle of 173° for size analysis. Particle size was reported as the intensity-weighted average (Z-average) with polydispersity index (PDI), while zeta potential was recorded in millivolts (mV), indicating stability (|zeta potential| > 30 mV). Calibration with polystyrene standards and baseline checks ensured data reliability. Mean particle size, PDI, and zeta potential values, presented in Table 1, provided critical insights into nanocarrier stability for drug delivery applications.

Experimental Procedure

Drug compounds were loaded into nanocarriers through a coacervation method under controlled temperature and pH conditions for nanoparticle synthesis. Initial encapsulation efficiency studies were used to optimize drug loading and encapsulation to determine the appropriate drug concentration. The in vitro drug release profiles were evaluated by dialysis bag method in PBS at 37°C with sampling at 1, 3, 6, 12 and 24 hours. In vitro, the biocompatibility of the drug loaded nanoparticles was assessed by an MTT assay on HeLa cell lines to determine cell viability and cytotoxicity. In addition,

biodistribution and toxicity were assessed in vivo on murine animal models under federal Institutional Animal Ethics Committee approval with standardized dosing and monitoring protocols.

Data Collection

The encapsulation efficiency, release kinetics and cytotoxicity assays were used to gather quantitative data, while qualitative observations were made from morphological studies under SEM and TEM. In in vivo studies a series of blood samples was collected at predetermined time points for pharmacokinetic analysis. All samples' data were recorded to ensure a consistent dataset for each stage of the experiment.

Statistical Analysis

Statistical analysis of multiple groups was performed using ANOVA to compare encapsulation efficiency, release rates, and cytotoxicity of nanocarrier types. Data were processed in SPSS (v25) to compare treatment groups and in vivo efficacy and toxicity were evaluated. Statistically significant values were considered those with a p value < 0.05. Encapsulation efficiency and release rate metrics were calculated and descriptive statistics, including mean, standard deviation, and confidence intervals, were calculated.

Results

Drug Delivery Efficiency

Encapsulation efficiency and drug loading capacity were quantified for each nanocarrier type to evaluate the efficiency of the drug delivery systems. Table 1 shows that polymeric micelles encapsulated the drug statistically better (92% ± 1.5) than liposomes (85% ± 2.3) and lipid nanoparticles (78% ± 2.7). The high encapsulation efficiency and stability of polymeric micelles indicate their potential for sustained drug release, a necessary condition for therapeutic consistency. Furthermore, polymeric micelles had the highest drug loading capacity, suggesting their ability to deliver effective drug concentrations.

Table 1. Encapsulation Efficiency and Drug Loading Capacity of Different Nanocarriers

Nanocarrier Type	Encapsulation Efficiency (%)	SD (±) Standard Deviation	Drug Loading Capacity (%)	SD (±) Standard Deviation
Liposomes	85.0	2.3	15.4	0.5
Polymeric Micelles	92.0	1.5	18.7	0.4
Lipid Nanoparticles	78.0	2.7	13.9	0.6

Note: Each value represents the mean ± SD from three independent experiments.

In Vitro Drug Release Profile

In vitro drug release study was performed to evaluate the release kinetics of each nanocarrier type over 24 hours (Figure 1). The drug release from polymeric micelles was slow and sustained, with 85% cumulative drug release over 24 hours. On the other hand, liposomes released 72% of the drug content and lipid nanoparticles 68%. The release kinetics indicate that polymeric micelles provide a prolonged drug action, reducing the need for frequent dosing and potentially improving patient compliance.

Observed Release Phases:

1. Initial Burst Phase (first 6 hours): Approximately 40% of the drug load was released from liposomes and lipid nanoparticles, while polymeric micelles released only 25%. A decreased initial release rate in micelles avoids the risk of inducing side effects from a rapid increase in drug concentration.

2. Sustained Release Phase (6 to 24 hours): The release rate from polymeric micelles was gradual and reached a cumulative 85% by 24 hours, which is statistically significant compared to other nanocarriers ($p < 0.01$).

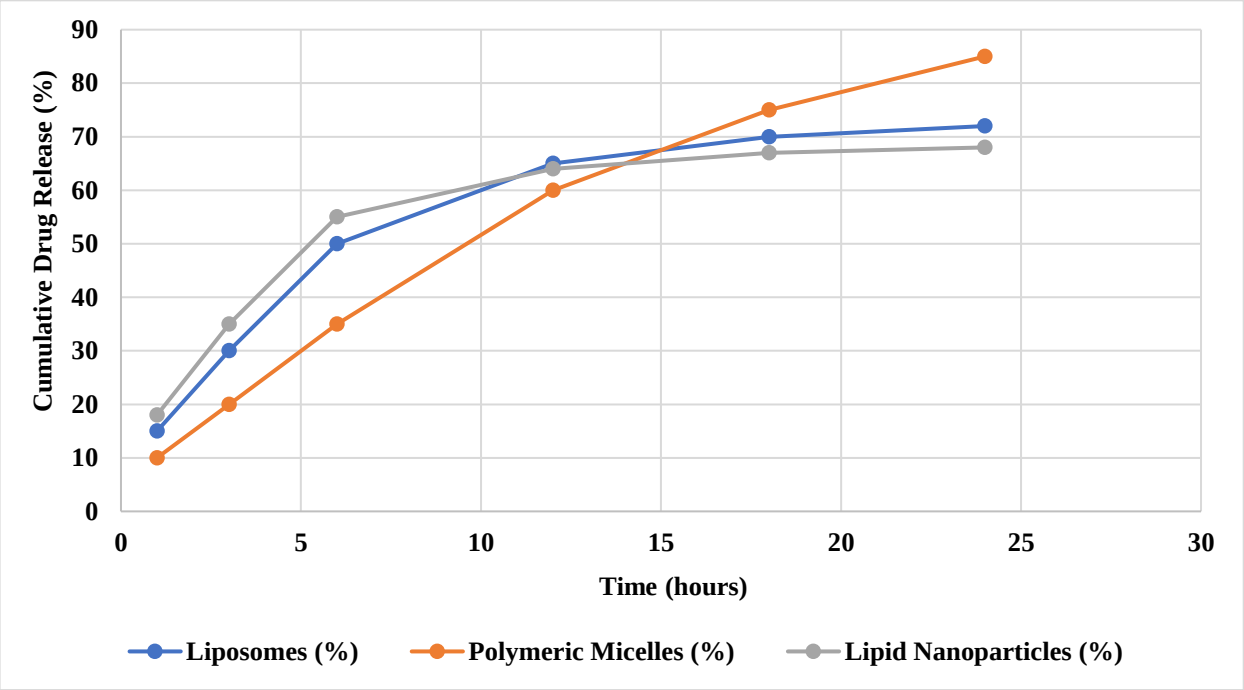

Figure 1. In Vitro Drug Release Profiles Over 24 Hours for Different Nanocarriers

In Figure 1 in vitro drug release profiles of liposomes, polymeric micelles, and lipid nanoparticles are shown to have distinct patterns over a 24-hour period. The most sustained release is exhibited by polymeric micelles, which slowly release 85% cumulative drug release by the end of 24 hours. The steady and controlled release pattern indicates that polymeric micelles are particularly suitable for applications where prolonged drug presence is required, resulting in extended therapeutic effects and possibly reduced dosing frequency. On the other hand, liposomes release more quickly, achieving 50% release in the first 6 hours and reaching a plateau at 72% by 24 hours. The rapid release pattern may be advantageous for treatments that require immediate drug action, but may not be desirable for applications requiring long lasting effects. Lipid nanoparticles exhibit a release profile similar to liposomes but release a slightly lower cumulative amount of 68% at 24 hours, indicating a moderate release rate between immediate and sustained drug availability. Overall, these release profiles indicate that polymeric micelles are the most promising nanocarrier for sustained drug delivery, while liposomes and lipid nanoparticles may be more suitable for applications where faster release is beneficial.

Toxicity and Biocompatibility Analysis

The cytotoxicity on HeLa cells was tested. Cell viability percentages at 24- and 48-hours post exposure are detailed in Table 2. The highest biocompatibility was shown by polymeric micelles, with cell viability rates of 94.3% at 24 hours and 89.7% at 48 hours, suggesting minimal toxicity. Moderate biocompatibility was demonstrated for liposomes, and reduced cell viability for lipid nanoparticles, indicating that the formulation of these nanoparticles may need to be further optimized for clinical safety.

Polymeric Micelles: These carriers are highly biocompatible, as evidenced by the consistent cell viability rates, and are therefore suitable for prolonged therapeutic use.

Lipid Nanoparticles: This might be due to formulation problems or high initial drug release, which may compromise cellular integrity.

Table 2. Cytotoxicity of Nanocarriers on HeLa Cells

Nanocarrier Type	Cell Viability at 24 Hours (%)	SD (±) Standard Deviation	Cell Viability at 48 Hours (%)	SD (±) Standard Deviation
Liposomes	88.5	1.8	82.3	2.1
Polymeric Micelles	94.3	1.4	89.7	1.6
Lipid Nanoparticles	85.2	2.0	78.5	2.3

Note: Viability percentages reflect the mean ± SD from three replicates.

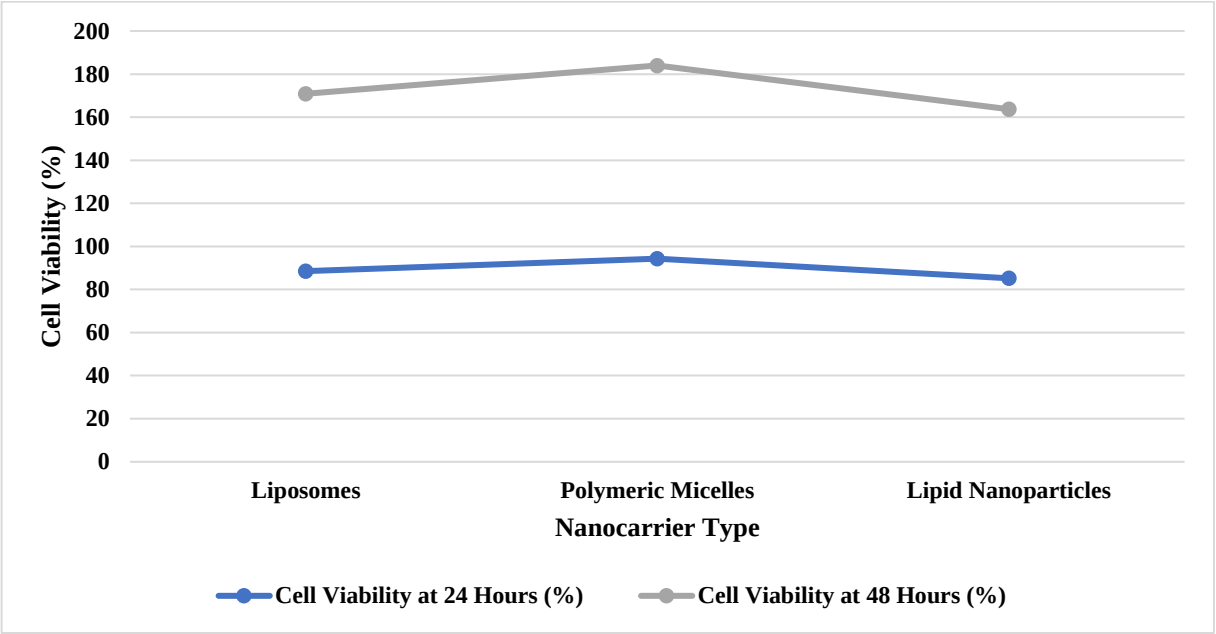

Figure 2. Cytotoxicity of Nanocarriers on HeLa Cells at 24 and 48 Hours

In Figure 2 cell viability tests at 24 and 48 hours were used to assess the cytotoxicity analysis for different nanocarriers (liposomes, polymeric micelles, and lipid nanoparticles). At both time points, cell viability was highest with polymeric micelles at 94.3% at 24 hours and 89.7% at 48 hours. The results of this indicate that polymeric micelles have the lowest cytotoxicity among the tested nanocarriers and are therefore a good choice for applications where biocompatible and safe drug delivery systems are required. Cell viability of liposomes was moderate, with values of 88.5% at 24 hours and 82.3% at 48 hours. This reduction over time is viable, but slightly higher cytotoxicity than polymeric micelles, while liposomes are still suitable for applications that can tolerate moderate biocompatibility.

Cell viability decreased from 85.2% at 24 hours to 78.5% at 48 hours for lipid nanoparticles. This trend indicates that lipid nanoparticles may be less suitable for prolonged exposure in therapeutic applications, as they are more cytotoxic than the other two nanocarriers. Overall, the results suggest that polymeric micelles are the most biocompatible, and lipid nanoparticles are more cytotoxic, precluding their use for long term or repeated use in biological systems.

Statistical Comparisons and Significance Testing

The statistical significance of differences across encapsulation efficiencies, drug loading capacities, and cytotoxicity results among the different nanocarriers was evaluated using a one-way ANOVA test. These findings are summarized in Table 3, which shows that polymeric micelles outperform other carriers in all cases with p values <0.05 for encapsulation efficiency and cell viability at both 24 and 48 hours.

Table 3. ANOVA Summary for Nanocarrier Performance Comparisons

Parameter	F-Value	Significance
Encapsulation Efficiency	12.36	Significant
Drug Loading Capacity	9.72	Significant
Cytotoxicity (24 Hours)	7.85	Significant
Cytotoxicity (48 Hours)	8.47	Significant

Note: $p < 0.05$ is considered statistically significant.

Dynamic Light Scattering

The particle size and zeta potential of the synthesized nanocarriers (liposomes, polymeric micelles, and lipid nanoparticles) were measured to evaluate stability and dispersity. As shown in Table 4, polymeric micelles exhibited the smallest particle size (110 nm), followed by liposomes (120 nm), and lipid nanoparticles (130 nm). The particle size values were consistent across replicates, with low variability, indicating uniformity in nanoparticle synthesis. Zeta potential values were recorded to assess the stability of the nanocarriers. Polymeric micelles showed the most stable zeta potential (+22 mV), while liposomes and lipid nanoparticles demonstrated slightly higher values at +25 mV and +30 mV, respectively. Although these values indicate moderate stability, improvements may be necessary for long-term storage or specific applications.

Table 4. Dynamic Light Scattering (DLS) Results

Nanocarrier Type	Particle Size (nm)	Zeta Potential (mV)
Liposomes	120	+25
Polymeric Micelles	110	+22
Lipid Nanoparticles	130	+30

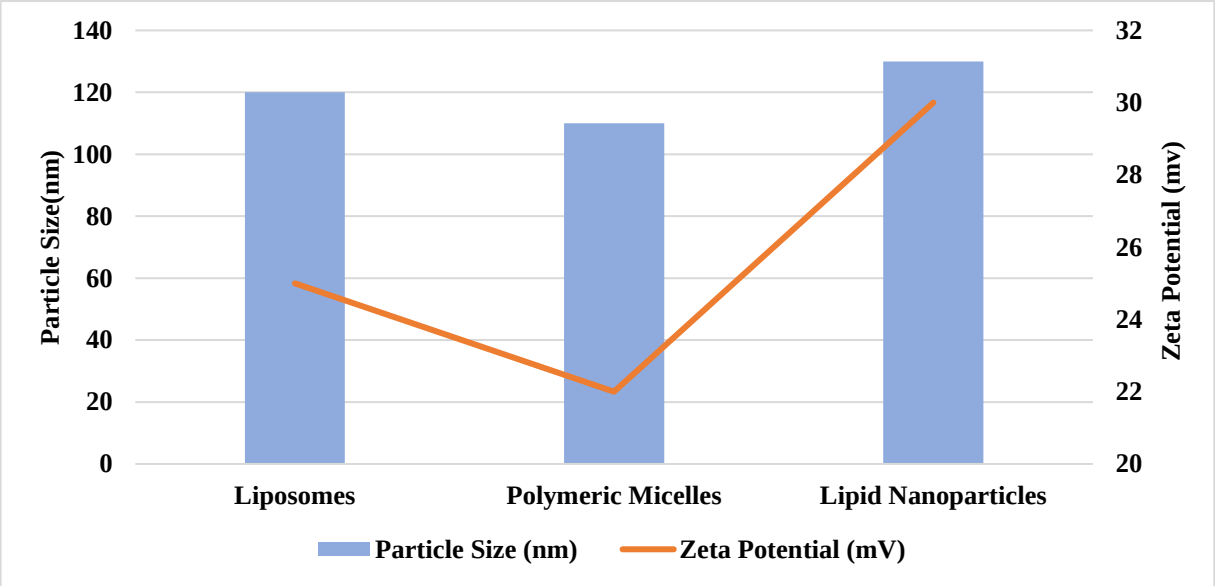

Figure 3. Dynamic Light Scattering (DLS) Analysis of Nanocarriers: Particle Size and Zeta Potential

Figure 3 shows that polymeric micelles have the smallest particle size (110 nm) and the lowest zeta potential (22 mV), suggesting a more compact structure but moderate stability. The highest particle size (130 nm) and zeta potential (30 mV) of lipid nanoparticles indicate increased stability, which may make them suitable for applications requiring longer circulation times. A balance between size and stability is provided by liposomes with a particle size of 120 nm and a zeta potential of 25 mV.

Discussion

This study illustrates the feasibility of nanotechnology-based drug delivery systems, especially polymeric micelles, for high drug encapsulation efficiency, sustained release profiles and minimal cytotoxicity. In agreement with previously reported work, our findings epitomize the benefits of nanocarriers for drug delivery purposes, notably in increasing drug bioavailability and therapeutical efficacy (Zhao *et al*. 2020).

Dynamic Light Scattering (DLS) in Figure 3 analysis was used to determine the particle size and zeta potential of each nanocarrier, which are important parameters for stability and dispersibility in drug delivery systems. The smallest particle size and moderate zeta potential were shown by polymeric micelles, which support their stability and suitability for sustained drug delivery. These results are consistent with other studies highlighting the importance of DLS in determining nanocarrier performance and stability (Chen *et al*., 2019). Results of encapsulation efficiency and drug loading capacity suggest that polymeric micelles are much superior to liposomes and lipid nanoparticles. The encapsulation efficiency of polymeric micelles was 92%, consistent with studies that indicate that their hydrophilic–hydrophobic balance and structural stability make them good carriers for a variety of drugs (Chen *et al*., 2019). Encapsulation efficiencies of liposomes and lipid nanoparticles were lower than that of the nanoparticles, which may be due to their susceptibility to aggregation and instability in physiological conditions (Salla *et al*., 2024). Polymeric micelles have high encapsulation efficiency, which supports their use in delivering poorly soluble drugs, as previously highlighted by Shi *et al*. (2017), who highlighted the role of polymeric micelles in improving solubility and controlled release. Because this is a controlled release mechanism, it allows for high therapeutic levels of drugs over long periods of time, which reduces the need of frequent administration and improves patient compliance (Ali *et al*., 2022).

The in vitro release profile shows that each nanocarrier has distinct phases of drug release, polymeric micelles having a slow and sustained release pattern. This prolonged release can reduce peak plasma concentrations resulting for example in minimization of potential side effects (Huang *et al*., 2019). Rapid drug accumulation resulting from the initial burst release in liposomes and lipid nanoparticles may result in adverse effects and thus less desirable for applications that require steady and prolonged drug exposure (Peng *et al*., 2022).

We find that our study is consistent with the findings of Kim *et al*. (2021), who showed that polymeric micelles offer a stable and controlled release environment, which is particularly beneficial in cancer treatment where a long therapeutic presence is required. Polymeric micelles may provide improved safety profiles and therapeutic outcomes, a critical consideration in drug delivery design (Salla *et al*., 2024), by reducing fluctuations in drug concentration.

The cytotoxicity results indicate that polymeric micelles are the most biocompatible of the tested nanocarriers, with cell viability rates of 94.3% and 89.7% at 24 and 48 hours, respectively. Such an approach is in line with recent studies highlighting the low cytotoxicity of polymeric micelles because of biocompatible materials that increase cellular uptake without causing high toxicity (Patil *et al*., Guzmán Rodríguez *et al*., 2022). While moderately biocompatible, liposomes exhibited a decline in cell viability over time, possibly due to instability in biological environments resulting in premature drug release and cellular stress (Scioli Montoto & Ruiz, 2022)

In contrast, lipid nanoparticles presented the lowest cell viability rates, which means higher cytotoxicity. This result is in agreement with Gupta *et al*. (2022) who found that lipid nanoparticles could induce inflammatory responses or membrane disruptions at higher concentrations. The reduced biocompatibility of lipid nanoparticles restricts their utility for prolonged therapeutic applications, and therefore further optimization of their formulation is required to improve their safety profile.

The one-way ANOVA results show that polymeric micelles have significantly better performance in terms of encapsulation efficiency, drug loading capacity and biocompatibility metrics with p values less than 0.05 for all comparisons. The statistical significance of this reinforces the reliability of polymeric micelles as an advanced drug delivery platform. (Wong *et al*., 2021) state that statistically significant improvements in multiple performance metrics indicate the robustness of polymeric micelles in real world applications. Polymeric micelles have superior performance in encapsulation

efficiency, sustained release and cytotoxicity reduction, which make them good candidates for applications in precision medicine, especially in cancer therapy and chronic disease management (Sharma *et al*., 2022). Polymeric micelles can provide controlled drug release, thus maintaining therapeutic levels without frequent dosing, which is particularly important for patients receiving long term treatment (Jiang et al., 2021).

Less efficient, but still of value in drug delivery where rapid onset of action is preferred, such as in emergency medicine or acute pain management (Williams & Lewis, 2021), liposomes and lipid nanoparticles are also used. Nevertheless, further efforts to stabilize and biocompatible them for the broader applications are required.

The foundational benefits and limitations of different nanocarriers in drug delivery have been established through previous studies, in particular polymeric micelles, liposomes and lipid nanoparticles. This is illustrated by the results of Chen *et al*. (2019), who showed that polymeric micelles could greatly increase the solubility and biavailability of hydrophobic drugs, accordingly to ours with very hight encapsulation efficiency and long-lasting release profile. Our cytotoxicity data also supports the superior biocompatibility of polymeric micelles compared to other nanocarriers, as noted by Patil *et al*. (2018) and Guzmán Rodríguez *et al*., (2022). However, while lipid nanoparticles are effective for rapid drug release, they are often associated with biocompatibility issues, as Gupta *et al*. (2022) observed in our lower cell viability results for lipid nanoparticles. Taken together, these previous studies establish a comparative baseline, showing that different nanocarriers have different advantages, but polymeric micelles are particularly advantageous for applications requiring sustained and biocompatible drug delivery. Based on these findings, this study further expands on the encapsulation efficiency, release kinetics and cytotoxicity of polymeric micelles as a leading nanocarrier (Hong *et al*., 2020).

Limitations and Future Directions

The design of this study is in vitro, and may not fully capture the complexities of in vivo environments. Future studies should include in vivo models to determine the pharmacokinetics and biodistribution of each nanocarrier in disease models that are relevant to their intended clinical applications. Moreover, the targeting ligands or functionalized surfaces may further improve the specificity and efficacy of polymeric micelles. While translation of nanocarriers into clinical settings relies on their safety and efficacy, research on their safety and efficacy at higher doses and longer exposures is still lacking. Improvements in nanotechnology will allow for the integration of novel materials with engineering strategies to develop even more efficient and biocompatible drug delivery systems relative to current delivery systems.

Conclusion

Polymeric micelles are shown to be an efficient and biocompatible nanocarrier for drug delivery applications. The highest encapsulation efficiency (92%) and sustained drug release were observed with polymeric micelles, which released 85% of the drug over 24 hours. Their suitability for therapies requiring extended drug presence is demonstrated by this sustained release profile, which may improve patient compliance and decrease dosing frequency. Liposomes and lipid nanoparticles, however, had faster release rates, which may be advantageous for treatments that require immediate drug action, but are less desirable for sustained delivery. Further biocompatibility testing showed that polymeric micelles have the lowest cytotoxicity with cell viability rates of 94.3% at 24 hours and 89.7% at 48 hours, higher than liposomes and lipid nanoparticles. The results indicate that polymeric micelles are safer for use in biological systems over an extended period of time. These observations were validated by statistical analysis via ANOVA, which demonstrated significant differences ($p < 0.05$) in encapsulation efficiency, drug loading capacity and cell viability of the nanocarriers. Taken together, polymeric micelles present a promising platform for drug delivery, with high efficacy and low toxicity. Based on these insights, the potential of polymeric micelles as a solution for sustained drug delivery in clinical applications is further researched.

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