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SOLID LIPID NANOPARTICLES: AN EMERGING PLATFORM FOR TARGETED DRUG DELIVERY AND BIOMEDICAL APPLICATIONS – A COMPREHENSIVE REVIEW

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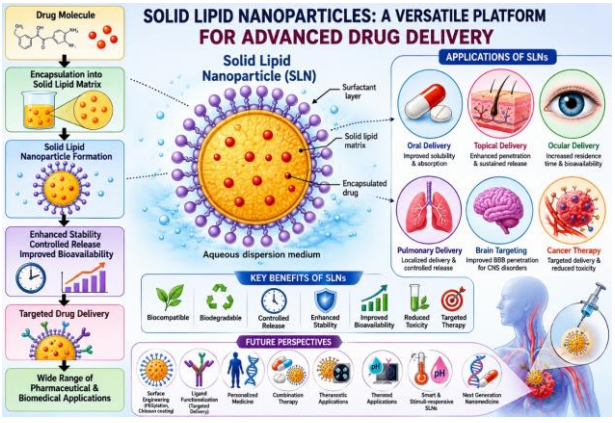
ABSTRACT

Solid Lipid Nanoparticles (SLNs) have emerged as a promising class of lipid-based nanocarriers for improving the delivery of therapeutic agents. Conventional drug delivery systems frequently encounter challenges such as poor aqueous solubility, low bioavailability, rapid degradation, and lack of site-specific targeting, which can compromise therapeutic efficacy. SLNs were developed to address these limitations by combining the advantages of traditional colloidal carriers with the safety and biocompatibility of physiological lipids. These nanoparticles are composed of solid lipids stabilized by surfactants and remain solid at both room and physiological temperatures, enabling efficient drug encapsulation and controlled release. The unique structural characteristics of SLNs facilitate enhanced drug stability, protection from chemical and enzymatic degradation, improved pharmacokinetic behavior, and reduced systemic toxicity. Various preparation methods, including high-pressure homogenization, microemulsion techniques, solvent emulsification, and ultrasonication, have been successfully employed to produce SLNs with desirable physicochemical properties. Comprehensive characterization using particle size analysis, zeta potential measurement, electron microscopy, differential scanning calorimetry, and X-ray diffraction is essential for ensuring formulation quality and stability. Owing to their versatility, SLNs have been extensively investigated for oral, topical, transdermal, ocular, pulmonary, parenteral, and brain-targeted drug delivery. Furthermore, they have demonstrated considerable potential in cancer therapy and the delivery of natural bioactive compounds. Despite certain limitations, including restricted drug-loading capacity and polymorphic transitions during storage, continuous advancements in formulation strategies and surface engineering have significantly expanded their therapeutic applications. This review summarizes the composition, preparation methods, characterization techniques, drug incorporation models, applications, advantages, limitations, and future prospects of SLNs, highlighting their growing importance in modern pharmaceutical and biomedical research.

KEYWORDS: Solid lipid nanoparticles, lipid-based nanocarriers, controlled drug delivery, bioavailability enhancement, targeted drug delivery, nanotechnology, pharmaceutical applications.

Graphical Abstract



1. INTRODUCTION

The successful treatment of diseases often depends not only on the pharmacological activity of a therapeutic agent but also on its ability to reach the desired site of action in adequate concentrations. Conventional dosage forms frequently suffer from poor aqueous solubility, rapid degradation, limited permeability, low bioavailability, and undesirable side effects, which collectively compromise therapeutic outcomes.[10] Consequently, significant research efforts have been directed toward the development of advanced drug delivery systems capable of overcoming these challenges and improving patient compliance.

Nanotechnology has revolutionized pharmaceutical research by enabling the design of nanoscale carriers that can alter the pharmacokinetic and pharmacodynamic behavior of therapeutic molecules.[11] Among the numerous nanocarrier systems investigated, including liposomes, polymeric nanoparticles, dendrimers, nanocapsules, nanoemulsions, and nanostructured lipid carriers, lipid-based nanoparticles have attracted particular interest due to their superior safety profile and physiological compatibility.[12]

Solid Lipid Nanoparticles (SLNs) were first introduced in the early 1990s as an alternative to conventional colloidal carriers such as liposomes and polymeric nanoparticles.[13] The concept was pioneered by Müller and Lucks, who envisioned a lipid-based carrier system combining the advantages of polymeric nanoparticles while eliminating concerns related to polymer toxicity and organic solvent residues.[14] Since then, SLNs have evolved into a versatile platform for the delivery of a wide range of therapeutic molecules.

SLNs are generally composed of solid lipids dispersed in an aqueous medium and stabilized by surfactants. The lipid matrix remains solid at physiological temperatures, allowing sustained drug release and enhanced protection of encapsulated compounds.[15] Commonly used lipids include glyceryl monostearate, stearic acid, glyceryl behenate, tristearin, cetyl palmitate, and various waxes, whereas surfactants such as polysorbates, lecithin, poloxamers, and bile salts contribute to nanoparticle stabilization.[16]

One of the major advantages of SLNs is their ability to improve the bioavailability of poorly water-soluble drugs. According to the Biopharmaceutics Classification System (BCS), a substantial proportion of newly discovered drug candidates exhibit poor aqueous solubility, which significantly limits their therapeutic effectiveness.[17] Encapsulation within SLNs enhances drug dissolution, protects the active ingredient from degradation, and facilitates absorption across biological membranes.[18]

In addition to oral administration, SLNs have demonstrated remarkable potential in parenteral, topical, transdermal, pulmonary, ocular, and intranasal drug delivery applications.[19] Their nanoscale dimensions facilitate close interaction with biological membranes, promoting improved cellular uptake and targeted delivery.[20] Furthermore, the use of physiological lipids minimizes the risk of chronic toxicity and immunogenic reactions, making SLNs particularly attractive for long-term therapeutic applications.[21]

The versatility of SLNs extends beyond conventional pharmaceuticals. Recent investigations have explored their utility in the delivery of proteins, peptides, nucleic acids, vaccines, and natural bioactive compounds such as curcumin, resveratrol, quercetin, and essential oils.[22] The emergence of personalized medicine and precision therapeutics has further stimulated interest in SLNs as customizable delivery vehicles capable of enhancing therapeutic specificity and reducing off-target effects.[23]

Despite numerous advantages, SLNs are not devoid of limitations. Challenges such as limited drug loading capacity, polymorphic transitions during storage, potential drug expulsion, and difficulties in large-scale manufacturing continue to impede their widespread commercialization.[24] Nevertheless, ongoing advances in formulation strategies, analytical techniques, and manufacturing technologies are expected to address these concerns and expand the clinical utility of SLN-based systems.[25]

Given the growing scientific and industrial interest in lipid-based nanocarriers, a comprehensive understanding of SLNs is essential for researchers, formulation scientists, and healthcare professionals. Therefore, this review critically examines the current state of knowledge regarding SLNs, emphasizing their formulation principles, preparation methods, characterization techniques, therapeutic applications, challenges, and future opportunities in drug delivery and biomedical research.

2. Composition and Structural Organization of Solid Lipid Nanoparticles

The therapeutic performance of Solid Lipid Nanoparticles (SLNs) is strongly influenced by their composition and internal structural arrangement. The selection of suitable lipids, surfactants, and stabilizing agents determines important formulation characteristics such as particle size, encapsulation efficiency, stability, drug release behavior, and biological performance.[26] Unlike conventional emulsions, SLNs contain a lipid matrix that remains solid at both room and physiological temperatures, enabling efficient drug entrapment and controlled release. The solid nature of the lipid core also provides protection against chemical and enzymatic degradation, thereby improving the stability of encapsulated therapeutic agents.[27]

2.1 Components of Solid Lipid Nanoparticles

SLNs are primarily composed of solid lipids, surfactants, and an aqueous dispersion medium. The lipid component forms the structural backbone of the nanoparticle and acts as a reservoir for drug incorporation. Commonly used solid lipids include stearic acid, palmitic acid, glyceryl monostearate, glyceryl behenate, tripalmitin, tristearin, cetyl palmitate, and various natural waxes.[28] These lipids are generally recognized as safe (GRAS) and exhibit excellent biocompatibility, making them suitable for pharmaceutical applications. The type of lipid selected significantly influences crystallinity, drug loading capacity, and release kinetics. Drugs exhibiting higher solubility in the lipid phase generally demonstrate better encapsulation efficiency and prolonged release profiles.[29]

Surfactants play an equally important role in maintaining nanoparticle stability. They reduce interfacial tension between the lipid and aqueous phases during formulation and prevent particle aggregation during storage. Non-ionic surfactants such as Poloxamer 188, Poloxamer 407, Tween 80, and Tween 20 are frequently employed because of their low toxicity and compatibility with biological systems.[30] Phospholipids including lecithin and phosphatidylcholine are also commonly used as stabilizers due to their ability to improve membrane interaction and enhance nanoparticle stability. In some formulations, co-surfactants such as polyethylene glycol, ethanol, or propylene glycol are incorporated to improve emulsification efficiency and reduce particle size.[31]

Table 1: Common Lipids Used in Solid Lipid Nanoparticles.

Lipid Type	Examples	Major Function
Fatty Acids	Stearic acid, Palmitic acid, Behenic acid	Drug encapsulation and matrix formation
Triglycerides	Tristearin, Tripalmitin, Trimyristin	Sustained drug release
Glycerides	Glyceryl monostearate, Glyceryl behenate, Precirol® ATO 5	Improved drug loading and stability
Waxes	Cetyl palmitate, Beeswax, Carnauba wax	Structural rigidity and prolonged release
Mixed Lipids	Compritol® 888 ATO, Softisan® 154	Enhanced encapsulation efficiency

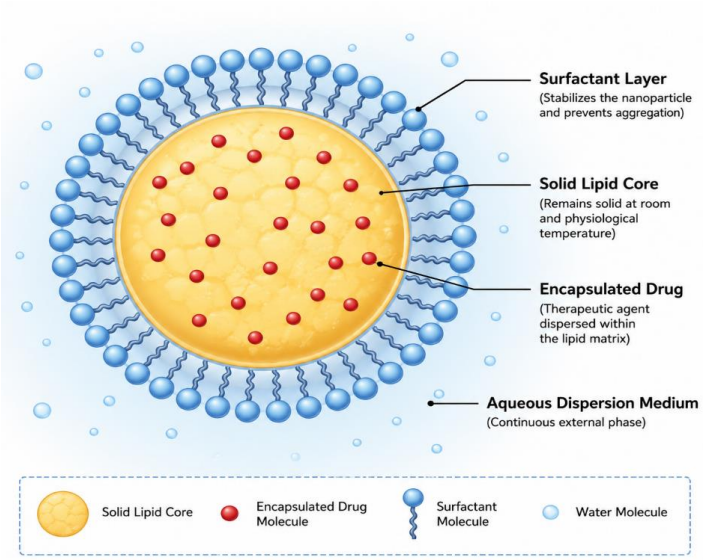


Figure 1: Schematic representation of the structural organization of Solid Lipid Nanoparticles showing the solid lipid core, encapsulated drug, surfactant layer, and aqueous dispersion medium.

2.2 Structural Organization of SLNs

Structurally, SLNs consist of a solid lipid core surrounded by a layer of surfactant molecules dispersed in an aqueous medium. The lipid matrix serves as a carrier for drug molecules, while the surfactant coating stabilizes the nanoparticles and minimizes aggregation. The internal distribution of the drug within the lipid matrix depends on several formulation variables, including drug solubility, lipid composition, manufacturing technique, cooling rate, and storage conditions.[32] These factors ultimately influence encapsulation efficiency and drug release behavior.

The crystalline properties of the lipid matrix are particularly important in determining the stability of SLNs. During nanoparticle formation, lipids may crystallize into different polymorphic forms, namely α, β′, and β structures. The α-form is less ordered and can accommodate larger amounts of drug, whereas the β-form represents the most stable and highly ordered crystalline arrangement.[33] Although transformation into the β-form improves thermodynamic stability, it may reduce the space available for drug molecules and lead to drug expulsion during storage. Consequently, controlling

lipid crystallization remains a critical aspect of SLN formulation development.

3. Types of Solid Lipid Nanoparticles

Based on composition and structural characteristics, SLNs can be classified into several categories. Conventional SLNs represent the first generation of lipid nanoparticles and consist solely of solid lipids dispersed in an aqueous surfactant solution.[34] These systems offer several advantages, including biocompatibility, protection of labile drugs, and controlled release properties. However, their highly ordered crystalline structure often limits drug loading and may contribute to drug leakage during storage.

To overcome these limitations, modified and surface-engineered SLNs have been developed. Surface modification strategies involve coating nanoparticles with polymers or functional molecules to improve stability, circulation time, and targeting efficiency. Polyethylene glycol (PEG) coating, commonly referred to as PEGylation, has been widely investigated because it reduces recognition by the reticuloendothelial system and prolongs systemic circulation.[35] Similarly, ligand-conjugated SLNs containing antibodies, peptides, folic acid, or aptamers facilitate active targeting of specific tissues and tumor cells. Chitosan-coated SLNs have also attracted attention due to their enhanced mucoadhesive properties and improved absorption across biological membranes.[36]

An important advancement derived from SLN technology is the development of Nanostructured Lipid Carriers (NLCs). Although NLCs are considered a second-generation lipid nanoparticle system rather than true SLNs, they were specifically designed to address the limitations associated with conventional SLNs.[37] NLCs contain a combination of solid and liquid lipids, creating an imperfect crystalline matrix that accommodates larger quantities of drug molecules. As a result, NLCs generally exhibit higher drug loading capacity, improved stability, reduced drug expulsion, and enhanced therapeutic performance compared with conventional SLNs.[38]

4. Drug Incorporation Models in Solid Lipid Nanoparticles

The manner in which a drug is incorporated within the lipid matrix significantly influences the physicochemical properties and therapeutic performance of SLNs. Based on the distribution pattern of drug molecules, three major drug incorporation models have been proposed: the homogeneous matrix model, the drug-enriched shell model, and the drug-enriched core model.[39]

In the homogeneous matrix model, drug molecules are uniformly distributed throughout the solid lipid matrix. This arrangement is typically obtained when both the lipid and drug solidify simultaneously during nanoparticle formation. The homogeneous distribution of drug molecules generally results in sustained release behavior and improved formulation stability.[40] Such systems are particularly useful when prolonged therapeutic action is desired.

The drug-enriched shell model develops when lipid crystallization occurs before drug precipitation during the cooling process. As a consequence, drug molecules become concentrated near the outer surface of the nanoparticles.[41] This arrangement often leads to an initial burst release because a significant proportion of the drug is located close to the particle surface. Although burst release may be undesirable in some controlled-release formulations, it can be advantageous when rapid therapeutic action is required.

Conversely, the drug-enriched core model is formed when drug precipitation occurs before lipid crystallization. In this case, a drug-rich core is surrounded by a lipid shell that acts as a diffusion barrier.[42] This structure generally reduces burst release and promotes sustained drug delivery over extended periods. Furthermore, the lipid shell provides additional protection against environmental degradation, making this model suitable for sensitive therapeutic agents.

Understanding these incorporation models is essential for the rational design of SLN formulations because drug localization directly affects encapsulation efficiency, release kinetics, and long-term stability. By carefully selecting formulation components and processing conditions, researchers can tailor SLNs to achieve desired therapeutic outcomes for a wide range of pharmaceutical applications.[43]

5. Preparation Methods of Solid Lipid Nanoparticles

The method employed for the preparation of Solid Lipid Nanoparticles (SLNs) plays a crucial role in determining particle size, drug loading efficiency, stability, and release characteristics. Over the past few decades, several techniques have been developed to produce SLNs with desired physicochemical properties. The choice of preparation method largely depends on the nature of the drug, lipid composition, scalability requirements, and intended route of administration.[44]

5.1 High-Pressure Homogenization

High-pressure homogenization (HPH) is the most widely used and commercially viable technique for the production of SLNs. In this method, a lipid phase containing the drug is dispersed in an aqueous surfactant solution and subjected to high pressure, resulting in the formation of nanoparticles through intense shear stress and cavitation forces.[45] HPH can be performed using either hot or cold homogenization approaches.

In hot homogenization, the drug-loaded lipid is melted above its melting point and emulsified in a heated aqueous surfactant solution. The resulting pre-emulsion is then homogenized under high pressure and cooled to form solid nanoparticles.[46] This method is particularly

suitable for lipophilic drugs but may not be ideal for thermolabile compounds.

Cold homogenization was developed to overcome the limitations associated with heat-sensitive drugs. In this approach, the drug-containing lipid melt is rapidly cooled, solidified, and milled into microparticles before homogenization at low temperatures. This technique minimizes drug degradation and reduces drug partitioning into the aqueous phase.[47]

5.2 Microemulsion Technique

The microemulsion method involves the preparation of a warm microemulsion composed of molten lipid, surfactant, co-surfactant, and water. Upon dispersion into cold water under continuous stirring, the lipid phase solidifies and forms nanoparticles.[48] This technique is relatively simple and reproducible; however, it often requires high concentrations of surfactants, which may limit its applicability in certain pharmaceutical formulations.

5.3 Solvent Emulsification-Evaporation Method

In this method, the lipid is dissolved in an organic solvent and emulsified into an aqueous phase containing surfactants. Subsequent evaporation of the solvent results in lipid precipitation and nanoparticle formation.[49] The technique is particularly useful for heat-sensitive compounds because it avoids exposure to elevated temperatures. Nevertheless, the use of organic solvents raises concerns regarding residual solvent toxicity and environmental safety.

5.4 Ultrasonication and High-Shear Homogenization

Ultrasonication utilizes ultrasonic energy to break down larger droplets into nanosized particles. Similarly, high-shear homogenization employs mechanical forces to reduce particle size and create stable dispersions.[50] These methods are relatively simple and cost-effective but may produce particles with broader size distributions compared with high-pressure homogenization.

5.5 Solvent Injection Method

The solvent injection technique involves dissolving lipid and drug in a water-miscible organic solvent followed by rapid injection into an aqueous surfactant solution. The rapid diffusion of solvent into the aqueous phase leads to lipid precipitation and nanoparticle formation.[51] This method is easy to perform and suitable for laboratory-scale production, although solvent removal remains a critical step.

Overall, high-pressure homogenization remains the most extensively utilized technique due to its scalability, reproducibility, and regulatory acceptance. However, the selection of an appropriate preparation method should be guided by the physicochemical characteristics of the drug and the intended therapeutic application.[52]

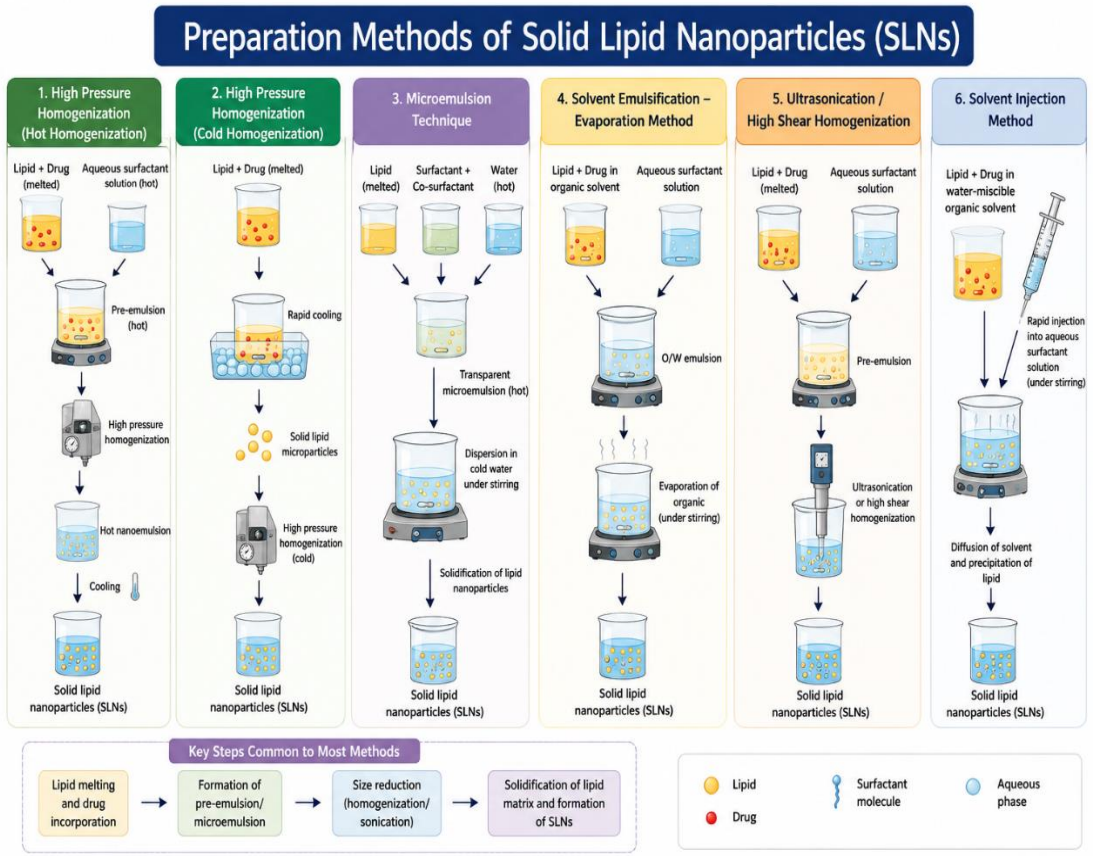


Figure 2: Various preparation methods employed for the fabrication of Solid Lipid Nanoparticles.

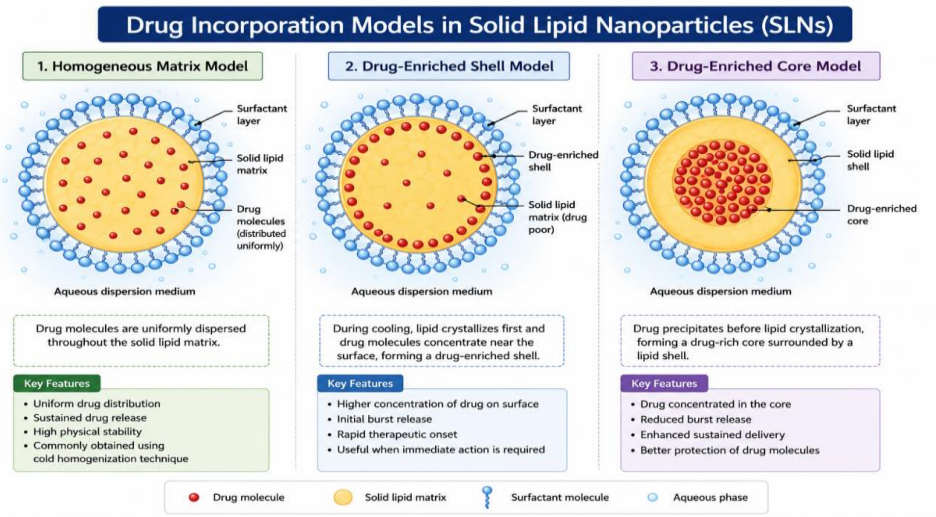


Figure 3: Drug incorporation models in SLNs: homogeneous matrix model, drug-enriched shell model, and drug-enriched core model.

Table 2: Preparation Methods of Solid Lipid Nanoparticles

Method	Principle	Advantages	Limitations
Hot Homogenization	Homogenization of molten lipid phase	Suitable for lipophilic drugs	Not ideal for thermolabile drugs
Cold Homogenization	Homogenization of solidified lipid	Reduced thermal degradation	Larger particle size
Microemulsion Technique	Dilution of warm microemulsion	Simple and reproducible	High surfactant requirement
Solvent Evaporation	Removal of organic solvent from emulsion	Suitable for heat-sensitive drugs	Residual solvent concerns
Ultrasonication	Application of ultrasonic energy	Cost-effective	Broad particle size distribution
Solvent Injection	Rapid precipitation of lipid phase	Simple laboratory-scale method	Solvent removal required

6. Characterization of Solid Lipid Nanoparticles

Comprehensive characterization of SLNs is essential for understanding their physicochemical properties and ensuring formulation quality. Various analytical techniques are employed to evaluate particle size, morphology, surface charge, crystallinity, drug loading, and release behaviour.[53]

Particle size and size distribution are among the most critical parameters because they influence stability, biodistribution, and cellular uptake. Dynamic Light Scattering (DLS) is commonly used to determine average particle size and polydispersity index (PDI). Generally, SLNs with particle sizes below 300 nm and low PDI values are considered suitable for pharmaceutical applications.[54]

Zeta potential measurement provides information regarding surface charge and colloidal stability. Nanoparticles with higher absolute zeta potential values exhibit stronger electrostatic repulsion and are less likely to aggregate during storage.[55]

Morphological characteristics are typically examined using Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), and Atomic Force Microscopy (AFM). These techniques provide valuable information regarding particle shape, surface texture, and structural integrity.[56]

Differential Scanning Calorimetry (DSC) and X-ray Diffraction (XRD) are frequently employed to evaluate lipid crystallinity and polymorphic transitions. These analyses help identify changes in the internal structure of the lipid matrix that may affect drug loading and release properties.[57]

Drug entrapment efficiency and drug loading capacity are important indicators of formulation performance. These parameters are generally determined using centrifugation, ultrafiltration, or chromatographic techniques such as HPLC.[58] In vitro drug release studies are subsequently conducted to assess release kinetics and predict in vivo behavior.

Collectively, these characterization techniques provide essential information required for the optimization, quality control, and successful development of SLN-based drug delivery systems.[59]

Table 3. Characterization Techniques of SLNs.

Parameter	Technique	Information Obtained
Particle Size	Dynamic Light Scattering	Average particle size and distribution
Surface Charge	Zeta Potential Analysis	Stability and aggregation tendency
Morphology	SEM, TEM, AFM	Shape and surface characteristics
Crystallinity	XRD	Crystal structure and polymorphism
Thermal Behavior	DSC	Lipid transitions and drug incorporation
Drug Content	HPLC/UV Spectroscopy	Drug loading and encapsulation efficiency
Drug Release	In vitro release studies	Release kinetics and mechanism

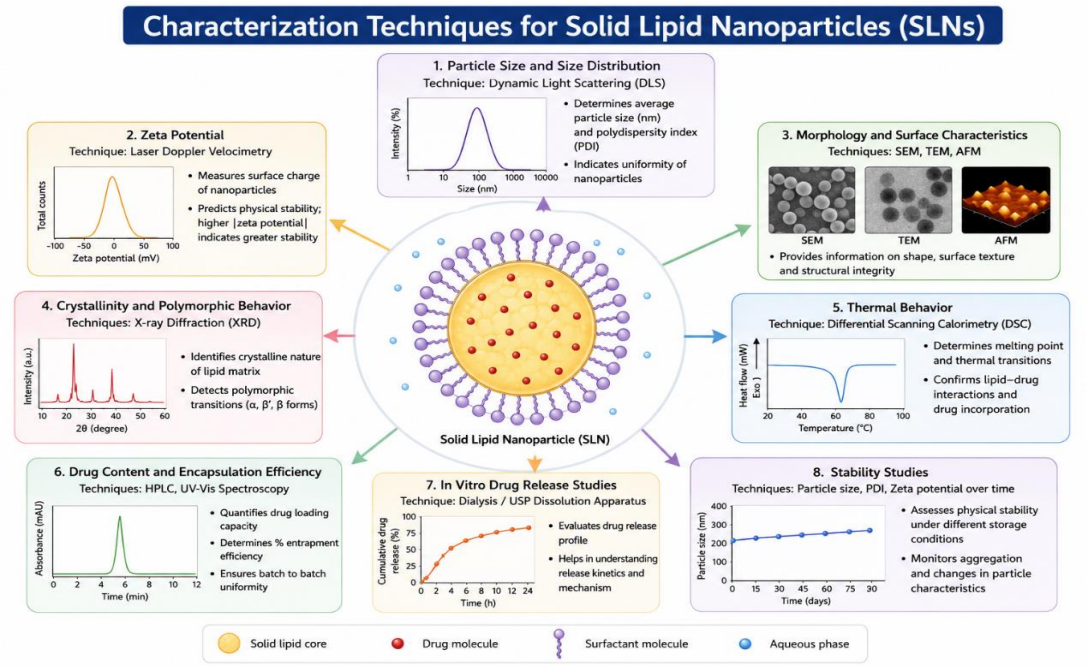


Figure 4: Characterization techniques used for evaluating physicochemical properties of Solid Lipid Nanoparticles.

7. Pharmaceutical and Biomedical Applications of Solid Lipid Nanoparticles

The unique properties of SLNs have led to their widespread investigation in numerous pharmaceutical and biomedical applications. Their ability to enhance drug stability, improve bioavailability, and provide controlled release has made them attractive carriers for various therapeutic agents.[60]

7.1 Oral Drug Delivery

One of the most extensively explored applications of SLNs is oral drug delivery. Many newly developed drug molecules exhibit poor aqueous solubility, resulting in limited oral bioavailability. Encapsulation within SLNs improves drug dissolution, protects against gastrointestinal degradation, and enhances intestinal absorption.[61] Several studies have demonstrated improved bioavailability of poorly soluble drugs such as curcumin, quercetin, and various anticancer agents following incorporation into SLNs.

7.2 Parenteral Drug Delivery

SLNs have shown considerable potential for intravenous administration due to their nanoscale size and biocompatible composition. These systems can prolong circulation time, improve drug distribution, and reduce systemic toxicity.[62] SLNs have been investigated for the delivery of anticancer drugs, antifungal agents, and anti-inflammatory compounds, offering enhanced therapeutic efficacy while minimizing adverse effects.

7.3 Topical and Transdermal Drug Delivery

Topical SLN formulations have gained significant attention in dermatological and cosmetic applications. The lipid matrix forms an occlusive film on the skin surface, increasing hydration and facilitating drug penetration through the stratum corneum.[63] SLNs have been successfully utilized for the delivery of corticosteroids, antifungal agents, anti-acne drugs, and antioxidant compounds. Their ability to provide sustained release further improves therapeutic outcomes.

7.4 Ocular Drug Delivery

Conventional ophthalmic formulations often suffer from poor retention time and limited bioavailability. SLNs enhance ocular residence time and facilitate sustained drug release, thereby improving therapeutic effectiveness.[64] Several investigations have reported improved delivery of anti-inflammatory and antimicrobial agents using SLN-based ocular formulations.

7.5 Pulmonary Drug Delivery

The lungs provide a large absorptive surface area and extensive vascularization, making pulmonary administration an attractive route for both local and systemic drug delivery. SLNs have been explored for inhalation therapy because of their ability to protect encapsulated drugs and provide controlled release within the respiratory tract.[65]

7.6 Brain Targeting and Central Nervous System Delivery

The blood-brain barrier (BBB) represents a major obstacle to the delivery of therapeutic agents to the central nervous system. SLNs have demonstrated promising potential for brain targeting due to their small particle size and ability to interact with biological membranes.[66] Surface-modified SLNs have been investigated for the treatment of neurodegenerative disorders such as Alzheimer's disease, Parkinson's disease, and epilepsy.

7.7 Cancer Therapy

Cancer treatment remains one of the most important applications of SLN technology. Encapsulation of anticancer drugs within SLNs can enhance drug accumulation at tumor sites, improve therapeutic efficacy, and reduce systemic toxicity.[67] Furthermore, ligand-functionalized SLNs enable active targeting of tumor cells, thereby improving treatment selectivity and minimizing damage to healthy tissues.

7.8 Delivery of Natural Bioactive Compounds

Many natural compounds possess significant therapeutic potential but suffer from poor solubility and stability. SLNs have been successfully employed to improve the delivery of curcumin, resveratrol, rutin, quercetin, and other phytoconstituents.[68] Enhanced bioavailability and prolonged circulation contribute to improved pharmacological activity.

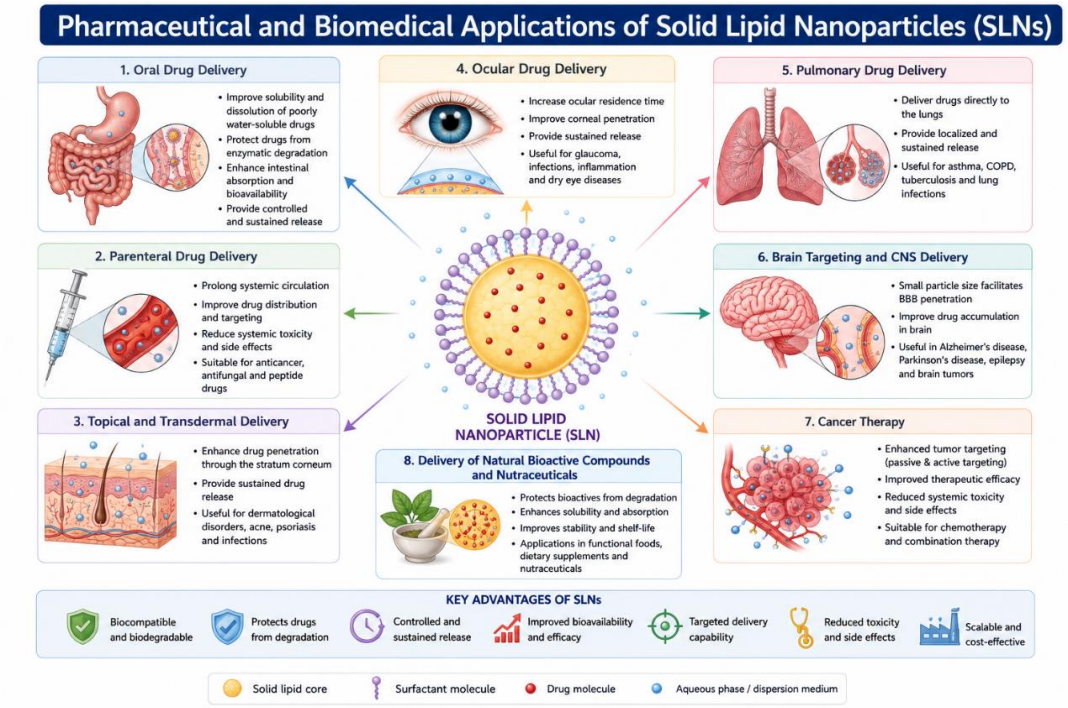


Figure 5: Pharmaceutical and biomedical applications of Solid Lipid Nanoparticles in different routes of administration.

8. Advantages and Limitations of Solid Lipid Nanoparticles

SLNs offer several advantages over conventional drug delivery systems. Their composition utilizes physiological lipids that are generally safe and biodegradable, reducing the risk of toxicity. SLNs provide protection against chemical degradation, enhance bioavailability, enable controlled drug release, and support large-scale manufacturing.[69] Additionally, they are suitable for multiple routes of administration, including oral, topical, parenteral, pulmonary, and ocular delivery.

Despite these advantages, certain limitations remain. The highly ordered crystalline structure of solid lipids may result in limited drug loading capacity and drug expulsion during storage.[70] Polymorphic transitions can further affect stability and release behavior. Moreover, optimization of formulation variables and manufacturing conditions remains challenging, particularly for large-scale industrial production.

Table 4: Pharmaceutical Applications of Solid Lipid Nanoparticles.

Application Area	Benefits
Oral Drug Delivery	Improved bioavailability and gastrointestinal stability
Parenteral Delivery	Reduced toxicity and prolonged circulation
Topical Delivery	Enhanced skin penetration and sustained release
Ocular Delivery	Increased corneal residence time
Pulmonary Delivery	Controlled release in respiratory tract
Brain Targeting	Improved BBB penetration
Cancer Therapy	Enhanced tumor targeting and reduced side effects
Nutraceutical Delivery	Improved stability and absorption of bioactive compounds

9. Future Perspectives

Recent advances in nanotechnology continue to expand the potential of SLNs in modern medicine. Emerging strategies such as surface functionalization, stimuli-responsive systems, ligand-mediated targeting, and combination therapy are expected to improve therapeutic precision and clinical efficacy.[71] The integration of SLNs with gene therapy, immunotherapy, and personalized medicine may further broaden their applications in the coming years.

In addition, continuous improvements in manufacturing technologies and regulatory frameworks are expected to facilitate the translation of SLN-based formulations from laboratory research to commercial products. Future investigations should focus on long-term safety, large-scale production, and clinical validation to fully realize the therapeutic potential of this promising nanocarrier system.[72]

10. CONCLUSION

Solid Lipid Nanoparticles have emerged as one of the most promising lipid-based nanocarrier systems for modern drug delivery. Their unique combination of biocompatibility, biodegradability, controlled release capability, and versatility makes them attractive for a wide range of pharmaceutical and biomedical applications. SLNs have demonstrated considerable success in enhancing drug stability, bioavailability, and therapeutic efficacy while minimizing adverse effects. Although challenges related to drug loading and long-term stability remain, ongoing advances in formulation science and nanotechnology are expected to overcome these limitations. Consequently, SLNs are likely to play an increasingly important role in the development of next-generation drug delivery systems and precision therapeutics.

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