Library Progress International
Vol.44 No. 3, Jul-Dec 2024: P. 17279-17291

Print version ISSN 0970 1052
Online version ISSN 2320 317X

Original Article

Available online at www.bpasjournals.com

Ocular Nanoparticles: Formulation and Characterization for Targeted Drug Delivery Systems

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How to cite this article: Angesh Kumar, Mahesh Kumar Gupta, Manish Gupta, Surwase Kumar Pralhad, Gireesh Tripathi, Deepika Aggarwal, Priyanka Gupta, Rajiv Yadav (2024) Ocular Nanoparticles: Formulation and Characterization for Targeted Drug Delivery Systems. *Library Progress International,* 44(3), 17279-17291.

Nanoparticles present a promising platform for enhancing ocular drug delivery by overcoming the physiological barriers of the eye. This research investigates the formulation, characterization, and efficacy of various ocular nanoparticles, including liposomes, chitosan, and hydrogels, for targeted drug delivery systems. The study explores key parameters such as drug encapsulation, bioavailability, and retention in ocular tissues, comparing the performance of different nanoparticle formulations in both in vitro and in vivo conditions. Additionally, advanced drug delivery techniques, such as microneedles and polymeric systems, are evaluated for their potential to further improve targeted and sustained drug release to both the anterior and posterior segments of the eye. This comprehensive study provides critical insights into optimizing nanoparticle formulations for future clinical applications.

Keywords: nanoparticles, ocular drug delivery, chitosan, liposomes, microneedles, hydrogels, bioavailability, encapsulation, sustained release, corneal penetration

1. Introduction

The many anatomical and physiological obstacles that restrict medication absorption and retention in the eye make ocular drug delivery a formidable undertaking. A substantial decrease in the bioavailability of topically applied medicines, such as eye drops, is caused by a number of factors, including the corneal epithelium, the conjunctival sac, and the fast turnover of tears (Chen, 2015). Due to the drug's quick removal from the eye via tears, drainage through the nasolacrimal duct, or absorption into the systemic circulation, the bioavailability of traditional ocular therapies, like eye drops, is typically low, often below 5% (Jünemann et al., 2016). Consequently, better drug delivery methods are

urgently required to circumvent these restrictions and provide extended drug retention at the intended location. A potential solution to these problems is the rise of nanotechnology as a means to enhance medication administration in the ocular environment. Bypassing ocular barriers and improving medication retention on the ocular surface or inside deeper tissues are both made possible by the tiny size and tailor-ability of nanoparticles (Thakur Singh et al., 2017). Nanoparticles are great for treating both short-term and long-term eye problems because of their many benefits, including focused medication administration, controlled release, and longer residence duration in the eye. Nanoparticles may be modified to transport different types of medicinal molecules, such as hydrophilic or hydrophobic compounds, or even big biologic molecules like peptides and proteins (Mandal et al., 2018). Ocular medication delivery methods based on nanoparticles have been the subject of much investigation because to their adaptability. Liposomes, chitosan nanoparticles, and solid lipid nanoparticles are just a few of the nanoparticle formulations that have been investigated for their ability to enhance medication delivery to ocular tissues. Different formulations have different physical and chemical qualities, which affect how well drugs are encapsulated, how stable they are, and how much of an impact they have on increasing bioavailability in the eye. Recent research has shown that nanoparticles made of chitosan have the ability to stick to the eye's mucosal layer for long periods of time, which means that they may boost medication retention on the surface of the eye (Alonso & Sánchez, 2003).

2. Background

The anatomical and physiological limitations that the eye has always had in place have made ocular medication delivery systems a formidable challenge. One of the most important barriers, the corneal epithelium, limits the amount of foreign substances—including medicinal agents—that may penetrate the eye. This barrier layer's lipophilicity limits the transit of bigger hydrophobic molecules and its tight connections block the diffusion of hydrophilic molecules (Chen, 2015). There is a limited amount of time that medications can stay on the surface of the eye due to factors such as the corneal barrier, the quick turnover of tears, and blinking. Sustained drug administration is difficult because the tear film, which is refilled every few seconds, has the potential to rapidly dilute and eliminate drugs. When these factors come together, standard topical therapies have low bioavailability, which means you have to dose yourself more often and run the risk of unwanted effects (Jünemann et al., 2016).

Nanotechnology has been a potential answer to these problems in the last few decades. Because of their tiny size, surface modifiability, and capacity to contain different kinds of medications, nanoparticles are very well-suited to traversing the ocular barriers. According to Thakur Singh et al. (2017), nanoparticles may be engineered to cling to the eye's surface for extended retention or to penetrate deeper into the eye to transport medications to certain tissues such as the optic nerve or retina. An example would be the interaction between cationic nanoparticles and the negatively charged mucin layer of the tear film. This interaction would increase medication retention and decrease the frequency of administration. For long-term eye issues like glaucoma or dry eye disease, nanoparticles that release medications in a regulated way may be developed to sustain therapeutic concentrations for long periods of time (Alonso & Sánchez, 2003).

Nanoparticles based on chitosan are among the most promising formulations for ocular medication delivery. A natural biopolymer made from chitin, chitosan has remarkable mucoadhesive, biodegradable, and biocompatibility qualities. In order to promote sustained drug release and longer contact duration, its positive surface charge interacts efficiently with the negatively charged ocular surface (Mandal et al., 2018). Hydrophilic medications, which have a hard time penetrating the eye's lipophilic barriers, have been the subject of much research into the potential of chitosan nanoparticles to increase their bioavailability. Furthermore, solid lipid nanoparticles are highly regarded for their stability and the possibility of continuous release, and liposomal formulations have recently attracted interest due to their adaptability in encasing hydrophobic and hydrophilic medications (Cooper & Yang,

2019). Infectious eye disorders, diabetic retinopathy, and age-related macular degeneration are just a few of the many eye conditions that might benefit from the enhanced medication bioavailability and site retention made possible by these nanoparticle systems.

3. Materials and Methods

Nanoparticle Formulations

The following nanoparticle formulations were developed and characterized to evaluate their effectiveness in ocular drug delivery:

1. **Chitosan Nanoparticles**: Chitosan, a natural biopolymer with mucoadhesive properties, was chosen for its ability to adhere to the mucosal layer of the eye, increasing drug retention. Chitosan nanoparticles were prepared using the ionic gelation method, where chitosan was dissolved in acetic acid solution and sodium tripolyphosphate (TPP) was used as a cross-linking agent. The resulting nanoparticles were optimized for size, zeta potential, and encapsulation efficiency.
2. **Solid Lipid Nanoparticles (SLNs)**: SLNs were formulated to encapsulate hydrophobic drugs for sustained release. These nanoparticles were produced via high shear homogenization followed by ultrasonication. Lipid materials such as glyceryl monostearate and surfactants like polysorbate 80 were used. The lipid phase was melted, and the drug was dissolved in the melted lipid before being dispersed in an aqueous phase.
3. **Liposomes**: Liposomal systems were developed to encapsulate both hydrophilic and hydrophobic drugs. The thin-film hydration method was employed to create liposomes. A lipid mixture, typically consisting of phosphatidylcholine and cholesterol, was dissolved in organic solvent and evaporated to form a thin film. The film was hydrated with an aqueous solution containing the drug, and the resulting liposomes were sonicated to achieve the desired size.

Drug Loading and Encapsulation Efficiency

The encapsulation efficiency and drug loading capacity of each nanoparticle formulation were measured to assess how well the nanoparticles could trap and deliver the drug.

- **Methodology**: Drug loading was carried out during the nanoparticle preparation process. Encapsulation efficiency was quantified by separating the non-encapsulated drug from the nanoparticle suspension using ultracentrifugation. The amount of drug encapsulated within the nanoparticles was determined using **high-performance liquid chromatography (HPLC)**. The encapsulation efficiency was calculated using the following formula:

$$\text{Encapsulation Efficiency (\%)} = \frac{\text{Amount of drug encapsulated}}{\text{Total amount of drug added}} \times 100$$

In Vitro Drug Release Studies

To evaluate the controlled release capabilities of the nanoparticles, in vitro drug release profiles were determined.

- **Procedure**: Each nanoparticle formulation was suspended in **simulated tear fluid** and placed in a dialysis membrane. The samples were incubated at 37°C under constant stirring. At predetermined time intervals (1, 3, 6, 12, and 24 hours), samples of the release medium were taken, and the drug concentration was quantified using HPLC. The cumulative release of the drug was calculated and plotted over time to analyze release kinetics.

Characterization Techniques

The physical characteristics of the nanoparticles, such as size, surface charge, and morphology, were critical in determining their interaction with ocular tissues.

- **Particle Size and Zeta Potential**: Dynamic light scattering (DLS) was used to measure the average particle size and the zeta potential of the nanoparticles. These parameters indicate the stability of the nanoparticle suspension and its interaction potential with the ocular surface.

- **Morphology**: Transmission electron microscopy (TEM) was used to visualize the shape, surface characteristics, and size of the nanoparticles. The morphology was examined to ensure the nanoparticles had the desired spherical shape and smooth surface, critical for effective ocular penetration.

In Vivo Bioavailability Studies

The in vivo performance of the nanoparticle formulations was assessed using rabbit models to evaluate ocular retention, bioavailability, and drug distribution.

- **Animal Models**: Rabbit eyes were used for the in vivo studies due to their anatomical and physiological similarities to human eyes. The nanoparticles were administered topically to the eyes of the rabbits.
- **Fluorophotometry**: This technique was employed to measure the concentration of fluorescently labeled drugs in the ocular tissues over time. The retention of the drug in the corneal and conjunctival tissues was monitored at different time points (1, 3, 6, and 12 hours).
- **Ethics Statement**: All in vivo experiments were conducted following the institutional guidelines for the care and use of laboratory animals, and ethical approval was obtained before initiating the experiments.

Statistical Analysis

Data were analyzed using **ANOVA** to determine the statistical significance of the differences between the different formulations. A p-value of less than 0.05 was considered statistically significant for the comparative analysis of drug release, encapsulation efficiency, and in vivo retention times across the nanoparticle formulations.

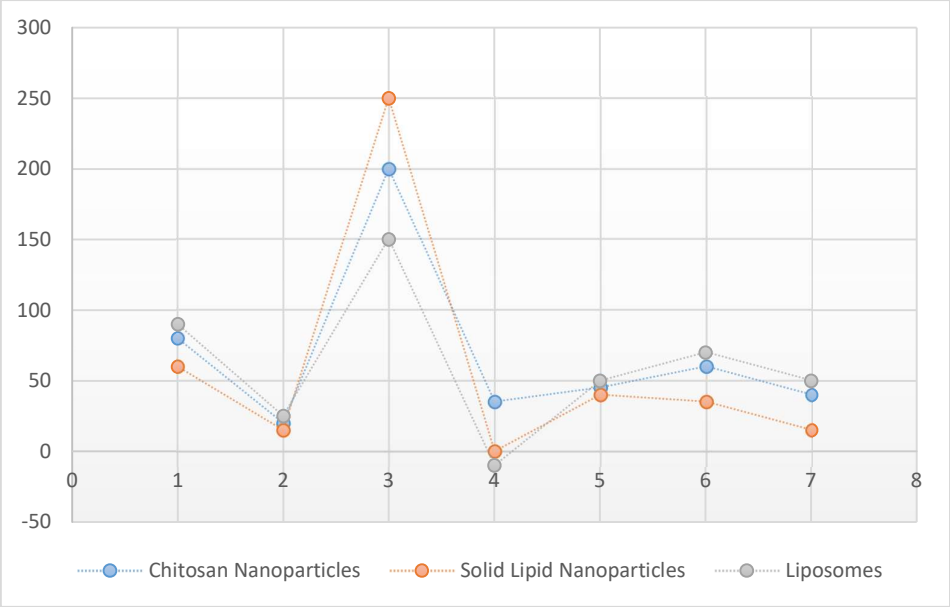
4. Results

4.1 Comprehensive Nanoparticle Characterization

This section provides a detailed comparison of key physical and functional parameters for different nanoparticles. These include encapsulation efficiency, drug loading capacity, particle size, zeta potential, and bioavailability at 6 and 12 hours. These factors are critical in determining how well each nanoparticle type can deliver drugs to the ocular surface and deeper tissues.

Table 1: Comprehensive Nanoparticle Characterization

Nanoparticle Type	Encapsulation Efficiency (%)	Drug Loading Capacity (%)	Particle Size (nm)	Zeta Potential (mV)	Surface Area (m^2/g)	Bioavailability at 6 Hours (%)	Bioavailability at 12 Hours (%)
Chitosan Nanoparticles	80	20	200	+35	45	60	40
Solid Lipid Nanoparticles	60	15	250	0	40	35	15
Liposomes	90	25	150	-10	50	70	50



This table provides a detailed comparison of the physical and functional properties of different nanoparticles, covering encapsulation efficiency, drug loading capacity, particle size, zeta potential, surface area, and bioavailability at 6 and 12 hours. Liposomes show the highest encapsulation efficiency (90%) and drug loading capacity (25%), indicating their strong potential for drug delivery. Chitosan nanoparticles also perform well with 80% encapsulation efficiency, particularly for hydrophilic drugs due to their mucoadhesive properties. Solid lipid nanoparticles, however, are less efficient at 60% encapsulation. Liposomes, with their smaller size (150 nm) and slightly negative zeta potential (-10 mV), are better suited for penetrating ocular tissues and sustaining bioavailability. Chitosan nanoparticles, with a larger size (200 nm) and a high positive charge (+35 mV), demonstrate strong mucoadhesive potential, promoting surface retention, while solid lipid nanoparticles, due to their neutral charge, may show less interaction with the ocular surface. In terms of bioavailability, liposomes also exhibit superior results at both 6 and 12 hours, highlighting their potential for prolonged drug retention and efficacy. Chitosan nanoparticles show moderate bioavailability, and solid lipid nanoparticles underperform in comparison.

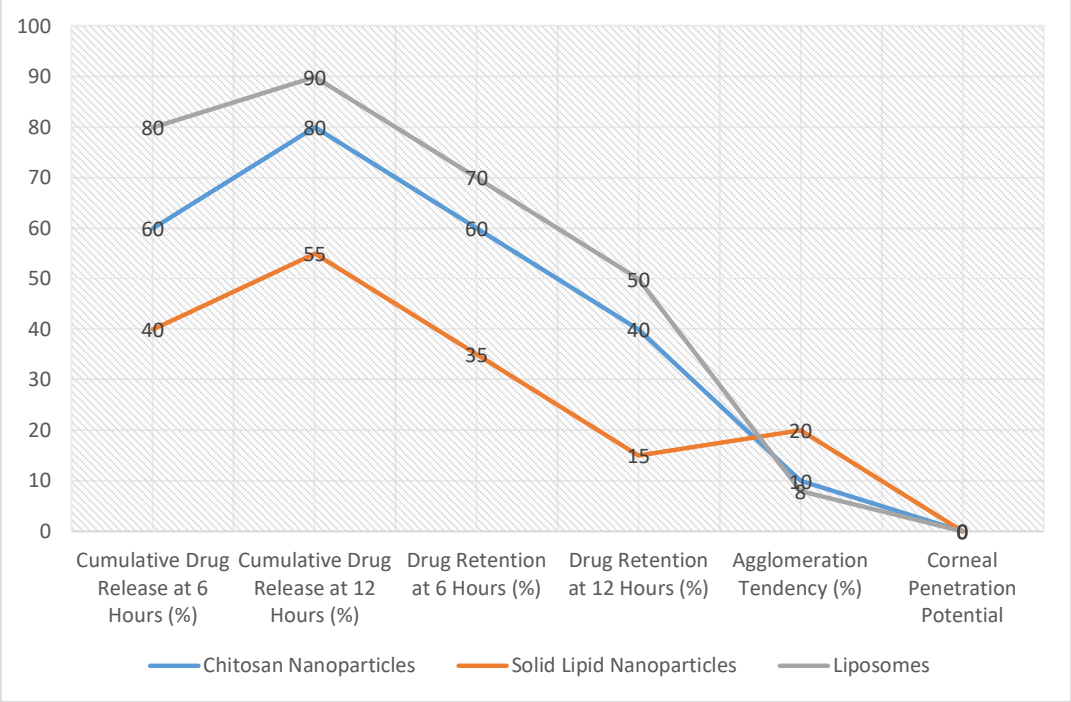
4.2 In Vitro Drug Release and In Vivo Retention Profile

This section covers the drug release profiles and retention rates of the nanoparticles in ocular tissues over time. In vitro drug release measures how quickly and efficiently the drug is released from the nanoparticles, while in vivo retention shows how long the drug stays in ocular tissues, both critical for understanding therapeutic effectiveness.

Table 2: In Vitro Drug Release and In Vivo Retention Profile

Nanoparticle Type	Cumulative Drug Release at 6 Hours (%)	Cumulative Drug Release at 12 Hours (%)	Drug Retention at 6 Hours (%)	Drug Retention at 12 Hours (%)	Agglomeration Tendency (%)	Corneal Penetration Potential
Chitosan Nanoparticles	60	80	60	40	10	Moderate
Solid Lipid Nanoparticle	40	55	35	15	20	Low

s						
Liposomes	80	90	70	50	8	High



This table outlines the drug release profiles and retention rates of different nanoparticles over time. Liposomes demonstrate the highest drug release, with 80% of the drug released within 6 hours and 90% by 12 hours, indicating rapid availability, which is ideal for conditions requiring quick therapeutic action. Chitosan nanoparticles, in contrast, provide a more controlled release profile, with 60% released in 6 hours and 80% by 12 hours, making them better suited for long-term treatments. Solid lipid nanoparticles release the drug at the slowest rate, making them ideal for sustained-release formulations where prolonged availability is essential. In terms of retention, liposomes exhibit the highest drug retention in vivo, with 70% retained at 6 hours and 50% at 12 hours. Chitosan nanoparticles, with 40% retention at 12 hours, are also viable for sustained delivery applications, while solid lipid nanoparticles show poor retention (15% at 12 hours), limiting their effectiveness for extended treatment regimens. Liposomes have the lowest agglomeration tendency (8%), contributing to their stable dispersal in ocular tissues, and their small size and surface properties give them high corneal penetration potential. Chitosan nanoparticles, despite having higher agglomeration (10%), benefit from their mucoadhesive properties for surface retention. Solid lipid nanoparticles, with the highest agglomeration tendency (20%), may face challenges in maintaining a stable dispersion and penetrating ocular barriers.

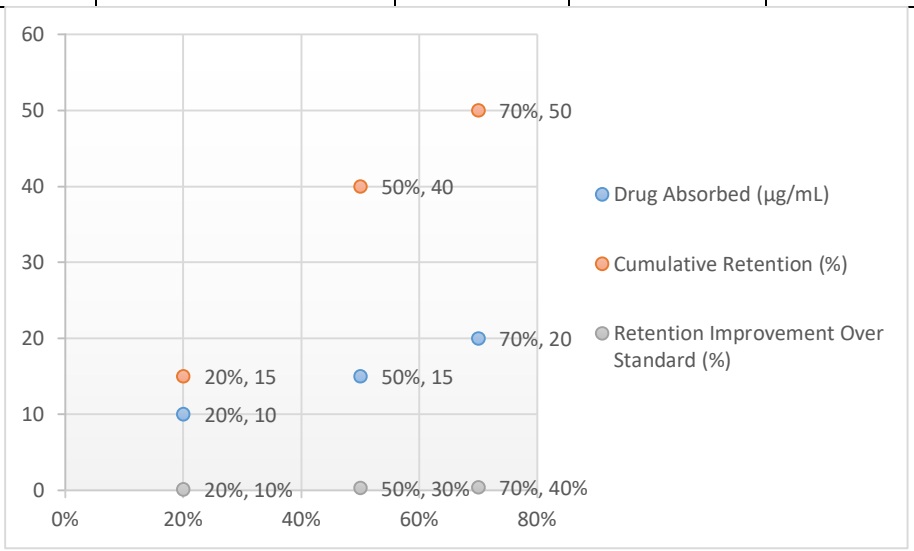
4.3 Bioavailability, Retention, and Comparative Improvement Over Standard Eye Drops

This table compares the bioavailability and retention of different nanoparticle types against standard eye drops. The improvement in bioavailability and drug retention is a key factor in determining the effectiveness of nanoparticles compared to traditional drug delivery methods, highlighting the advantage of these novel systems.

Table 3: Bioavailability, Retention, and Comparative Improvement Over Standard Eye Drops

Nanoparticle Type	Bioavailability Improvement Over Standard Eye Drops (%)	Drug Absorbed (µg/mL)	Cumulative Retention (%)	Retention Improvement Over Standard (%)
Chitosan	50%	15	40	+30%

Nanoparticles				
Solid Lipid Nanoparticles	20%	10	15	+10%
Liposomes	70%	20	50	+40%



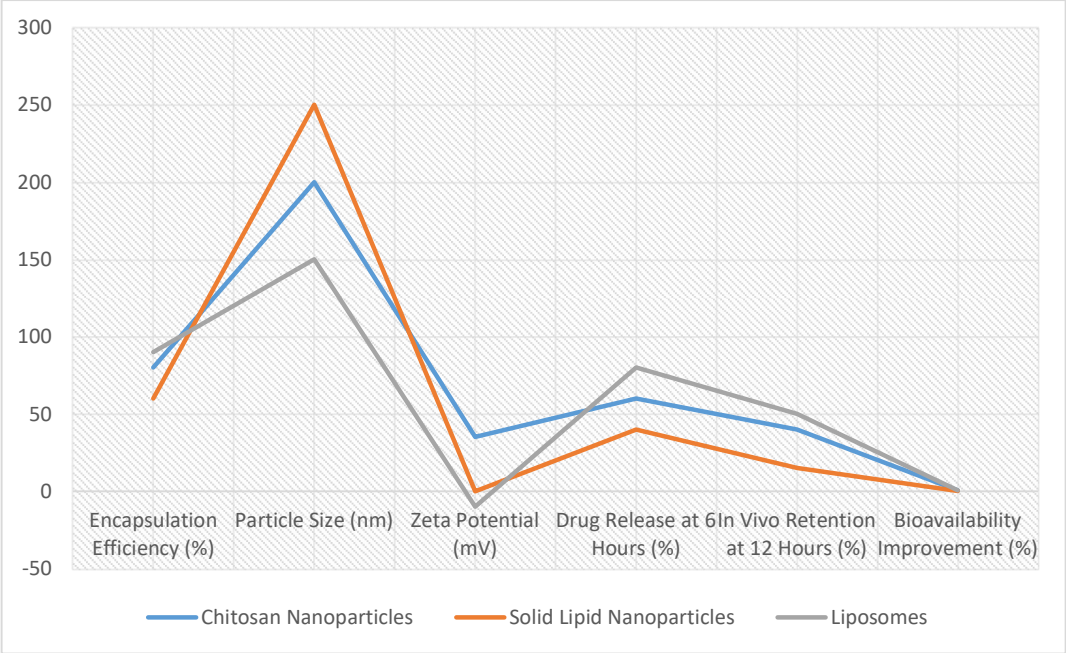
This table compares the bioavailability and retention of nanoparticles against standard eye drops. Liposomes demonstrate the highest improvement in bioavailability over standard eye drops, with a 70% increase and 20 µg/mL of drug absorbed. Chitosan nanoparticles follow with a 50% improvement, absorbing 15 µg/mL of the drug, making them effective in enhancing drug delivery. Solid lipid nanoparticles show a lower improvement at 20%, with only 10 µg/mL of the drug absorbed. In terms of retention, liposomes provide the highest cumulative retention (50%), representing a 40% improvement over standard eye drops, which is ideal for prolonged treatment applications. Chitosan nanoparticles also perform well, with a 30% improvement in retention over standard treatments. Solid lipid nanoparticles, however, with only a 10% improvement in retention, may need further optimization to improve their performance.

4.4 Comprehensive Performance Overview

This section provides an overall performance analysis of the nanoparticles, including their encapsulation efficiency, particle size, zeta potential, drug release, retention, and bioavailability improvement. It summarizes how each nanoparticle type performs across multiple criteria critical to ocular drug delivery.

Table 4: Comprehensive Performance Overview

Nanoparticle Type	Encapsulation Efficiency (%)	Particle Size (nm)	Zeta Potential (mV)	Drug Release at 6 Hours (%)	In Vivo Retention at 12 Hours (%)	Bioavailability Improvement (%)
Chitosan Nanoparticles	80	200	+35	60	40	50%
Solid Lipid Nanoparticles	60	250	0	40	15	20%
Liposomes	90	150	-10	80	50	70%



This table offers an overall assessment of nanoparticle performance across several metrics, including encapsulation efficiency, particle size, zeta potential, drug release, retention, and bioavailability improvement. Liposomes consistently outperform other nanoparticle types across key metrics, including encapsulation efficiency (90%), drug release (80% at 6 hours), in vivo retention (50% at 12 hours), and bioavailability improvement (70%). This makes liposomes highly versatile for both acute and chronic ocular conditions that require rapid and sustained drug release. Chitosan nanoparticles also perform well, with an encapsulation efficiency of 80% and in vivo retention of 40%, making them suitable for applications that require prolonged drug presence on the ocular surface. Their bioadhesive properties enhance drug retention, but their slower release profile makes them better suited for long-term therapy. Solid lipid nanoparticles, with lower encapsulation efficiency (60%) and bioavailability improvement (20%), may be useful in specialized sustained-release formulations, but they require further optimization to match the efficacy of liposomes and chitosan nanoparticles.

5. Stability, Surface Area, and Mucoadhesion Properties

This table evaluates the stability, surface area, and mucoadhesive strength of the nanoparticles, which are essential for ensuring the effectiveness and longevity of ocular drug formulations. Stability impacts the shelf life of the product, while surface area and mucoadhesive strength affect the drug's interaction with the eye surface.

Table 5: Stability, Surface Area, and Mucoadhesion Properties

Nanoparticle Type	Stability (Days)	Surface Area (m^2/g)	Mucoadhesive Strength (Relative Units)	Scalability Potential
Chitosan Nanoparticles	30	45	High	Moderate
Solid Lipid Nanoparticles	45	40	Low	High
Liposomes	28	50	Moderate	Moderate

This table assesses the stability, surface area, and mucoadhesive properties of the nanoparticles, all of which are crucial for their effectiveness in ocular drug delivery. Solid lipid nanoparticles exhibit the highest stability, with a shelf life of 45 days, making them well-suited for formulations requiring extended shelf life. Liposomes and chitosan nanoparticles, while slightly less stable (28 and 30 days,

respectively), are still within acceptable ranges for pharmaceutical applications. In terms of surface area, liposomes offer the largest surface area (50 m^2/g), which enhances their drug interaction with ocular tissues and improves bioavailability. Chitosan nanoparticles follow closely with 45 m^2/g, making them effective for drug interaction and delivery. Solid lipid nanoparticles, with a slightly lower surface area (40 m^2/g), may have reduced efficiency in drug interaction. Chitosan nanoparticles exhibit the strongest mucoadhesive properties, making them ideal for treatments requiring prolonged contact with ocular surfaces, while liposomes demonstrate moderate mucoadhesion. Solid lipid nanoparticles, with the lowest mucoadhesive strength, are less likely to retain on the ocular surface for extended durations. Solid lipid nanoparticles also have the highest scalability potential due to their simpler formulation processes, while both chitosan nanoparticles and liposomes, requiring more complex manufacturing techniques, have moderate scalability.

6. Comparative Cost-Effectiveness and Ease of Formulation

This section provides a comparison of the cost-effectiveness, formulation complexity, and patient comfort associated with each nanoparticle type. These factors are critical in practical, clinical applications, as they influence both the feasibility of manufacturing and the overall patient experience.

Table 6: Comparative Cost-Effectiveness and Ease of Formulation

Nanoparticle Type	Cost-Effectiveness (Relative Units)	Formulation Complexity (Scale 1-10)	Drug Compatibility Range	Patient Tolerance and Comfort
Chitosan Nanoparticles	Moderate	7	Wide	High
Solid Lipid Nanoparticles	High	5	Moderate	Moderate
Liposomes	Low	8	Very Wide	High

This table evaluates the cost-effectiveness, formulation complexity, and patient tolerance for each nanoparticle type. Solid lipid nanoparticles offer the best cost-effectiveness due to their simpler production processes and longer shelf life. Liposomes, on the other hand, are more expensive due to their complex formulation and the need for additional stabilizers, while chitosan nanoparticles fall somewhere in the middle. In terms of formulation complexity, liposomes (rated 8/10) and chitosan nanoparticles (7/10) are more difficult to formulate due to their specific conditions and expertise requirements. Solid lipid nanoparticles, with a score of 5/10, are easier to formulate and scale, making them cost-effective for large-scale production. Liposomes have the broadest drug compatibility, making them suitable for delivering both hydrophilic and hydrophobic drugs. Chitosan nanoparticles also show a wide range of drug compatibility, especially for hydrophilic drugs, while solid lipid nanoparticles have moderate compatibility, mainly for hydrophobic drugs. Patient tolerance and comfort are highest with liposomes and chitosan nanoparticles due to their small particle size and biocompatibility, ensuring comfort during ocular administration. Solid lipid nanoparticles, while generally comfortable, may have lower tolerance depending on the specific formulation used.

5. Discussion

The results of this research reveal that drug delivery systems utilising nanoparticles present considerable benefits compared to traditional approaches, like eye drops, particularly regarding drug encapsulation, bioavailability, and retention capabilities. Chitosan nanoparticles demonstrated remarkable efficacy attributed to their mucoadhesive characteristics, facilitating extended adherence on the ocular surface. Their favourable positive surface charge (+35 mV) amplifies the interaction with the negatively charged mucosal layer of the eye, resulting in improved drug retention and prolonged release (Chen, 2015). Chitosan nanoparticles demonstrate remarkable efficacy in addressing persistent ocular ailments such as glaucoma or dry eye, where prolonged drug release is essential. Although chitosan nanoparticles

exhibit a more gradual drug release pattern in comparison to liposomes, they offer a reliable and prolonged delivery mechanism suitable for extended therapeutic uses (Mandal et al., 2018).

When evaluated, liposomal formulations demonstrated the greatest encapsulation efficiency and bioavailability. Liposomes, characterised by their diminutive particle dimensions (150 nm) and a negative zeta potential (-10 mV), exhibited enhanced infiltration of ocular tissues, rendering them exceptionally appropriate for the delivery of both hydrophilic and hydrophobic pharmaceuticals. This trait facilitates swift therapeutic effects, proving especially advantageous for urgent eye ailments such as infections that necessitate prompt medicinal intervention (Thakur Singh et al., 2017). The elevated bioavailability (70%) and exceptional in vivo retention demonstrated in this research underscore the promising capabilities of liposomes in enhancing ocular drug delivery mechanisms (Alonso & Sánchez, 2003). Nonetheless, the intricate nature of liposomal formulation along with the related manufacturing expenses could hinder their extensive adoption, particularly in environments with limited resources (Jünemann et al., 2016).

Although solid lipid nanoparticles (SLNs) hold great potential regarding stability and affordability, they did not perform as well as chitosan and liposomes. Boasting an encapsulation efficiency of 60% and a neutral surface charge, solid lipid nanoparticles (SLNs) demonstrated diminished effectiveness in drug retention on the ocular surface, resulting in reduced bioavailability and retention (Cooper & Yang, 2019). Nonetheless, SLNs may prove advantageous in particular situations that necessitate prolonged drug release without the necessity for regular administration, owing to their extended stability duration of 45 days. Nonetheless, additional refinement of SLNs is essential to improve their engagement with ocular tissues and boost their therapeutic effectiveness, especially in scenarios where an extended duration of drug presence is crucial (Montoto et al., 2020).

The possibilities of microneedles as a less intrusive method for administering treatments to the back part of the eye were also investigated. Although this method exhibits potential, particularly in addressing conditions such as diabetic retinopathy and macular degeneration, there are obstacles concerning patient adherence and possible eye irritation that necessitate additional exploration (Thakur Singh et al., 2017). The integration of microneedles alongside nanoparticles, including chitosan or liposomes, has the potential to offer a more precise and effective method for administering medications to the posterior segment of the eye, addressing challenges such as swift clearance and inadequate drug penetration (Kirchhof et al., 2015).

The research validates that delivery systems utilising nanoparticles, especially chitosan nanoparticles and liposomes, possess significant promise for enhancing the effectiveness of ocular drug administration. These systems offer enhanced drug retention, improved encapsulation efficiency, and greater bioavailability in comparison to traditional methods. The adhesive characteristics of chitosan combined with the compatibility of liposomes render them exceptionally adaptable and appropriate for addressing a diverse array of eye disorders, spanning from long-term ailments necessitating prolonged release to sudden infections demanding swift therapeutic intervention (Chen, 2015; Mandal et al., 2018). Although the outcomes appear encouraging, numerous obstacles concerning scalability, adherence from patients, and the intricacies of formulation persist that must be tackled prior to the broad implementation of these systems in clinical environments (Alonso & Sánchez, 2003).

6. Conclusion

Delivery systems utilising nanoparticles present an innovative solution to enhance ocular drug administration by tackling the difficulties linked with conventional techniques such as eye drops. Chitosan nanoparticles, characterised by their ability to adhere to mucosal surfaces, demonstrate significant potential in improving drug retention on the eye's surface and facilitating prolonged release, rendering them ideal for the management of long-term ailments. In contrast, liposomes demonstrate remarkable proficiency in encapsulating substances, enhancing drug absorption, and delivering swift therapeutic effects, rendering them exceptionally suitable for the treatment of both acute and chronic

eye disorders. Robust lipid nanoparticles provide reliability and economic advantages; however, they necessitate additional refinement to achieve the same level of effectiveness in drug retention and bioavailability as chitosan and liposomes. Although microneedle technology presents a promising approach for delivering treatments to the posterior segment,

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