RESEARCH PAPER

ADVANCES IN NANOSTRUCTURED LIPID CARRIER–BASED DRUG DELIVERY SYSTEMS FOR THE TREATMENT OF IMPETIGO

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ABSTRACT

This abstract illustrates the therapeutic potential of nanostructured lipid carriers (NLCs) as an advanced topical drug delivery system for the treatment of impetigo, a contagious superficial skin infection. The schematic begins by depicting infected epidermal layers colonized by Staphylococcus aureus and Streptococcus pyogenes, highlighting the challenges posed by conventional topical antibiotics, which often fail due to poor penetration, rapid drug clearance, and limited retention. In contrast, NLC-based formulations are shown to penetrate deeper into the epidermis, ensuring enhanced drug deposition, sustained release, and prolonged therapeutic action. The lipid nanoparticles interact with bacterial cell membranes and biofilms, leading to disruption of biofilm architecture, increased bacterial killing, and accelerated lesion healing. This mechanism not only improves antibacterial efficacy but also reduces recurrence and resistance potential. The abstract further emphasizes the multifunctional advantages of NLCs, including their ability to encapsulate both conventional antibiotics and natural antimicrobial agents. Their biocompatibility, safety, and ease of application make them particularly suitable for pediatric, patient-centric therapy, positioning NLCs as a next-generation strategy in dermatological drug delivery.

Nanostructured lipid carriers enable targeted, sustained, and safer topical therapy for effective management of impetigo.

Keywords: Nanostructured lipid carriers; Impetigo; Topical drug delivery; Antibacterial therapy; Biofilm targeting; Pediatric dermatology; Natural antimicrobial agents; Sustained release.

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1. Introduction

Impetigo is a superficial bacterial infection of the skin that spreads rapidly and is most frequently seen in infants and young children, though adolescents and adults may also be affected. The condition is primarily attributed to *Staphylococcus aureus* and *Streptococcus pyogenes*, which produce characteristic erythematous patches, vesicles, pustules, and the classic honeycolored crusts. It is particularly prevalent in warm, humid environments and is often linked to poor hygiene, minor skin injuries, and overcrowded living conditions . While impetigo is not usually life-threatening, its high transmissibility, recurrent nature, and potential complications make it an important global public health issue. Traditional management relies on topical or systemic antibiotics such as mupirocin, fusidic acid, retapamulin, and, in severe cases, oral β-lactams or macrolides. However, conventional topical therapies often suffer from limitations, including poor skin penetration, short drug residence time, frequent dosing requirements, and reduced patient adherence . The growing prevalence of antibiotic-resistant strains, particularly methicillin-resistant *Staphylococcus aureus* (MRSA), further undermines the effectiveness of existing treatment strategies. Advances in nanotechnology have introduced innovative drug delivery systems for dermatological infections. Among these, nanostructured lipid carriers (NLCs) have attracted significant attention due to their ability to enhance solubility, improve dermal penetration, provide controlled drug release, and reduce local irritation. As second-generation lipid nanoparticles composed of both solid and liquid lipids, NLCs offer superior drug loading capacity and stability compared to earlier lipid-based systems . These attributes make them highly suitable for topical administration of

antibacterial agents in impetigo therapy. This review highlights recent progress in NLC-based drug delivery approaches for impetigo, focusing on formulation design, evaluation parameters, therapeutic applications, and future perspectives. The potential of NLCs to address the shortcomings of conventional treatments and improve clinical outcomes is critically examined .

1.1 Clinical Forms, Pathogenesis, and Therapeutic Challenges of Impetigo

Impetigo manifests in two principal clinical variants: non-bullous and bullous. The non-bullous form, which is more prevalent, is typically associated with *Streptococcus pyogenes* or *Staphylococcus aureus*. It presents as small vesicles that rupture and evolve into thick, honeycolored crusts . In contrast, bullous impetigo is largely attributed to toxin-producing strains of *Staphylococcus aureus* and is characterized by larger, fluid-filled bullae that rupture easily, leaving behind erosive lesions. Both forms commonly affect exposed regions such as the face, arms, and legs, and can spread rapidly through autoinoculation .

The pathogenesis of impetigo begins with bacterial colonization of the stratum corneum, often following minor trauma, insect bites, eczema, or other pre-existing dermatoses. Bacterial toxins and enzymes compromise the integrity of the skin barrier, leading to inflammation, epidermal damage, and lesion development. This disruption not only facilitates bacterial proliferation but also hinders effective topical drug delivery, making it difficult to achieve therapeutic concentrations at the site of infection . Current treatment strategies rely on topical and systemic antibiotics, yet they face significant limitations. Poor drug penetration into infected skin layers, rapid removal of topical agents due to sweating or washing, and the requirement for multiple daily applications reduce therapeutic efficiency and patient adherence. Moreover, prolonged antibiotic use contributes to resistance, treatment failure, and recurrence, underscoring the need for improved therapeutic approaches. Nanostructured lipid carriers (NLCs) have emerged as a promising solution to these challenges. Their lipid-based composition mimics the skin's natural lipid matrix, enabling stronger adhesion to the skin surface, enhanced penetration into epidermal layers, and sustained release of antibacterial agents. These properties make NLCs an attractive and effective platform for the topical management of impetigo, with the potential to overcome the shortcomings of conventional therapies .

2. Nanostructured Lipid Carriers (NLCs): Concept, Composition, and Advantages

Nanostructured lipid carriers (NLCs) represent a second-generation lipid-based nanocarrier system designed to overcome the drawbacks of solid lipid nanoparticles (SLNs). They are composed of a mixture of solid lipids and liquid lipids (oils), stabilized with appropriate surfactants. This combination produces a partially crystalline, highly disordered lipid matrix that allows greater drug loading capacity, minimizes drug expulsion during storage, and enhances physicochemical stability compared to SLNs . The rationale behind NLC development was to improve the delivery of poorly soluble drugs while ensuring safety and biocompatibility. Their nanoscale dimensions and lipidic composition confer strong affinity for the skin and excellent occlusive properties, making them particularly suitable for topical applications .

When applied, NLCs form a thin lipid film that reduces trans epidermal water loss, increases hydration, and facilitates deeper penetration of the encapsulated drug into epidermal layers. For the treatment of impetigo, NLCs provide several therapeutic benefits. They enable localized drug deposition, sustained release of antibacterial agents, reduced dosing frequency, and limited systemic absorption. Because their lipid components closely mimic the physiological lipids of the stratum corneum, NLCs interact effectively with the skin barrier, ensuring better retention of drugs at the site of infection . These attributes make them an ideal carrier system for topical antibiotics, antimicrobial peptides, and natural antibacterial agents. Another advantage of NLCs is their versatility in formulation. They can be incorporated into conventional dosage forms such as gels, creams, and ointments, thereby improving patient compliance and acceptability. Additionally, NLCs protect unstable drugs from degradation and enhance therapeutic efficacy, positioning them as a promising platform for the management of bacterial skin infections, including impetigo .

2.1 Composition and Structural Features of Nanostructured Lipid Carriers

Nanostructured lipid carriers (NLCs) are built from three essential components: solid lipids, liquid lipids, and surfactants. Solid lipids such as glyceryl monostearate, stearic acid, cetyl palmitate, and compritol provide the structural backbone of the nanoparticle matrix. To this framework, liquid lipids like oleic acid, mediumchain triglycerides, and isopropyl myristate are incorporated. Their presence introduces imperfections into the crystalline lattice, which prevents drug expulsion and enhances entrapment efficiency . Surfactants and co-surfactants—including polysorbates, poloxamers, and lecithin—are critical for stabilizing the dispersion. By

lowering interfacial tension and preventing particle aggregation, they ensure uniformity and long-term stability. The type and concentration of surfactants directly influence key parameters such as particle size, zeta potential, and overall formulation robustness .

Structurally, NLCs are categorized into three distinct types:

- **Imperfect crystal type** – a disordered matrix formed by solid and liquid lipids, offering high drugloading capacity.
- **Amorphous type** – designed to remain noncrystalline, thereby minimizing the risk of drug expulsion during storage.
- **Multiple oilinfatinwater type** – characterized by oil nanocompartments embedded within a solid lipid matrix, enabling controlled and sustained drug release.

This structural diversity allows NLCs to be tailored for specific therapeutic needs, making them versatile carriers for topical drug delivery see the figure 1.

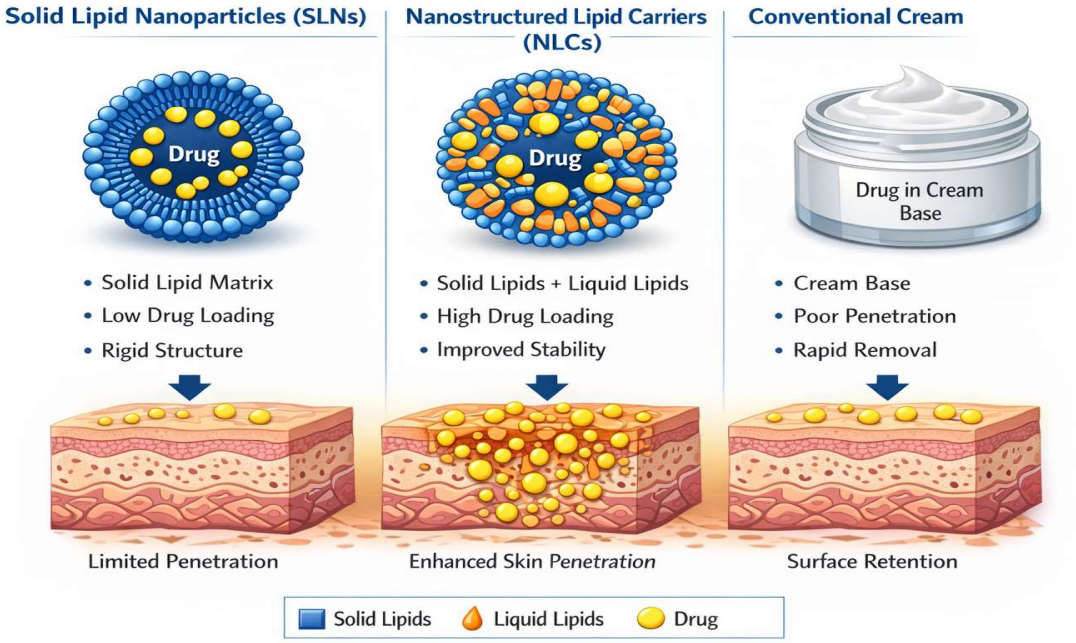

Figure 1: Structural Comparison of Lipid-Based Drug Delivery Systems

Schematic representation illustrating the structural difference between solid lipid nanoparticles (SLNs), nanostructured lipid carriers (NLCs), and conventional topical formulations. The incorporation of liquid lipids into the solid lipid matrix of NLCs creates structural imperfections, resulting in enhanced drug loading, improved stability, and sustained drug release.

3. Formulation Strategies of Nanostructured Lipid Carriers

The successful formulation of nanostructured lipid carriers (NLCs) requires strategic selection of lipids, surfactants, and processing techniques to achieve desirable particle size, stability, drug entrapment, and therapeutic performance. A defining feature of NLCs is their hybrid lipid matrix—comprising both solid and liquid lipids—which introduces structural imperfections that enhance drug loading and prevent drug expulsion during storage. These formulation principles are particularly critical for topical applications in impetigo therapy, where improved skin penetration, sustained drug release, and localized antibacterial action are essential .

Key physicochemical attributes of NLCs—such as particle size distribution, surface charge (zeta potential), entrapment efficiency, and drug release kinetics—are highly sensitive to formulation variables. These include the type and ratio of lipids, concentration of surfactants, and the method of preparation (e.g., high-pressure homogenization, ultrasonication). Careful optimization of these parameters ensures strong skin adhesion, extended residence time, and enhanced therapeutic efficacy

against the bacterial pathogens responsible for impetigo .

3.1 Selection of Lipid Components

3.1.1 Solid Lipids

Solid lipids serve as the structural foundation of nanostructured lipid carriers (NLCs), playing a pivotal role in maintaining nanoparticle stability and ensuring effective drug retention. Commonly employed solid lipids include glyceryl monostearate, stearic acid, cetyl palmitate, compritol 888 ATO, and Precirol. These lipids are selected based on key criteria such as biocompatibility, melting point, and their capacity to solubilize the active pharmaceutical ingredient. In topical NLC formulations for impetigo, solid lipids also contribute to occlusive effects, which enhance skin hydration and promote deeper drug penetration .

3.1.2 Liquid Lipids

Liquid lipids—such as oleic acid, mediumchain triglycerides, isopropyl myristate, and miglyol—are incorporated into the solid lipid matrix to introduce structural imperfections. These imperfections increase the free volume within the lipid core, thereby improving drug entrapment efficiency and minimizing the risk of drug expulsion during storage. Additionally, certain liquid lipids function as penetration enhancers, facilitating the delivery of antibacterial agents into deeper layers of infected skin .

3.1.3 Surfactants and Cosurfactants

Surfactants are essential for stabilizing NLC dispersions by lowering interfacial tension and preventing particle aggregation. Non-ionic surfactants such as polysorbates (e.g., Tween 80), poloxamers, and lecithin are preferred due to their low toxicity and excellent skin compatibility. The type and concentration of surfactants significantly influence critical formulation parameters, including particle size, polydispersity index, and zeta potential. Cosurfactants may be added to further enhance dispersion stability and improve formulation homogeneity. See Table 1 for components and their roles in NLC formulations

Table 1: Components of NLCs and Their Roles

Component	Examples	Primary Role	Impact on Formulation
Solid Lipids	Glyceryl monostearate, Stearic acid, Cetyl palmitate, Compritol 888 ATO, Precirol	Provide structural backbone; ensure stability; aid drug retention	Occlusive properties → enhance hydration & penetration; determine melting point & solubility
Liquid Lipids	Oleic acid, Medium-chain triglycerides, Isopropyl myristate, Miglyol	Introduce imperfections in the crystalline matrix; act as penetration enhancers	Increase drug entrapment efficiency; reduce drug expulsion; improve dermal delivery
Surfactants	Polysorbates (Tween 80), Poloxamers, Lecithin	Stabilize dispersion; reduce interfacial tension; prevent aggregation	Influence particle size, polydispersity index, zeta potential; improve skin compatibility
Co-surfactants	Short-chain alcohols, bile salts	Support surfactant action; enhance stability and homogeneity	Improve dispersion quality; ensure long-term stability

3.2 Preparation Methods of Nanostructured Lipid Carriers

The method of preparation is a decisive factor in shaping the physicochemical properties, stability, and therapeutic performance of nanostructured lipid carriers (NLCs). Critical parameters such as particle size, polydispersity index, drug entrapment efficiency, and release kinetics are directly influenced by the fabrication technique employed. For topical applications in impetigo therapy, the preparation process must yield nanoparticles with uniform size distribution, high stability, and minimal reliance on toxic solvents to ensure compatibility with the skin .

A variety of conventional and advanced approaches have been explored for NLC production. Among these, high-pressure homogenization, microemulsion-based techniques, and solvent evaporation methods are the most widely reported. Each technique offers distinct

advantages in terms of scalability, reproducibility, and control over particle characteristics, making them valuable tools in the design of effective NLC formulations for antibacterial therapy .

3.2.1 High-Pressure Homogenization (HPH)

High-pressure homogenization (HPH) is the most widely adopted and industrially scalable technique for producing nanostructured lipid carriers (NLCs). In this process, the lipid phase is first melted, and the drug is either dissolved or dispersed within the molten lipids. This mixture is then emulsified with an aqueous surfactant solution and subjected to homogenization under high pressure. The resulting nanoemulsion is subsequently cooled to room temperature, leading to lipid solidification and the formation of stable NLCs .

HPH offers several distinct advantages, including a narrow particle size distribution, high reproducibility, and suitability for large-scale manufacturing. For topical antibacterial formulations, this method ensures uniform drug dispersion within the lipid matrix and promotes improved penetration into the skin. However, the requirement for elevated temperatures and exposure to mechanical stress may restrict its use for thermostable or sensitive drug molecules .

3.2.2 Microemulsion-Based Technique

The microemulsion technique relies on the formation of a thermodynamically stable system composed of melted lipids, surfactants, co-surfactants, and water. When this microemulsion is diluted with cold water under controlled stirring, the lipid phase precipitates, leading to the formation of nanostructured lipid carriers (NLCs). This method is particularly valued for its simplicity, low energy requirement, and ability to generate nanoparticles with a small particle size and high drug entrapment efficiency . In topical drug delivery, microemulsion-based NLCs have demonstrated significant potential by improving skin permeation and enabling sustained release of encapsulated agents. These attributes make the technique especially suitable for developing NLC formulations aimed at the effective management of impetigo .

3.2.3 Solvent Evaporation Method

The solvent evaporation method involves dissolving both lipids and the drug in a suitable organic solvent, followed by emulsification into an aqueous surfactant phase. Once the emulsion is formed, the organic solvent is removed under reduced pressure, leading to lipid precipitation and the subsequent formation of nanostructured lipid carriers (NLCs). This technique offers precise control over particle size and drug loading capacity, making it a useful approach for tailoring NLC properties . However, the reliance on organic solvents introduces challenges related to residual toxicity and regulatory compliance. For topical formulations intended to treat pediatric skin infections such as impetigo, careful selection of solvents and complete removal during processing are essential to ensure safety, biocompatibility, and therapeutic reliability .

3.2.4 Emerging and Modified Techniques

Recent innovations in nanostructured lipid carrier (NLC) technology have led to the development of modified preparation methods as shown in figure 2 designed to overcome the limitations of conventional techniques. Approaches such as ultrasonication-assisted homogenization, melt-emulsification, and cold homogenization have been introduced to enhance formulation efficiency and improve product quality . These methods are particularly advantageous as they help to minimize thermal stress, thereby protecting heat-sensitive drugs, while simultaneously improving drug stability and offering greater control over particle size and distribution. By tailoring the preparation technique, researchers can achieve more consistent drug entrapment and controlled release profiles. The choice of method ultimately depends on the physicochemical properties of the drug, the desired release kinetics, and the intended clinical application. For topical therapies such as impetigo treatment, these emerging techniques provide valuable flexibility in designing NLCs that combine safety, stability, and therapeutic effectiveness .

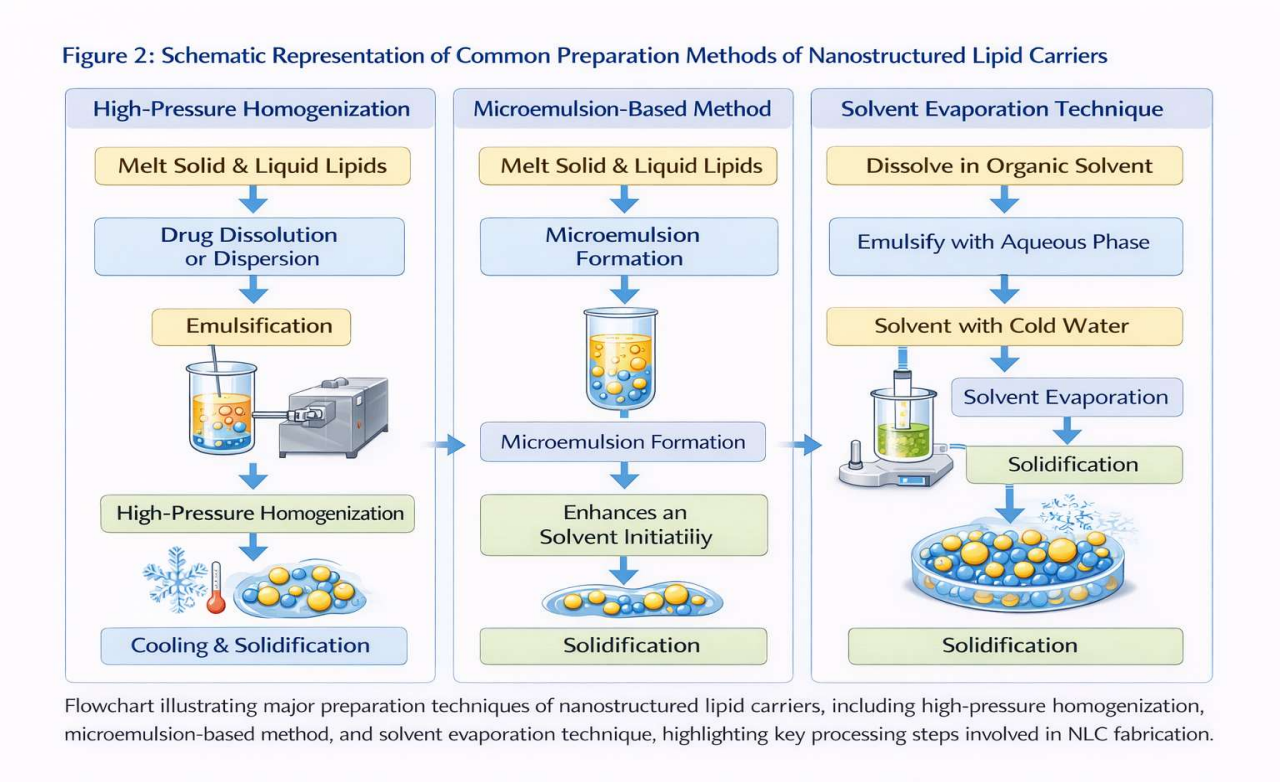

Figure 2: Schematic Representation of Common Preparation Methods of Nanostructured Lipid Carriers

Flowchart illustrating major preparation techniques of nanostructured lipid carriers, including high-pressure homogenization, microemulsion-based method, and solvent evaporation technique, highlighting key processing steps involved in NLC fabrication.

4. Evaluation Parameters of Nanostructured Lipid Carriers

Thorough evaluation of nanostructured lipid carriers (NLCs) is critical to ensure their physicochemical stability, safety, and therapeutic efficacy, particularly for topical applications in impetigo management. Comprehensive characterization provides essential data on parameters given in Table 2, such as particle size distribution, surface charge (zeta potential), drug-loading capacity, release kinetics, and skin permeation potential . These attributes collectively influence the clinical performance of NLC formulations and their ability to deliver antibacterial agents effectively to infected epidermal layers. For dermatological use—especially in pediatric conditions like impetigo—evaluation must also include skin compatibility, irritation potential, and localized drug retention. These factors are vital for ensuring patient safety, minimizing adverse reactions, and achieving sustained therapeutic action at the site of infection .

4.1 Particle Size and Polydispersity Index (PDI)

Particle size is a key determinant of the skin penetration ability, physical stability, and drug release profile of nanostructured lipid carriers (NLCs). For topical applications, especially in impetigo therapy, nanoparticles within the range of 50–300 nm are considered ideal . This size range promotes strong adhesion to the stratum corneum and facilitates drug diffusion into superficial skin layers while minimizing systemic absorption. The polydispersity index (PDI) reflects the uniformity of particle size distribution. A PDI value below 0.3 indicates a narrow and homogeneous size range, which is desirable for consistent formulation behavior. Together, smaller particle size and low PDI contribute to enhanced physical stability, predictable drug release, and reliable therapeutic performance—attributes that are particularly important for treating localized bacterial infections such as impetigo .

4.2 Zeta Potential

Zeta potential represents the surface charge of nanoparticles and is a critical parameter for assessing colloidal stability. Nanostructured lipid carriers (NLCs) with values exceeding ±20 mV are generally regarded as stable, as the electrostatic repulsion between particles prevents aggregation. In topical formulations, surface charge not only governs dispersion stability but also influences interactions with the negatively charged skin surface . This directly

impacts drug retention at the application site and facilitates penetration into epidermal layers. Maintaining an appropriate zeta potential is therefore essential to ensure long-term stability of NLC dispersions, minimize particle aggregation during storage, and optimize therapeutic performance in impetigo treatment .

4.3 Entrapment Efficiency and Drug Loading

Entrapment efficiency (EE) refers to the proportion of drug successfully incorporated within the lipid matrix of nanostructured lipid carriers (NLCs). One of the key advantages of NLCs over conventional lipid nanoparticles lies in their imperfect crystalline structure, generated by the inclusion of liquid lipids . These structural irregularities create additional space within the matrix, allowing higher drug entrapment and minimizing the risk of drug expulsion during storage. High drug loading capacity is particularly beneficial for topical therapy, as it enables sustained release of antibacterial agents and reduces the need for frequent application. This not only enhances therapeutic effectiveness but also improves patient compliance, which is especially important in the management of recurrent infections such as impetigo .

4.4 Morphological Characterization

Morphological assessment of nanostructured lipid carriers (NLCs) is typically performed using advanced imaging techniques such as transmission electron microscopy (TEM) and scanning electron microscopy (SEM). These analyses provide detailed information on particle shape, surface features, and internal structure . NLCs generally display a spherical or near-spherical morphology with smooth surfaces, which is advantageous for uniform application on the skin and facilitates effective penetration into superficial layers .

4.5 In Vitro Drug Release Studies

In vitro drug release experiments are essential for evaluating the release kinetics of antibacterial agents from NLC formulations . Sustained and controlled release is a highly desirable property in impetigo therapy, as it ensures prolonged maintenance of therapeutic drug levels at the site of infection. NLCs typically exhibit a biphasic release profile, characterized by an initial burst release followed by a gradual, extended release from the lipid matrix. This dual-phase behaviour enhances both immediate antibacterial action and long-term efficacy .

4.6 Ex Vivo Skin Permeation and Retention Studies

Ex vivo permeation studies, conducted using excised animal or human skin models, provide valuable insights into the penetration and retention characteristics of NLCs . Compared to conventional topical formulations such as creams and ointments, NLCs demonstrate significantly higher drug retention within the epidermal and dermal layers, while minimizing systemic absorption. This localized delivery is particularly beneficial in reducing systemic side effects and improving therapeutic outcomes in impetigo management .

4.7 Skin Irritation and Safety Assessment

Safety evaluation is critical for topical NLC formulations, especially those intended for pediatric use. Skin irritation and compatibility studies confirm the tolerability of NLCs composed of biocompatible lipids and non-ionic surfactants . These formulations generally exhibit minimal irritation potential, supporting their suitability for repeated topical application . Such findings reinforce the safety profile of NLCs and validate their use in long-term management of bacterial skin infections like impetigo.

Table 2: Evaluation Parameters of Nanostructured Lipid Carriers

Parameter	Technique	Purpose	Relevance to Impetigo Treatment
Particle size	Dynamic light scattering (DLS)	Determines penetration & stability	Enhances skin localization
PDI	DLS	Measures homogeneity	Ensures formulation uniformity
Zeta potential	Electrophoretic mobility	Indicates stability	Prevents aggregation
Entrapment efficiency	Centrifugation/UV analysis	Measures drug loading	Sustained antibacterial action

Morphology	TEM/SEM	Particle shape & surface	Uniform topical application
In vitro release	Dialysis method	Release kinetics	Prolonged drug availability
Ex vivo permeation	Franz diffusion cell	Skin penetration	Localized drug delivery

5. Latest Applications of Nanostructured Lipid Carriers in the Treatment of Impetigo

5.1 NLC-Based Delivery of Conventional Antibiotics for Impetigo

Impetigo, a highly contagious superficial skin infection, is predominantly caused by Staphylococcus aureus and Streptococcus pyogenes. The growing incidence of antibiotic resistance and biofilm formation has significantly reduced the effectiveness of conventional topical therapies, necessitating advanced delivery systems . Nanostructured lipid carriers (NLCs) have emerged as promising vehicles capable of overcoming these limitations by enhancing drug penetration, prolonging retention, and improving antimicrobial efficacy directly at the site of infection . NLCs have been widely investigated for the topical delivery of conventional antibiotics such as mupirocin, fusidic acid, erythromycin, clindamycin, and gentamicin . Encapsulation of these agents within NLCs confers several therapeutic advantages, including:

Improved drug solubility and stability

- Enhanced penetration into infected skin layers
- Prolonged residence time at the site of infection
- Reduced dosing frequency and minimized systemic exposure

Evidence from multiple studies demonstrates that mupirocin-loaded NLCs exhibit markedly higher antibacterial activity against *S. aureus* compared to conventional ointments, attributed to sustained drug release and improved follicular penetration. Similarly, fusidic acid-loaded NLCs have demonstrated superior skin permeation and extended antimicrobial activity, making them particularly effective for treating superficial bacterial infections, such as impetigo. In addition, NLC-based formulations reduce local irritation and enhance patient compliance—an especially important consideration in pediatric impetigo therapy .

These findings underscore the potential of NLCs as superior carriers for conventional antibiotics; however, recent research has expanded their application toward addressing biofilm-associated infections and drug resistance mechanisms. See Table 3 NLC-Based Antibiotic Formulations Investigated for Impetigo Treatment and Figure 3 Mechanism of Enhanced Antibacterial Activity of NLCs in Impetigo.

Table 3: NLC-Based Antibiotic Formulations Investigated for Impetigo Treatment

Antibiotic	Type of NLC	Key Outcomes	Therapeutic Advantage	References
Mupirocin	Solid–liquid lipid NLC	Sustained release, enhanced skin retention	Reduced dosing frequency	
Fusidic acid	Topical NLC gel	Improved permeation	Prolonged antimicrobial effect	
Erythromycin	NLC dispersion	Increased antibacterial activity	Better bioavailability	
Clindamycin	NLC hydrogel	Enhanced follicular targeting	Improved patient compliance	

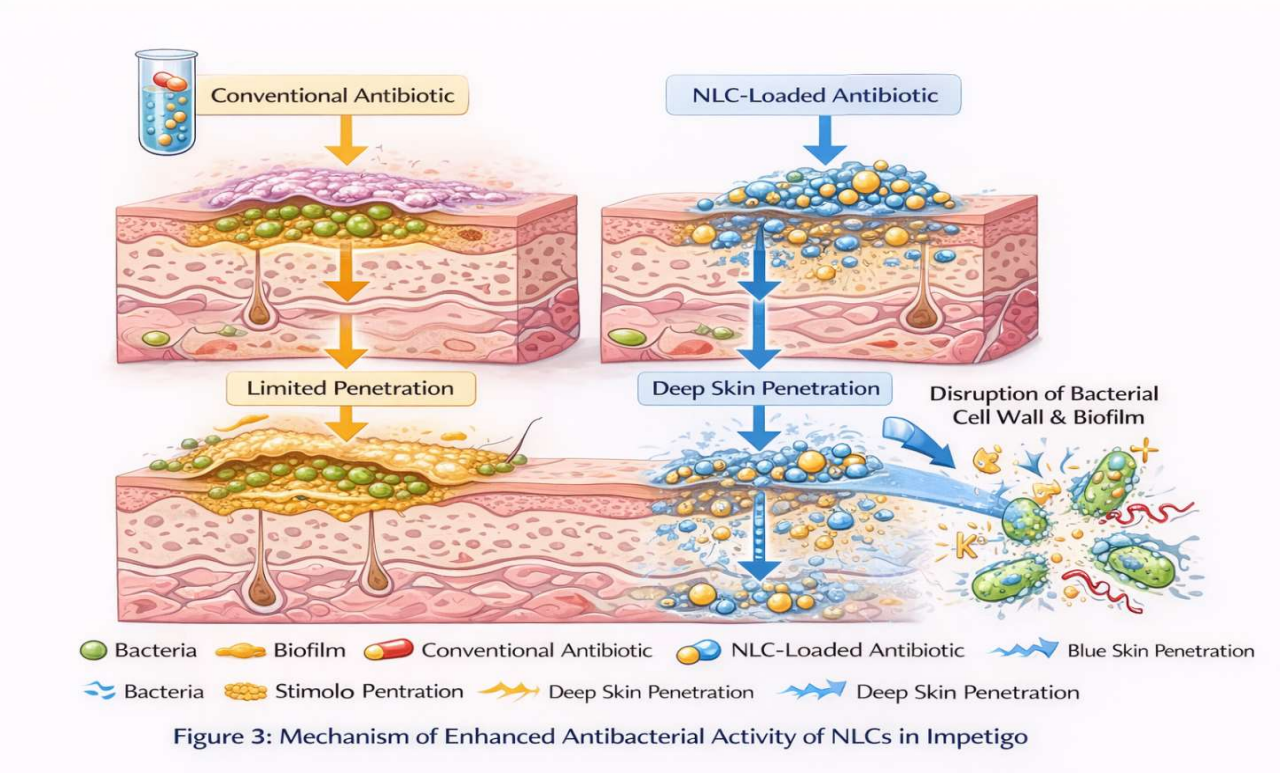

Figure 3: Mechanism of Enhanced Antibacterial Activity of NLCs in Impetigo

Figure 3: Mechanism of Enhanced Antibacterial Activity of NLCs in Impetigo

5.2 NLCs for Bio-film Targeted Impetigo Therapy

The development of bacterial biofilms is a major contributor to therapeutic failure and recurrence in impetigo, particularly in infections caused by *Staphylococcus aureus*. Biofilms form a protective extracellular polymeric matrix (EPS) that restricts antibiotic penetration and enhances bacterial resistance, thereby reducing the effectiveness of conventional topical formulations. Nanostructured lipid carriers (NLCs) offer a promising strategy for biofilm-targeted therapy due to their nanoscale dimensions, lipidic composition, and sustained drug release capabilities . The lipid matrix of NLCs enables close interaction with bacterial membranes and the EPS, facilitating deeper penetration and improved drug delivery to embedded bacterial cells. Encapsulation of antibiotics within NLCs has been shown to markedly enhance antibiofilm efficacy by maintaining prolonged therapeutic concentrations at the site of infection. This sustained exposure disrupts biofilm architecture, increases bacterial membrane permeability, and promotes effective bacterial eradication. Furthermore, the occlusive properties of NLCs improve skin hydration, which enhances drug diffusion into infected tissues .

The biofilm-disrupting potential of NLCs is particularly valuable in pediatric impetigo, where treatment safety and compliance are critical. By reducing dosing frequency and improving localized antibacterial action, NLC-based systems minimize irritation and lower the risk of resistance development. In summary, NLC-mediated biofilm targeting represents an advanced and clinically relevant approach for improving therapeutic outcomes in both acute and recurrent impetigo .

5.3 NLC-Based Delivery of Natural Antimicrobial Agents for Impetigo Treatment

The rising incidence of antibiotic resistance, recurrent infections, and safety concerns has stimulated interest in natural antimicrobial agents as alternative or adjunct therapies for impetigo. Phytochemicals and essential oils are known for their broad-spectrum antibacterial, anti-inflammatory, and wound-healing properties . However, their direct clinical use is restricted by poor aqueous solubility, volatility, instability, and inadequate skin penetration. Nanostructured lipid carriers (NLCs) provide an effective solution by encapsulating natural actives within a biocompatible lipid matrix, thereby improving their stability, bioavailability, and therapeutic performance .

5.3.1 Essential Oils-Loaded NLCs

Essential oils such as tea tree oil, eucalyptus oil, and thyme oil exhibit potent antibacterial activity against Staphylococcus aureus and Streptococcus species commonly implicated in impetigo. Tea tree oil, in particular, demonstrates strong bactericidal and anti-inflammatory effects, but its volatility and potential for irritation limit direct topical use .

Encapsulation of essential oils into NLCs:

- Reduces volatility and degradation
- Controls release of active constituents
- Minimizes skin irritation
- Enhances penetration into infected skin layers

Tea tree oil-loaded NLCs have shown superior antibacterial efficacy and prolonged activity compared to conventional oil formulations, making them suitable for pediatric topical applications .

5.3.2 Curcumin-Loaded NLCs

Curcumin, a natural polyphenol derived from Curcuma longa, possesses antibacterial, anti-inflammatory, and wound-healing properties. Despite its therapeutic potential, curcumin suffers from poor solubility, rapid degradation, and limited skin penetration. NLC-based systems significantly improve curcumin's stability and retention within the skin . Curcumin-loaded NLCs have demonstrated enhanced antibacterial activity against Gram-positive bacteria, reduced inflammation, and accelerated lesion healing. These multifunctional effects make curcumin-loaded NLCs particularly valuable for inflamed and crusted impetigo lesions .

5.3.3 Neem-Based NLC Formulations

Neem (Azadirachta indica) extracts are well recognized for their antibacterial, antifungal, and immunomodulatory properties. Active compounds such as nimbidin and azadirachtin show efficacy against skin pathogens, but their poor bioavailability and formulation challenges limit clinical use. Incorporating neem extracts into NLCs enhances antimicrobial activity by improving skin penetration and sustained release. Neem-based NLCs represent a promising, natural, and safer alternative for long-term management of superficial skin infections, particularly in children .

5.3.4 Advantages of Natural Active-Loaded NLCs in Impetigo

NLC-based delivery of natural antimicrobials offers several distinct advantages:

- Reduced risk of antimicrobial resistance
- Improved skin tolerability
- Synergistic antibacterial and anti-inflammatory effects
- Enhanced patient acceptance, especially in pediatric care

These systems can be employed either alone or in combination with conventional antibiotics, providing superior therapeutic outcomes in impetigo management .

The incorporation of natural antimicrobial agents into nanostructured lipid carriers (NLCs) represents a sustainable, patient-centric, and clinically relevant strategy for the effective management of impetigo. By combining the biocompatibility and safety profile of natural actives with the advanced delivery capabilities of NLCs, this approach not only addresses the challenges of antibiotic resistance and recurrent infections but also enhances therapeutic outcomes while ensuring better tolerability in pediatric patients .

5.4 Pediatric-Friendly and Patient-Centric NLC Formulations

Impetigo is most prevalent among infants and young children, making safety, tolerability, and ease of application essential considerations in topical therapy. Conventional antibiotic ointments often present drawbacks such as skin irritation, greasy texture, frequent dosing requirements, and poor compliance, underscoring the need for pediatric-friendly and patient-centric drug delivery systems. Nanostructured lipid carriers (NLCs) are particularly well suited for pediatric dermatology due to their composition of biocompatible lipids, mild surfactants, and non-irritating excipients . Their nanoscale dimensions enable precise drug localization within superficial skin layers while minimizing systemic absorption, thereby reducing the risk of adverse effects. NLC formulations can be incorporated into gels, creams, and hydrogels with favorable sensory attributes such as non-greasy texture, smooth spreadability, and rapid absorption. Their sustained release behaviour reduces dosing frequency, significantly improving adherence among pediatric patients and caregivers .

Additionally, NLCs provide enhanced skin hydration through occlusive effects, which accelerate lesion healing and alleviate discomfort such as itching and inflammation. The ability to encapsulate both synthetic antibiotics and natural antimicrobial agents further supports the development of safer, combination therapies tailored to pediatric needs . In summary, patient-centric NLC formulations represent a clinically relevant advancement in impetigo management, aligning with the principles of pediatric dermatological care by prioritizing safety, comfort, and therapeutic effectiveness .

Despite their promise, the clinical translation of NLC-based systems hinges on overcoming regulatory approval, manufacturing consistency, and scalability challenges to ensure safe, effective, and widely accessible therapies for impetigo.

6. Future Trends and Clinical Translation of Nanostructured Lipid Carriers

Future research on NLCs is moving toward advanced designs such as surface-modified and ligand-functionalized systems for improved skin targeting and bacterial specificity. Combination therapies, especially antibiotic–natural active co-delivery, aim to reduce resistance and enhance outcomes. Smart, stimuli-responsive NLCs that release drugs in response to pH, enzymes, or bacterial toxins promise precise, on-demand treatment.

For clinical translation, challenges in scale-up, stability, and regulatory approval must be addressed through standardized protocols and large-scale studies. With continued progress, NLCs are expected to become a next-generation platform for impetigo therapy, offering superior efficacy, safety, and patient compliance in pediatric care.

CONCLUSION

Nanostructured lipid carriers (NLCs) are emerging as an innovative and versatile nanotechnological system with immense potential to transform topical therapy for impetigo. These lipid-based nanoparticles are designed to overcome the limitations of conventional treatments by offering enhanced drug penetration through the skin, sustained release of therapeutic agents, and improved patient compliance. Their unique structure allows the incorporation of both traditional antibiotics and natural antimicrobial compounds, thereby broadening the therapeutic spectrum while reducing the risk of resistance. In pediatric skin infections such as impetigo, where safety, efficacy, and ease of application are critical, NLCs provide a patient-centric approach. They not only ensure localized delivery with minimal systemic exposure but also maintain therapeutic concentrations for longer durations, reducing the frequency of application. Furthermore, their adaptability enables tailoring formulations to meet diverse clinical needs, making them highly relevant for future dermatological practice. With their biocompatibility, stability, and multifunctional capabilities, NLCs stand out as a next-generation solution poised to redefine the management of impetigo and improve outcomes in pediatric care.

REFERENCES

1. Ramireddy AR, Behara DK. QbD-Based Formulation Development and Optimisation of Ozenoxacin Topical Nano-Emulgel and Efficacy Evaluation Using Impetigo Mice Model. AAPS PharmSciTech 2024 25:5 [Internet]. 2024 Apr 22 [cited 2026 Jan 20];25(5):90-. Available from: https://link.springer.com/article/10.1208/s12249-024-02805-x
2. Gahlawat G, Tesfaye W, Bushell M, Abrha S, Peterson GM, Mathew C, et al. Emerging Treatment Strategies for Impetigo in Endemic and Nonendemic Settings: A Systematic Review. Clin Ther [Internet]. 2021 Jun 1 [cited 2026 Jan 20];43(6):986–1006. Available from: https://www.dermatologytimes.com/view/emerging-treatment-strategies-for-impetigo
3. Barbieri E, Porcu G, Dona' D, Falsetto N, Biava M, Scamarcia A, et al. Non-bullous Impetigo: Incidence, Prevalence, and Treatment in the Pediatric Primary Care Setting in Italy. Front Pediatr. 2022 Mar 31;10.
4. May PJ, Tong SYC, Steer AC, Currie BJ, Andrews RM, Carapetis JR, et al. Treatment, prevention and public health management of impetigo, scabies, crusted scabies and fungal skin infections in endemic populations: a systematic review. Trop Med Int Health. 2019 Mar 1;24(3):280–93.
5. Gahlawat G, Tesfaye W, Bushell M, Abrha S, Peterson GM, Mathew C, et al. Emerging Treatment Strategies for Impetigo in Endemic and Nonendemic Settings: A Systematic Review. Clin Ther. 2021 Jun 1;43(6):986–1006.
6. Gahlawat G, Tesfaye W, Bushell M, Abrha S, Peterson GM, Mathew C, et al. Emerging Treatment Strategies for Impetigo in Endemic and Nonendemic Settings: A Systematic Review. Clin Ther [Internet]. 2021 Jun 1 [cited 2026 Jan 20];43(6):986–1006. Available from: https://www.sciencedirect.com/science/article/pii/S0149291821002083
7. Antonara L, Triantafyllopoulou E, Chountoulesi M, Pippa N, Dallas PP, Rekkas DM. Lipid-Based Drug Delivery Systems: Concepts and Recent Advances in Transdermal Applications. Nanomaterials 2025, Vol 15, [Internet]. 2025 Aug 28 [cited 2026 Jan 20];15(17). Available

from: https://www.mdpi.com/2079-4991/15/17/1326
8. Alotaibi AR, Alshahrani RM, Alanazi AA, Almalki M khalil I, Alsaadoon SA, Mahjari AAA, et al. Overview on the Causes and Updated Management of Impetigo. J Pharm Res Int. 2021 Dec 11;50–7.
9. D'Cunha NM, Peterson GM, Baby KE, Thomas J. Impetigo: A need for new therapies in a world of increasing antimicrobial resistance. J Clin Pharm Ther. 2018 Feb 1;43(1):150–3.
10. Nanostructured lipid carriers for topical drug delivery: A comprehensive review of design, mechanisms, and therapeutic advances. Next Nanotechnology [Internet]. 2026 Jun 1 [cited 2026 Jan 20];9:100367. Available from: https://www.sciencedirect.com/science/article/pii/S2949829526000069
11. Nimtrakul P, Sermsappasuk P, Tiyaboonchai W. Strategies to enhance oral delivery of amphotericin B: a comparison of uncoated and enteric-coated nanostructured lipid carriers. Drug Deliv. 2020 Jan 1;27(1):1054–62.
12. Khan AA, Mudassir J, Akhtar S, Murugaiyah V, Darwis Y. Freeze-dried lopinavir-loaded nanostructured lipid carriers for enhanced cellular uptake and bioavailability: Statistical optimization, in vitro and in vivo evaluations. Pharmaceutics. 2019 Feb 1;11(2).
13. Liang J, Liu Y, Liu J, Li Z, Fan Q, Jiang Z, et al. Chitosan-functionalized lipid-polymer hybrid nanoparticles for oral delivery of silymarin and enhanced lipid-lowering effect in NAFLD. J Nanobiotechnology. 2018 Sep 4;16(1).
14. Shahzadi I, Fürst A, Knoll P, Bernkop-Schnürch A. Nanostructured lipid carriers (Nlcs) for oral peptide drug delivery: About the impact of surface decoration. Pharmaceutics. 2021 Aug 1;13(8).
15. Yang G, Wu F, Chen M, Jin J, Wang R, Yuan Y. Formulation design, characterization, and in vitro and in vivo evaluation of nanostructured lipid carriers containing a bile salt for oral delivery of gypenosides. Int J Nanomedicine. 2019;14:2267–80.
16. Dudhipala N, Janga KY, Gorre T. Comparative study of nisoldipine-loaded nanostructured lipid carriers and solid lipid nanoparticles for oral delivery: preparation, characterization, permeation and pharmacokinetic evaluation. Artif Cells Nanomed Biotechnol. 2018 Nov 5;46(sup2):616–25.
17. Rouco H, Diaz-Rodriguez P, Gaspar DP, Gonçalves LMD, Cuerva M, Remuñán-López C, et al. Rifabutin-loaded nanostructured lipid carriers as a tool in oral anti-mycobacterial treatment of crohn's disease. Nanomaterials. 2020 Nov 1;10(11):1–18.
18. Zhu Q, Chen Z, Paul PK, Lu Y, Wu W, Qi J. Oral delivery of proteins and peptides: Challenges, status quo and future perspectives. Acta Pharm Sin B. 2021 Aug 1;11(8):2416–48.
19. Soni K, Rizwanullah M, Kohli K. Development and optimization of sulforaphane-loaded nanostructured lipid carriers by the Box-Behnken design for improved oral efficacy against cancer: in vitro, ex vivo and in vivo assessments. Artif Cells Nanomed Biotechnol. 2018 Oct 31;46(sup1):15–31.
20. Haider M, Abdin SM, Kamal L, Orive G. Nanostructured lipid carriers for delivery of chemotherapeutics: A review. Pharmaceutics. 2020 Mar 1;12(3).
21. Tan SLJ, Billa N. Improved bioavailability of poorly soluble drugs through gastrointestinal muco-adhesion of lipid nanoparticles. Pharmaceutics. 2021 Nov 1;13(11).
22. Plaza-Oliver M, Santander-Ortega MJ, Lozano MV. Current approaches in lipid-based nanocarriers for oral drug delivery. Drug Deliv Transl Res. 2021 Apr 1;11(2):471–97.
23. Palagati S, Sv S, Kesavan BR. Application of computational tools for the designing of Oleuropein loaded nanostructured lipid carrier for brain targeting through nasal route. DARU, Journal of Pharmaceutical Sciences. 2019 Dec 1;27(2):695–708.
24. Yu Y, Feng R, Li J, Wang Y, Song Y, Tan G, et al. A hybrid genipin-crosslinked dual-sensitive hydrogel/nanostructured lipid carrier ocular drug delivery platform. Asian J Pharm Sci. 2019 Jul 1;14(4):423–34.
25. Mulia K, Safiera A, Pane IF, Krisanti EA. Effect of high speed homogenizer speed on particle size of polylactic acid. J Phys Conf Ser. 2019 May 10;1198(6).

26. Mendes M, Basso J, Silva J, Cova T, Sousa J, Pais A, et al. Biomimeting ultra-small lipid nanoconstructs for glioblastoma treatment: A computationally guided experimental approach. Int J Pharm. 2020 Sep 25;587.
27. Reinholz J, Landfester K, Mailänder V. The challenges of oral drug delivery via nanocarriers. Drug Deliv. 2018;25(1):1694–705.
28. Ajiboye AL, Nandi U, Galli M, Trivedi V. Olanzapine loaded nanostructured lipid carriers via high shear homogenization and ultrasonication. Sci Pharm. 2021 Jun 1;89(2).
29. Chauhan I, Yasir M, Verma M, Singh AP. Nanostructured lipid carriers: A groundbreaking approach for transdermal drug delivery. Adv Pharm Bull. 2020;10(2):150–65.
30. Olechowski F, Müller RH, Pyo SM. Bergacare smartLipids: Commercial lipophilic active concentrates for improved performance of dermal products. Beilstein Journal of Nanotechnology. 2019;10.
31. Ghasemiyeh P, Mohammadi-Samani S. Solid lipid nanoparticles and nanostructured lipid carriers as novel drug delivery systems: Applications, advantages and disadvantages. Res Pharm Sci. 2018 Aug 1;13(4):288–303.
32. Agrawal S, Giri TK, Tripathi DK, Ajazuddin, Alexander A. A review on novel therapeutic strategies for the enhancement of solubility for hydrophobic drugs through lipid and surfactant based self micro emulsifying drug delivery system: A novel approach. American Journal of Drug Discovery and Development. 2012;2(4):143–83.
33. Shadambikar G, Marathe S, Ji N, Almutairi M, Bandari S, Zhang F, et al. Formulation development of itraconazole PEGylated nano-lipid carriers for pulmonary aspergillosis using hot-melt extrusion technology. Int J Pharm X. 2021 Dec 1;3.
34. Alshamsan A, Kazi M, Badran MM, Alanazi FK. Role of alternative lipid excipients in the design of self-nanoemulsifying formulations for fenofibrate: Characterization, in vitro dispersion, digestion and ex vivo gut permeation studies. Front Pharmacol. 2018 Nov 6;9(NOV).
35. Duong VA, Nguyen TTL, Maeng HJ, Chi SC. Data on optimization and drug release kinetics of nanostructured lipid carriers containing ondansetron hydrochloride prepared by cold high-pressure homogenization method. Data Brief. 2019 Oct 1;26.
36. Krstić M, Medarević Đ, Đuriš J, Ibrić S. Self-nanoemulsifying drug delivery systems (SNEDDS) and self-microemulsifying drug delivery systems (SMEDDS) as lipid nanocarriers for improving dissolution rate and bioavailability of poorly soluble drugs. Lipid Nanocarriers for Drug Targeting. 2018 Jan 1;473–508.
37. Scioli Montoto S, Muraca G, Ruiz ME. Solid Lipid Nanoparticles for Drug Delivery: Pharmacological and Biopharmaceutical Aspects. Front Mol Biosci. 2020 Oct 30;7.
38. Krstić M, Medarević Đ, Đuriš J, Ibrić S. Self-nanoemulsifying drug delivery systems (SNEDDS) and self-microemulsifying drug delivery systems (SMEDDS) as lipid nanocarriers for improving dissolution rate and bioavailability of poorly soluble drugs. Lipid Nanocarriers for Drug Targeting. 2018 Jan 1;473–508.
39. Elmowafy M, Al-Sanea MM. Nanostructured lipid carriers (NLCs) as drug delivery platform: Advances in formulation and delivery strategies. Saudi Pharmaceutical Journal. 2021 Sep 1;29(9):999–1012.
40. Kumar P, Sharma DK, Ashawat MS. Topical creams of piperine loaded lipid nanocarriers for management of atopic dermatitis: development, characterization, and in vivo investigation using BALB/c mice model. J Liposome Res. 2022;32(1):62–73.
41. Flühmann B, Ntai I, Borchard G, Simoens S, Mühlebach S. Nanomedicines: The magic bullets reaching their target? European Journal of Pharmaceutical Sciences. 2019 Feb 1;128:73–80.
42. Kumar P, Sharma DK, Ashawat MS. Topical creams of piperine loaded lipid nanocarriers for management of atopic dermatitis: development, characterization, and in vivo investigation using BALB/c mice model. J Liposome Res. 2022;32(1):62–73.
43. Duong VA, Nguyen TTL, Maeng HJ. Preparation of solid lipid nanoparticles and nanostructured lipid carriers for drug delivery and the effects of

preparation parameters of solvent injection method. Molecules. 2020 Oct 1;25(20).
44. Khan S, Sharma A, Jain V. An Overview of Nanostructured Lipid Carriers and its Application in Drug Delivery through Different Routes. Adv Pharm Bull [Internet]. 2022 [cited 2026 Jan 20];13(3):446. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC10460807/
45. Kumar P, Sharma DK, Ashawat MS. Topical creams of piperine loaded lipid nanocarriers for management of atopic dermatitis: development, characterization, and in vivo investigation using BALB/c mice model. J Liposome Res. 2022;32(1):62–73.
46. Patil GB, Patil ND, Deshmukh PK, Patil PO, Bari SB. Nanostructured lipid carriers as a potential vehicle for Carvedilol delivery: Application of factorial design approach. Artif Cells Nanomed Biotechnol. 2016 Jan 1;44(1):12–9.
47. González-Minero FJ, Bravo-Díaz L. The use of plants in skin-care products, cosmetics and fragrances: Past and present. Cosmetics. 2019 Sep 1;5(3).
48. Supe S, Takudage P. Methods for evaluating penetration of drug into the skin: A review. Skin Research and Technology. 2021 May 1;27(3):299–308.
49. Mall J, Naseem N, Haider MF, Rahman MA, Khan S, Siddiqui SN. Nanostructured lipid carriers as a drug delivery system: A comprehensive review with therapeutic applications. Intelligent Pharmacy. 2025 Aug 1;3(4):243–55.
50. Patel J, King A, Malempati M, Patel M. Understanding nootropics and cognitive enhancement: mechanism of action and ethical considerations. Health Open Research. 2024 Jan 9;6:2.
51. Saberi Y, Javadi K, Mirzaei A, Halaji M. Mupirocin: A Useful Antibiotic for Methicillin-Resistant Staphylococcus aureus Decolonization: A Narrative Review. Microbial Drug Resistance. 2025 Aug 1;31(8):250–61.
60. Santos Pimentel L, Sommerfeld S, Fernanda de Sousa Braga P, Flores Coleto A, Beatriz Fonseca B, Machado Bastos L, et al. Antitumor activity
52. Huang X, Shen QK, Guo HY, Quan ZS, Li X. Research, development and pharmacological activity of fusidic acid and its derivatives. J Mol Struct. 2023 Nov 5;1291.
53. Platon VM, Dragoi B, Marin L. Erythromycin Formulations—A Journey to Advanced Drug Delivery. Pharmaceutics [Internet]. 2022 Oct 1 [cited 2026 Jan 21];14(10):2180. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC9608461/
54. Del Rosso JQ, Armillei MK, Lomakin IB, Grada A, Bunick CG. Clindamycin: A Comprehensive Status Report with Emphasis on Use in Dermatology. J Clin Aesthet Dermatol [Internet]. 2024 Aug 1 [cited 2026 Jan 21];17(8):29. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC11324192/
55. Yukuyama MN, Kato ETM, Lobenberg R, Bou-Chacra NA. Challenges and Future Prospects of Nanoemulsion as a Drug Delivery System. Curr Pharm Des. 2016 Nov 3;23(3):495–508.
56. Khan S, Sharma A, Jain V. An Overview of Nanostructured Lipid Carriers and its Application in Drug Delivery through Different Routes. Adv Pharm Bull [Internet]. 2022 [cited 2026 Jan 21];13(3):446. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC10460807/
57. Jaiswal P, Gidwani B, Vyas A. Nanostructured lipid carriers and their current application in targeted drug delivery. Artif Cells Nanomed Biotechnol. 2016 Jan 1;44(1):27–40.
58. Mall J, Naseem N, Haider MF, Rahman MA, Khan S, Siddiqui SN. Nanostructured lipid carriers as a drug delivery system: A comprehensive review with therapeutic applications. Intelligent Pharmacy. 2025 Aug 1;3(4):243–55.
59. Cortesi R, Valacchi G, Muresan XM, Drechsler M, Contado C, Esposito E, et al. Nanostructured lipid carriers (NLC) for the delivery of natural molecules with antimicrobial activity: production, characterisation and in vitro studies. J Microencapsul. 2017 Jan 2;34(1):63–72.
of essential oils-based nanostructured lipid carriers on prostate cancer cells. Int J Pharm. 2024 May 25;657.

61. Almeida LF, Gil GA, Moraes LN, Furtado FB, Kakuda L, Grotto RMT, et al. Nanostructured lipid carriers loaded with essential oils: a strategy against SARS-CoV-2. J Microencapsul. 2024;41(4):284–95.
62. Can Karaca A, Rezaei A, Qamar M, Assadpour E, Esatbeyoglu T, Jafari SM. Lipid-based nanodelivery systems of curcumin: Recent advances, approaches, and applications. Food Chem. 2025 Jan 15;463.
63. Madane RG, Mahajan HS. Curcumin-loaded nanostructured lipid carriers (NLCs) for nasal administration: design, characterization, and in vivo study. Drug Deliv. 2016 May 3;23(4):1326–34.
64. Nemati S, Mohammad Rahimi H, Hesari Z, Sharifdini M, Jalilzadeh Aghdam N, Mirjalali H, et al. Formulation of Neem oil-loaded solid lipid nanoparticles and evaluation of its anti-Toxoplasma activity. BMC Complement Med Ther. 2022 Dec 1;22(1).
65. Shinde G, Sonchhatra A, Shelke S, Pathan I. Design, optimization and in-vivo characterization of mupirocin loaded nanostructured lipid carrier based gel for effective treatment of impetigo. J Drug Deliv Sci Technol. 2022 Jan 1;67.
66. Pareek A, Kapoor DU, Yadav SK, Rashid S, Fareed M, Akhter MS, et al. Advancing lipid nanoparticles: A pioneering technology in cosmetic and dermatological treatments. Colloids and Interface Science Communications. 2025 Jan 1;64.
67. Bruns C, Ober M. Development and Preparation of Oral Suspensions for Paediatric Patients – a Challenge for Pharmacists. Pharm Technol Hosp Pharm. 2018 Jun 1;3(2):113–9.
68. Tan DCT, Khong YM, Mount S, Galella E, Mitra B, Charlton S, et al. Pediatric formulation development – Challenges of today and strategies for tomorrow: Summary report from M−CERSI workshop 2019. European Journal of Pharmaceutics and Biopharmaceutics. 2021 Jul 1;164:54–65.
69. Ogbonna JDN, Cunha E, Attama AA, Ofokansi KC, Ferreira H, Pinto S, et al. Overcoming Challenges in Pediatric Formulation with a Patient-Centric Design Approach: A Proof-of-Concept Study on the Design of an Oral Solution of a Bitter Drug. Pharmaceuticals [Internet]. 2022 Nov 1 [cited 2026 Jan 21];15(11):1331. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC9694284/
70. Medina A, Brown MN, Cox E, Donegan S, Dragulin-Otto S, Flores K, et al. Drug product development and case studies for patient centric pediatric protein-based therapeutics. J Pharm Sci. 2025 Feb 1;114(2):681–9.