

Nanostructured lipid carriers: A prospective dermal drug delivery system for natural active ingredients

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Abstract

Nanostructured lipid carriers (NLCs) are versatile tools used for several purposes, including drug release modification, adhesion to the skin, film-forming ability followed by hydration of the superficial layers of the skin, as well as high penetration with permeation into and across deeper skin layers. During the formulation of active ingredients sourced from nature into dosage forms, NLCs play a crucial role in overcoming challenges associated with the process. These challenges include poor solubility and skin permeability, sensitivity to light, heat, and oxygen, leading to degraded quality, reduced potency, and probable risks of skin irritation or allergic reactions. Therefore, this review aimed to provide a comprehensive overview of NLCs as effective delivery system through the skin for natural active ingredients. The extensive discussion covers the advantages and disadvantages of a dermal delivery system for these ingredients, focusing on various types, lipids, and surfactants used in the formulation, preparation, and characterization process. Additionally, the recent developments in NLCs technology are explored. The result showed that NLCs would advance into a more efficient, precise, and safe system to transport natural active ingredients dermally.

Keywords

Dermal drug delivery, Lipids, Nanostructured lipid carriers, Natural active ingredients, Surfactants

Introduction

Natural active ingredients are chemical substances derived from various organisms, such as plants, microbes, or animals, renowned for pharmacological, therapeutic, antioxidant, and antibacterial effects. These ingredients have gained importance in modern medicine due to their potential as effective therapies for treating diseases with fewer side effects and cost-effectiveness with adequate administration compared to most pharmaceutical drugs (Thakur

et al. 2011). In recent years, natural active ingredients have become increasingly popular in skincare products. This widespread application is attributed to therapeutic benefits to the skin, including wound-healing, antimicrobial, and anti-inflammatory properties (Kamel and Mostafa 2015; Shen et al. 2015; Sanad and Abdel-Bar 2017; Ghodrati and Farahpour 2018). These ingredients are often selected to target specific skin concerns or conditions, such as acne, aging, dryness, and inflammation (Okonogi and Rianganapatee 2015; Chen et al. 2017; Pivetta et al. 2018).

Despite the numerous benefits, natural ingredients in topical dosage forms are still difficult to deliver through the skin without reducing their effectiveness (Thakur et al. 2011). A significant challenge is poor skin permeability, inhibiting penetration into the outermost layer and the stratum corneum. This phenomenon prevents natural ingredients from reaching the deeper layers for optimal effectiveness (Okonogi and Rianganapatee 2015; Chen et al. 2016). Natural ingredients are also sensitive to light, heat, and oxygen, which potentially degrade and reduce their potency when exposed (Liu et al. 2015). Due to the variability in skin permeability, solubility, and other physical properties, formulating natural ingredients into skin products can be challenging (Wang et al. 2014). Compared to synthetic materials, natural ingredients can still cause skin irritation or allergic reactions in some people, raising safety concerns (Chen et al. 2016).

Lipid-based drug delivery systems (LBDDS) capable of mimicking the skin barrier function have been proposed to improve the delivery and performance of natural active ingredients (Aditya et al. 2014). LBDDS is known to enhance skin permeability and protect natural ingredients from degradation to improve stability and bioavailability while reducing toxicity (Qi et al. 2017; Poovi and Damodharan. 2018). At least five types of LBDDS have been identified, including lipid solutions or suspensions,

emulsions, self-emulsifying or self-nanoemulsifying drug delivery systems, liposomes, and lipid particulate systems (solid lipid nanoparticles and nanostructured lipid carriers) (Akbari et al. 2015; Pradhana and Ritthidej 2023). LBDDS is often liquid form physically but may also be solid or semi-solid at room temperature when high melting lipids are used or adsorbed onto the carrier. Alternatively, it can also appear as lipid multi-particulates (Feeney et al. 2016). Figs 1, 2 show the schematic classification and the morphological models of some LBDDS (oil-in-water emulsion, solid lipid nanoparticle, and nanostructured lipid carrier).

Nanostructured lipid carriers (NLCs) are drug delivery system comprising a mixture of solid and liquid lipids as a core matrix. Furthermore, NLCs are second-generation lipid nanoparticles that have an unstructured matrix with high drug loading capacity, which are suitable for drug delivery system (Chen et al. 2014; Weber et al. 2014). Due to these unique characteristics, several studies have investigated NLCs as alternate carriers for the dermal delivery of pharmaceuticals, particularly natural active ingredients. Among the associated benefits discovered include biocompatible ingredients, drug release modification, adhesion to the skin, film-forming ability with hydration of the superficial skin layers, as well as increased penetration and permeation into deeper skin layers.

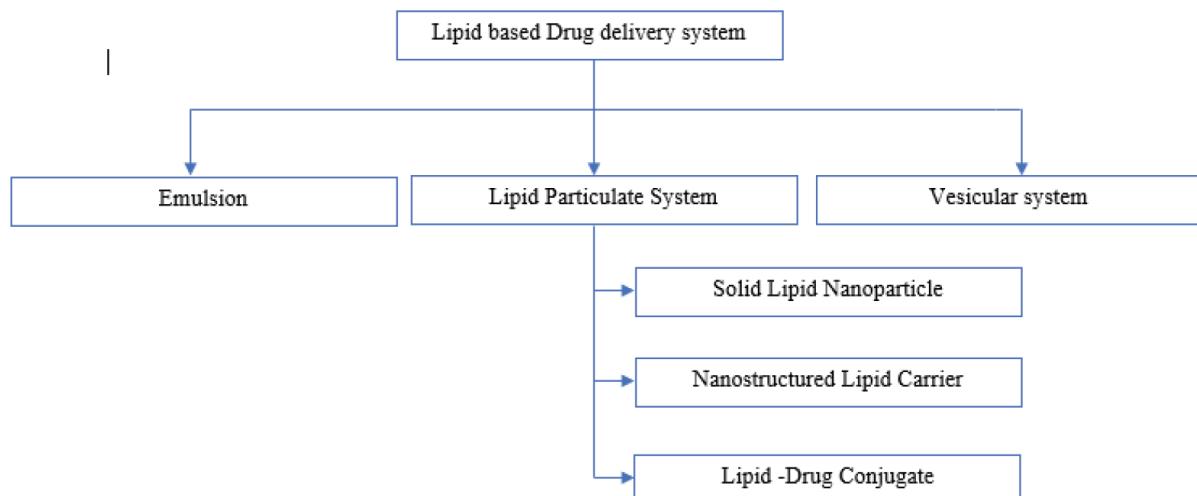


Figure 1. Lipid-based drug delivery system.

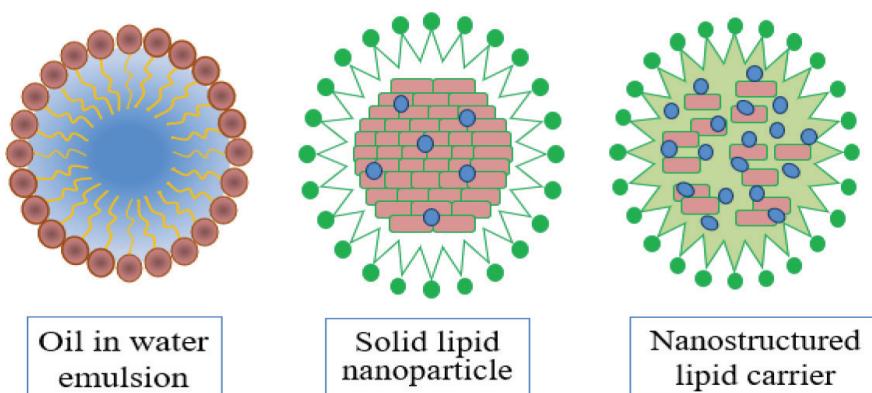


Figure 2. Morphological models of emulsion, SLN, and NLC.

Based on the background above, this review is designed to provide a comprehensive overview of NLCs as an effective delivery system through the skin for natural active ingredients. In addition to the dermal delivery system, the advantages and limitations are explored, including various types, lipids, and surfactants used in the formulation, preparation methods, and characterization. Recent developments are also discussed, showing the promising potential of NLCs for enhancing the dermal delivery of natural active ingredients.

An electronic search was conducted across PubMed, Springer Link, Science Direct, and Google Scholar to explore the application of NLCs in Dermal Drug Delivery System for Natural Active Ingredients. A comprehensive systematic search was performed by using several keywords, including Dermal drug delivery, NLCs, Natural active ingredients, NLCs for dermal delivery, NLCs for natural active ingredients, Natural active ingredients for dermal. Studies were included in the analysis after meeting the inclusion criteria, namely (1) the study was published between 2007 and 2023, and in English text (2) complete article, and (3) provides data that is appropriate to the scope of the review, specifically transdermal and topical dermal delivery. However, studies were excluded when published in a proceeding and not in a complete article.

Dermal delivery system for natural active ingredient

Dermal delivery system plays a crucial role in transporting drugs or active ingredients through the skin to achieve therapeutic benefits (Brown et al. 2008). Over the past two decades, extensive research has been conducted to overcome the skin barrier, enhancing the effectiveness of pharmaceutical and cosmetic products (Kim et al. 2020). This method includes applying a substance to the skin, which is absorbed and delivered to the target organ or tissue.

Several advantages are associated with dermal delivery system over other drug administration techniques such as through the oral route or by injection. This method allows for a more consistent and predictable dose of medication, minimizing the risk of side effects related to other techniques. Due to convenience and non-invasiveness, patients who have difficulty swallowing pills or require long-term therapy prefer dermal delivery system. Furthermore, it is a versatile method suitable for both therapeutics and cosmetics to provide sustained as well as controlled release of drugs and other substances (Garcès et al. 2018; Kim et al. 2020).

Despite these numerous benefits, dermal delivery possesses some limitations, hindering its suitability for some drugs due to physicochemical properties. These include poor water solubility, slow permeability/absorption, and poor stability, with the skin barrier limiting the amounts of drugs penetrated. Additionally, skin irritation or other adverse effects may occur at the application site. To overcome these limitations, several strategies can be employed such

as using carrier systems including nanostructured lipid carriers (NLCs) (Garcès et al. 2018; Mahant et al. 2018).

Nanostructured Lipid Carriers (NLCs)

Nanostructured lipid carriers (NLCs) are delivery system comprising the combination of solid and liquid lipids as core matrix. This system has an unstructured matrix with a high loading capacity, enhancing its suitability as drug delivery system (Chen et al. 2014). NLCs were developed to address the limitations of early solid lipid nanoparticle (SLN) generation by incorporating a mixture of solid and liquid lipids, along with surfactants, to create a solid or semi-solid core matrix. Generally, surfactants play a crucial role in stabilizing the lipid core, resulting in improved size distribution, homogeneity, and stability of the final NLCs product, with particle diameter ranging from 10 to 1000 nm (Cirri et al. 2012; Guo et al. 2015; Karaman 2015; Garcès et al. 2018).

NLCs have gained significant attention in recent years due to their potential applications in dermal drug delivery. Specifically, NLCs have shown promise as a solution for limited drug penetration, showing improved stability, skin permeation, retention, and therapeutic efficacy. These unique characteristics contribute to the extensive use of NLCs in the dermal delivery of numerous therapeutics in skin disorders, indicating potential in treating skin diseases (Garcès et al. 2018; Mahant et al. 2018; Souto et al. 2020).

Several studies are focused on the development of NLCs for targeted dermal applications of antifungals such as luliconazole, quercetin, and fluconazole to show their potential in treating fungal skin infections (Nogueira et al. 2022). Luliconazole, an antifungal agent, showed high antifungal activity against *Trichophyton* spp., causing dermatophytosis. However, the limitations associated with Luliconazole include less skin retention, low aqueous solubility, and poor skin penetration. To overcome these drawbacks, Baghel et al. (2020) explored NLCs as a delivery system for luliconazole. Another study investigated the deposition and permeation of quercetin, a natural antifungal compound, from NLCs into the skin. The results showed that the amount of quercetin deposited into the epidermis and dermis from NLCs was significantly higher, suggesting enhanced delivery of antifungal agents into the skin (Elmowafy et al. 2021). Furthermore, the topical delivery of fluconazole, an antifungal drug, has been evaluated to show its potential therapeutic efficacy in treating cutaneous fungal infections. In the experiment, NLCs showed good skin-targeting effects, resulting in effective localized treatment and sustained release of fluconazole. The lowest number of colony-forming units (cfu/ml) was detected in subjects receiving fluconazole-loaded NLCs (Gupta et al. 2017).

Due to good skin-targeting effects, NLCs are a promising option for topical drug delivery. Previous studies

have tested the potential for treating psoriasis, dermatitis, bacterial infections, skin cancer, and atopic dermatitis (eczema) (Mahant et al. 2018; Waikar et al. 2022). The results showed a significant efficiency in improving the dermal applications of N-acetyl glucosamine for skin diseases (Aliasgharlow et al. 2016) and lipophilic calcipotriol and hydrophilic methotrexate for psoriasis treatment (Jaiswal et al. 2014). Topical formulations have also been developed with this system to treat systemic inflammatory autoimmune diseases, such as rheumatoid arthritis. In other studies, NLCs are examined for the topical delivery of antioxidants, showing their ability to protect the skin from the harmful effects of free radicals and UV radiation, leading to oxidative stress and photoaging. Moreover, NLCs loaded with both alpha-mangosteen and resveratrol showed enhanced antioxidant activity when topically applied (Samprasit et al. 2022). It was also reported that propolis extract-loaded NLCs increased phenolic and flavonoid contents, indicating enhanced skin regenerative capacity (Elkhateeb et al. 2022). Additionally, the topical application of idebenone-loaded NLCs showed a high sun protection factor (SPF) value of 23, hindering 94–96% of ultraviolet-B rays (Salunkhe et al. 2013).

NLCs have also gained popularity in the cosmetic industry due to potential benefits, such as improved skin hydration, occlusion, bioavailability, and targeting (Chauhan et al. 2020). Arsenie et al. (2020) conducted a study utilizing nanostructured lipid carriers (NLCs) provided with three active ingredients—azelaic acid (AzA), white willow bark extract (WBE), and panthenol—in their investigation of cosmetic formulations. An advanced cosmetic formulation was produced by incorporating NLC-AzA-WBE-Ph into a Carbopol gel; this formulation guarantees an extensive hydration effect. The adherence of lipid nanoparticles to the epidermis results in the formation of a film, which subsequently induces an occlusion effect. An increase in occlusion can be achieved by either diminishing the particle size at a given lipid concentration or increasing the number of particles at a given lipid concentration (Muller et al. 2007). An example of the stabilizing impact of the NLC can be observed with the chemical compound retinol. Retinol has found wide use in the cosmetic industry as an active ingredient against wrinkles. Nonetheless, air oxidation of retinol constituted a significant obstacle to its implementation in the cosmetics industry. In an effort to optimize the components of NLC, Jun et al. (2021) utilized a variety of lipid species to create gradients of carbon chain C8-22, resulting in an amorphous structure. Sufficient spaces were estimated within the capsules to accommodate retinol through DSC analysis, which also revealed a lower enthalpy change and peak shift. The retinol-loaded NLC exhibited a restricted size distribution with a PDI value below 0.3, a scaled particle size of less than 200 nm, and an all-negative surface charge of approximately -50 mV. It retained a stable retinol concentration of 90% or higher after four weeks of storage at temperatures of 25, 40, and 50 °C.

The use of NLCs requires certain qualities and properties for effective topical or transdermal administration. For instance, NLCs for cutaneous delivery of drugs typically have particles in the submicron size ranging from 40 to 1000 nm, based on the composition of lipids. A smaller particle ensures close contact with the stratum corneum (SC) to improve the skin penetration of the loaded active compound. When used topically, NLCs should be biocompatible and skin-safe, without causing irritation or other unpleasant effects (Chauhan et al. 2020).

In addition to size and safety considerations, NLCs should enable high drug loading to ensure a sufficient amount of the active ingredient is encapsulated for therapeutic efficacy. Drug loading is improved by optimizing formulation parameters, such as the types and concentrations of lipids, surfactants, and co-surfactants. Generally, NLCs have a higher drug-loading capacity than SLNs and encapsulate from 5% to over 20% active substances, accommodating 30% of some formulations. To guarantee stability, controlled release, and effective dermal distribution while avoiding potential side effects or irritation, the exact amount of the loaded drug should be optimized during the formulation process.

Advantages and limitations

NLCs enhance the chemical stability of active ingredients by minimizing the release of loaded unstable compounds from the lipid structure and maintaining the physical quality of topical formulations during storage. Due to the less ordered structural arrangement, this improved version of SLNs also has a controlled-release characteristic and less proneness to aggregation when compared to emulsions. Other advantages include the ability of NLCs to reduce the water content of emulsion, ensure transdermal permeation with nanosized particles, prolonged half-life, and enable tissue-targeted drug delivery (Mahant et al. 2018; Nogueira et al. 2022). Additionally, NLCs enhance the efficacy and potency of active ingredients and can regulate the release of drugs while delivering active ingredients with varying polarity (Shi et al. 2016; Huang et al. 2017; Ahmad et al. 2018; de Barros et al. 2022).

Despite the promising drug delivery, NLCs technology has several drawbacks. These include the selection of surfactants cautiously to avoid irritation and sensitivity. Applications and efficiencies of NLCs in delivering proteins and peptide drugs and for targeted gene delivery are still not fully investigated. Furthermore, there are limited pre-clinical and clinical studies on NLCs (Khosa et al. 2018; Chauhan et al. 2020; Haider et al. 2020).

Different types of NLCs

The summaries of three types of NLCs are stated below (Balamurugan and Chintamani 2018; Nogueira et al. 2022):

1. Type 1 NLCs (Imperfect).

Type I NLCs have an imperfect crystal core structure due to the partial replacement of a portion of solid lipid with liquid or oil. Moreover, this type has a high loading capacity and excellent drug release profiles.

2. Type 2 NLCs (Amorphous/structureless).

Mixing solid lipids with specific lipids that stay in a polymorph after solidification leads to the production of type 2 NLCs. The use of medium-chain triglycerides, hydroxyoctacosanyl, hydroxy stearate, or isopropyl myristate in conjunction with solid lipids has been found to yield the desired outcome. This type is generally preferred due to the absence of crystallization and the drug remains incorporated in the amorphous matrix. Consequently, drug release induced by the crystallization process to β forms during storage can be avoided.

3. Type 3 NLCs (Multiple).

Type 3 NLCs are conceptually developed from w/o/w emulsion. When the loaded drug has high oil solubility, this method can be used to formulate NLCs with increased loading capacity and stability. In this method, small droplets of oil are consistently dispersed throughout a solid lipid matrix in an aqueous phase.

The morphological models of all types of NLCs are shown in Fig. 3.

Lipids

NLCs are formulated using several excipients, including both solid (fats) and liquid lipids (oils), surfactants, and water. Creating the right lipid mixture is essential to producing NLCs with acceptable characteristics. Moreover, the selection of lipids and their proportions is based on the solubility of the active pharmaceutical ingredient and

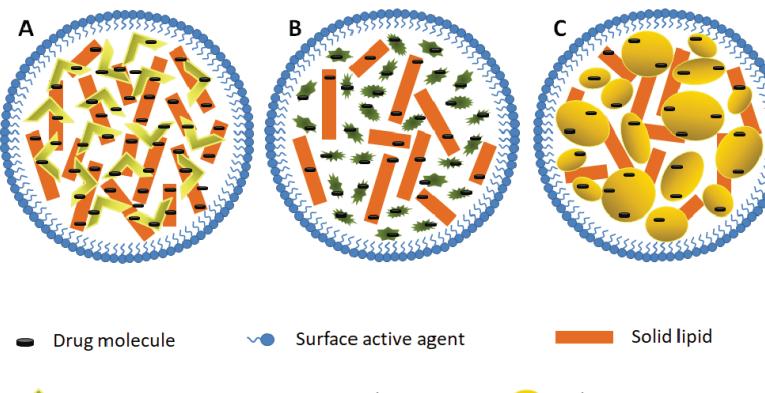
characteristics within the lipids such as types of carbon chains, length in solid lipids, polarity, solubility, and viscosity. Several lipids have been used to build a nano-lipid carrier matrix in NLCs, including phospholipids, fatty acids, wax esters, and triglycerides (Muller et al. 2007; Tamjidi et al. 2013; Wang et al. 2014; Khosa et al. 2018; Chauhan et al. 2020; Haider et al. 2020; Elmowafy and Al-Sanea. 2021; Pradhana and Rithidej 2023)

Phospholipids

Phospholipids contain a phosphate group and are commonly found in biological membranes. Due to good biocompatibility and stability, phospholipids have been frequently used to improve the stability of NLCs and drug delivery properties. Moreover, their application as lipids can affect the characteristics of the resulting NLCs, such as size, drug-loading capacity, and release pattern. For every formulation, suitable phospholipids are selected based on the specific needs of the drugs or the bioactive components to be encapsulated. Phospholipids that have been applied include soy lecithin, phosphatidylcholine, dipalmitoylphosphatidylcholine (DPPC), and synthetic phospholipids.

Fatty acids

Fatty acids comprise a long chain of carbon atoms derived from natural sources, such as olive, coconut, and palm oils. Furthermore, fatty acids are frequently used in the formulation of NLCs to create a stable lipid matrix for drug delivery. Examples of commonly used fatty acids include oleic, stearic, palmitic, and arachidic acids. Oleic acid is a monounsaturated fatty acid serving as a liquid lipid component that modulates the drug-loading capacity and stability of the carriers. Stearic, palmitic, and arachidic (C20) acids are saturated fatty acids used as the solid lipid that shapes the carrier's structure and stability.



Different types of NLCs.
(A) Imperfect; (B) Amorphous; and (C) Oil-in-fat-in-water

Figure 3. Morphological models of different types of nanostructured lipid carriers (NLCs).

Wax esters

Wax esters are composed of a long-chain fatty acid and alcohol. With a high melting point and good stability, this lipid is suitable as a solid lipid carrier in NLCs. Furthermore, wax esters stabilize the carrier's lipid matrix and can be combined to produce the required properties. Some commonly used wax esters are palmitate esters, carnauba wax, beeswax, and propolis wax.

Triglycerides

Triglycerides are composed of a glycerol molecule and three fatty acids. This type of lipid is used in the formulation of NLCs to improve the encapsulated active component chemical stability, film generation, and controlled occlusion. Furthermore, triglycerides produce cosmetics with favorable skin hydration and bioavailability. Some frequently used triglycerides are medium-chain triglycerides (MCTs), such as caprylic triglyceride, and glyceryl behenate.

Cationic lipids

Cationic lipids are positively charged and are commonly used in NLCs for nucleic acid delivery, such as gene therapy. Furthermore, cationic NLCs (cNLCs) can be identified through the presence of at least one cationic lipid, which accounts for the distinct characteristics. Furthermore, their interaction with negatively charged nucleic acids through electrostatic interactions enhances encapsulation and delivery. DOTAP (1,2-dioleoyl-3-trimethylammonium-propane) and octadecylamine (OA) are examples of cationic lipids used in NLC formulation (Xu et al. 2022; Tucak-Smajic et al. 2023).

Ionizable lipids

Depending on the surrounding pH, ionizable lipids can be protonated or deprotonated. This characteristic is essential in the transport of mRNA through lipid nanoparticles. Ionizable lipids, such as Dlin-MC3-DMA, SM-102, and ALC-0315 (Zhang et al. 2023), can be positively charged in acidic endosomal compartments. These characteristics enable endosomal escape and cytoplasmic delivery, which is crucial for lipid nanoparticles, particularly NLCs, in nucleic acid delivery, such as mRNA. Apart from Dlin-MC3-DMA, SM-102 has also received more attention for its use in lipid nanoparticle formulations for mRNA vaccines. In these nanoparticles, SM-102 serves as a lipid system component behind their ability to carry mRNA payloads into cells. ALC-0315 is a third ionizable lipid found in approved lipid nanoparticles, playing a significant part in nucleic acid transport (Gonzalez-Rioja et al. 2023).

Several factors are considered during the selection of lipids in developing a nanolipid carrier structure for

natural ingredients. The selected lipid should possess the ability to solubilize the natural ingredient while maintaining its stability and activity. Compatibility with the natural ingredient and biocompatibility are also crucial, ensuring no adverse effects on the skin or other tissues. Additionally, good thermodynamic stability and desirable physicochemical properties are required. The melting point, viscosity, and surface tension of the lipid should be appropriate for processing and formulation.

Surfactants

Surfactants play a crucial role in shaping the colloidal properties such as viscosity and capacity of NLCs to dissolve hydrophobic components and preserve the stability of nanosized lipid particles. Furthermore, the selection for NLC formulation is based on several factors, namely desired route of administration, hydrophilic-lipophilic balance (HLB), potential lipid and particle size modification, including contributions to *in vivo* lipid degradation. Surfactants have an amphiphilic structure that lowers surface tensions and promotes particle partitioning into hydrophilic (attracted to water) and hydrophobic (attracted to lipids) groups. This behavior is considered in selecting and obtaining physicochemically compatible surfactants and lipids. The HLB value measures the hydrophilicity/lipophilicity degree of a surfactant molecule from the strength and size of its lipophilic and hydrophilic moieties. Surfactants can be cationic, amphoteric, anionic, or non-ionic. Pluronic F68, polysorbate (Tween), polyvinyl alcohol, poloxamer 188, and sodium deoxycholate, are the most widely used hydrophilic emulsifiers. Lecithin and Span® 80 are two examples of lipophilic and amphiphilic emulsifiers frequently added to the NLC formula. Moreover, the combination of more than one emulsifier leads to the effective inhibition of inhibits particle aggregation (Muller et al. 2007; Tamjidi et al. 2013; Wang et al. 2014; Khosa et al. 2018; Chauhan et al. 2020; Haider et al. 2020).

Table 1 shows the examples of natural active ingredients loaded into NLCs, and their preparation mechanism, including the lipids and surfactants used from numerous published articles.

NLC Preparation methods

Natural ingredients can be loaded into nano lipid carriers to create advanced product formulation in numerous techniques and systems. These include high-pressure homogenization (HPH), high-shear homogenization followed by ultrasonication, microemulsion, solvent emulsification/evaporation, membrane contactors, phase inversion (separation), and coacervation (Ganesan and Narayanasamy 2017; Khosa et al. 2018; Chauhan et al. 2020; Duong et al. 2020; Haider et al. 2020).

Table 1. List of different natural active ingredients incorporated into nanostructured lipid carriers (NLCs) in the literature.

Natural active ingredient	Excipient Use		Particle size (nm)	Reference
	Lipid	Surfactant		
Alfa lipoic acid	MCT, Campritol 888-ATO	Soya lecithin	60.1	Li et al. 2021
Astaxanthin	Stearic acid, Glyceryl palmitostearate (Precirol® ATO 5)	Poloxamer 407	100	Salatti-dorado et al. 2019
Baicalin	Miglyol® 812, Precirol® ATO 5 GMS, MCT	Pluronic® F68 Soybean lecithin	92 244.7	Shi et al. 2016 Luan et al. 2015
Cardamom essential oil	Olive oil, Cocoa butter	Tween 80	<150	Keivani-Nahr et al. 2018
Curcumin	Caprylic/capric triglyceride, GMS Caprylic/capric triglycerides, stearic acid MCT, stearic acid	Soya lecithin, Pluronic F-127 Tween 80 and Pluronic F127 Tween 80	263.9 225.8 200–500	Chen et al. 2016 Behbahani et al. 2019 Chanburee and Tiyaboonchai 2017
Curcuminoid	MCT, Precirol® ATO 5	Poloxamer 188, Span 80	148–225	Dolatabadi et al. 2021
Ferulic Acid	IPM Cetyl palmitate, Gliceryl Oleate, isopropyl myristate, isopropyl palmitate, and isopropyl stearate (IPS)	Kolliphor RH40, Labrafil, Softisan 100	<150 <100	Carbone et al. 2020 Carbone et al. 2014
Ganoderma triterpenoids	MCT, Oleanolic acid, GMS	Poloxamer F68	164.42	Shen et al. 2015
Genistein	GMS, MCT	Poloxamer F68	304.8	Andrade et al. 2014
Hesperetin	MCT, Gliseryl behenate GMS, hexadecyl palmitate, amaranth oil, pumpkin seed oil	Sorbitan monooleate, POE-40 hydrogenated castor oil (HCO-40), Tween 20, phosphatidylcholine, Synperonic PE	100 110–125	Simao et al. 2020 Lacatusu et al. 2018
Quaracetin	MCT, Stearic acid MCT	Soya lecithin Tween 80, Span 20, lecithin	215.2 34–47	Chen-yu et al. 2012 Aditya et al. 2014
Rosmarinus officinalis L., Lavandula Origanum vulgare and Thymus capitatus essential oils	Isopropyl myristate (IPM)	Kolliphor RH40 (Polyoxyxl 40 hydrogenated castor oil), Labrafil (Oleoyl Macrogol-6 Glycerides), Softisan 100 (Hydrogenated Coco-Glycerides)	< 200	Carbone et al. 2018
Silybin	GMS, MCT	lecithin, Pluronic F68	232.1	Jia et al. 2010
Thymol	Calendula oil, illipe butter	Pluronic F68	107.7	Pivetta et al. 2018
Turmeric extract	Miglyol 812, Campritol 888-ATO	Poloxamer 407	112.4	Karimi et al. 2018
Ursolic acid	Capryol-90, Glyceryl Monostearate (GMS)	Tween 80	120	Ahmad et al. 2018

High-pressure homogenization (HPH)

A high-pressure homogenizer (HPH) is a compartment where excipients are passed through a micro-size nozzle at a high pressure ranging from 100 to 2000 bar. This process exerts mechanical and thermodynamic pressures on the excipients, generating high shear stress from strong turbulent eddies and cavitation forces, simultaneously reducing pressure along the nozzle. HPH can break down the lipid matrix and emulsify natural ingredients into nanosized droplets, offering technical feasibility that facilitates production upscaling to formulate NLCs. However, this mechanism produces sub-micrometer particles, which is the main drawback of HPH.

High-shear homogenization (HSH) and ultrasonication

High-shear homogenization is a straightforward dispersal method for producing NLCs. The process commences with melting solid lipid at 5–10 °C, followed by stirring the heated lipid with an aqueous phase (surfactant) to the same temperature at high speed to form an emulsion. Subsequently,

the mixture is dispersed through a homogenization valve and ultrasonicated to reduce the size of the resulting droplets. The warm emulsion is gradually cooled to a temperature at which lipids crystallize to create nanosized dispersions and ultracentrifuged to obtain concentrated dispersions. The resulting lipid nanoparticles have physicochemical and biopharmaceutical characteristics suitable for topical applications. However, the combination of this technique generates microparticles as a byproduct that impairs the nanocarrier quality. In addition, ultrasonication can introduce metal contaminants to the formulation.

Microemulsion

Microemulsion is a simple method for developing NLCs, although the use of organic solvents is not recommended. This method exposes active drugs to high temperatures, which can be challenging for thermolabile substances. Initially, the bulk lipid is melted at 10 °C higher above its melting point, followed by the solubilization of the drug. The melted phase is added to the heated aqueous phase, such as surfactant and co-surfactants, and disturbed mechanically to produce an oil-in-water (o/w) microemulsion.

Subsequently, the microemulsion can be cooled rapidly to 2–3 °C in an ice-water bath while simultaneously agitated or added to the cold aqueous phase dropwise. The sudden temperature change causes lipids to crystallize, forming NLCs.

Solvent emulsification/evaporation

Precipitating an o/w emulsion in an aqueous phase is essential to create NLCs using the solvent emulsification/evaporation method. In an aqueous phase, bulk lipids dissolved in a water-impermeable organic solvent are emulsified and the remaining solution is immediately precipitated to form nanoparticles. Compared to microemulsion, solvent evaporation does not include thermal stress induction but entails the dissolution of natural ingredients in a suitable solvent and evaporation, leaving behind nanosized lipid particles. However, organic solvents such as acetone, dichloromethane, ethyl acetate, and acetic acid may be present in the final product, which is a limitation of this technique.

Membrane contactors

Melted lipid is forced through the membrane pores by a cylindrical device called a membrane contactor, resulting in the formation of tiny droplets. These droplets are removed by surfactants while moving through the aqueous phase inside the membrane module. The aqueous phase is maintained at the lipid melting point. NLCs are created when nanoparticles near the pore outlets are cooled to room temperature. This technique can change the membrane pore size to alter particle size.

Phase inversion temperature (PIT)

Phase inversion is the interconversion between o/w and w/o emulsions due to thermal modifications, occurring at ‘phase inversion temperature’ (PIT). In this method, nanoparticles are formed by several mechanisms, including spontaneous inversion through freezing-and-heating cycles and lipid crystallization induced by irreversible thermal shocks that break emulsions.

Coacervation

The technique forms nanoparticles from the coacervation of oppositely charged lipids and natural ingredients. In coacervation, NLCs are prepared by acidifying a micellar solution consisting of alkali salts of fatty acids. Before acidification, a polymeric stabilizer is added to water and heated to create a stock solution. To create a clear solution, the stock solution is heated above its Krafft temperature, while continuously agitated. The sodium salts of fatty acids are added, evenly distributed, and heated. The drug (dissolved in ethanol) is added to the clear solution while stirred continuously until a separate phase is formed. The mixture is added with coacervate gradually by acidification to produce a suspension. Subsequently, the suspension is cooled in a water bath and constantly agitated to obtain well-dispersed drug-loaded nanoparticles. Among the above techniques, several NLCs have been developed and tested using HPH due to its inclusion of cooling technology, energy efficiency, sustainability, and environmental friendliness. The preparation methods of NLCs are tabulated in Fig. 4, while Table 2 summarizes both the techniques and lipids used.

Table 2. Overview of methods, solid lipids, and liquid lipids used to prepare nanostructured lipid carriers (NLCs).

Method	Solid Lipid	Liquid Lipid	Particle size (nm)	Reference
Emulsion evaporation	GMS (monoglyceride)	Caprylic/capric triglyceride (triglyceride)	263.9	Chen et al. 2016
	Stearic acid (fatty acid)	Caprylic/capric triglyceride (triglyceride)	263.9	Chen et al. 2016
	Stearic acid (fatty acid)	MCT (triglyceride)	215.2	Chen-yu et al. 2012
Hot melt emulsification	Compritol 888 ATO (fatty acid ester)	MCT (triglyceride)	60.1	Li et al. 2021
	Illipe butter (triglyceride)	Calendula oil (fatty acid, triacylglycerol)	107.7	Pivetta et al. 2018
High-pressure homogenization	GMS (monoglyceride)	MCT (triglyceride)	164.42	Shen et al. 2015
	GMS (monoglyceride)	Oleanolic acid	164.42	Shen et al. 2015
	Precirol® ATO 5 (fatty acid ester)	Miglyol® 812 (triglyceride)	92	Shi et al. 2016
High-shear homogenization	Compritol 888-ATO (fatty acid ester)	Miglyol 812 (triglyceride)	112.4	Karimi et al. 2018
	Compritol 888-ATO (fatty acid ester)	MCT oil (triglyceride)	148–225	Dolatabadi et al. 2021
	Cocoa butter (triglyceride)	Olive oil (triglyceride)	<150	Keivani-Nahr et al. 2018
	Precirol® ATO 5 (fatty acid ester)	Squalene (triterpenoid hydrocarbon)	190–310	Huang et al. 2008
	Precirol® ATO 5 (fatty acid ester)	MCT (triglyceride)	148–225	Dolatabadi et al. 2021
Microemulsion	Stearic acid (fatty acid)	Caprylic/capric triglycerides (triglyceride)	225.8	Behbahani et al. 2019
	Stearic acid (fatty acid)	MCT (triglyceride)	200–500	Chanburee and Tiyaboonchai 2017
Phase inversion temperature	Glyceryl behenate (fatty acid)	MCT (triglyceride)	100	Simao et al. 2020
Probe-ultrasonication	Stearic acid (fatty acid)	Oleic acid (fatty acid)	240	Kelidari et al. 2016

GMS: Glyceryl monostearate; MCT: medium-chain triglyceride.

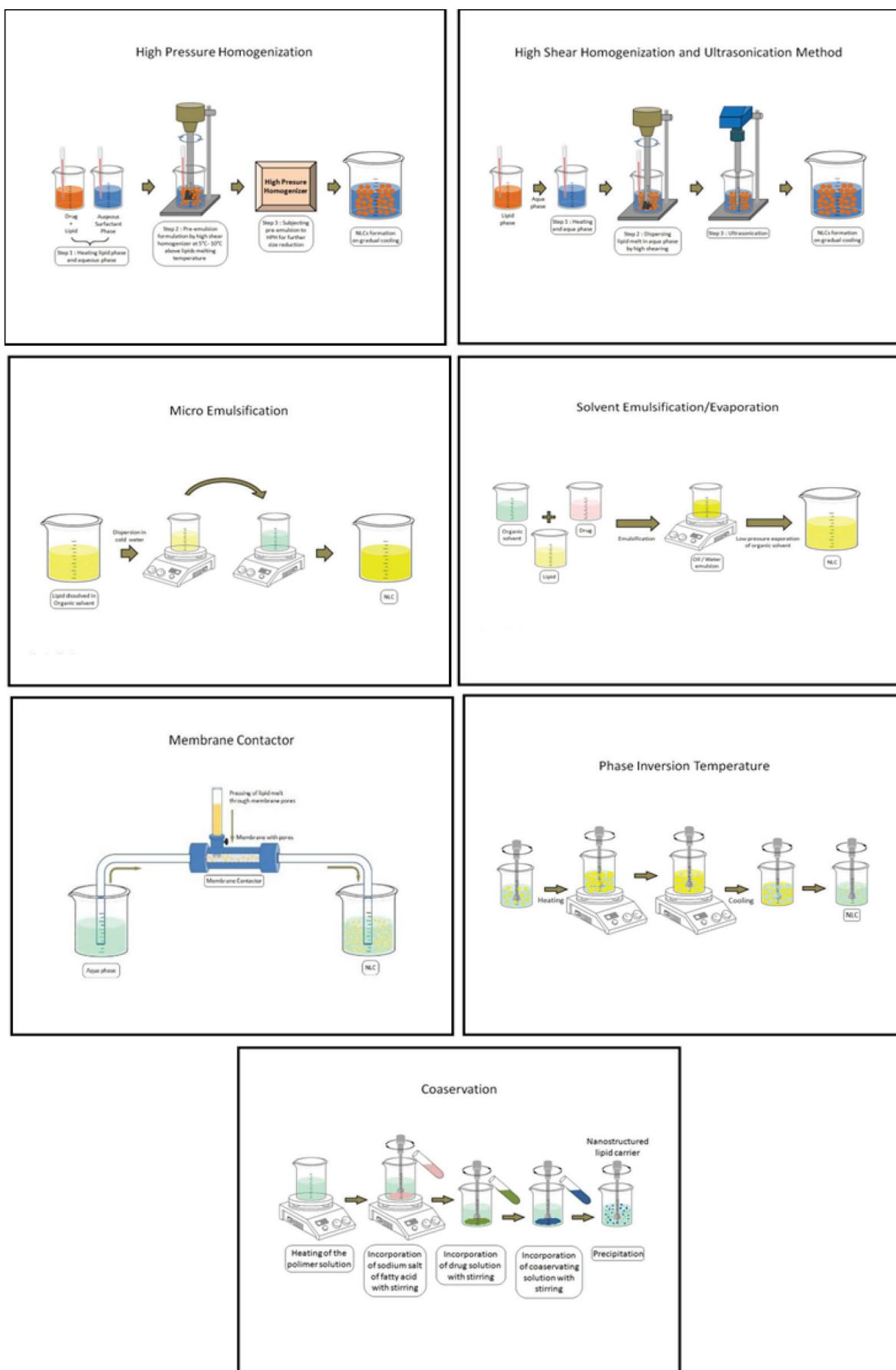


Figure 4. NLC Preparation Methods: High pressure homogenization; High shear homogenization and ultrasonication, Microemulsion, Solvent emulsification/ evaporation, Membrane contractor, Phase inversion temperature, Coacervation.

NLC Characterization

Physicochemical characterization is required to control and confirm the quality and stability of NLCs produced. Furthermore, information on physical and chemical properties can facilitate the optimization of design for improved efficacy, stability, and safety. Some common techniques used to characterize NLCs are stated below (Chauhan et al. 2020; Nogueira et al. 2022).

1. Particle size analysis.

Particle size is an essential parameter affecting the stability, bioavailability, and cellular uptake of NLCs. To measure the size distribution, techniques such as dynamic light scattering (DLS) and nanoparticle tracking analysis (NTA) can be used. Generally, NLCs for cutaneous delivery of drugs typically have submicron particle sizes ranging from 40 to 1000 nm based on the lipids composition.

2. Zeta potential analysis.

The zeta potential (ZP) is a determining factor of the nano dispersion's stability, describing the surface charge and showing long-term stability. Furthermore, ZP is calculated using electrophoretic mobility of the particle in aqueous media. At higher values, particle aggregation due to electrostatic repulsion has a lower probability of occurrence. Meanwhile, at lower ZP, there is a higher possibility for dispersions to coagulate or flocculate, potentially reducing stability. For electrostatically stable NLCs, the ZP of dispersion should be less than -30 mV or above +30 mV. The value of ZP can be measured using electrophoretic light scattering.

3. Morphology analysis.

Transmission and scanning electron microscopies (TEM, SEM) including atomic force microscopy (AFM) are used to examine the surface morphology of NLCs. These techniques are effective for the dimensional and structural characterization of NLCs. TEM is a strong imaging technology enabling a high-resolution study of the internal structure and morphology of NLCs. It is capable of providing information on lipid nanoparticle's size, shape, and distribution. Meanwhile, SEM is used to investigate the surface morphology including roughness and shape of NLC particles. For this analysis, the sample is prepared by placing it on a gold or copper grid with a known mesh size, followed by staining using a heavy metal salt solution for high contrast in the electron microscope. After drying, the sample is examined under an electron microscope, where nanoparticles are identified against a dark background. Moreover, dehydration during sample preparation can alter the initial shape or structure of nanocarriers.

AFM is used at the nanoscale to analyze the surface topography and mechanical characteristics of NLC particles, producing data on particle height and roughness. This method is a simple and non-in-

vasive technology used to monitor and control the morphology as well as the size of lipid nanoparticles. The samples used in AFM are prepared by removing water to avoid alteration in the emulsifier phase and polymorphism in lipids. This method does not use beams or radiations but rather a sharp-tipped scanning probe attached to the free end of a spring-like cantilever. The interaction between the tip and surface of the specimen is assessed through deflection, oscillation, or shift in resonance frequency of cantilever motion.

4. Entrapment efficiency

Entrapment efficiency (EE) is defined as the ratio of entrapped drug weight to total drug weight added to the dispersion. Subsequently, an ultrafiltration-centrifugation method is used to determine the amounts of drugs encapsulated per unit weight of the NLCs. A known NLC dispersion is prepared, and centrifugation is carried out in a centrifuge tube fitted with an ultrafilter. After suitable dilution, an appropriate analysis method is used to determine the amount of free drug supernatant.

5. *In vitro* release studies

An *in vitro* release study evaluates the kinetics of drug release from NLCs under simulated physiological conditions. In this analysis, NLCs are designed for targeted drug delivery, enabling specific drug localization inside the skin layers. Furthermore, NLCs enable sustained drug release, which is useful for prolonged therapeutic activity. To accomplish this, the lipid matrix is modified for controlling drug release.

6. Crystallinity and polymorphism

The crystallinity and polymorphism of lipids used in NLCs are essential factors in achieving controlled drug release and improving stability as well as efficiency. Meanwhile, differential scanning calorimetry (DSC) is carried out to obtain information about the lipid state, melting, and crystallization behavior of solid lipids in nanostructures. DSC is also used to analyze pure drugs, lipids, and nanoparticles. By conducting DSC, information about the structure of NLCs can be obtained, particularly regarding the mixing behavior of solid and liquid lipids. Increased liquid lipid content also reduces crystallinity and improves imperfections in the highly ordered structure of NLCs. In principle, DSC operates based on varying enthalpy and melting points for different lipid modifications, where lower values result in smaller NLCs with a higher surface area and more surfactants.

Another important tool for determining polymorphic structural changes in compounds is X-ray diffraction (XRD) analysis. The monochromatic X-ray beam is diffracted at different angles based on the type and arrangement of the atoms as well as the spacing between the planes in the crystals. In this process, lipids can cluster in several arrays, resulting in various polymorphic forms such as micelles, lamellar phases, tubular arrangements, and cubic phases.

The layer configuration, crystal structure, phase, and polymorphism of lipid and drug molecules are investigated using wide-angle and small-angle X-ray scattering techniques (WAXS, SAXS). WAXS and SAXS patterns also provide information on the length of the short and long spacings of the lipid lattice and the location of the active substance.

Recent developments in the use of NLCs for natural active ingredient delivery

NLCs are a promising delivery method for hydrophobic drugs (Teeranachaideekul et al. 2008; Soleimanian et al. 2018; Shimojo et al. 2019; Tortorici et al. 2022). In several studies, NLCs show promising results in the delivery of natural products, particularly in improving stability and bioavailability. NLCs also enhance pharmacological activities and provide higher protection from toxicity compared to other nanolipid-based delivery systems (Thakur et al. 2011; Aditya et al. 2014; Krasodomska et al. 2016; Bhise et al. 2017; Huang et al. 2017; Elmowafy et al. 2018). Examples of NLCs are given in this section to highlight their potential as a delivery system for natural medicines, as presented in Table 1.

NLCs increase the effectiveness and bioactivity of natural active ingredients

Several studies have shown that NLCs function as a carrier to enhance the bioactivity and efficacy of natural substances. Quercetin is the flavonoid with the most potent antioxidant activity. In addition to this particular activity, it demonstrates additional pharmacological properties, including anti-inflammatory effects. Chen-Yu et al. (2012) demonstrated that NLC increased the anti-oxidative and anti-inflammatory properties of quercetin, thereby offering potential benefits in the management of inflammatory disorders. Comparatively to the quercetin-containing polyethylene glycol solution, NLC additionally enhanced permeation and increased the quantity of substance retained in the epidermis.

In 2022, de Barros et al. looked into how loading quercetin onto nanostructured lipid carriers made from natural plant oils would work together to fight bacterial skin infections. Five nanostructured lipid carrier systems were designed, each comprising a distinct oil (sunflower, olive, corn, coconut, and castor). The encapsulation of quercetin increased the antioxidant capacity of nanocarriers and decreased their cytotoxicity. Additionally, it was shown that the antibacterial activity of systems containing quercetin against *Staphylococcus aureus* was enhanced (de Barros et al. 2022).

Sesamol, a phenolic compound with antioxidant activity, was one of the ingredients incorporated into NLC.

By incorporating sesamol into an NLC/SLN, Puglia et al. (2017) were able to regulate the rate of sesamol diffusion through the epidermis, thus preserving high concentrations of sesamol in the uppermost layers of skin. Moreover, NLC and SLN extended by 40 hours the antioxidant activity of sesamol.

In Badea et al. (2015), NLCs were developed by combining the active natural ingredient basil oil with the antifungal nystatin. The final products showed high antioxidant activity, 93–96%, while maximum antifungal activity against *Candida albicans* was observed in NLCs with 2% basil oil and 1% nystatin. Karimi et al. (2018) found that turmeric extract had significantly enhanced antioxidant activity when delivered in NLCs. Similarly, antimicrobial activity against all the gram-negative bacilli was observed in microbiological tests by agar dilution.

Furthermore, Chen et al. (2016) through an in vivo study, found that NLC-based curcumin gel showed a significant anti-inflammatory effect when topically administered to rats with auricular edema, without skin irritation. In Shen et al. (2015), GTs showed better therapeutic effects against inflammation when delivered in NLCs than in emulgels.

NLCs increase the stability of natural active ingredients

NLCs are also appropriate for the delivery of unstable natural active ingredients. Mitri et al. (2011) documented an elevation in the chemical and photostability of the carotenoid lutein and lutein subsequent to their integration into NLC. Additionally, compared to free lutein, the NLC formulation increased penetration rates and sustained the release of the active ingredient. Lycopene is another carotenoid that possesses anti-inflammatory and antioxidant properties. This pigment is one of the most potent antioxidants known and is lipophilic. Okonogi and Riangjanapatee (2015) developed NLC to safeguard lycopene, thereby postponing its chemical degradation due to its extreme instability.

Jiamphun and Chainaya (2023) conduct research on the development of nanostructured lipid carriers (NLCs) and assess their efficacy in increasing the stability and delivery of vanillic and ferulic acid in an aqueous enzymatic extract derived from glutinous rice husk. In contrast to a solution, it was observed that NLCs with high entrapment efficiencies effectively encapsulate and protect both vanillic and ferulic acid.

Zheng et al. (2023) analyze co-loaded nanostructured lipid carriers (NLC) with perilla seed oil (PSO) and formononetin (FMN). The formulation design for enhancing the stability and antioxidant activity of FMN while postponing the oxidation of PSO. FMN-PSO-NLC was synthesized melt-emulsification ultrasonic method. The stability and antioxidant capability of FMN-PSO-NLC were notably enhanced.

Cinnamon essential oil (CEO) possesses a number of advantageous characteristics and exhibits promising po-

tential as a nutraceutical. However, it is important to acknowledge that it may also possess certain drawbacks, including inadequate stability against heat, oxygen, and light during processing and storage, as well as an unpleasant taste. Bashiri et al. (2020) did research in which they made NLC that was loaded with cinnamon essential oil (CEO). They did this by mixing different solid lipids (cocoa butter), liquid consumable oils (sesamol, sweet almond, and black seed oil), and a surfactant (Tween 80). The NLC derived from almond oil exhibited encouraging characteristics in terms of enhancing the stability and protection of CEO across various conditions.

Lacatusu et al. (2018), Tsai et al. (2012), and Ruktanonchai et al. (2009) reported that NLCs can enhance the stability of numerous natural active ingredients, including mangiferin, alpha-lipoic acid, baicalein, and hesperidin.

NLCs control drug release and deliver natural active ingredients with different polarity

NLCs have the ability to regulate drug release into the systemic circulation and minimize systemic side effects. This lipid-based system provides a controlled release profile for various active components. According to Lasaón et al. (2016), the terpene release pattern from an NLCs matrix is biphasic, indicating that all active components are gradually released after an initial burst effect. Early initial release (burst effect) can be attributed to large amounts of medicinal ingredients such as oils accumulating in the outer shell of nanoparticles.

The release rate of zedoary turmeric oil from SLNs can also be increased through NLCs, adjusted by modifying

the oil content in the formula (Zhao et al. 2010). Additionally, genistein is released from NLCs gradually than from SLNs (Andrade et al. 2014). In a study by Jia et al. (2010), silybin-loaded NLCs showed larger areas under the tissue concentration-time curve (AUCs) and were circulated in the bloodstream longer compared to silybin solution. This indicated that NLCs offered a sustained release and a targeting system for the antihepatopathic agent. Ahmad et al. (2018), Huang et al. (2017), and Shi et al. (2016) successfully showed the ability of NLCs to prolong the release of several natural active ingredients, including ursolic acid, baicalin, and quercetin.

Conclusion

In conclusion, this review showed the effectiveness of NLCs as drug delivery system with high loading capacity and sustained release patterns suitable for treating skin diseases. The results showed that NLCs had been used for delivering antioxidants, gaining much attention in the cosmetic industry due to their potential benefits in improving skin hydration, occlusion, bioavailability, and skin targeting. This lipid-based system could also be prepared using various techniques and characterized through particle size, ZP, morphology analyses, and drug encapsulation efficiency measurement. However, there are still limitations associated with the technology, such as cytotoxic effects, the need for careful selection compatible with lipids, as well as limited preclinical and clinical studies. To overcome these limitations, further research was recommended to explore the applications of NLCs in delivering proteins, peptide drugs, and targeted genes.

References

- Aditya NP, Macedo AS, Doktorovova S, Souto EB, Kim S, Chang P (2014) Development and evaluation of lipid nanocarriers for quercetin delivery: A comparative study of solid lipid nanoparticles (SLN), nanostructured lipid carriers (NLC), and lipid nanoemulsions (LNE). *LWT – Journal of Food Science and Technology* 59: 115–121. <https://doi.org/10.1016/j.lwt.2014.04.058>
- Ahmad A, Abuzinadah MF, Alkreathy HM, Banaganapalli B, Mujeeb M (2018) Ursolic acid rich *ocimum sanctum* L leaf extract loaded nanostructured lipid carriers ameliorate adjuvant induced arthritis in rats by inhibition of COX-1, COX-2, TNF- α and IL-1. *Pharmacological and docking studies. PLOS ONE* 3: 1–22 [e0193451]. <https://doi.org/10.1371/journal.pone.0193451>
- Akbari Z, Amanlou M, Karimi-sabet J, Golestani A, Niassar MS (2015) Production of ibuprofen-loaded solid lipid nanoparticles using rapid expansion of supercritical solution. *Journal of Nano Research* 31: 15–29. <https://doi.org/10.4028/www.scientific.net/JNanoR.31.15>
- Aliasgharlow L, Ghanbarzadeh S, Azimi H, Zarritan MH, Hamishehkar H (2016) Nanostructured lipid carrier for topical application of N-acetyl glucosamine. *Advanced Pharmaceutical Bulletin* 6(4): 581–587. <https://doi.org/10.15171/apb.2016.072>
- Andrade LM, De Fátima Reis C, Maione-Silva L, Anjos JL V, Alonso A, Serpa RC (2014) Impact of lipid dynamic behavior on physical stability, *in vitro* release and skin permeation of genistein-loaded lipid nanoparticles. *European Journal of Pharmaceutics and Biopharmaceutics* 88(1): 40–47. <https://doi.org/10.1016/j.ejpb.2014.04.015>
- Arsenie LV, Lacatusu I, Oprea O, Bordei N, Bacalum M, Badea N (2020) Azelaic acid-willow bark extract-panthenol – Loaded lipid nanocarriers improve the hydration effect and antioxidant action of cosmetic formulations. *Industrial Crops and Products* 154: 112658. <https://doi.org/10.1016/j.indcrop.2020.112658>
- Badea G, Bors AG, Lacatusu I, Oprea O, Ungureanu C, Stan R (2015) Influence of basil oil extract on the antioxidant and antifungal activities of nanostructured carriers loaded with nystatin. *Comptes Rendus Chimie* 18(6): 668–677. <https://doi.org/10.1016/j.crci.2014.09.012>
- Baghel S, Nair VS, Pirani A, Sravani AB, Bhemisetty B, Ananthamurthy K, Aranjani JM, Lewis SA (2020) Luliconazole loaden nanostructured lipid carriers for topical treatment of superficial Tinea infections. *Dermatologic Therapy* 33(6): e13959. <https://doi.org/10.1111/dth.13959>
- Balamurugan K and Chintamani P (2018) Lipid nanoparticulate drug delivery: An overview of emerging trend. *Journal of Pharmaceutical*

- Innovation 7(7): 779–789. <https://www.thepharmajournal.com/archives/2018/vol7issue7/PartM/7-6-166-872.pdf>
- Bashiri S, Ghanbarzadeh B, Ayaseh A, Dehghannya J, Ehsani A, Ozyurt H (2020) Essential oil-loaded nanostructured lipid carriers: the effects of liquid lipid type on the physicochemical properties in beverage models. Food Bioscience 35: 100526. <https://doi.org/10.1016/j.fbio.2020.100526>
- Behbahani ES, Ghaedi M, Abbaspour M, Rostamizadeh K, Dashtian K (2019) Curcumin loaded nanostructured lipid carriers: *in vitro* digestion and release studies. Polyhedron 164: 113–122. <https://doi.org/10.1016/j.poly.2019.02.002>
- Bhise K, Kashaw SK, Sau S, Iyer AK (2017) Nanostructured lipid carriers employing polyphenols as promising anticancer agents: Quality by design (QbD) approach. International Journal of Pharmaceutics 526(1–2): 506–15. <https://doi.org/10.1016/j.ijpharm.2017.04.078>
- Brown MB, Martin GP, Jones SA, Akomeah FK (2008) Dermal and transdermal drug delivery systems: current and future prospects. Drug Delivery 13(3): 175–187. <https://doi.org/10.1080/10717540500455975>
- Carbone C, Carla C, Maria AG, Daniela EM, Antonio S, Teresa M (2020) Ferulic acid-NLC with Lavandula Essential oil: A Possible Strategy for Wound Healing. Nanomaterials 10: 898. <https://doi.org/10.3390/nano10050898>
- Carbone C, Campisi A, Musumeci T, Raciti G, Bonfanti R, Puglisi G (2014) FA-loaded lipid drug delivery systems: preparation, characterization and biological studies. European Journal of Pharmaceutical Sciences 52: 12–20. <https://doi.org/10.1016/j.ejps.2013.10.003>
- Carbone C, Martins-Gomes C, Caddeo C, Silva AM, Musumeci T, Pignatello R, Puglisi G, Souto EB (2018) Mediterranean essential oil as precious matrix component and active ingredients of lipid nanoparticle. International Journal of Pharmaceutics 548(1): 217–226. <https://doi.org/10.1016/j.ijpharm.2018.06.064>
- Chanburee S, Tiyaboonchai W (2017) Mucoadhesive nanostructured lipid carriers (NLC) as potential carriers for improving oral delivery of curcumin. Drug Development and Industrial Pharmacy 43(3): 432–440. <https://doi.org/10.1080/03639045.2016.1257020>
- Chauhan I, Yasir M, Verma M, Singh AP (2020) Nanostructured lipid carriers : a groundbreaking approach for transdermal drug delivery. Advanced Pharmaceutical Bulletin 10(2): 150–165. <https://doi.org/10.34172/apb.2020.021>
- Chen J, Wei N, Lopez-Garcia M, Ambrose D, Lee J, Annelin C (2017) Development and evaluation of resveratrol, Vitamin E, and epigallocatechin gallate loaded lipid nanoparticles for skin care applications. European Journal of Pharmaceutics and Biopharmaceutics 117: 286–291. <https://doi.org/10.1016/j.ejpb.2017.04.008>
- Chen P, Zhang H, Cheng S, Zhai G, Shen C (2016) Development of curcumin loaded nanostructured lipid carrier based thermosensitive *in situ* gel for dermal delivery. Colloids and Surfaces a Physicochemical and Engineering Aspect 506: 356–362. <https://doi.org/10.1016/j.colsurfa.2016.06.054>
- Chen Y, Quan P, Liu X, Wang M, Fang L (2014) Novel chemical permeation enhancers for transdermal drug delivery. Asian Journal of Pharmaceutical Sciences 9(2): 51–64. <https://doi.org/10.1016/j.ajps.2014.01.001>
- Chen-yu G, Chun-fen Y, Qi-lu L, Qi T, Yan-wei X, Wei-na L, Guang-xi Z (2012) Development of a quercetin loaded nanostructured lipid carrier formulation for topical delivery. International Journal of Pharmaceutics 430: 292–298. <https://doi.org/10.1016/j.ijpharm.2012.03.042>
- Cirri M, Bragagni M, Mennini M, Mura P (2012) Development of a New Delivery System Consisting “Drug-in Cyclodextrin-in
- Nanostructured Lipid Carriers for Ketoprofen Topical Delivery. European Journal of Pharmaceutics and Biopharmaceutics 80(1): 46–53. <https://doi.org/10.1016/j.ejpb.2011.07.015>
- de Barros, DPC, Santos R, Reed P, Fonseca LP, Oliva A (2022) Design of Quercetin-Loaded Natural Oil-Based Nanostructured Lipid Carriers for the Treatment of Bacterial Skin Infections. Molecules 27(24): 8818. <https://doi.org/10.3390/molecules27248818>
- Dolatabadi S, Karimi M, Nasirizadeh S, Hatamipour M, Golmohammadzadeh S, Jaafari MR (2021) Preparation, characterization and in vivo pharmacokinetic evaluation of curcuminooids loaded solid lipid nanoparticles (SLNs) and nanostructured lipid carriers (NLCs). Journal of Drug Delivery Science and Technology 62: 102352. <https://doi.org/10.1016/j.jddst.2021.102352>
- Duong V, Nguyen T, Maeng H (2020) Preparation of solid lipid nanoparticles and nanostructured lipid carriers for drug delivery and the effects of preparation parameters of solvent injection method. Molecules 25: 4781. <https://doi.org/10.3390/molecules25204781>
- Elkhateeb OM, Badawy ME, Noreldin AE, Ahmed HA, el-Kammar MH, Elkheneany HA (2022) Comparative evaluation of propolis nanostructured lipid carrier and its crude extract for antioxidants, antimicrobial activity, and skin regeneration potential. BMC Complementary Medicines and Therapies 22: 256. <https://doi.org/10.1186/s12906-022-03737-4>
- Elmowafy M, Al-sanea MM (2021) Nanostructured lipid carriers (NLCs) as drug delivery platform: Advances in formulation and delivery strategies. Saudi Pharmaceutical Journal 29(9): 999–1012. <https://doi.org/10.1016/j.jsps.2021.07.015>
- Elmowafy M, Shalaby K, Badran MM, Ali HM, Abdel-bakky MS, Ibrahim HM (2018) Multifunctional carbamazepine loaded nanostructured lipid carrier (NLC) formulation. International Journal of Pharmaceutics 550(1–2): 359–371. <https://doi.org/10.1016/j.ijpharm.2018.08.062>
- Feehey OM, Crum MF, McEvoy CL, Trevaskis NL, Williams HD, Pouton CW (2016) 50 years of oral lipid-based formulations: Provenance, progress and future perspectives. Advanced Drug Delivery Review 101: 167–194. <https://doi.org/10.1016/j.addr.2016.04.007>
- Ganesan P, Narayanasamy D (2017) Lipid nanoparticles: Different preparation techniques , characterization , hurdles , and strategies for the production of solid lipid nanoparticles and nanostructured lipid carriers for oral drug delivery. Sustainable Chemistry and Pharmacy 6: 37–56. <https://doi.org/10.1016/j.scp.2017.07.002>
- Garcés A, Amaral MH, Sousa Lobo JM, Silva AC (2018) Formulations based on solid lipid nanoparticles (SLN) and nanostructured lipid carriers (NLC) for cutaneous use: A review. European Journal of Pharmaceutical Sciences 112: 159–67. <https://doi.org/10.1016/j.ejps.2017.11.023>
- Ghodrati M, Farahpour M (2018) Encapsulation of Peppermint essential oil in nanostructured lipid carriers: *In-vitro* antibacterial activity and accelerative effect on infected wound healing. Colloids and Surfaces A: Physicochemical and Engineering Aspect 564: 161–169. <https://doi.org/10.1016/j.colsurfa.2018.12.043>
- Gonzalez-Rioja R, Salazar VA, Bastus NG, Puntes V (2023) The development of highly dense highly protected surfactant ionizable lipid RNA loaded nanoparticles. Frontiers in. Immunology 14: 1129296. <https://doi.org/10.3389/fimmu.2023.1129296>
- Guo F, Wang J, Ma M, Tan F, Li N (2015) Skin targeted lipid vesicles as novel nano-carrier of ketoconazole : characterization, *in vitro* and *in vivo* evaluation. Journal of Material Science: Materials in Medicine 26: 1–13. [175] <https://doi.org/10.1007/s10856-015-5487-2>

- Gupta M, Sharma V, Chauhan NS (2017) Chapter 11 - Promising novel nanopharmaceuticals for improving topical antifungal drug delivery. In: Grumezescu AM (Ed.) Nano-and Microscale Drug Delivery System, 197–228. <https://doi.org/10.1016/B978-0-323-52727-9.00011-X>
- Haider M, Abdin AM, Kamal L, Orive, G (2020) Nanostructured lipid carriers for delivery of chemotherapeutics: A review. *Pharmaceutics* 12: 288. <https://doi.org/10.3390/pharmaceutics12030288>
- Huang J, Wang Q, Li T, Xia N, Xia Q (2017) Nanostructured lipid carrier (NLC) as a strategy for encapsulation of quercetin and linseed oil: Preparation and *in vitro* characterization studies. *Journal of Food Engineering* 215: 1–12. <https://doi.org/10.1016/j.jfoodeng.2017.07.002>
- Huang Z, Hua S, Yang Y, Fang J (2008) Development and evaluation of lipid nanoparticles for camptothecin delivery: a comparison of solid lipid nanoparticles , nanostructured lipid car-riers, and lipid emulsion. *Acta Pharmacologica Sinica* 29(9): 1094–1102. <https://doi.org/10.1111/j.1745-7254.2008.00829.x>
- Jaiswal P, Gidwani A, Vyas A (2014) Nanostructured lipid carriers and their current application in targeted drug delivery. *Artificial cells, Nanomedicine and Biotechnol ogy* 44(1): 27–40. <https://doi.org/10.3109/21691401.2014.909822>
- Jia L, Zhang D, Li Z, Duan C, Wang Y, Feng F (2010) Nanostructured lipid carriers for parenteral delivery of silybin: Biodistribution and pharmacokinetic studies. *Colloids Surfaces B: Biointerfaces* 80(2): 213–218. <https://doi.org/10.1016/j.colsurfb.2010.06.008>
- Jiamphun S, Chainaya W (2023) Enhancing skin delivery and stability of vanillic and ferulic acids in aqueous enzymatically extracted glutinous rice husk by nanostructured lipid carriers. *Pharmaceutics* 15(7): 1961. <https://doi.org/10.3390/pharmaceutics15071961>
- Jun S, Kim H, Lee H, Song JE, Park SG, Kang N (2021) Synthesis of retinol-loaded lipid nanocarrier via vacuum emulsification to improve topical skin delivery. *Polymers* 13(5): 826. <https://doi.org/10.3390/polym13050826>
- Kamel R, Mostafa DM (2015) Rutin nanostructured lipid cosmeceutical preparation with sun protective potential. *Journal of Photochemistry and Photobiology B: Biology* 153: 59–66. <https://doi.org/10.1016/j.jphotobiol.2015.09.002>
- Karaman EF (2015) Formulation and characterization of solid lipid nanoparticles, nanostructured lipid carriers and nanoemulsion of lornoxicam for transdermal delivery. *Acta Pharmaceutica* 65: 1–13. <https://doi.org/10.1515/acph-2015-0009>
- Karimi N, Ghanbarzadeh B, Hamishehkar H, Mehramuz B, Kafil HS (2018) Antioxidant, Antimicrobial and Physicochemical Properties of Turmeric Extract-Loaded Nanostructured Lipid Carrier (NLC). *Colloids and Interface Science Communications* 22: 18–24. <https://doi.org/10.1016/j.colcom.2017.11.006>
- Keivani-Nahr F, Ghanbarzadeh B, Hamishehkar H, Samadi Kafil H (2018) Food grade nanostructured lipid carrier for cardamom es-sential oil: Preparation, characterization and antimicrobial activ-ity. *Journal Functional Foods* 40: 1–8. <https://doi.org/10.1016/j.jff.2017.09.028>
- Kelidari HR, Saeedi M, Hajheydari Z, Akbari J, Morteza-Semnani K, Akhtari J (2016) Spironolactone loaded nanostructured lipid carrier gel for effective treatment of mild and moderate acne vulgaris: A ran-domized, double-blind, prospective trial. *Colloid and Surfaces B: Bio-interfaces* 146: 47–53. <https://doi.org/10.1016/j.colsurfb.2016.05.042>
- Khosa A, Reddi S, Saha R (2018) Nanostructured lipid carriers for site specific drug delivery. *Biomedicine and Pharmacotherapy* 103: 598–613. <https://doi.org/10.1016/j.biopha.2018.04.055>
- Kim B, Cho HE, Moon SH, Ahn HJ, Bae S, Cho HD, An S (2020) Trans-dermal delivery systems in cosmetics. *Biomedical Dermatology* 4: 10. <https://doi.org/10.1186/s41702-020-0058-7>
- Krasodomksa O, Paolicelli P, Cesa S, Casadei MA, Jungnickel C (2016) Protection and viability of fruit seeds oils by nanostructured lipid carrier (NLC) nanosuspensions. *Journal of Colloid and Interface Sci-ence* 479: 25–33. <https://doi.org/10.1016/j.jcis.2016.06.041>
- Lacatusu I, Arsenie LV, Badea G, Popa O, Oprea O, Badea N (2018) New cosmetic formulations with broad photoprotective and antioxi-dative activities designed by amaranth and pumpkin seed oils nano-carriers. *Industrial Crops and Products* 123: 424–433. <https://doi.org/10.1016/j.indcrop.2018.06.083>
- Lasoń E, Sikora E, Ogonowski J, Tabaszewska M, Skoczylas Ł(2016) Re-lase study of selected terpenes from nanostructured lipid carriers. *Colloids and Surfaces A: Physicochemical and Engineering Aspects* 510: 87–92. <https://doi.org/10.1016/j.colsurfa.2016.06.021>
- Li Q, Gong S, Yao W, Yu Y, Liu C, Wang R, Pan H, Wie M (2021) PEG-interpenetrated genipin-crosslinked dual-sensitive hydrogel/ nanostructured lipid carrier compound formulation for topical drug administration. *Artificial Cells Nanomedicine and Biotechnology* 49(1): 345–353. <https://doi.org/10.1080/21691401.2021.1879104>
- Liu Y, Feng N (2015) Nanocarriers for the delivery of active ingredients and fractions extracted from natural products used in traditional Chinese medicine (TCM). *Advances in Colloid and Interface Science* 221: 60–76. <https://doi.org/10.1016/j.cis.2015.04.006>
- Luan J, Zheng F, Yang X, Yu A, Zhai G (2015) Nanostructured lipid car-riers for oral delivery of baicalin: *In vitro* and *in vivo* evaluation. *Col-loids and Surface A: Physicochemical and Enginering Aspects* 466: 154–159. <https://doi.org/10.1016/j.colsurfa.2014.11.015>
- Mahant S, Rao R, Nanda S (2018) Chapter 3 - Nanostructured lipid carriers: Revolutionizing skin care and topical therapeutics. In: Grumezescu AM (Ed.) Applied Science Publishers, 97–135. <https://doi.org/10.1016/B978-0-12-813667-6.00003-6>
- Mitri K, Shegokar R, Gohla S, Anselmi C, Müller RH (2011) Lipid nano-carriers for dermal delivery of lutein: Preparation, characterization, stability, and performance. *International Journal of Pharmaceutics* 414: 267–275. <https://doi.org/10.1016/j.ijpharm.2011.05.008>
- Muller RH, Petersen RD, Hommoss A, Pardeike J (2007) Nanostructured lipid carriers (NLC) in cosmetic dermal products. *Advanced Drug Deliv-ery Review* 59(6): 522–530. <https://doi.org/10.1016/j.addr.2007.04.012>
- Nogueira NC, de Sa LLF, Carvalho AL (2022) Nanostructured lipid car-riers as novel strategy for topical antifungal therapy. *AAPS Pharm-SciTech* 23(1): 32. <https://doi.org/10.1208/s12249-021-02181-w>
- Okonogi S, Rianganapatee P (2015) Physicochemical characterization of lycopene-loaded nanostructured lipid carrier formulations for topical administration. *International Journal of Pharmaceutics* 478: 726–735. <https://doi.org/10.1016/j.ijpharm.2014.12.002>
- Pivetta TP, Simões S, Araújo MM, Carvalho T, Arruda C, Marcato PD (2018) Development of nanoparticles from natural lipids for topical delivery of thymol: Investigation of its anti-inflammatory proper-ties. *Colloids and Surfaces B: Biointerfaces* 164: 281–90. <https://doi.org/10.1016/j.colsurfb.2018.01.053>
- Poovi G, Damodharan N (2018) Lipid nanoparticles: A challenging approach for oral delivery of BCS Class-II drugs. *Future Journal of Pharmaceutical Sciences* 4(2): 191–205. <https://doi.org/10.1016/j.fjps.2018.04.001>
- Pradhana AT, Ritthidej G (2023) Spray drying of Asiatic-palm oil in Maltodextrin: Improfing the nanoemulsion characteristics.

- International Journal of Nanoscience and Nanotechnology 19(1): 21–33. <https://doi.org/10.22034/ijnn.2023.554021.2206>
- Puglia C, Lauro MR, Offerta A, Crasci L, Micicchè L, Panico AM, Bonina F, Puglisi G (2017) Nanostructured Lipid Carriers (NLC) as vehicles for topical administration of sesamol: *In vitro* percutaneous absorption study and evaluation of antioxidant activity. *Planta Medica* 83: 398–404. <https://doi.org/10.1055/s-0042-105293>
- Qi J, Zhuang J, Lu Y, Dong X, Zhao W (2017) In vivo fate of lipid-based nanoparticles. *Drug Discovery Today* 22(1): 166–172. <https://doi.org/10.1016/j.drudis.2016.09.024>
- Ruktanonchai U, Bejrapha P, Sakulkhu U, Opanasopit P, Bunyapraphatsara N, Junyaprasert V (2009) Physicochemical Characteristics, Cytotoxicity, and Antioxidant Activity of Three Lipid Nanoparticulate Formulations of Alpha-lipoic Acid. *AAPS PharmSciTech* 10(1): 21–22. <https://doi.org/10.1208/s12249-009-9193-6>
- Salatti-Dorado JA, Garcia-Gomez D, Rodriguez-Ruiz V, Gueguen V, Pavon-Djavid G, Rubio S (2019) Multifunctional green supramolecular solvents for cost-effective production of highly stable astaxanthin-rich formulations from *Haematococcus pluvialis*. *Food Chemistry* 279: 294–302. <https://doi.org/10.1016/j.foodchem.2018.11.132>
- Salunkhe SS, Bhatia N, Pokharkar V, Thorat JD, Bhatia M (2013) Topical delivery of idebenone using nanostructured lipid carriers: Evaluations of sun protection and antioxidant effects. *Journal of Pharmaceutical Investigation* 43: 287–303. <https://doi.org/10.1007/s40005-013-0079-y>
- Sampasit W, Vasarach C, Opanasopit P, Sriamornsak P, Chamsai B (2022) Topical nanostructured lipid carriers of alpha-mangostin and resveratrol for synergistic antioxidant activity. *Pharmaceutical Nanotechnology* 10(3): 220–231. <https://doi.org/10.2174/221173851066220426112508>
- Sanad RAB, Abdel-Bar HM (2017) Chitosan-hyaluronic acid composite sponge scaffold enriched with Andrographolide-loaded lipid nanoparticles for enhanced wound healing. *Carbohydrate Polymers* 173: 441–450. <https://doi.org/10.1016/j.carbpol.2017.05.098>
- Shen CY, Dai L, Shen B De, Zhou X, Bai JX, Xu H (2015) Nanostructured lipid carrier based topical gel of Ganoderma Triterpenoids for frostbite treatment. *Chinese Journal of Natural Medicine* 13(6): 454–460. [https://doi.org/10.1016/S1875-5364\(15\)30039-X](https://doi.org/10.1016/S1875-5364(15)30039-X)
- Shi F, Wei Z, Zhao Y, Xu X (2016) Nanostructured lipid carriers loaded with baicalin: An efficient carrier for enhanced antidiabetic effects. *Pharmacognoc Magazine* 12(47): 198–202. <https://doi.org/10.4103/0973-1296.186347>
- Shimojo AAM, Fernandez AR, Ferreira NR, Sanchez-lopez E, Santana MHA, Souto EB (2019) Evaluation of the influence of process parameters on the properties of resveratrol-loaded NLC using 22 full factorial design. *Antioxidants* 8: 272. <https://doi.org/10.3390/antiox8080272>
- Simao DO, Honorato TD, Gobo GG, Piva HI, Goto PL, Rolim LA, Turrin C, Blanzat M, Tedesco AC, Siqueira-Moura MP (2020) Preparation and cytotoxicity of lipid nanocarriers containing a hydrophobic flavanone. *Colloids and Surfaces A: Physicochemical and Engineering Aspects* 601: 124982. <https://doi.org/10.1016/j.colsurfa.2020.124982>
- Soleimanian Y, Goli SAH, Varshosaz J, Maestrelli F (2018) Propolis wax nanostructured lipid carrier for delivery of B sitosterol: effect of formulation variables on physicochemical properties. *Food Chemistry* 260: 97–105. <https://doi.org/10.1016/j.foodchem.2018.03.145>
- Souto EB, Baldim I, Oliveira WP, Rao R, Yadav N, Gama FM, Mahant S (2020) SLN and NLC for topical , dermal and transdermal drug delivery. *Expert Opinion on Drug Delivery* 17(3): 357–377. <https://doi.org/10.1080/17425247.2020.1727883>
- Tamjidi F, Shahedi M, Varshosaz J, Nasirpour A (2013) Nanostructured lipid carriers (NLC): A potential delivery system for bioactive food molecules. *Innovative Food Science and Emerging Technologies* 19: 29–43. <https://doi.org/10.1016/j.ifset.2013.03.002>
- Teeranachaideekul V, Boonme P, Souto EB, Müller RH, Junyaprasert VB (2008) Influence of oil content on physicochemical properties and skin distribution of Nile red-loaded NLC. *Journal of Control Release* 128(2): 134–141. <https://doi.org/10.1016/j.jconrel.2008.02.011>
- Thakur L, Ghodasra U, Patel N, Dabhi M (2011) Novel approaches for stability improvement in natural medicines. *Pharmacognosy Reviews* 5(9): 48. <https://doi.org/10.4103/0973-7847.79099>
- Tortorici S, Cimino C, Ricupero M, Musumeci T, Biondi A, Siscaro G, Carbone C (2022) Nanostructured lipid carriers of essential oils as potential tools for the sustainable control of insect pests. *Industrial Crops and Products* 181: 114766. <https://doi.org/10.1016/j.indcrop.2022.114766>
- Tsai MJ, Wu PC, Huang Y Bin, Chang JS, Lin CL, Tsai YH (2012) Baicalein loaded in tocol nanostructured lipid carriers (tocol NLCs) for enhanced stability and brain targeting. *International Journal of Pharmaceutics* 423(2): 461–470. <https://doi.org/10.1016/j.ijpharm.2011.12.009>
- Tucak-Smajic A, Ruseska I, Letofsky-Papst I, Vranic E, Zimmer A (2023) Development and characterization of cationic nanostructured lipid carriers as drug delivery systems for miRNA-27a. *Pharmaceutics* 16(7): 1007. <https://doi.org/10.3390/ph16071007>
- Waikar S, Patel D, Singh A (2022) Nanostructured lipid carrier based dermal gel of cyclosporine for atopic dermatitis *in vitro* and *in vivo* evaluation. *Journal of Drug Delivery Science and Technology* 72: 103365. <https://doi.org/10.1016/j.jddst.2022.103365>
- Wang S, Su R, Nie S, Sun M, Zhang J, Wu D (2014) Application of nanotechnology in improving bioavailability and bioactivity of diet-derived phytochemicals. *The Journal of Nutritional Biochemistry* 25(4): 363–376. <https://doi.org/10.1016/j.jnutbio.2013.10.002>
- Weber S, Zimmer A, Pardeike J (2014) Solid Lipid Nanoparticles (SLN) and Nanostructured Lipid Carriers (NLC) for pulmonary application: A review of the state of the art. *European Journal of Pharmaceutics and Biopharmaceutics* 86(1): 7–22. <https://doi.org/10.1016/j.ejpb.2013.08.013>
- Xu L, Wang X, Liu Y, Yang G, Falconer RJ, Zhao C (2022) Lipid Nanoparticle for Drug Delivery. *Advanced NanoBiomed Research* 2: 2100109. <https://doi.org/10.1002/anbr.202100109>
- Zhang W, Jiang Y, He Y, Boucetta H, Wu J, Chen Z, He W (2023) Lipid carriers for mRNA delivery. *Acta Pharmaceutica Sinica B* 3(10): 4105–4126. <https://doi.org/10.1016/j.apsb.2022.11.026>
- Zhao XL, Yang CR, Yang KL, Li KX, Hu HY, Chen DW (2010) Preparation and characterization of nanostructured lipid carriers loaded traditional Chinese medicine, zedoary turmeric oil. *Drug Development and Industrial Pharmacy* 36(7): 773–80. <https://doi.org/10.3109/03639040903485716>
- Zheng L, Xu H, Zhang H, Shi C, Zhou W, Zhang X (2023) Nanostructured lipid carrier as a strategy for encapsulation of formononetin and perilla seed oil: *In vitro* characterization and stability studies. *Food BioScience* 53: 102707. <https://doi.org/10.1016/j.fbio.2023.102707>