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Advances in Lipid-Based Nanocarriers for Anti-Aging: "Comparative Insight into SLN and NLC for Dermal Delivery"

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ABSTRACT:

Skin aging is a complex biological process influenced by intrinsic and extrinsic factors, leading to the structural and functional deterioration of the skin. Conventional topical formulations often suffer from limited penetration, instability of active ingredients, and reduced efficacy. Lipid-based nanocarriers, particularly Solid Lipid Nanoparticles (SLN) and Nanostructured Lipid Carriers (NLC), have emerged as promising delivery systems to overcome these limitations. This review provides a comparative evaluation of SLN and NLC in anti-aging and skin rejuvenation applications, focusing on their structure, formulation, mechanisms of skin penetration, and therapeutic performance. While SLN offer advantages such as controlled release and occlusive effects, NLC demonstrate superior drug loading capacity, stability, and enhanced dermal penetration. Overall, NLC show greater potential in advanced anti-aging formulations, although both systems hold significant promise.

Keywords: SLN; NLC; lipid nanocarriers; anti-aging; dermal delivery; nanotechnology

1. INTRODUCTION:

Skin aging is a natural process that causes visible changes such as wrinkles, fine lines, dryness, sagging, and pigmentation. As healthy and youthful skin is closely associated with appearance and confidence, the demand for anti-aging skincare products has increased rapidly worldwide. Conventional formulations like creams, gels, and lotions are commonly used, but they often show limited effectiveness because of poor skin penetration, low stability of active ingredients, and reduced bioavailability [1].

To overcome these limitations, nanotechnology has emerged as an advanced approach in cosmetic science. Nano-sized carriers improve the penetration of active ingredients into deeper skin layers, enhance stability, and provide controlled release of bioactive compounds. Different nanocarriers, especially lipid-based nanoparticles, are widely used because of their biocompatibility and improved delivery efficiency [2,3].

The cosmetics industry has grown significantly due to increasing awareness of skincare and personal grooming. The anti-aging segment is a major part of this market, with the global anti-aging market valued at around USD 77–80 billion in 2025 and expected to reach nearly USD 149 billion by 2035 at a CAGR of 6–7% [4]. Similarly, the anti-aging cosmetics and dermo-cosmetics markets are also expanding rapidly, reflecting the rising demand for scientifically advanced and effective skincare products [5].

Anti-aging formulations commonly contain both synthetic and natural active ingredients. Synthetic compounds such as titanium dioxide, zinc oxide, and oxybenzone are widely used as UV filters to protect the skin from harmful radiation. However, concerns regarding their possible toxicity and adverse skin interactions have encouraged researchers to explore safer and more effective alternatives [6]. Natural compounds, especially phytochemicals such as resveratrol, quercetin, and curcumin, have gained considerable attention because of their antioxidant, anti-inflammatory, and skin-rejuvenating properties. These bioactive compounds help reduce oxidative stress, protect against UV-induced damage, minimize wrinkles, and improve overall skin health [7,8].

Despite their benefits, many natural compounds show poor solubility and low bioavailability in conventional formulations. Nanotechnology helps overcome these challenges by improving the delivery, penetration, and stability of these active molecules. Nanoparticles can effectively pass through intercellular pathways and deliver active ingredients directly to the target site. Among different nanocarriers, lipid-based systems are particularly beneficial because of their biocompatibility, ability to enhance intracellular delivery, and controlled drug release properties [9].

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Overall, nanotechnology has become an important and rapidly growing area in modern cosmetology because of its ability to improve the permeability, stability, bioavailability, and effectiveness of active ingredients. It also enhances product texture and overall user experience, making nano-based anti-aging skincare formulations more efficient, stable, and consumer-friendly [9,10].

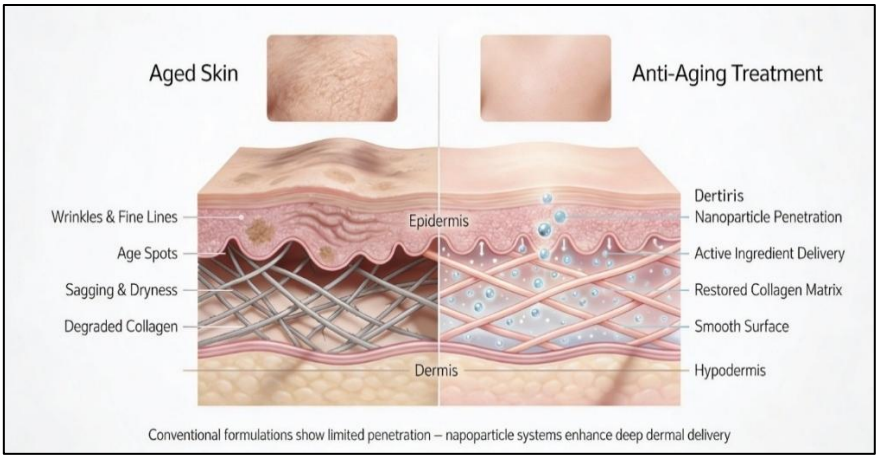

Fig. No. 1 Overview of skin aging and antiaging therapy as need of advanced delivery system

2. Pathophysiology of Skin Aging:

Skin ageing is a complex biological process caused by both intrinsic and extrinsic factors, leading to gradual structural and functional changes in the skin. Several molecular mechanisms, including cellular senescence, telomere shortening, oxidative stress, mitochondrial DNA damage, chronic inflammation, impaired DNA repair, and reduced metabolic activity, contribute to the weakening of skin integrity over time [11]. Ageing is a gradual biological process in which both intrinsic and extrinsic factors contribute to the progressive decline in structural integrity and physiological function of the skin [12].

2.1 Intrinsic Factors:

Intrinsic ageing is a natural and genetically programmed process associated with hormonal changes, reduced collagen synthesis, decreased hydration, and loss of skin elasticity. Factors such as ethnicity, skin pigmentation, skin thickness, and lipid composition also influence the extent of ageing, while higher melanin levels provide better protection against UV-induced damage. Intrinsic ageing represents only a small proportion of total skin ageing and is characterized by reduced cell proliferation and increased cellular senescence [13].

2.2 Extrinsic Factors:

Extrinsic ageing mainly occurs due to environmental exposure and lifestyle habits and is considered more preventable. Prolonged exposure to UV radiation is the major cause of premature skin ageing, while pollution, temperature, and humidity further impair skin health. Lifestyle factors such as smoking, poor nutrition, inadequate sleep, and lack of physical activity also accelerate ageing by damaging collagen and elastin. In addition, repetitive facial expressions and long-term exposure to chemicals, cosmetics, and certain medications may contribute to wrinkle formation and skin damage [12,13].

Table No.1 Molecular Mechanism of Skin aging

Mechanism	Description	Effect in Ageing	Reference
Cellular Senescence & Reduced Regeneration	Decline in cell division and repair capacity due to reduced stem cell activity	Slower skin regeneration, thinning of skin, delayed wound healing	[14]
Reactive Oxygen Species (ROS) Production	Increased generation of free radicals during metabolism and external exposure	Oxidative damage to lipids, proteins, and DNA leading to wrinkles and loss of elasticity	[15]
Telomere Shortening	Progressive shortening of chromosome ends during cell division	Limits cell replication, promotes ageing, wrinkle formation, and tissue degeneration	[15], [23], [24]
Glycation (AGEs Formation)	Non-enzymatic reaction between sugars and proteins forming AGEs	Collagen cross-linking, increased stiffness, loss of skin elasticity, ECM damage	[16]

Free Radical Damage (FRTA)	Accumulation of highly reactive molecules with unpaired electrons	Cellular damage, mitochondrial dysfunction, and acceleration of intrinsic ageing	[17], [18]
Chronic Oxidative Stress	Continuous imbalance between ROS production and antioxidant defense	Cumulative cellular damage, inflammation, and premature ageing	[19], [20]
Apoptosis (Programmed Cell Death)	Increased cell death due to accumulated damage	Loss of skin cells, thinning, and reduced tissue repair	[15], [21]
Cell Cycle Dysregulation	Impaired control of cell division by pathways like p53, p21, Rb	Abnormal cell proliferation, DNA damage accumulation, and ageing	[22]
Hormonal Decline & Reduced Circulation	Decrease in hormones and blood flow with age	Tissue atrophy, reduced nutrient supply, and decreased skin vitality	[21]

3. Conventional Anti- Aging Approaches:

Anti-ageing skincare approaches provide several benefits for maintaining healthy and youthful skin. Sunscreens protect against UV rays, blue light, and pollutants, while antioxidants such as vitamin C, vitamin E, and niacinamide help reduce oxidative stress and skin damage. Ingredients like retinoids, bakuchiol, and AHAs improve collagen production, skin renewal, and texture, whereas moisturizers maintain hydration and strengthen the skin barrier. Nanotechnology-based formulations further enhance the stability, penetration, and effectiveness of active ingredients [25].

However, these approaches also have certain limitations. Regular and long-term us e is required for visible results, and some active ingredients may cause irritation, dryness, or sensitivity. Natural compounds often show poor stability and low bioavailability, while nanoformulations may involve higher costs and safety concerns. Additionally, these treatments can reduce but not completely prevent the natural ageing process [25].

Table No. 2 Conventical Strategies for Prevention and Management of Skin Ageing

Strategy	Benefits	Limitations
Sun Protection (Sunscreens SPF ≥30, ZnO, TiO_2, chemical filters)	Protects against UV radiation, prevents photoageing, reduces wrinkles and pigmentation	Requires frequent reapplication, may cause irritation or white cast (physical filters)
Protection from Blue Light & Pollution	Reduces oxidative stress (ROS), prevents pigmentation and premature ageing	Limited awareness, fewer specialized products available
Antioxidants (Vitamin C, E, Niacinamide, CoQ10, Polyphenols)	Neutralize free radicals, improve skin repair, enhance brightness and elasticity	Stability issues (e.g., Vitamin C), may require proper formulation
Natural Compounds (Resveratrol, Curcumin, Quercetin)	Anti-aging, anti-inflammatory, and photoprotective effects	Poor solubility and bioavailability in conventional formulations
Healthy Lifestyle (Diet, hydration, exercise, no smoking)	Improves overall skin health, reduces oxidative damage, supports collagen synthesis	Requires long-term consistency, results are gradual
Skin Renewal Agents (Retinoids, Bakuchiol, AHAs)	Increase collagen production, improve skin texture, reduce wrinkles	May cause irritation, dryness, photosensitivity
Moisturizers (Occlusives & Humectants)	Maintain hydration, strengthen skin barrier, improve smoothness	Temporary effect, requires regular use
Advanced Therapies (Peptides, Growth Factors, Nanoformulations)	Enhance skin regeneration, targeted delivery, improved efficacy of actives	Expensive, requires advanced formulation and stability considerations

4. Lipid-Based Nanocarriers for Dermal Delivery

The stratum corneum, the outermost layer of the skin, acts as the main protective barrier and controls the movement of substances through the skin. It consists of corneocytes embedded in a lipid matrix, which plays an important role in drug permeation. Any disruption in this barrier or lipid composition due to skin disorders can significantly affect drug absorption [26–29].

To overcome these limitations, lipid-based vesicular systems have been developed to improve skin permeability and enhance drug delivery into deeper skin layers. Lipid-based nanocosmeceuticals such as nanoemulsions, liposomes, solid lipid nanoparticles (SLNs), and nanostructured lipid carriers (NLCs) are commonly used because of their small particle size (50–300 nm), high surface area, and improved interaction with the skin surface. These nanocarriers enhance the solubility of poorly water-soluble compounds, protect sensitive ingredients like vitamins and peptides, and allow deeper penetration into the skin and hair follicles [30,31,32].

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In addition, lipid-based nanocarriers provide controlled and sustained release of active ingredients, improving therapeutic efficacy and reducing the need for frequent application. Their high biocompatibility, similarity to natural skin lipids, and ability to form an occlusive film help reduce transepidermal water loss, improve hydration, support skin barrier repair, and enhance drug penetration. They are also less likely to cause irritation compared to conventional systems, making them highly suitable for dermatological and skincare applications [33,34].

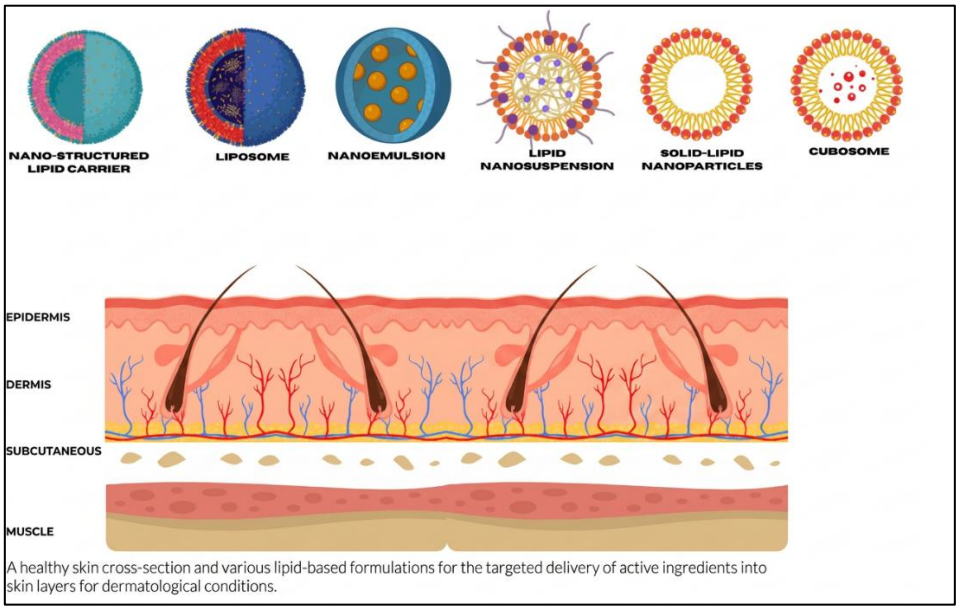

Fig. No. 2 Lipid Based approach to dermal therapy

4.1 Solid lipid nanoparticles (SLNs)

4.1.1 Composition and Structure

Solid Lipid Nanoparticles (SLNs) were first introduced in the early 1990s by Müller and Lucks [35], and later the term "SLN" was formally used in further studies [36]. SLNs are composed of physiological lipids that remain solid at both room and body temperature, along with surfactants and an aqueous phase [37–39].

The lipid phase typically includes steroids, mono-, di-, or triglycerides, glyceride mixtures, or waxes, used in concentrations ranging from 0.1% to 30% (w/v). Surfactants are generally present in concentrations of 0.5% to 5% (w/v) and are mostly recognized as safe (GRAS). In some formulations, a combination of surfactants is used to improve stability and dispersion [38–43]. The internal structure of SLNs depends on formulation composition, drug solubility, and preparation method, which ultimately influence drug loading and release behaviours.[44]

4.4.2 Types of SLN

Three main structural models of SLNs have been described [37,44]:

Type I: Homogeneous Matrix Model

In this model, the drug is uniformly dispersed within the lipid matrix. It is usually prepared by hot or cold homogenization and is suitable for highly lipophilic drugs.

Type II: Drug-Enriched Shell Model

This structure is typically produced using hot homogenization. During cooling, lipid molecules crystallize first, forming the core, while the drug becomes concentrated in the outer layer. This results in the formation of a drug-rich shell around the lipid core.

Although this model may not provide prolonged drug release, it can enhance drug penetration, particularly in topical applications due to the occlusive effect of SLNs.

Type III: Drug-Enriched Core Model

This type forms when the drug concentration approaches its solubility limit in the melted lipid. In this case, the drug precipitates first due to saturation in the melted lipid, forming the core, while the outer shell consists mainly of lipid. This structure supports controlled drug release.

4.4.3 Advantages and Limitations of SLNs [37-47]

Advantages

- Use of physiological lipids ensures biocompatibility and low toxicity
- Provides controlled and sustained drug release
- Protects sensitive active ingredients such as vitamins and peptides from degradation
- Enhances skin hydration due to occlusive film formation
- Improves dermal drug penetration and bioavailability

Limitations

- Limited drug loading capacity due to highly ordered crystalline lipid matrix
- Risk of drug expulsion during storage due to lipid crystallization
- Possible gelation tendency during long-term storage
- Less formulation flexibility compared to nanostructured lipid carriers

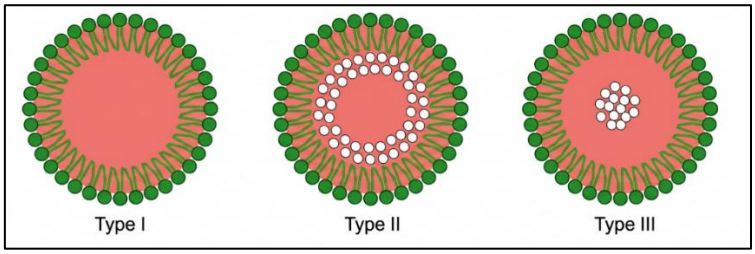

Fig No.3 Structure of 3 different type of SLN: homogenous matrix model (Type I), drug-enriched shell model (Type II), and drug-enriched core model (Type III).

4.2 Nanostructured lipid carriers (NLCs)

4.2.1 Composition and Structure

Nanostructured Lipid Carriers (NLCs) are considered the second generation of lipid-based nanocarriers and were developed in the late 1990s to overcome the limitations associated with Solid Lipid Nanoparticles (SLNs) [37,44].

NLCs are composed of a blend of solid and liquid lipids, typically in ratios up to 70:30, along with an aqueous phase containing surfactants [48,49]. The lipids used are generally biocompatible and biodegradable, which reduces toxicity and makes NLCs highly suitable for pharmaceutical and cosmetic applications [50].

The incorporation of liquid lipids into the solid lipid matrix results in a less ordered and more imperfect internal structure. This imperfect arrangement creates additional space within the matrix, enhancing drug-loading capacity and improving formulation stability compared to SLNs [51].

4.2.2 Types of NLC

Based on their internal structure, NLCs are classified into three main types:

Type I: Imperfect Crystal Type

This type is formed by mixing lipids with different chain lengths or combining mono-, di-, and triglycerides. The resulting matrix contains imperfections and void spaces, which allow better accommodation of drug molecules and improve drug loading [51].

Type II: Amorphous Type

This structure is obtained by using medium-chain triglycerides along with solid lipids. The lipid matrix remains in an amorphous (non-crystalline) state after cooling, which prevents drug expulsion during storage and enhances the stability and shelf life of the formulation [51].

Type III: Multiple Type

This type is produced by incorporating oils such as oleic acid or medium- and long-chain triglycerides into solid lipids. When the oil exceeds its solubility in the solid lipid, tiny oil nanocompartments are formed within the solid matrix during cooling. These compartments significantly improve drug loading capacity and stability [44,45,51].

4.2.3 Advantages of NLCs over SLNs [44-51]

- Higher drug-loading capacity due to imperfect lipid matrix
- Reduced drug expulsion during storage
- Improved stability and longer shelf life
- Enhanced flexibility in formulation design
- Better controlled and sustained drug release
- Improved therapeutic performance compared to SLNs

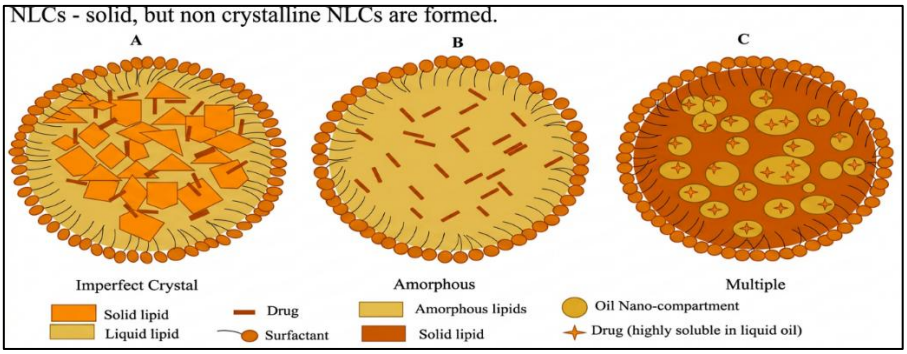

Fig. No.4 Structure of 3 different types of NLC: imperfect crystal (Type I), amorphous (Type II), and multiple type (Type III).

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5. Comparative Analysis of SLN vs NLC

Solid lipid nanoparticles (SLNs) have been extensively studied as drug delivery systems for multiple routes, including oral, parenteral, and topical administration. Their structure can be optimized based on the properties of active ingredients and excipients, offering several formulation advantages. However, the drug release behavior of SLNs is strongly influenced by the solid-state characteristics of the lipid matrix, such as crystallization and other physicochemical transitions. In some cases, incomplete or delayed crystallization can result in low drug-loading capacity. Lipid matrices also tend to undergo molecular rearrangement over time, forming a more ordered and densely packed structure. This change can alter the internal arrangement and create unfavourable conditions for drug incorporation. As a result, drug-loading efficiency depends not only on the physicochemical properties of the drug but also on the type of lipid matrix used. Drugs that are not properly incorporated may adsorb onto the nanoparticle surface or even cause instability and separation of the system [45,52-57].

To overcome these limitations, a less ordered and more imperfect matrix is desirable. This can be achieved by introducing lipids with different structural characteristics. Nanostructured lipid carriers (NLCs) were developed based on this concept. NLCs are prepared by combining solid and liquid lipids in ratios typically ranging from 70:30 to 99:1, while maintaining a solid state at both room and body temperatures. By adjusting the proportion of liquid lipids, improved drug incorporation and immobilization can be achieved.

In SLNs, drug molecules are mainly dispersed in a uniform molecular form within the lipid matrix. In contrast, the presence of both solid and liquid lipids in NLCs creates structural imperfections, which provide additional space for drug incorporation. This allows drugs to be accommodated not only in molecular form but also as amorphous clusters, thereby increasing drug-loading capacity. Moreover, this imperfect matrix helps prevent drug expulsion during storage, improving stability and overall performance [45,52-57].

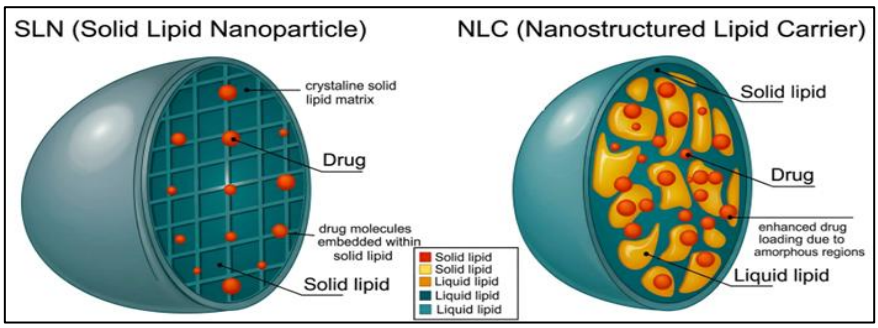

Fig. No.5 Structural Matrix of SLN and NLC

Table No. 3 Comparison between Solid Lipid Nanoparticles (SLNs) and Nanostructured Lipid Carriers (NLCs)

Parameter	SLNs	NLCs
Lipid Composition	Only solid lipids	Mixture of solid and liquid lipids
Matrix Structure	Highly ordered crystalline structure	Less ordered, imperfect matrix
Drug Loading Capacity	Limited due to dense packing of lipids	Higher due to structural imperfections and void spaces
Drug Distribution	Mainly molecular dispersion in lipid matrix	Molecular + amorphous clusters + oil compartments
Crystallization Behavior	High crystallinity; may lead to drug expulsion	Reduced crystallinity; prevents drug expulsion
Stability	Lower stability due to lipid rearrangement over time	Improved stability due to imperfect matrix
Drug Expulsion Risk	High during storage due to lipid reorganization	Minimal due to presence of liquid lipids
Flexibility in Formulation	Limited flexibility	More flexible due to adjustable lipid ratios
Drug Incorporation Efficiency	Depends strongly on drug-lipid compatibility	Enhanced due to additional space in matrix
Overall Performance	Moderate	Superior in terms of loading, stability, and release

6. Method of SLN & NLCs Preparations:

Different techniques are available for the preparation of solid lipid nanoparticles (SLNs) and nanostructured lipid carriers (NLCs), and the choice of method depends on factors such as the nature of the drug, formulation stability, and the required properties of the nanoparticles. These methods are mainly designed to produce nanoparticles with uniform size, good stability, improved drug loading, and effective controlled drug release. Some of the commonly used preparation methods include high-pressure homogenization, microemulsion technique, emulsification–solvent diffusion, solvent injection, and phase inversion technique. Each method offers specific benefits as well as certain limitations that can affect the overall performance and quality of the final formulation. [74-86]

Table No. 4 Commonly Used methods of preparation for SLNs & NLCs

Method	Principle	Advantages	Limitations	Reference
High-Pressure Homogenization (HPH)	High pressure reduces lipid particles to nanosize through shear and cavitation forces.	Fast, scalable, solvent-free, cost-effective.	High temperature may affect heat-sensitive drugs.	[74–76]
Hot HPH	Melted lipid-drug mixture is homogenized at high temperature and cooled.	Suitable for lipophilic drugs and uniform particles.	Risk of drug degradation and leakage.	[77–80]
Cold HPH	Drug-loaded lipid is cooled, ground, and homogenized at low temperature.	Suitable for heat-sensitive drugs.	Higher energy requirement and larger particles.	[74,76,77,80]
Microemulsion Technique	Microemulsion is formed and dispersed in cold water to produce nanoparticles.	Simple process under mild conditions.	Requires high surfactant concentration.	[78,81,82]
Emulsification–Solvent Diffusion	Solvent diffusion causes lipid solidification and nanoparticle formation.	Simple, reproducible, low thermal stress.	Needs purification and concentration steps.	[83,84]
Solvent Injection	Lipid solution is injected into aqueous phase causing lipid precipitation.	Rapid and efficient method.	Organic solvent removal is required.	[85]
Phase Inversion Method	Heating–cooling cycles followed by thermal shock form nanoparticles.	Solvent-free method.	Time-consuming process.	[86]

8. Characterization of SLN & NLC:

Characterization of solid lipid nanoparticles (SLNs) and nanostructured lipid carriers (NLCs) is essential to evaluate their quality, stability, and performance. Different parameters such as particle size, zeta potential, drug loading, morphology, and drug release help in understanding the behaviour of nanoparticles. Techniques like DLS, TEM, DSC, XRD, and HPLC are commonly used to analyse these properties and ensure the effectiveness of the formulation.

Table No. 5 Characterization of SLN & NLC

Parameter	Technique	Purpose	Findings	Reference
Particle Size & PDI	Dynamic Light Scattering (DLS/PCS), Laser Diffraction (LD)	To determine particle size and size distribution of nanoparticles.	Smaller particle size and lower PDI indicate better stability and uniformity of SLN and NLC formulations.	[88–94]
Zeta Potential	Laser Doppler Velocimetry	To measure surface charge and predict nanoparticle stability.	Zeta potential values above +30 mV or below –30 mV generally indicate good physical stability.	[89,95,96]
Encapsulation Efficiency (EE) & Drug Loading (DL)	HPLC, Spectroscopy	To evaluate the amount of drug entrapped and loaded in nanoparticles.	High encapsulation efficiency is commonly observed with lipophilic drugs due to strong lipid affinity.	[91,95,97–99]

In Vitro Release Studies	Dialysis Method, Franz Diffusion Cell, HPLC, UV Spectrophotometry	To study the drug release profile from nanoparticles.	SLNs and NLCs usually show biphasic release with initial rapid release followed by sustained release.	[95,96,99–103]
Stability Studies	DSC, Particle Size Analysis, PDI Evaluation	To assess physical and chemical stability during storage.	Stability depends on particle size, zeta potential, lipid polymorphism, and formulation composition.	[104–106]
Morphology of SLN & NLC	Transmission Electron Microscopy (TEM)	To examine particle shape, structure, and aggregation.	Morphology is influenced by surfactants, lipid type, and drug concentration.	[93,105,107]
Lipid Matrix Properties & Particle Structure	DSC, XRD, NMR	To study crystallinity and internal lipid arrangement.	Lipid polymorphic transitions may affect drug release and nanoparticle stability during storage.	[88,95,97,108–110]

9. Comparative Studies of SLNs and NLCs in Anti-Aging Applications;

Active Ingredient	Formulation	Key Findings	Outcome / Significance	Reference
Vitamin A	SLN gel vs conventional suspension gel	SLN showed enhanced permeation in Franz diffusion studies	Improved skin penetration and localized anti-aging effect	[111]
Coriander Essential Oil	NLC (CEO-NLC) vs SLN	Smaller particle size, lower PDI, higher zeta potential	Better stability, improved skin interaction, enhanced release	[111,112]
***Mangifera indica* extract**	NLC formulation	Increased antioxidant activity and improved absorption	Enhanced anti-aging efficacy with good safety profile	[113]
***Citrus sinensis* extract**	NLC formulation	Increased collagen & SOD, reduced PGE2, COX2, MDA, elastin	Strong anti-aging and reduced oxidative stress	[114,116]
Heptapeptide	SLN formulation	Small size (~173 nm), high entrapment (90.8%), reduced UV damage	Effective photoprotection and anti-aging activity	[115]
Coenzyme Q10	SLN vs NLC	Both improved penetration and controlled release	SLN: better penetration; NLC: better antioxidant & skin-brightening effects	[34]

10. Challenges & Future Perspectives

10.1 Commercial Applications

Solid lipid nanoparticles (SLNs) and nanostructured lipid carriers (NLCs) have gained considerable attention in commercial applications, particularly in the cosmetics industry, due to their ability to efficiently encapsulate active ingredients, enhance stability, and provide controlled drug release. These nanocarriers are widely incorporated into formulations such as anti-aging creams, sunscreens, and moisturizers, where they improve skin hydration, enhance the penetration of active compounds, and prolong therapeutic effects. Commercial products such as Eucerin Sunscreen and Sebamed Anti-Aging Q10 Lifting Eye Cream demonstrate the practical application of these technologies in skincare formulations [117].

10.2 Safety Considerations

SLNs and NLCs are generally regarded as biocompatible systems because they are composed of physiological lipids and excipients that are recognized as safe. Studies have indicated minimal toxicity following various routes of administration, including oral, dermal, parenteral, and ocular. However, limited data are available regarding their long-term safety, particularly in terms of tissue distribution, metabolism, and potential accumulation within the body. Additionally, certain formulation components, such as surfactants, may trigger immune responses, highlighting the need for further investigation into their biological interactions [117].

10.3 Scale-Up and Manufacturing Challenges

Despite their advantages, several challenges exist in the large-scale production of SLNs and NLCs. Maintaining consistency in critical parameters such as particle size, drug distribution, and encapsulation efficiency is complex and requires stringent quality control. Variability in lipid sources and sensitivity to processing conditions, including temperature, pressure, and agitation, can significantly influence the final product characteristics. Furthermore, sterilization techniques involving heat or radiation may induce lipid polymorphism, potentially affecting stability and therapeutic efficacy [117].

10.4 Cost and Regulatory Challenges

The production cost of SLNs and NLCs is relatively high due to the requirement for advanced techniques such as high-pressure homogenization and ultrasonication, along with expensive equipment. In addition, strict regulatory requirements for safety, quality, and efficacy increase the complexity of commercialization, posing challenges for large-scale industrial application [117].

10.5 Future Perspectives

With proper optimization and standardization of formulation and manufacturing processes, SLNs and NLCs hold significant future potential. Beyond cosmetics, these systems can be widely applied in pharmaceuticals, personalized medicine, and the food industry, where they may enhance product stability, bioavailability, and shelf life. Continued research and development are expected to improve their safety profile, scalability, and overall performance, making them promising platforms for advanced delivery systems [117].

Conclusion:

This review highlights the growing importance of lipid-based nanocarriers, particularly solid lipid nanoparticles (SLNs) and nanostructured lipid carriers (NLCs), in the development of advanced anti-aging skincare systems. Traditional topical formulations often struggle with issues such as poor skin penetration, instability of active ingredients, and limited effectiveness. In comparison, SLNs and NLCs provide a more efficient approach by improving the delivery, stability, and sustained release of active compounds within the skin.

SLNs, as first-generation lipid nanocarriers, offer several benefits including good biocompatibility, enhanced skin hydration, and improved penetration due to their occlusive nature. However, their tightly packed lipid structure can limit drug-loading capacity and may lead to drug leakage over time. To address these limitations, NLCs were developed by combining solid and liquid lipids, creating a more flexible and less ordered structure. This allows higher drug loading, better stability, and reduced chances of drug expulsion during storage. From a comparative perspective, SLNs are more effective in enhancing drug penetration into deeper skin layers, while NLCs generally provide better overall performance in terms of stability, drug loading, and long-term effectiveness. The use of these nanocarriers with antioxidants, natural extracts, and bioactive compounds has shown promising results in reducing oxidative stress, improving collagen production, and protecting the skin from environmental damage—key factors involved in skin aging.

Despite these advantages, some challenges still remain, including high production costs, scale-up difficulties, and the need for more long-term safety studies. However, with continuous research and technological improvements, these issues are likely to be addressed in the future. Overall, SLNs and NLCs represent a modern and highly promising strategy for anti-aging dermal delivery. Their ability to enhance the effectiveness of active ingredients makes them an important part of next-generation skincare and cosmeceutical products.

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