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Review Article

Solid Lipid Nanoparticles as Drug Carriers: Design and Applications of Programmable Nanoparticulate Delivery Systems

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ABSTRACT

(SLNs) or Solid Lipid Nanoparticles: These are very small balls of safe fats that help transport medicines throughout the body. These tiny fat particles can serve to shield the drug, help it work better and last longer in the body. They're formulated with all-natural lipids, and safe helpers called surfactants and co-surfactants help keep them stable so they don't glob together. Various strategies, such as heating, mixing and cooling, are exploited by the scientists to fabricate SLNs in the correct size and shape. The nanoparticles can deliver drugs through the mouth, skin, eyes and nose, in addition to by means of injections into the blood or lungs. They already serve as treatment for many diseases, including cancer, infections and brain disorders. The newer vehicle, such as SLN are far superior than older vehicle in term of being biocompatible and less toxic, cost effective and slow and sustained release of drug. Occasionally, however, drugs can leak or degrade while in storage. These days, scientists are designing smarter SLNs with the help of new concepts such as green technology and artificial intelligence. In the future, those smart SLNs could be used for vaccines and special treatments to help people heal faster and stay healthy.

INTRODUCTION

A new field of 'nanomedicine' has now been born, which attempts to approach medical biology and disease prevention in terms of nanotechnology. It centres on the nanoscopic particles for producing the new drug release systems in which the therapeutically potent drug is encapsulated for specific application and controlled release at the diseased point [1]. Regulating drug release so as not to cause an overdose and delivering the medicine to the correct place in the body is a significant challenge for researchers of modern medicine [2]. Examples of particulate drug carriers are oil-in-water (O/W) emulsion, liposome, nanosponge, and microsphere composed of synthetic polymer or natural macromolecule [3]. They are able to engage hydrophobic and hydrophilic compounds [4].

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Small amounts of liquid lipids are added to the structure of SLN and NLC to cause restructuring in the matrix. As the crystallolic structure of SLN grew with time, by that point, the drug which was incorporated, had already been released into the external media [5]. It is well known due to the extensive use of lipid particles for oral drug delivery [3]. Improvement in the solubility, stability and targeted delivery of APIs, especially in challenging therapeutic areas, has been achieved by advances in nanoparticles usage, either organic or inorganic [6].

Liposomes and their multiple derivatives have been used in liposomal drug delivery systems since the 1960s, and may be considered classic examples. Polymer degradation, fusion and drug leakage, no large-scale technology for production, cytotoxicity and polymer matrix degradation, as well as phospholipid degradation are some of the drawbacks and poor qualities that have been identified with liposomes in the previous reports [7]. In 1991, SLNs were introduced [8]. The terms Solid Lipid

Nanoparticles and Nanostructured lipid carriers were introduced by Muller et al., in 2002 as concept for nano size concepts (but with not nanoparticle) built directly from Bulk state in opposition to other particles like Niosomes, Colloides from emulsion etc. Characteristic of the nanoparticles is that they are safe solid materials disperse a liquid/solid matrix (gases also taken into inclusion), Nanostructured lipid carriers. The topical use of the first-generation nanoparticles, solid lipid nanoparticles (SLN), has been limited by some drawbacks; therefore, a second generation called nanostructured lipid carriers was developed to overcome the disadvantages of SLNs [7].

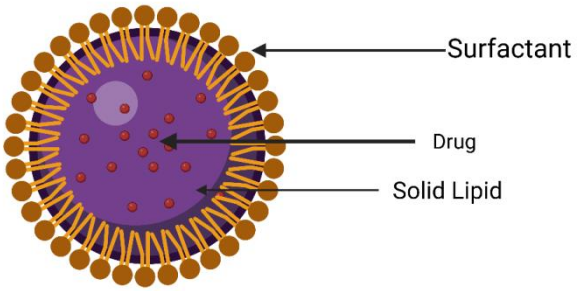

Figure 1: Structure of solid lipid nanoparticle

Advantages:

- Excellent stability.
- Scaling up is possible.
- Fewer toxicities
- Enhanced bioavailability of poorly water-soluble compounds
- Focused medication administration
- Defence on drug entrapment in a sensitive environment [9].

Disadvantages:

- Poor drug loading capacity,
- Expulsion of the drug after polymer transition during storage
- Comparatively high water content of the dispersions [10]
- Increase in particle size
- Lipid dispersion gelation
- Limited transdermal medication delivery [11]

Preparation and Characterization of Solid Lipid Nanoparticles

1. Lipid Selection:

The core lipid(s) of SLNs play a critical role in drug release, dispersion stability and masking efficiency. SLN dispersions originate from biocompatible and biodegradable lipids, such as fatty acids, lipids, and waxes. The utilized lipids are GRAS (generally accepted as Safe), physiologically acceptable and reasonably priced. Common lipids mentioned include: glyceryl monostearate, glyceryl behenate, glyceryl palmitostearate, stearic, behenic, palmitic, and decanoic acid.

2. Surfactant and Cosurfactant:

The lipid type affects the drug loaded, particle size, shape and *in vitro* release rate of SLNs. To ensure consistent formulations suitable for topical delivery, the choice depends on drug-lipid compatibility, melting point and release profile [12].

Surfactants:

Surfactants are employed in the formulation to prevent particle agglomeration and increase the colloidal stability of SLNs. They help in stabilising nanoparticles post-cooling as well as distributing the lipid melt in the aqueous phase. The choice and concentration of surfactants also affects the particle size, stability and drug release. Common surfactants include: Poloxamer 188, Poloxamer 407, Poloxamine 908 and Polysorbate 80.

Co-surfactants:

Co-surfactants help surfactants in advancing the interface stability and modifying SLN crystallization and stability. Due to the presence of hydrophilic and lipophilic moieties, amphiphilic molecules are also capable of contributing to emulsification-promoting effects, thereby stabilizing particles too. Common co-surfactants include: Butanol, glycocholate, tyloxapol, taurocholate sodium salt and taurodeoxycholic acid sodium salt [13].

3. Variables Influencing Solid Lipid Nanoparticles:

3.1. Lipid Type: The choice of lipid affects the drug loading capacity, stability, crystallinity, and particle size of SLNs. The melting temperatures, solubility, and medication compatibility of different lipids may vary.

3.2. Surfactant Nature: The size, zeta potential, and drug release of SLN may all be influenced by the type, concentration, and ratio of surfactant to lipid.

3.3. Preparation Procedures: High-pressure homogenization (HPH), microemulsion, solvent injection, and sonication are some of the methods used to prepare SLNs. Each of these techniques has advantages and disadvantages, and they will all have an impact on the efficiency and physicochemical characteristics of SLNs.

3.4. Process Parameters: The quality and characteristics of SLNs may also be influenced by other process-related factors such as temperature, pressure, speed, time, and solvent type. The lipid, surfactant, and technique used determine the most advantageous process parameters [14].

3.5. Drug-lipid Compatibility: The compatibility of the drug within the lipid matrix also has an impact upon drug encapsulation efficiency and release profile [15].

3.6. Solvent Selection: the solvent(s) used during preparation can affect characteristics of the SLN. The solvents are to be chosen and used judiciously based on lipid compatibility, drug compatibility with the solvent and other components of the formulation [16].

3.7. Antioxidants/Stabilizers: Additions of antioxidants and stabilizers can help improve the stability of SLN by avoiding lipid oxidation and particle aggregation during storage [17].

3.8. Particle Size and Distribution: Particle size management and distribution are crucial for SLN performance. Lipid composition, the ratio of surfactant to lipid, and other variables all affect particle size and dispersion [18].

3.9. Sterilization and Storage Stability: Sterilization method and storage conditions (e.g., temperature, humidity) have an impact on SLN stability and shelf life [19].

3.10. Scale-up Aspects: Sterilization techniques and storage (e.g., temperature and humidity) can influence the SLN stability and shelf life [9].

Preparation Techniques

SLN could be obtained by dispersing hot oil-in-water (o/w) microemulsions in cold water; the internal phase of the microemulsion consists on solid lipids with low melting points [20].

1. High-Pressure Homogenization Method:

An efficient and scalable foundation for the production of parenteral emulsions, lipid drug conjugates, solubilized SLNs, and NLCs is high-pressure homogenization. High-pressure Pressure Homogenization forces lipids through a tiny hole that is just a few microns in size by applying high pressure (100–200 bar). And cavitation and shear force are the mechanical forces that break up particles in submicron size. In contrast with the earlier preparation procedures, High-Pressure Homogenisation does not display any scaling-up problem [21].

a. Hot Homogenization Technique:

The lipid phase is heated to 90°C, and the surfactant-containing aqueous phase dissolves it at the same temperature. Three high-pressure homogenizing stages, each round a5 × 107 Pa, are used to homogenize the pre-emulsion at 90°C. SLNs in a solid form are then obtained by cooling the oil-in-water emulsion to room temperature [22].

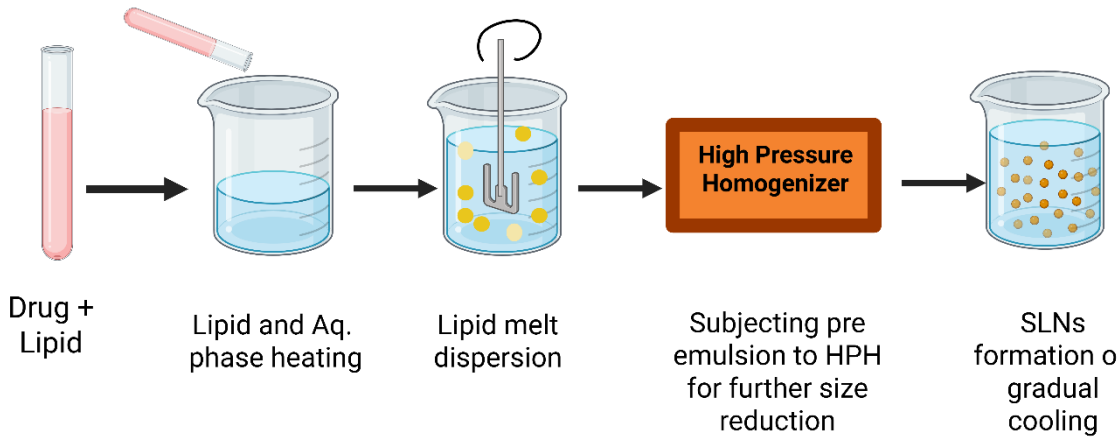

Figure 2: Hot Homogenization Technique

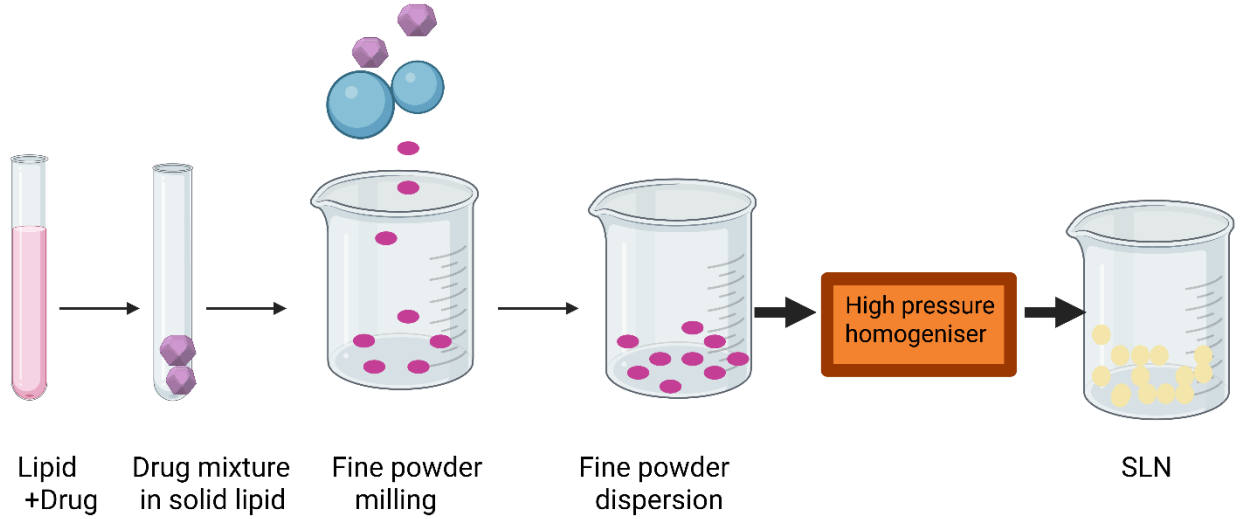

Figure 3: Cold Homogenization Technique

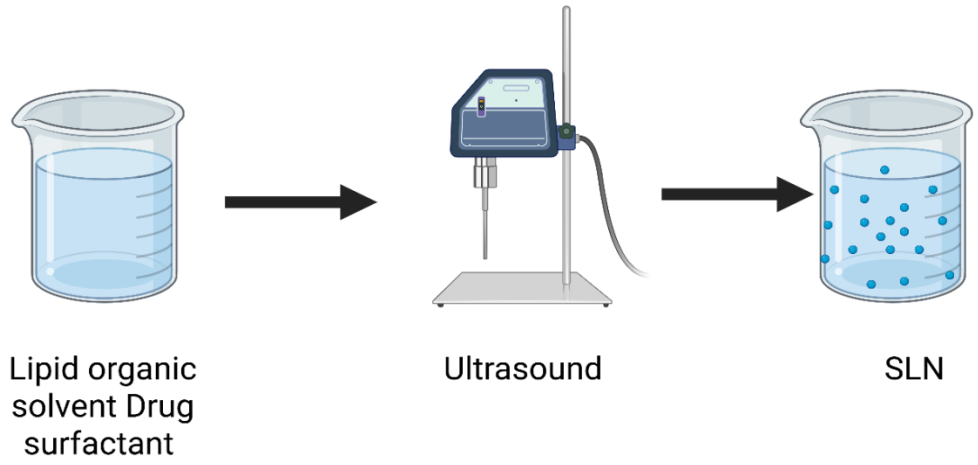

Figure 4: Ultrasonication Method

Organic solvent avoidance, simple scaling up, quick processing times, equipment accessibility, and lack of regulatory issues [23]. Alex MR et al. used glyceryl behenate to create solid lipid nanoparticles of oral lopinavir, which is poorly soluble. The impact of surfactant surface covering on the formation and stability of trypamitin solid lipid nanoparticles stabilized by Tween 20 particles was shown by Helgason T. et al. Silva AC et al. created risperidone-containing solid lipid nanoparticles [24].

b. Cold Homogenization Technique:

The main step of cold homogenisation for preparing solid lipid nanoparticles is similar to the hot homogenisation [24]. After the lipid is cooled and solidified, the molten lipid phase of the second dispersion system is blasted to make a lipid microparticle. Thereafter the pre-suspension is homogenized five times at room temperature and pressure by means of a high pressure homogeniser [22].

2. High-speed Homogenization/Ultra-Sonication Method:

A drug and a lipid are mixed with organic solutions, and the mixed solutions are squeezed through lipids, rotated, or evaporated to obtain a lipid film. SLNs are formulated by sonication probe when the emulsifier solution is added into the lipid film. The oleanolic acid SLNs were prepared by the film-ultrasonic method based on soybean phospholipid as a carrier [21].

3. Microemulsion Formation Technique:

The dilution of microemulsions is the basis of this method. Micro-emulsions (e.g., o/w microemulsions) are two-phase systems, including: an inner phase and an outer phase [25]. This process involves melting the lipids at the

proper temperature and heating the aqueous/surfactant phase to the same temperature. A heated aqueous phase is added to the heated mixture of melted lipids while being stirred at the same temperature. When hot oil is added to cold water at a ratio of 1:50, the hot oil in H_2O microemulsion solidifies [22].

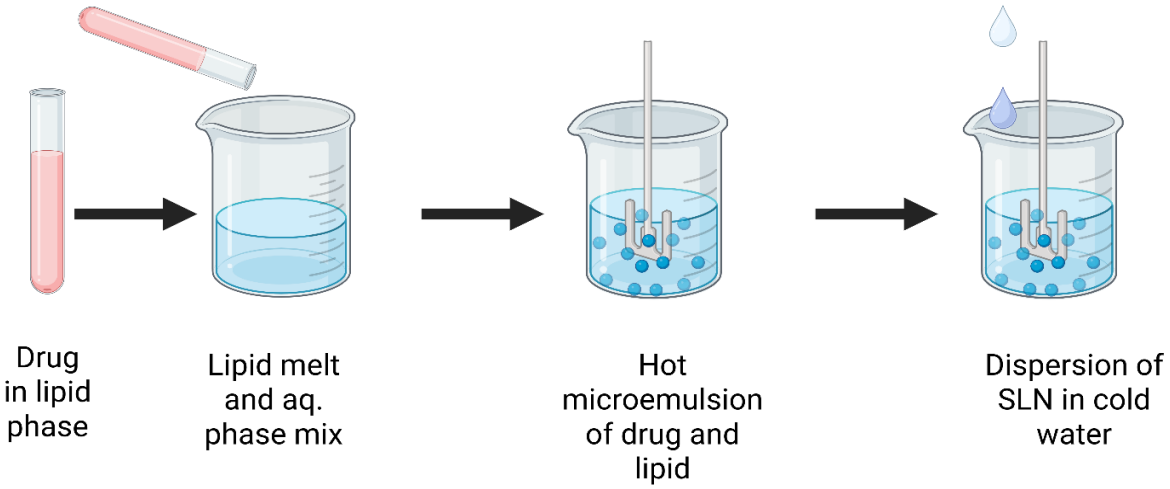

Figure 5: Microemlsion Technique

4. The Technique of Solvent Emulsification and Diffusion

a. Evaporation and Emulsification of Solvents:

O/W nanoparticle dispersion. The lipophilic material was dissolved in cyclohexane, an organic solvent that is insoluble in water, and then emulsified into an aqueous phase. When the solvent evaporates and the lipid settles in the phase of water, a suspension of nanoparticles is created. The mean diameter of the resultant particles, which were made using lecithin mixtures with sodium glycocholate as emulsifiers and triglyceride acetate as the model drug, was 25 nm.The reproducibility of the result was ensured by Siekmann and Westesen (1996), who prepared cholesterol acetate nanoparticles with an average size of 29 nm [10].

b. Solvent Emulsification-Diffusion:

The initial stage in synthesizing liposome nanoparticles using the solvent diffusion approach is to create a solvent in water emulsion with a partly water miscible solvent that includes the lipid [26]. The average particle size is dependent on the kind of emulsifier and the amount of lipid in the organic phase. Particles with an average size of 30 to 100 nm may be produced with this technique. This strategy's primary advantage is that it doesn't need heat. In this case, a matrix of lipids is dissolved in an organic solvent that is water immiscible and then emulsified into an aqueous phase. After the solvent evaporates at lower pressure, it also creates a colloidal particle dispersion and precipitates the lipid in an aqueous phase [10].

5. Green Technologies:

Although some parasitic diseases, such as malaria, have been treated using green technology but the production of lipid nanoparticles for parasitic disease by chemical-free approaches is still sparely and to be studied further. The use of non-toxic materials is cost-effective and simple [27].

Solid Lipid Nanoparticle Characterization

1. The Polydispersity Index and Particle Size:

Particle size is one of the main variables affecting the physical stability of SLNs. Laser diffraction (LD) and photon correlation spectroscopy (PCS) are the best techniques for determining particle size. PCS, also known as DLS, tracks changes in the intensity of scattered light caused by particle motion. The size range of 3 nm^{-3} µm can be probed by photon correlation spectroscopy (PCS), and that of 100 nm-180 µm is accessible to laser diffraction [10]. Other authors have described that lipids with higher melting points led to an increase in the average size of SLN dispersions [28]. However, PDI values higher than 0.5 indicate broad dispersion and that there is potentially instability in the system, which would end up producing LN aggregation [29].

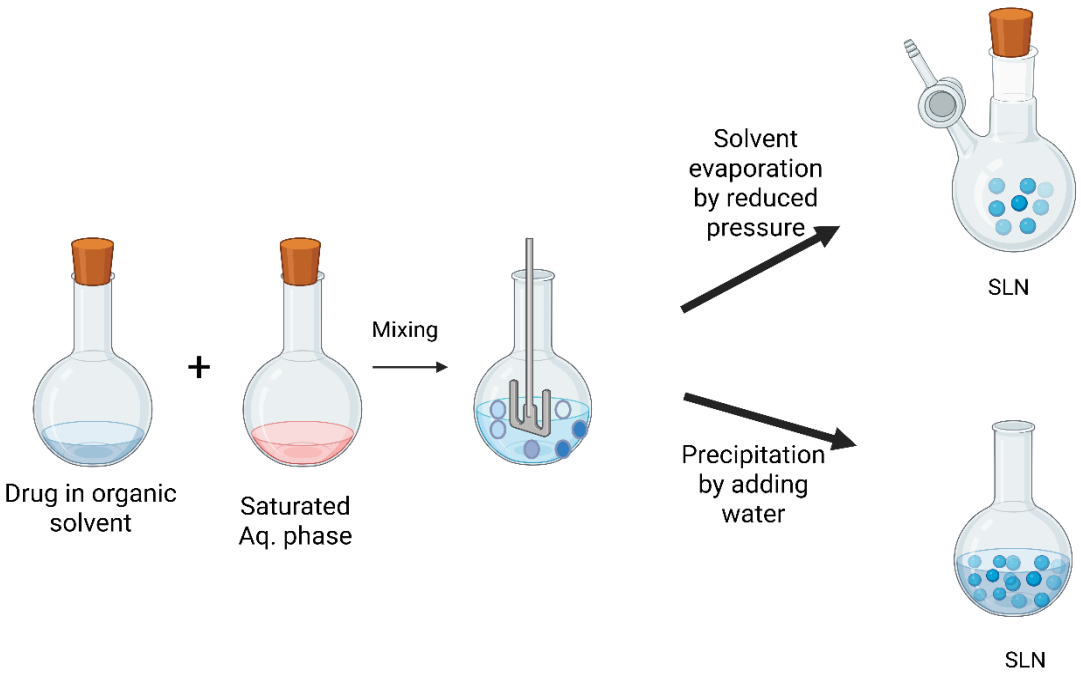

Figure 6: Solvent Emulsification – Evaporation and Diffusion

PDI is described by the following formula:

$$PDI = \frac{\Delta d}{davg} \quad (1)$$

Where,
Δd is the width of distribution and davg is the average particle size MV (nm) in particle size data sheet [2].

2. Zeta Potential:

The net charge that a particle can obtain in a given medium is characterised by the zeta potential (ZP) [30]. With the help of zeta potentials, it is possible to make an estimate as to the store ability of colloidal dispersions [10]. The electrokinetic zeta potential is the capability of colloids to migrate in an electrical field. At a more negative zeta potential, for example, of less than 30 mV or of less than −30 mV. Electrostatic repulsion usually decreases particle interaction and aggregation [31].

The Zetasizer 3000, laser diffraction, was used to assess the particle size and zeta potential of SLNs [32].

3. DL and EE:

The anti-tumour drugs loading capacity was calculated with the following formulaenary drug encapsulated efficicancy, Cooperation of nanoparticles; where the drug in nanoparticles m installed amount, W0 is the proportion of anti-tumour drugs. The high EE and LC represent the two most desirable criteria for an LN delivery system to be considered successful in entrapping bioactive compounds. EE is the ratio of the total. A growing body of evidence from *in vitro* and *in vivo* studies 37 to 39 suggests that LNs improve antibacterial activity by providing a sustained delivery system. Cannot (Q5 :) be dissociated from the encapsulated drug? The taking materials and methods of preparation will affect the EE value, and in turn, the release properties of the ratio of the total amount of lipid phase to the amount of encapsulated molecules is known as the loading capacity (LC).

The LC is affected by a number of variables, including the drug's solubility in the lipid phase, its physical makeup in LNs, and overall polymorphous form. Position C.LC indicates the lipid matrix's capacity to transport the necessary bioactive substances to the adsorption site. The range of LC values is 0% (low) to 100% (high) [29].

4. Morphology and Crystallinity:

a. Electron Microscopy :

Nanoparticles can also be characterized through TEM and SEM. But much value exists in SEM for morphological examination.

b. Differential Scanning Calorimetry (DSC):
To determine the degree of crystallinity, the particle dispersion is examined using powder X-ray diffractometry and DSC. By comparing the melting enthalpy per gram of dispersion and bulk material, the DSC technique may determine the degree of crystallinity (Xc) [10].

5. Drug Release in Vitro:
The drug's diffusion into the lipid matrix allowed for its release. Drug release from SLNs is directly influenced by the manufacturing process, drug solubility in the lipid, drug/lipid ratio, surfactant selection, and lipid matrix composition. The kinetics and mechanism of drug release are shown by the *in vitro* release profile. SLNs usually release in two phases, with controlled release coming after burst release. The release profile of SLNs showed an early burst release phenomenon, which has the following explanation: Normal drugs adsorbed on the surface of SLN tend to spread away from the nanoparticle. The drug will be subsequently released slowly with degradation of the lipid matrix [31].

6. Stability and Shelf-Life Evaluation:
Consistency: The capacity of an emulsion to maintain its characteristics over time is known as stability. Two variables significantly impact the physical stability of liposomes. In the first, destabilizing processes such as amalgamation, flocculation, creaming, and sedimentation have an impact on the uniformity of LN dispersion. The second is the solid lipid matrix's resistance over time, or recrystallization. A gel-like network of crystallized particles may result from recrystallization brought on by polymorphic mutations [29].

Drug Delivery Application SLN:
1. Oral Drug Delivery:
Oral drug delivery is the most frequently utilized route for the delivery of drugs due to maximum patient compliance. Nanoparticulate drug delivery systems were regarded as an effective tool for enhancing oral bioavailability. Lipid nanoparticles like SLNs and NLCs possess continuous release of drug, ideal for sustaining a steady state plasma level. Moreover, the faster disintegration of nanoparticles that have a greater specific surface area and saturation solubility can contribute to an early initiation of pharmacological response [22].

2. Topical and Transdermal Delivery:
Topical lipids the most commonly used topically are stearic acid and glycerol behenate. Being similar in physicochemical properties to natural lipids [33], these lipids are suitable for topical administration. The goal is to restrict the pharmacology or other activity of the drug at the skin surface [34]. All lipid nanoparticles are initially bound to the surface of the skin and can exchange lipids with the outermost layers of the stratum corneum by contacting these resident lipids in the skin; this is because there are more lipids in the epidermis, which form the outer layer of our skin. Furthermore, topical and transdermal vehicle dispersion seems to be auspicious. In order for the skin to be able to adequately absorb SLN carriers, a low lipid concentration is desired. A molecule of high molecular weight that has no first-pass metabolism is best suited for transdermal drug delivery. This technique can achieve up to 1 week of controlled medicine delivery [31].

3. Ocular Delivery:
The ocular drug delivery can increase the efficacy and minimize side effects, making it an attractive approach to treat ocular diseases [35]. Ocular bioavailability is frequently addressed as a problem by researchers because of the intricate structure and protective function of the eye. The low viscosity of the eye drops and, hence, the short residence time of the drug in the eye would also ads into this poor concentration of drug at the target site. All these benefits are presented by solid lipid nanoparticles, besides being biocompatible, biodegradable, scalable and sterilisable. The advantages of their stepwise surface treatment were a longer ocular residency time, better effectiveness and enhanced permeation [36].

4. Pulmonary and Nasal Routes:
One of the most vital regions, as in any living organism, that delineates internal physiology from the external environment is the lungs. As a result, this interface is ever under stress of attack from foreign particles and infective micro-organisms. Acute and chronic respiratory diseases, some of the most popular and familiar human states to humans [37]. Delivery to the lung is a more recent trade and has many benefits. It is a non-invasive method of administering the drug locally and systemically. This direct delivery concept will minimise the adverse effects of drug by using lower drug dose. SLNs and NLCs are lipid nanoparticles which have

been investigated for the pulmonary delivery. Their advantages include increased stability, reduced toxicity, biocompatibility and biodegradability, and sustained release of drugs [22].

5. Parenteral Delivery:

Nanomedicine and nanotechnology play an important role in enhancing parenteral drug delivery [22]. Radionuclide use in the body. For systemic delivery, SLNs are ideal because their components are biocompatible. SLNs are also not taken up by macrophages, if applied intravenously, when a hydrophilic coating is present and they are indeed small enough to enter the microvascular system. Although this solution led to more distribution into the liver and kidneys, SLN was responsible for higher drug levels in lung, spleen, and brain [38]. Therefore, SLNs have been proposed for viral and non-viral gene transfection [10].

Table 1: Drug Delivery Application

Sr. No.	API	Lipid used	Drug Delivery Application	Reference
1.	Raloxifene	Glyceryl Monosterate	Oral Delivery	[22]
2.	Gliconazol	Compritol	Oral Delivery	[22]
3.	Fluorometholone	Glyceryl Monooleate	Ocular Delivery	[35]
4.	Carvacrol	Glycerides	Pulmonary	[37]
5.	Rifampicin	Mannosylated SLN	Pulmonary	[37]
6.	Itraconazol	Glyceryl Monoosterate	Parentral	[22]

Therapeutic Application

1. Anticancer Drug Delivery:

Cancer is a set of diseases marked by the uncontrolled growth of cells and the ability to invade or spread [39]. Based on its different types, cancer is recognized as one of the most dangerous diseases in the world [40]. Innovative approaches to early cancer diagnosis, including improved imaging devices, ultra-sensitive biosensing platforms and personalized treatments, can be developed using nanoparticles and nanomedicines [41]. Solid lipid nanoparticles (SLNs) are employed for successful nano-targeted cancer treatment drug delivery [31]. Possibly, drug-SLN combinations can be exploited to tailor cell and tissue-specific clinical therapies that are geared to maximize therapeutic effects while minimizing adverse effects. The result suggests that SLNs may prove to be an ideal approach for the treatment of colon cancers. The potential to inhibit cell growth in HT-29 and GCT116 adenocarcinoma cells was reported for SLNs more than that of free fatty acids through a rise in apoptotic activation [40].

2. Antiviral and Antibacterial Therapies:

Nanocarrier drug delivery systems (NDDS) utilize various methods for efficient transport and release of drugs [42]. Fungi can induce allergies and infections in skin, hair, nails and mucosa [43]. Patients with herpes simplex virus are given the antiviral drug acyclovir. High rate and high amount acupuncture is recommended in order to achieve the best therapeutic effects because of its deficient oral bioavailability. The use of SLNs as a new method and alternative route for improving the oral bioavailability of acyclovir could be considered a significant advance in the treatment of HSV infections. The oral bioavailability of acyclovir from SLNs was found to be higher than that from the commercial acyclovir solution in oral bioavailability study. The A50 drug concentration of acyclovir-loaded SLNs was four times higher than the commercial liquid suspension [44, 45].

3. Anti-inflammatory Application:

Solid lipid nanoparticles have gained prominence as a modern topical delivery of anti-inflammatory drugs. In order to reduce inflammation where it is occurring, anti-inflammatory medications are designed to penetrate the stratum corneum and act on deeper skin layers. SLNs improve this by prolonging drug retention and exhibiting a sustained release pattern. SLNs as a safe and efficient topical delivery system for anti-inflammatory drugs. Thereby, the process of SLNs, through which the skin penetration and retention of therapeutic concentrations at the site are achieved effectively, is crucial to the therapeutic effect when applied with any anti-inflammatory topical medication. For example, with skin drug delivery in this case compared to traditional intravenous administration include

increased penetration of the drug through skin, altered pharmacokinetics and sustained duration of action enhancement [12].

4. SLNs for CNS Disorder:

Nanomedicine has led to targeting the signalling pathways and pathophysiology that are directly related to CNS diseases Alzheimer, Parkinson's disease, Huntington's disease. In order to deliver the active therapeutics across the blood-brain barrier (BBB) and reach their target site in the brain, SLNs have been developed as a drug carrier system. This offers an alternative in terms of controlled release, extended circulation time, targeted delivery approaches, higher efficacy, and—most importantly—biomimetic reduction in toxicity. The therapeutic effects of the majority of pharmacopeia's formulations for treatments associated with CNS (central nervous system) disorders are, hindered by BBB. Since SLNs can mediate drugs across the BBB barriers, they are one of the most innovative biological approaches [46]. Intranasal administration for CNS diseases has also been reported to help the drugs reach the CNS and penetrate through BBB faster [47].

Table 2: Therapeutic Application of SLNs

Sr. No.	API	Lipid	Therapeutic Application	References
1.	Paclitaxel	Cholesterol	Anticancer	[39]
1.	Erlotinil	Poly(lactic-co-glycolic acid)	Anticancer	[39]
2.	Acyclovir	Glycerylpalmito Sterate	Antiviral	[44]
4.	Diclofenac	Solid Lipid	Anti-inflammatory	[12]
5.	Ibuprofen	Solid Lipid	Anti-inflammatory	[12]
6.	Camptothecine	Solid Lipid	CNS Disorder	[46]
7.	Doxorubicin	Stearic acid and Epikuron 200	CNS Disorder	[46]

Challenges and Limitations:

1. Stability and Polymorphism:

One of the major limitations of SLNs is the character of lipid matrix which has crystalline and polymorphic transition. Lipids may switch to more stable polymorphous forms (α forms vs. ß forms) during storage and this might alter the particle morphology, release properties or even expel incorporated drug. These modifications can lead to shelf life stability, release profile and drug loading liabilities [7].

2. Drug Leakage and Burst Release:

Leaching of the drug and burst release by a fraction of the drug which was at or nearest to the particle surface (incorrect distribution). In the storage or *in vivo* condition, SLNs could exhibit leakage and burst release. This reduces the advantage of controlled release and may even lead to a lack of dose control or safety issues [13].

3. Scale-up and Industrial Production:

Although many SLN preparations are described at a laboratory scale, the production is not reproducible in the larger scale. Problems include obtaining particles which are uniform in size, have similar surface properties and loading of drug mass, removing residual solvent, sterilisation and cost. The scale-up to GMP-compatible GM manufacturing is a significant obstacle for clinical translation [21].

4. Regulatory and Toxicological Considerations:

The formulation with nanoparticles adds additional regulatory control (dimensions, bio distribution, clearance, protein corona, immunogenicity) although typically the SLN components are not harmful. Remaining concerns towards safety, long-term toxicity, accumulation in organs and batch-to-batch overlapping behaviour remain [13].

Future Perspective and Innovation:

Solid lipid nanoparticles (LNs) are recent nanocarriers that have shown great potential for improving drug delivery. They may increase bioavailability, control release and protect sensitive drugs. Recent developments and innovations are making new SLNs smarter, more effective. The use of AI / QbD in design formulations is one such major development. Whereas QBD ensures consistent and high-quality manufacturing, AI can help to predict the best combination of lipids and surfactants. Due to lesser experimentation, these methods enhance the replicability of the SLNs development [7].

Furthermore, SLNs are gaining interest in precision and personalized medicine. SLNs are also able to be customised based on a patients' genetic make-up or testament according to his/her disease state, due to their possibility of being constructed as drug carriers with specific drugs designed for certain cells or organs. And this manner effectively reduces the side-effect and increases therapeutic effects. Furthermore, smart and hybrid SLNs are being developed by associating lipids with polymers or other nanomaterials. These systems can deliver the drug exactly where and when it is required in response to stimuli such as temperature, pH or enzymes [48].

SLN use in mRNA and vaccines is growing rapidly. SLNs are being considered a more cost-effective and stable alternative to nucleic acid vaccines after the success of lipid nanoparticles (LNPs) in COVID-19 vaccination. Their dense matrix could contribute to improving the long-term stability of storage as well as protecting DNA or mRNA against degradation. Furthermore, SLNs could contribute to the oral or nasal administration of vaccines, an approach which would greatly increase patient compliance and convenience [38].

Enhancing treatment efficacy and targeting have been the objectives of drug carrier systems designed in recent years [49]. Nanotechnology, artificial intelligence and biotechnology. The convergence of nanotechnology, AI and biotech makes SLNs likely to be an even more sophisticated platform for next-generation drugs and vaccines in the future years. These improvements will help in addressing current limitations including drug loss, mass production, and product stability.

CONCLUSION

Solid Lipid Nanoparticles (SLNs) are established as the next generation drug carriers with a great potential for improving therapeutic efficacy across various clinical daydreams. The biocompatible lipid matrix enables the encapsulation of delicate drugs in a safe manner and enhances their stability, solubility and bioavailability. SLN are advantageous due to their controlled release, target delivery and fractional systemic toxicity aspects which are suitable for the oral, ocular, dermal, pulmonary and parenteral modes of administration. Their significance in such fields as anticancer, antiviral, antibacterial, anti-inflammatory and CNS therapies underlines their wide therapeutic applicability. Nevertheless, commercial translation of this class of compounds is still being hampered by issues such as drug ejection during storage, polymorphic transitions, burst release and scale-up problems. Among various formulation strategies, the development of green techniques, hybrid nanoparticles and optimizing surfactants seems to hold promise in combating such problems. The application of artificial intelligence and QbD methodology advocates integrating them for more precise predictions of the optimal formulation parameters in order to further optimize SLN development. Novel applications in gene delivery, mRNA protection and vaccine technology reveal the broadening role of SLNs further than drug carrier system. As further research proceeds SLNs should become key constituents of advanced nanomedicine. The capacity for safe, efficient and precise delivery made these platforms as a potential manufactory for novel personalized or targeted therapies. From every point of view, SLNs have tremendous potential to revolutionize current drug delivery approaches, and thus attain better therapeutic outcomes.

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