RESEARCH PAPER

Nanoemulsion-Based Strategies for Enhanced Bioavailability and Targeting

Kaushal Kumar[1], Saniya Parveen[2], Mohit Kumar[2], Anjum Parveen[2], Gaurav Kumar[2], Mohd Zafar[*2], Manish Kumar Saxena[2]

1. Department of Pharmacy, M. J. P. Rohilkhand University, Bareilly, U. P., India
2. Samrat Prithviraj Chauhan College of Pharmacy, Kashipur, U. S. Nagar Uttarakhand, India

Corresponding Author: Mohd Zafar, Associate Professor, Samrat Prithviraj Chauhan College of Pharmacy, Kashipur, U. S. Nagar, Uttarakhand- 244713. mohdzafar8273@gmail.com

ABSTRACT

Nanoemulsions are colloidal dispersions with droplet sizes typically ranging from 20 to 200 nanometers, offering remarkable advantages such as enhanced stability, solubility, and bioavailability of active compounds. Their high surface area-to-volume ratio and kinetic stability make them ideal carriers for controlled and targeted delivery systems. In pharmaceutical applications, nanoemulsions improve the absorption and therapeutic efficacy of poorly soluble drugs, enabling site-specific action and reduced dosing frequency. Similarly, in cosmetics, food, and agriculture, they facilitate efficient delivery of bioactives, improve product stability, and enhance sensory attributes. Recent advances in nanoemulsion technology include the optimization of emulsifier systems, the use of green and biocompatible surfactants, and the adoption of innovative fabrication techniques such as high-pressure homogenization, ultrasonication, and microfluidization. These methods allow precise control of droplet size, stability, and release kinetics, leading to scalable and reproducible formulations. Additionally, incorporation of functional nanocarriers, stimuli-responsive components, and hybrid lipid-polymer systems has broadened the scope of nanoemulsion-based delivery platforms. Despite significant progress, challenges such as long-term stability, large-scale production, and regulatory concerns remain. Addressing these limitations through advanced characterization, predictive modeling, and sustainable formulation strategies willbe crucial for clinical translation. Overall, nanoemulsions represent a rapidly evolving frontier in nanotechnology, with the potential to revolutionize drug delivery and other bioactive applications, ultimately improving therapeutic outcomes and patient compliance.

Keywords: Nanoemulsion, Advantages, Disadvantages, Techniques, Evaluation and Application.

How to cite this article: Kaushal Kumar1 Saniya Parveen2 Mohit Kumar2 Anjum Parveen2 Gaurav Kumar2 Mohd Zafar*2 Manish Kumar Saxena2. Nanoemulsion-Based Strategies for Enhanced Bioavailability and Targeting. Int J Drug Deliv Technol. 2026;16(90s):869-892. DOI: 10.25258/ijddt.16.90s.87.

Introduction

The effectiveness of modern pharmaceuticals is closely tied to the efficiency of their drug delivery systems. Conventional formulations often encounter significant limitations, including poor solubility, low bioavailability, rapid degradation, and inadequate targeting, which can compromise therapeutic outcomes. These challenges have driven the development of advanced nanotechnology-based delivery platforms capable of enhancing drug performance and patient compliance. Among these, nanoemulsions have emerged as a versatile and promising strategy in drug delivery. Nanoemulsions are colloidal dispersions of nanoscale droplets, typically ranging from 20 to 200 nanometers, formed by dispersing one immiscible liquid within another using surfactants or co-surfactants (1). Despite being thermodynamically unstable, they exhibit kinetic stability, which prevents phase separation and enhances shelf-life. The small droplet size of nanoemulsions results in a high surface area-to-volume ratio, improved optical transparency, and favorable interfacial properties, making them ideal carriers for pharmaceutical and biomedical applications.One of the primary advantages of nanoemulsions is their ability to enhance the solubility and bioavailability of hydrophobic drugs, which constitute a significant proportion of therapeutic compounds (2). By encapsulating these drugs within nanosized droplets, nanoemulsions facilitate dissolution and absorption, improving systemic availability and therapeutic efficacy. Additionally, they provide protection against enzymatic degradation, pH fluctuations, and other environmental factors, preserving the stability of sensitive molecules such as peptides, proteins, and nucleic acids. The flexibility of nanoemulsions also enables controlled and sustained drug release, as well as the possibility of targeted delivery through surface functionalization with ligands, antibodies, or other targeting moieties, thereby reducing off-target effects and enhancing treatment precision (3). Recent technological advances have significantly improved the preparation, reproducibility, and scalability of nanoemulsions. Techniques such as high-pressure homogenization, ultrasonication, microfluidization, and phase inversion methods allow precise control of droplet size, polydispersity, and stability. The

development of biocompatible and environmentally friendly surfactants has further increased their safety profile, facilitating translation to clinical and commercial applications. Emerging trends include hybrid nanoemulsions, stimuli-responsive formulations, and integration with other nanocarriers, which expand their functional capabilities and therapeutic potential (4). Nano-emulsion drug delivery systems (NEDDS) have witnessed substantial progress in both formulation science and therapeutic application, yet critical research gaps persist. Recent advancements have focused on optimizing particle size, improving drug loading, and enhancing stability, across multiple administration routes including oral, transdermal, ocular, nasal, and intra-articular delivery (5). A major driver behind this innovation has been the push to address the bioavailability and solubility limitations typical of poorly water-soluble drugs. Researchers have fine-tuned component selection, surfactant and cosurfactant ratios, used advanced preparation techniques like high-pressure homogenization and ultrasonication, and explored surface functionalization with targeting moieties and mucoadhesive agents (6). Such strategies have been notably effective in overcoming distinct biological barriers-such as gastrointestinal enzymatic degradation, stratum corneum in skin, and limited permeability in ocular and nasal routes-leading to improved therapeutic outcomes, particularly in challenging areas such as cancer therapy, neuropharmaceutical delivery, and even vaccine administration. Self-nanoemulsifying drug delivery systems (SNEDDS) have further broadened the landscape, allowing for spontaneous formation of nano-droplets upon contact with biological fluids, significantly enhancing oral absorption and protecting drugs from harsh environments (7). Nanoemulsions have also seen increased application for hydrophobic drug molecules like paclitaxel and cyclosporine, with consistent findings of both heightened absorption and drug stability. From a formulation science perspective, methods of preparation such as high-pressure homogenization and ultrasonication have matured, with statistical experimental design and ternary phase diagrams now routinely employed for optimizing droplet size, stability, and emulsification time. In-situ characterization techniques, particularly transmission electron microscopy (TEM) and scanning electron microscopy (SEM), provide detailed insight into particle morphology and structure, while modern in vitro and ex vivo models allow for robust evaluation of release profiles and biological performance (8). Advances in surfactant chemistry have also enabled the use of safer and more biocompatible agents, reducing toxicity concerns and expanding the feasible clinical applications. There has been marked innovation in the incorporation of functional excipients such as permeation enhancers, mucoadhesive polymers, and ligands for targeted therapy, creating hybrid systems capable of simultaneous therapeutic and diagnostic functions-theranostics(9). Moreover, the scope of therapeutic agents delivered via NEDDS has broadened. Beyond small molecule drugs, nanoemulsions have now been adapted for peptides, proteins, nucleic acids, and vaccines, enabling not just drug therapy but also gene and immunotherapy in recent clinical pipelines. Despite these advancements, significant knowledge gaps remain, constraining the translation of NEDDS from research laboratories to mainstream clinical practice (10). One major unresolved question is the precise biological fate and long-term toxicity of nanoemulsion components, especially after repeated administration. While short-term in vivo studies often indicate good biocompatibility, there remains an absence of systematic, longitudinal safety data, particularly regarding the accumulation of oil phases and surfactant residues in organs like the liver or spleen. The interplay of droplet size, surface charge, and stability with complex physiological conditions such as varying pH, digestive enzymes, and protein corona formation is still only partially understood . A further translational challenge-especially for hydrophobic drugs and biologicals-is the risk of instability during large-scale manufacturing, including issues of Oswald ripening, phase separation, and unpredictable aggregation, which affect reproducibility and shelf-life. Additionally, common regulatory hurdles stem from the lack of standardized methods for characterizing complex NEDDS, and from insufficient harmonization of guidelines among different regulatory jurisdictions (11).

Recent reviews also underscore a persisting gap in the mechanistic understanding of nanoemulsion interactions with biological barriers, such as epithelial tight junction modulation or endocytosis/exocytosis pathways. While functionalization with peptides or antibodies has shown to improve targeting, there is limited predictability and control over biodistribution and off-target effects, especially in vivo (12). Clinical translation is further hampered by the diversity of excipients used in proprietary formulations, for which scalable sourcing, reproducibility, and established safety profiles cannot always be guaranteed. Another knowledge gap lies in the development of reliable, predictive *in vitro* and *in silico* models for correlating nanoemulsion properties with in vivo performance. Such models are crucial for the rational design of NEDDS and for accelerating preclinical development, but remain underdeveloped, especially

for non-oral or combination therapies (13). Future research must address these gaps through several avenues: improved longitudinal safety studies in animals and humans, advances in real-time imaging and tracking of nanoemulsion biodistribution, harmonization of regulatory frameworks, and better predictive modeling for both efficacy and toxicity (14). The design of "smart" nanoemulsions capable of controlled release and environmental responsiveness, the use of natural biodegradable components, and the adoption of green chemistry for formulation could mitigate present risks and broaden clinical adoption. Additionally, clinical trials evaluating not just pharmacokinetics but also long-term outcomes and patient-centered metrics will be crucial in validating the full potential of NEDDS for diverse therapeutic areas. Consequently, while the last five years have seen the implementation of impressive technological and scientific innovations in nano-emulsion drug delivery systems, their widespread clinical use still awaits the resolution of key translational, safety, and regulatory questions that are only starting to be systematically addressed (15).

1.1 Advantages of nanoemulsion

Nanoemulsion are a cutting-edge medication delivery method with many advantages over conventional systems (16). Nanoemulsions' nano-sized droplets and capacity to incorporate hydrophilic and lipophilic medicines provide them these advantages. (Fig No.1)



Figure No.1: Advantages of Nanoemulsions

As a result, nanoemulsions have emerged as a versatile and efficient platform for enhancing the delivery of therapeutic agents, addressing several limitations faced by traditional formulations (17). These advantages are as follows: see in the **Table No.1**

- **Enhanced Stability:**Nanoemulsions have high stability and can remain stable for long periods without separating or undergoing phase separation. The small droplet size reduces the gravitational forces acting on the droplets, preventing coalescence and maintaining a homogeneous mixture (18).
- **Improved Bioavailability:**Nanoemulsions' small droplets increase target site surface area, improving active ingredient absorption and bioavailability. Pharmaceutical applications benefit from increased bioavailability, which boosts drug efficacy (19).
- **Targeted Delivery:**Nanoemulsions can target specific tissues or places. By changing droplet characteristics on the surface or adding targeting ligands, nanoemulsions can transport medications or active components to specific cells or tissues, improving efficacy and decreasing side effects (20).
- **Enhanced Solubility:**Nanoemulsions may help insoluble medications or components dissolve. The small droplet size increases the surface area available for dissolution, allowing for better dispersion and solubilization of hydrophobic compounds (21).
- **Improved Sensory Properties:**Nanoemulsions increase product appearance, texture, and flavor. They can create a smooth and creamy texture in food products, enhance the spreadability and absorption of cosmetic formulations, and improve the clarity and stability of emulsions (22).
- **Versatility:** Many hydrophilic and lipophilic chemicals can be used to make nanoemulsions. Nanoemulsions can include medications, antioxidants, vitamins, and essential oils due to their adaptability (23).
- **Scalability:**Nanoemulsion production is readily adaptable for commercial use. High-pressure homogenization and micro fluidization can make nanoemulsions in huge quantities without affecting their stability and characteristics (24).

Overall, nanoemulsions offer a promising solution for the advanced formulations development with enhanced bioavailability, improved stability, targeted delivery, and enhanced sensory properties.

Table No.1 Studies on Advantages of Nanoemulsion

Study	Author & Year	Key Findings	Application Field
Applications of Nanoemulsions in Food Manufacturing	(25)	Increased bioavailability, stability, and consumer demand for healthier food products.	Food Industry
Nanoemulsion characteristic	(26)	Enhanced oil recovery processes	Oil Industry

s, Formation and oil industry applications		due to stability and modified rheology.	
Nanoemulsion-based delivery approaches for nutraceuticals	(27)	Better delivery and bioavailability of nutraceuticals.	Food Industry
Nanoemulsion overview: development concepts and cosmeceutical applications	(28)	High kinetic stability and sensorial advantage for cosmetics and dermatology.	Cosmetics and Dermatology
Healthcare Applications of Nanoemulsions	(29)	Utilized for various drug delivery routes due to stability and small size.	Healthcare and Drug Delivery
Current Perspectives on Nanoemulsions in Targeted Drug Delivery	(30)	Increased drug loading, solubility, and targeted delivery.	Drug Delivery
Ultrasonic nano-emulsification - A review	(31)	Benefits of ultrasonic emulsification in nanoemulsions production.	Nanotechnology
Nanoemulsions Applications (Current) in Cancer Therapeutics	(32)	Potential in efficient and safe tumor treatment.	Cancer Therapy
Nanoemulsions: Importance in Pharmaceutical Nanotechnology	(33)	Improved drug solubility and bioavailability.	Pharmaceutical Nanotechnology

1.2 Disadvantages of nanoemulsion

While nanoemulsions offer numerous advantages in drug delivery, it is essential to acknowledge and address potential disadvantages associated with their use (34). (Fig No.2)

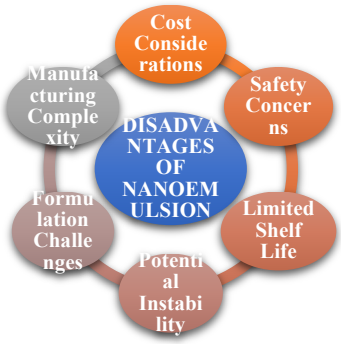

Figure No.2: Disadvantages of Nanoemulsion

These drawbacks, although not prohibitive, warrant consideration in the development and application of nanoemulsion-based formulations (35–38). Below are some notable disadvantages of nanoemulsions: see in the **Table 2**

- **Manufacturing Complexity:** The production of nanoemulsions can be more complex and time-consuming compared to traditional emulsions. Specialized equipment and techniques, such as microfluidization or homogenization (high-pressure), may be required. This can increase the cost and complexity of manufacturing processes (39).
- **Formulation Challenges:** Formulating nanoemulsions can be challenging due to the need for precise control over the properties and composition of the emulsion. The selection of suitable emulsifiers, co-solvents, and other formulation components is crucial to achieve stability and desired performance. Formulation optimization may require extensive trial and error (40).
- **Potential Instability:** While nanoemulsions are generally more stable than traditional emulsions, they can still be susceptible to destabilization under certain conditions. Ionic strength, pH, and temperature can cause nanoemulsions to phase separate or aggregate droplets. Careful formulation and storage conditions are necessary to maintain stability (41).

- **Limited Shelf Life:** Despite their improved stability, nanoemulsions may still have a limited shelf life compared to other delivery systems. Over time, the droplets in the emulsion may undergo physical or chemical changes, leading to degradation or loss of functionality. Protecting nanoemulsion products from light and controlling temperature extends their shelf life (42).
- **Safety Concerns:** The use of certain emulsifiers or co-solvents in nanoemulsion formulations may raise safety concerns. It is important to corroborate that the selected ingredients are safe for use in the intended application and comply with regulatory requirements. Additionally, the potential for increased penetration of active ingredients in nanoemulsions may require careful consideration of their safety profiles (43).
- **Cost Considerations:** Nano emulsion production can be more expensive compared to emulsions (traditional) due to the need for specialized equipment and formulation optimization. The cost of raw materials, such as emulsifiers and co-solvents, may also be higher for nanoemulsion formulations. These factors can impact the overall cost-effectiveness of nanoemulsion-based products.

Continued development and research in the field of nanoemulsions aim to address these challenges and further improve their performance and applicability (44).

Table 2 Studies on Disadvantages of Nanoemulsion

Study Title	Authors and Year	Key Points
Nanoemulsions: Factory for Food, Pharmaceutical and Cosmetics	(45)	Discusses challenges in high and low energy formation methods.
Nanoemulsion-based active packaging for food products	(46)	Mentions pros and cons in ensuring the quality and safety of food products.
Nanoemulsion: An emerging technology for oilfield applications between limitations and potentials	(47)	Covers synthesis challenges, advantages, and disadvantages in oil and gas industry.
Nanoemulsion: Importance in Pharmaceutical Nanotechnology	(48)	Highlights disadvantages, including preparation and stability challenges.
Nanoemulsions and Their Potential Applications in Food Industry	(49)	Touches on limitations and challenges in delivering nutraceuticals in food products.
Nanoemulsion as Oral Drug Delivery - A Review	(50)	Discusses limitations and challenges in oral drug delivery.
A Review on Novel Drug Delivery System Nanoemulsion	(51)	Outlines potential for enhanced drug solubility and bioavailability and stability challenges.
Current Applications of Nanoemulsions in Cancer Therapeutics	(52)	Highlights potential and challenges in cancer therapy.
Applications of Nanoemulsions in Food Manufacturing	(53)	Discusses advantages and challenges in food product encapsulation.
Formation, characteristics and oil industry applications of nanoemulsions: A review	(54)	Includes insight on synthesis challenges in the oil and gas industry.

2 Nanoemulsions for mRNA/Vaccine Delivery, Human Safety, and Industrial Scale-Up

Nanoemulsions have emerged as a promising platform for mRNA and vaccine delivery due to their ability to encapsulate, protect, and efficiently deliver nucleic acids to target cells. These colloidal systems, typically composed of oil, water, surfactants, and co-surfactants, form kinetically stable nanoscale droplets that enhance the bioavailability and cellular uptake of therapeutic agents. In the context of mRNA vaccines, nanoemulsions help prevent mRNA degradation by enzymes and facilitate endosomal escape, improving translation efficiency and immunogenicity. This is

particularly relevant for vaccines against infectious diseases and cancer, where rapid and durable immune responses are crucial (55). Human safety is a major consideration in the development of nanoemulsion-based carriers. Biocompatible and biodegradable constituents-such as natural lipids, phospholipids, and nonionic surfactants—are preferred to minimize toxicity, inflammation, or immunogenic side effects. Extensive preclinical and clinical evaluations are required to ensure safe systemic administration, focusing on biodistribution, metabolism, and clearance pathways. Additionally, the risk of unintended immune activation or accumulation in non-target tissues must be carefully assessed (56). From an industrial perspective, scaling up nanoemulsion production poses both opportunities and challenges. Techniques like high-pressure homogenization, microfluidization, and spontaneous emulsification enable the reproducible fabrication of uniform droplets with controlled physicochemical properties. However, maintaining stability, sterility, and consistent batch quality during large-scale manufacturing requires stringent process optimization and quality control (57). Regulatory guidelines for nanoformulations emphasize robust characterization, validated analytical methods, and documentation to meet Good Manufacturing Practice (GMP) standards. As the global demand for rapid vaccine deployment grows, scalable nanoemulsion technologies offer a cost-effective and flexible platform for mass production, storage, and distribution of mRNA-based vaccines. Integration of advanced formulation strategies and automated production systems will further enhance their translational potential in ensuring both safety and efficacy for human applications (**Table 3**) (58).

Table 3 Recent Advancement in nanoemulsion

S. No.	Research Area	Recent Advancements (2021–2025)	Gaps / Challenges	Foresee	References
1.	**mRNA and Vaccine Delivery**	Nanoemulsions developed as lipid-based carriers for mRNA and antigen delivery with enhanced immune response, stability, and cold-chain resilience.	Limited clinical translation and human immunogenicity data; excipient biodegradability uncertain.	Conduct controlled human trials and long-term safety studies; standardize NE-mRNA formulation.	(59)
2.	**Cationic/Hybrid Nanoemulsions**	Ionizable and cationic nanoemulsions improve nucleic acid encapsulation and endosomal escape; hybrid lipid–polymer systems enhance stability.	Potential cytotoxicity of cationic lipids and unclear interfacial mechanisms.	Optimize charge ratio and hybrid composition; explore biodegradable cationic lipids.	(60)
3.	**Thermostable & Needle-Free Vaccines**	Thermostable and intranasal nanoemulsion vaccines for COVID-19 and influenza developed to improv	Lack of standardized thermostability assessment and cold-chain alternatives.	Develop validated protocols for thermostability and large-scale lyophilization.	(61)

		e accessibility.			
4.	**Targeted & Stimuli-Responsive Nanoemulsions**	Smart NEs responding to pH, enzyme, and temperature for site-specific release.	Poor reproducibility of in vivo activation; limited quantitative trigger thresholds.	Quantify physiological stimuli in disease microenvironments; develop reproducible response models.	(62)
5.	**Safety & Regulatory Aspects**	Progress in excipient safety studies, early regulatory discussions, and toxicity evaluation frameworks.	Absence of harmonized global NE-specific regulatory standards; limited chronic toxicity data.	Establish unified regulatory guidance and long-term biodistribution databases.	(63)
6.	**Clinical Translation**	Several NE formulations entering early-phase trials with favorable pharmacokinetic outcomes.	Few late-stage trials; limited pharmacovigilance and human variability data.	Expand clinical pipeline and develop standardized endpoints for efficacy and safety evaluation.	(64)
7.	**Industrial Scale-Up & Manufacturing**	Continuous emulsification, microfluidics, and QbD frameworks introduced for reproducibility.	Droplet instability, process cost, and poor inter-lab standardization during scale-up.	Implement automated PAT tools and open-access scale-up case repositories.	(65)
8.	**Solid-State and Oral NE Systems**	Solid nanoemulsions (SNEs) and SNEDDS extend shelf life and enable oral delivery of hydrophobic drugs.	Structural instability and recrystallization risk post-solidification.	Develop surfactant–oil matrices with enhanced solid-state stability.	(66)
9.	**AI-Assisted Design**	Machine learning used for predicting droplet size, stability, and release kinetics.	Small datasets and lack of experimental validation.	Build open NE datasets and train hybrid experimental-computational models.	(67)
10.	**Sustainability & Green Manufacturing**	Green surfactants and biodegradable oils gaining attention to reduce toxicity and waste.	Scale-up cost and variability in natural surfactant sources.	Optimize biogenic surfactant production and life-cycle assessment models.	(68)

3 Composition

The nanoemulsion composition typically contains 3 main components: oil phase, aqueous phase, and surfactants. Each component plays a crucial role in stabilizing the nano-sized droplets and facilitating the delivery of drugs or active ingredients (69). (Fig No.3)

:



Figure No.3: Component of Nanoemulsion

a. Oil Phase: Serves as the core of the nanoemulsion droplets and can include various types of oils or lipids. Commonly used oils are as follows:

- Medium-chain triglycerides (MCTs)-
- Long-chain triglycerides (LCTs)
- Soybean oil
- Corn oil
- Olive oil
- Caprylic/capric triglyceride
- Castor oil
- Essential oils (for specific applications)

The oil phase (selection) depends on characteristics such as the solubility of the drug, stability requirements, and desired route of administration (70).

b. Aqueous Phase: This phase surrounds the oil droplets and is typically composed of water or water-based solutions. The aqueous phase may contain:

- Distilled water
- Saline solutions
- Buffer solutions (e.g., phosphate-buffered saline)
- Hydrophilic active ingredients or drugs

The aqueous phase provides a medium for dispersing hydrophilic drugs or active ingredients and contributes to the nanoemulsion stability (71).

c. Surfactants: Amphiphilic surfactants stabilize nanoemulsion droplets by lowering oil-aqueous interfacial tension. They are necessary to prevent droplet coalescence and maintain oil phase dispersion in the aqueous medium (72).

Surfactants can include:

- Nonionic surfactants (e.g., polysorbates, Tweens, Span)
- Anionic surfactants (e.g., sodium dodecyl sulfate)
- Cationic surfactants
- Amphoteric surfactants

The selection and concentration of surfactants are critical for achieving optimal stability and preventing issues such as Ostwald ripening and phase separation (73).

d. Additional Components

Depending on the specific application and desired properties, additional components may be incorporated into the nanoemulsion formulation, including:

- **Co-surfactants:** These can enhance the stability of the nanoemulsion by working synergistically with surfactants.
- **Co-solvents:** Solvents may be added to ameliorate thehydrophobicdrugssolubility or active ingredients in the oil phase.
- **Antioxidants:** Antioxidants such as tocopherols or butylated hydroxytoluene (BHT) may be included to protect sensitive compounds from degradation.
- **pH adjusters:** Buffering agents may be used to adjust the pH of the nanoemulsion to a desired range for stability or compatibility with biological systems (74).

4 Types of nanoemulsions

Nanoemulsions can be categorized based on various characteristics such as the nature of their components, droplet size, method of preparation, and structural features (75). (Fig No.4)

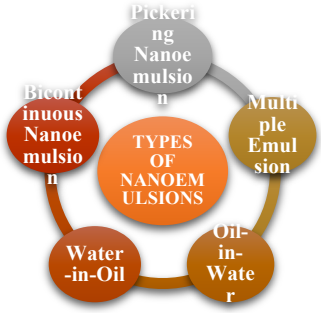

Figure No.4: Types of Nanoemulsions

By understanding these classifications, researchers can tailor nanoemulsion formulations to suit specific drug delivery requirements and optimize their performance for various applications (76). There are several types of nanoemulsions based on the nature of the liquids used. Some common types include:

- **Oil-in-water (O/W) nanoemulsion:** Oil droplets diffuse in a continuous water phase. Pharmaceutical, cosmetic, and food industries employ O/W nanoemulsions(77).
- **Water-in-oil (W/O) nanoemulsion:** In this type, droplets of water are diffused within a continuous oil phase. W/O nanoemulsions are often used in the formulation of creams, lotions,

and sunscreens which are oil-based products (78).

- **Multiple emulsions:** Also known as O/W/O (oil-in-water-in-oil) or W/O/W (water-in-oil-in-water) nanoemulsion, this type consists of multiple layers of emulsion droplets. These types of emulsions are used in applications where controlled release or encapsulation of active ingredients is desired (79).
- **Pickering nanoemulsion:** Solid particles like colloidal particles or nanoparticles at the oil-water interaction increase this nanoemulsion. Pickering nanoemulsions are stable and can be employed in medicine delivery and food preparation (80).
- **Bicontinuousnanoemulsion:** In this type, both phases (oil and water) form a continuous network, resulting in a bicontinuous structure. Bicontinuousnanoemulsions have unique properties and can be used in applications such as controlled release systems and nanoreactors (81).

5 Applications

Nanoemulsions find diverse applications across various fields, particularly in pharmaceuticals, cosmetics, food, and agriculture (82). Their unique properties make them suitable for a wide range of uses. Here are some key applications related to nanoemulsions. (Fig No.5)



Figure No.5 Application of Nanoemulsion

- **Drug Delivery:**Nanoemulsions help administer medications effectively in the drug industry. They can improve drug stability, bioavailability, and targeted distribution to specific body regions. Nanoemulsions can administer drugs orally, topically, transdermally, and intravenously (83).
- **Cosmetics and Personal Care:**Nanoemulsions have found their way into the world of beauty products and personal care products, enhancing the effectiveness of delivering the active components to the skin. They have the potential to improve the absorption of moisturizers, vitamins, antioxidants, and other beneficial compounds, resulting in increased effectiveness. Products can be formulated using nanoemulsions to achieve sensory characteristics that are highly valued, including a smooth texture and enhanced Spreadability(84).
- **Food and Beverage Industry:**Nanoemulsions find wide-ranging uses in the food and beverage sector, serving a multitude of purposes. Enhancing the stability and prolonging the lifespan of emulsified items, like dressings, sauces, and beverages, is possible. Nanoemulsions also improve bioactive chemical stability and bioavailability, including colors, tastes, and nutraceuticals. They can also control the release and encapsulation of delicate compounds (85).
- **Agrochemicals:**Nanoemulsions find application in the agricultural sector to effectively transport herbicides, pesticides, and other agrochemicals. Enhancements can be made to enhance the effectiveness and precision of these substances, resulting in a reduction in the quantity of chemicals needed and a decrease in environmental consequences. Nanoemulsions can improve the stability and dispersibility of agrochemical formulations (86).
- **Biotechnology and Nanomedicine:** Nanoemulsions find wide-ranging uses in the fields of biotechnology and nanomedicine. They have the ability to encapsulate and transport biomolecules, including peptides, proteins, and nucleic acids. Nanoemulsions can also be used for diagnostic purposes, like serving as contrast agents for imaging techniques. In addition, there are potential uses in therapy with genes and targeted drug transport systems (87).
- **Energy and Environmental Applications:**Nanoemulsions have potential applications in the energy and environmental sectors. They can be used for enhanced oil recovery, where nanoemulsions are injected into oil reservoirs to improve oil extraction. Functional materials can be encapsulated and delivered using nanoemulsions for ecological remediation applications, like removing contaminants from water or dirt (88).

6 Technique of preparation

The creation of stable nanoemulsions involves overcoming various challenges, including achieving small droplet sizes, ensuring uniform distribution, and maintaining long-term stability. [90][91] Researchers employ a variety of methods, each with its own intricacies and advantages, to produce nanoemulsions tailored to specific applications. By understanding the principles behind these techniques, it becomes possible to harness the full potential of

nanoemulsions in drug delivery, cosmetics, food, and other industries (89). (Fig No.6)

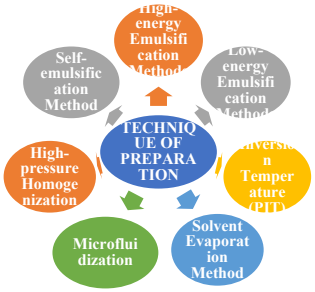

Figure No.6 Technique of Preparation

Some common techniques include:

- **High-energy emulsification methods:** These technologies use extreme shear pressures to break up larger droplets. High-pressure homogenization, ultrasonication, and microfluidization can be used for high-energy emulsification (90).
- **Low-energy emulsification methods:** The generation of nanoemulsions is performed by applying moderate shear pressures to the surrounding environment. Phase inversion composition (PIC) and spontaneous emulsification are two examples of emulsification procedures that need very little energy. These techniques are just a couple of examples (91).
- **Solvent evaporation method:** This approach forms nanoemulsions by dissolving oil and water in a shared solvent and evaporating it (92).
- **Phase inversion temperature (PIT) method:** This method involves the manipulation 8of the temperature to induce phase inversion and form nanoemulsions. The PIT method is commonly used for the preparation of water-in-oil nanoemulsions(93).
- **Self-emulsification method:** This method involves the use of self-emulsifying systems, which are mixtures of oil, surfactant, and co-surfactant that spontaneously form nanoemulsions when dispersed in water (94).
- **High-pressure homogenization:** This method forms nanoemulsions by forcing oil and water through a narrow space under high pressure (95).
- **Microfluidization:** This method forms nanoemulsions by forcing water and oil through microchannels with high-pressure pumps (96).

Several methods are utilized to make nanoemulsions. Type of liquids, desired droplet size, and nanoemulsion application determine the process

7 Evaluation of nanoemulsion

Evaluation of nanoemulsion optimization, characterization, and assessment parameters is a critical aspect in the development of stable, effective, and targeted drug delivery systems (**Table 4**). Optimizing involves a careful balance between formulation composition, preparation methods, and performance characteristics to achieve desired physicochemical stability, bioavailability, and therapeutic efficacy. The optimization process usually begins with the selection of appropriate oil phases, surfactants, and co-surfactants based on their solubilizing capacities and compatibility with the intended drug. Techniques such as pseudo-ternary phase diagrams are employed for identifying the emulsification region, providing insight into the concentration ranges that yield stable nanoemulsions(97).

Table 4 Evaluation of nanoemulsion optimization, characterization, and assessment parameters

S. No.	Category	Parameter	Purpose	Methods	References
1	Optimization Parameters	Selection of Oil Phase	The choice of oil directly influences solubilization of the drug and affects droplet size and stability. Oils with higher solubilizing capacity and compatibility enhance entrapment efficiency and stability.	Drug solubility screening using UV–Vis spectroscopy or HPLC; phase behavior studies.	(98)
2		Surfactant and Co-surfactant Selectio	Surfactants reduce interfacial tension,	Pseudo-ternary phase diagram analysis and	(99)

		n	while co-surfactants improve flexibility of the interfacial film. Selection depends on HLB values, biocompatibility, and emulsification efficiency.	visual observation of nanoemulsion regions.	
3		Smix Ratio (Surfactant to Co-surfactant Ratio)	Determines formation of stable nanoemulsion region and influences particle size, viscosity, and clarity.	Constructing phase diagrams at various Smix ratios; Design of Experiment (DoE) for optimization.	(100)
4		Oil:Surfactant Ratio	Affects nanoemulsion stability and drug encapsulation; optimal balance minimizes phase separation and maximizes solubilization.	Titration method and centrifugation stability testing.	(101)
5		Emulsification Method	The method (e.g., high-energy: ultrasonication, microfluidization; low-energy: spontaneous emulsification) affects droplet uniformity and size distribution.	Comparative study using high-speed homogenizer, probe sonicator, or phase inversion.	(102)
6		Mixing Speed and Time	Directly impacts droplet dispersion and stability; excessive energy may cause coalescence or overheating.	DoE optimization, monitoring via particle size analysis.	(103)
7		Temperature of Formulation	Temperature influences solubility, viscosity, and interfacial film elasticity; critical for thermosensitive drugs.	Thermogravimetric analysis (TGA), visual observation, and temperature cycling tests.	(104)

8	Characterization Parameters	Droplet Size and Size Distribution	Determines stability, bioavailability, and release rate. Smaller droplet size (<200 nm) enhances drug absorption and physical stability.	Dynamic Light Scattering (DLS) using a Zetasizer.	(105)
9		Polydispersity Index (PDI)	Indicates uniformity of droplet size distribution; lower PDI (<0.3) denotes monodisperse and stable system.	DLS / Particle Size Analyzer.	(106)
10		Zeta Potential	Represents surface charge and predicts electrostatic repulsion between droplets. High absolute values (±30 mV) indicate stability against aggregation.	Electrophoretic Light Scattering (ELS) using a Zetasizer.	(107)
11		Morphological Analysis	Reveals structural integrity, shape, and surface topology of droplets.	Transmission Electron Microscopy (TEM), Scanning Electron Microscopy (SEM), or Atomic Force Microscopy (AFM).	(108)
12		Refractive Index	Confirms isotropy and transparency; indicates formation of oil-in-water (O/W) nanoemulsion.	Abbe refractometer.	(109)
13		Viscosity and Rheological Behavior	Evaluates flow and spreadability; important for topical, oral, or injectable formulations.	Brookfield viscometer or Rheometer.	(110)
14		pH and Conductivity	Determines formulation compatibility	pH meter and Conductometer.	(111)

			with biological systems and identifies emulsion type (O/W or W/O).		
15		Drug Loading and Encapsulation Efficiency	Quantifies drug incorporated into the nanoemulsion; affects therapeutic efficacy and stability.	Centrifugation followed by UV–Vis / HPLC quantification of supernatant.	(112)
16		Thermodynamic Stability Studies	Confirms physical stability under stress (heating–cooling, centrifugation, freeze–thaw cycles). Unstable formulations show creaming or phase separation.	Centrifugation, temperature cycling, freeze–thaw test.	(113)
17	Biological & Functional Assessment	In Vitro Drug Release Profile	Determines drug release kinetics and	Dialysis membrane or Franz diffusion cell,	(114)
	Parameters		diffusion mechanism, predicting in vivo performance.	analyzed by HPLC.	
18		Ex Vivo Permeation Study	Measures drug permeation through biological membranes (skin, mucosa, or intestinal tissue).	Franz diffusion cell using animal or human excised membrane.	(115)
19		Cytotoxicity and Cell Viability	Evaluates safety and biocompatibility on cell lines (e.g., HaCaT, HepG2).	MTT assay, Alamar Blue, or LDH leakage test.	(116)
20		Hemocompatibility / Hemolysis Test	Assesses compatibility with red blood cells, critical for parenteral formulations.	Spectrophotometric measurement of released hemoglobin.	(117)
21		Antimicrobial / Anticancer Efficacy	Tests the biological functionality	MIC determination, Zone of inhibition, or cell	(118)

			of drug-loaded nanoemulsions in disease models.	apoptosis assays.	
22		In Vivo Pharmacokinetic Study	Determines absorption, distribution, metabolism, and elimination of the nanoemulsion formulation.	Animal model studies analyzed via LC–MS/MS.	(119)
23		Biodistribution and Targeting Efficiency	Evaluates accumulation of nanoemulsion in specific organs/tissues; confirms targeting potential.	Fluorescence imaging, radio-labeling, or MRI contrast study.	(120)
24		Stability Studies (ICH Guidelines)	Ensures long-term chemical and physical stability under accelerated conditions.	ICH Q1A(R2) protocols (e.g., 40°C ± 2°C / 75% ± 5% RH).	(121)
25		Scale-up and Industrial Feasibility	Assesses reproducibility and process robustness during large-scale production.	Pilot-scale homogenization or microfluidization trials.	(122)
26		Regulatory and Safety Evaluation	Ensures the formulation meets toxicity and quality standards for clinical use.	OECD toxicity tests, FDA/EMA guidelines, Good Manufacturing Practice (GMP) compliance.	(123)

Experimental design tools such as the Design of Experiments (DoE), Box-Behnken, or Central Composite designs are often used to statistically optimize formulation and process variables including surfactant concentration, homogenization speed, and time to achieve the smallest droplet size and narrowest distribution. Characterization of optimized nanoemulsions is essential to ensure quality, reproducibility, and suitability for their intended application. The most fundamental parameters assessed are droplet size, polydispersity index (PDI), and zeta potential. Droplet size and PDI are typically measured using dynamic light scattering (DLS), where smaller droplet sizes indicate better stability and bioavailability, while a PDI value less than 0.3 reflects uniform size distribution and formulation homogeneity. Zeta potential provides information about the surface charge and electrostatic repulsion between droplets; a higher absolute zeta potential value, typically greater than ±30 mV, suggests better physical stability by preventing coalescence through electrostatic repulsion. Transmission Electron Microscopy (TEM) or Scanning Electron Microscopy (SEM) can also be used to visually confirm droplet morphology and size, often revealing spherical, well-dispersed particles in an optimized nanoemulsion(124–129). Other important assessment parameters include viscosity, refractive index, pH, conductivity, and thermodynamic stability. Rheological behavior (viscosity) determines the flow characteristics and suitability of the formulation for various routes of administration, such as oral, topical, nasal, or parenteral use. Refractive index analysis helps to verify transparency and nano-size droplet formation. pH measurement ensures the compatibility

of the formulation with human tissues and drugs, avoiding irritation or degradation. Conductivity testing can differentiate between oil-in-water (O/W) and water-in-oil (W/O) systems, providing insights into the nature of the dispersion. Thermodynamic stability evaluations, including centrifugation, heating-cooling cycles, and freeze–thaw stress tests, are performed to assess the resistance of nanoemulsions to phase separation, flocculation, or creaming during storage or temperature fluctuations. Drug content determination and encapsulation efficiency are also crucial in assessing formulation performance, typically evaluated through UV–Visible spectroscopy or High-Performance Liquid Chromatography (HPLC). These parameters indicate how effectively the drug is loaded and maintained within the nanocarrier system. In vitro release studies provide insights into release kinetics, often showing sustained or controlled drug release owing to the small droplet size and large surface area (Fig No.7). Finally, biological assessments such as *in vitro* cytotoxicity, permeability studies, and *in vivo* biodistribution further validate the optimized nanoemulsion's therapeutic potential (130–133).



Figure No.7 Assessment of Nanoemulsion

8 Recent advances and future directions

Nanoemulsions, in particular, have won attention for their unusual features and varied uses in medication solubility, bioavailability, and targeted delivery (134). the latest innovations in nanoemulsion-based drug delivery systems, including novel formulation strategies (**Table 3**), advanced characterization techniques, and emerging applications, their potential to address unmet medical needs and propel the future of healthcare are as follows.

a. Novel Formulation Strategies:

- **Hybrid Nanoemulsions**: Researchers have been exploring the development of hybrid nanoemulsions by combining polymeric nanoparticles or liposomes, with nanoemulsions to achieve synergistic effects in drug delivery. These hybrid systems offer improved stability, controlled release, and enhanced targeting capabilities (135).
- **Multifunctional Nanoemulsions:** Novel formulations are being designed to incorporate multiple functionalities into nanoemulsions, such as targeting ligands, stimuli-responsive components, and imaging agents. This approach enables the development of smart nanoemulsion systems capable of targeted delivery, triggered release in vivo (136).
- **Long-Acting Nanoemulsions:** Efforts are underway to develop long-acting nanoemulsions capable of sustained drug release over extended periods. Strategies include incorporating biodegradable polymers or hydrogels into nanoemulsion formulations to prolong drug release kinetics while maintaining therapeutic efficacy (137).

b. Advanced Characterization Techniques:

- **Nanoparticle Tracking Analysis (NTA):** NTA has emerged as a powerful technique for characterizing nanoemulsions, allowing for the real-time measurement of particle size distribution and concentration in suspension. This technique provides valuable insights into nanoemulsion stability, colloidal behavior, and aggregation dynamics (138).
- **Cryo-Transmission Electron Microscopy (Cryo-TEM):** It provides detailed information about particle morphology, internal structure, and phase behavior. This technique facilitates the visualization of nanoemulsion components at the nanoscale, aiding in the optimization of formulation parameters and understanding their impact on drug delivery performance (139).
- **Dynamic Light Scattering (DLS):** DLS is commonly used to characterize nanoemulsion size distribution and colloidal stability. DLS instrumentation and data analysis techniques have improved, making nanoemulsion features including particle size, polydispersity, and zeta potential more accurately characterized (140).

c. Emerging Applications:

- **Personalized Medicine:** Nanoemulsion-based systems for drug delivery can customize therapeutic agents to human traits and illness profiles, promising personalized treatment. Clinicians can optimize treatment regimens and patient outcomes by adding biomarkers, imaging agents, and tailored ligands to nanoemulsions(141).
- **Combination Therapy:** Nanoemulsions enable synergistic therapeutic effects and overcome medication resistance in complicated disorders like cancer by co-delivering numerous medicines with distinct physicochemical properties. Emerging research focuses on optimizing the formulation and administration of combination therapies using nanoemulsion-based delivery systems to enhance efficacy while minimizing side effects (142).

- **Intracellular Drug Delivery:** Nanoemulsions are being investigated for intracellular drug delivery applications, particularly for the treatment of intracellular infections and diseases. By engineering nanoemulsions with cell-penetrating peptides or endosomal escape mechanisms, researchers aim to improve drug uptake and release within target cells, enhancing therapeutic efficacy and minimizing off-target effects (143).

9 Conclusion

The food and beverages sector, the pharmaceutical industry, the pharmaceutical delivery industry, the beauty sector, the agricultural industry, and the textile industry are all potential applications for nanoemulsions. Nanoemulsions include unique characteristics that empower them to be utilized in a wide variety of purposes. These characteristics include a small droplet size, high stability, and enhanced solubility capabilities. Nanoemulsions have an opportunity to improve the transportation of bioactive chemicals, as well as contribute to the enhancement of the sensory qualities and lifespan of beverages and food items. When it comes to the subject of medicine, nanoemulsions are extremely important since they are able to specifically target particular cells and tissues within the body, while also increasing the bioavailability and solubility of medications. There are a number of possible uses for nanoemulsions in the field of agriculture, particularly in the treatment of contaminated soil and the enhancement of the delivery of fertilizer and pesticides. Nanoemulsions present a possibly profitable opportunity to enhance the efficiency of beauty products for the transportation of active ingredients and to improve their overall effectiveness. Nanoemulsions have the ability to transform the textile industry by enhancing the comfort and safety of wearers, as well as the overall performance and longevity of textile materials.

To completely comprehend the effects of nanoemulsions on the environment and human health, however, as well as to create practical techniques for commercialization and mass manufacturing, further study is required. Notwithstanding these difficulties, nanoemulsions have a lot of potential advantages that could assist a lot of different businesses in the future.

ACKNOWLEDGEMENT

The author expresses gratitude to Dr.Prevesh Kumar for her unwavering support during the formulation process, as well as to Diksha for their advice throughout the study project.Dr. Navneet Verma offered technical assistance in order to solve the issue encountered throughout the research.

CONFLICT OF INTEREST

I declare that there is no conflict of interest.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

Not Applicable

HUMAN AND ANIMAL RIGHTS

No humans or animals were involved in the studies.

CONSENT FOR PUBLICATION

Not Applicable

AVAILABILITY OF DATA AND MATERIALS

The data supporting the findings of this study can be found within the article.

FUNDING

None

CONFLICT OF INTEREST

The authors declare absence of any conflict of interest, whether financial or otherwise.

10 REFERENCE

1. Ezike TC, Okpala US, Onoja UL, Nwike CP, Ezeako EC, Okpara OJ, et al. Advances in drug delivery systems, challenges and future directions. Heliyon [Internet]. 2023 Jun 1 [cited 2025 Oct 9];9(6):e17488. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC10320272/
2. Rosner D, Clark J. Formulations for Bacteriophage Therapy and the Potential Uses of Immobilization. Pharmaceuticals (Basel) [Internet]. 2021 Apr 13 [cited 2025 Oct 29];14(4). Available from: http://www.ncbi.nlm.nih.gov/pubmed/33924739
3. Tayeb HH, Felimban R, Almaghrabi S, Hasaballah N. Nanoemulsions: Formulation, characterization, biological fate, and potential role against COVID-19 and other viral outbreaks. Colloid Interface Sci Commun [Internet]. 2021 Nov 1 [cited 2025 Oct 9];45:100533. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC8526445/
4. Allam OG, Ramadan MM, Ismail SA, Hebeish A. Preparation and application of lemon peel oil (Citrus aurantifolia) to improve microbial resistance of wool and viscose fabrics. Egypt J Chem. 2022 Aug 1;65(8):511–21.
5. Chatzidaki MD, Mitsou E. Advancements in Nanoemulsion-Based Drug Delivery Across Different Administration Routes. Pharmaceutics [Internet]. 2025 Mar 1 [cited 2025 Oct 9];17(3). Available from: https://pubmed.ncbi.nlm.nih.gov/40143001/
6. Liu X, Zhao L, Wu B, Chen F. Improving solubility of poorly water-soluble drugs by protein-based strategy: A review. Int J Pharm [Internet]. 2023 Mar 5 [cited 2025 Oct 9];634:122704. Available from: https://www.sciencedirect.com/science/article/abs/pii/S0378517323001242
7. Lou J, Duan H, Qin Q, Teng Z, Gan F, Zhou X, et al. Advances in Oral Drug Delivery Systems: Challenges and Opportunities. Pharmaceutics [Internet]. 2023 Feb 1 [cited 2025 Oct 9];15(2):484. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC9960885/
8. Wu HR, Wang CQ, Wang JX, Chen JF, Le Y. Engineering of long-term stable transparent

nanoemulsion using high-gravity rotating packed bed for oral drug delivery. Int J Nanomedicine. 2020;15:2391–402.

9. Shaban SM, Kang J, Kim DH. Surfactants: Recent advances and their applications. Composites Communications [Internet]. 2020 Dec 1 [cited 2025 Oct 9];22:100537. Available from: https://www.sciencedirect.com/science/article/abs/pii/S2452213920302655
10. Sun X, Setrerrahmane S, Li C, Hu J, Xu H. Nucleic acid drugs: recent progress and future perspectives. Signal Transduct Target Ther [Internet]. 2024 Dec 1 [cited 2025 Oct 9];9(1):1–31. Available from: https://www.nature.com/articles/s41392-024-02035-4
11. Madni A, Jameel F, Bajwa SZ, Rehman A, Khan WS. Toxicity, biological fate, and bioavailability of nanoemulsion formulations. Bio-Based Nanoemulsions for Agri-Food Applications [Internet]. 2022 Jan 1 [cited 2025 Oct 9];91–104. Available from: https://www.sciencedirect.com/science/article/abs/pii/B9780323898461000115
12. Kenry, Yeo T, Manghnani PN, Middha E, Pan Y, Chen H, et al. Mechanistic Understanding of the Biological Responses to Polymeric Nanoparticles. ACS Nano [Internet]. 2020 Apr 28 [cited 2025 Oct 9];14(4):4509–22. Available from: https://pubs.acs.org/doi/abs/10.1021/acsnano.9b10195
13. Younis MA, Tawfeek HM, Abdellatif AAH, Abdel-Aleem JA, Harashima H. Clinical translation of nanomedicines: Challenges, opportunities, and keys. Adv Drug Deliv Rev [Internet]. 2022 Feb 1 [cited 2025 Oct 9];181:114083. Available from: https://www.sciencedirect.com/science/article/abs/pii/S0169409X21004762
14. Banati P. Conclusion: The Future of Longitudinal Research. Sustainable Human Development Across the Life Course [Internet]. 2021 Feb 24 [cited 2025 Oct 9];233–48. Available from: https://www.researchgate.net/publication/368828513_Conclusion_The_Future_of_Longitudinal_Research
15. Zhang H, Zhao X, Chen X, Xu X. Thoroughly review the recent progresses in improving O/W interfacial properties of proteins through various strategies. Front Nutr [Internet]. 2022 Oct 26 [cited 2025 Oct 29];9:1043809. Available from: http://www.ncbi.nlm.nih.gov/pubmed/36386920
16. Iskandar B, Liu TW, Mei HC, Kuo IC, Surboyo MDC, Lin HM, et al. Herbal nanoemulsions in cosmetic science: A comprehensive review of design, preparation, formulation, and characterization. J Food Drug Anal. 2024;32(4):428–58.
17. (PDF) NANOEMULSIONS: A VERSATILE PLATFORM FOR ENHANCED DRUG DELIVERY SYSTEMS [Internet]. [cited 2025 Oct 9]. Available from: https://www.researchgate.net/publication/383739825_NANOEMULSIONS_A_VERSATILE_PLATFORM_FOR_ENHANCED_DRUG_DELIVERY_SYSTEMS
18. Lu WC, Huang DW, Wang CCR, Yeh CH, Tsai JC, Huang YT, et al. Preparation, characterization, and antimicrobial activity of nanoemulsions incorporating citral essential oil. J Food Drug Anal. 2018 Jan 1;26(1):82–9.
19. Wik J, Bansal KK, Assmuth T, Rosling A, Rosenholm JM. Facile methodology of nanoemulsion preparation using oily polymer for the delivery of poorly soluble drugs. Drug DelivTransl Res. 2020 Oct 1;10(5):1228–40.
20. Shankar R, Upadhyay PK, Kumar M. Nanoemulsions a Delivery System in the Making for Tumor Targeting Therapeutics: Evaluation and Characterization to Meet Clinical Challenges. Curr Pharm Biotechnol [Internet]. 2025 Apr 3 [cited 2025 Oct 9];26(7):1069–87. Available from: https://pubmed.ncbi.nlm.nih.gov/38566389/
21. Al-Hussaniy HA, Almajidi YQ, Oraibi AI, Alkarawi AH. Nanoemulsions as medicinal components in insoluble medicines. Pharmacia 70(3): 537-547 [Internet]. 2023 Jul 27 [cited 2025 Oct 9];70(3):537–47. Available from: https://pharmacia.pensoft.net/article/107131/
22. Abdou ES, Galhoum GF, Mohamed EN. Curcumin loaded nanoemulsions/pectin coatings for refrigerated chicken fillets. Food Hydrocoll. 2018 Oct 1;83:445–53.
23. Lee SJ, Choi SJ, Li Y, Decker EA, McClements DJ. Protein-stabilized nanoemulsions and emulsions: Comparison of physicochemical stability, lipid oxidation, and lipase digestibility. J Agric Food Chem. 2011 Jan 12;59(1):415–27.
24. Dammak I, de Carvalho RA, Trindade CSF, Lourenço RV, do Amaral Sobral PJ. Properties of active gelatin films incorporated with rutin-loaded nanoemulsions. Int J BiolMacromol. 2017 May 1;98:39–49.
25. Al-Bakre DA. Modeling the invasive potential of the opuntia cactus in arid ecosystems by assessing current and future distribution trends. Sci Rep. 2025 Dec 1;15(1).
26. Al-Anazi MS, Al-Khaldi MH, Fuseni A, Al-Marshad KM. Use of Nano-emulsion surfactants during hydraulic fracturing treatments. Society of Petroleum Engineers - 30th Abu Dhabi International Petroleum Exhibition and Conference, ADIPEC 2014: Challenges and Opportunities for the Next 30 Years. 2014;4:2498–512.
27. Li G, Zhang Z, Liu H, Hu L. Nanoemulsion-based delivery approaches for nutraceuticals: fabrication, application, characterization, biological fate, potential toxicity and future trends. Food Funct [Internet]. 2021 Mar 7 [cited 2025 Oct 9];12(5):1933–53.

Available from: https://pubmed.ncbi.nlm.nih.gov/33596279/
28. Marzuki NHC, Wahab RA, Hamid MA. An overview of nanoemulsion: Concepts of development and cosmeceutical applications. Biotechnology and Biotechnological Equipment. 2019;33(1):779–97.
29. Malik DrS, Kishore S, Kumari SA, Kumari A. Healthcare Applications of Nanoemulsions. https://services.igi-global.com/resolvedoi/resolve.aspx?doi=104018/978-1-7998-8378-4.ch023 [Internet]. 1AD Jan 1 [cited 2025 Oct 9];517–37. Available from: https://www.igi-global.com/chapter/healthcare-applications-of-nanoemulsions/295481
30. Zeytunluoglu A, Arslan I. Current Perspectives on Nanoemulsions in Targeted Drug Delivery. 2021 Dec 24;118–40.
31. Modarres-Gheisari SMM, Gavagsaz-Ghoachani R, Malaki M, Safarpour P, Zandi M. Ultrasonic nano-emulsification – A review. UltrasonSonochem [Internet]. 2019 Apr 1 [cited 2025 Oct 9];52:88–105. Available from: https://www.sciencedirect.com/science/article/pii/S1350417718312690
32. Wu Y, Zhang Y, Zhang W, Sun C, Wu J, Tang J. Reversing of multidrug resistance breast cancer by co-delivery of P-gp siRNA and doxorubicin via folic acid-modified core-shell nanomicelles. Colloids Surf B Biointerfaces. 2016 Feb 1;138:60–9.
33. Sugumaran A, Mathialagan V. Topical Delivery of Methocarbamol Loaded Nanoemulgel-in vitro Characterization. Indian Journal of Pharmaceutical Education and Research. 2022 Jan 1;56(1):144–52.
34. McClements DJ. Nanoemulsion-based oral delivery systems for lipophilic bioactive components: Nutraceuticals and pharmaceuticals. TherDeliv. 2013;4(7):841–57.
35. Fraga M, Schuh RS, Poletto É, de Carvalho TG, França RT, Pinheiro CV, et al. Gene Therapy of Mucopolysaccharidosis Type I Mice: Repeated Administrations and Safety Assessment of pIDUA/Nanoemulsion Complexes. Curr Gene Ther. 2021 Feb 12;21(5):464–71.
36. Czerniel J, Gostyńska A, Jańczak J, Stawny M. A critical review of the novelties in the development of intravenous nanoemulsions. European Journal of Pharmaceutics and Biopharmaceutics [Internet]. 2023 Oct 1 [cited 2025 Oct 9];191:36–56. Available from: https://www.sciencedirect.com/science/article/pii/S0939641123002126
37. Santos DCM dos, de Souza MLS, Teixeira EM, Alves LL, Vilela JMC, Andrade M, et al. A new nanoemulsion formulation improves antileishmanial activity and reduces toxicity of amphotericin B. J Drug Target. 2018 Apr 21;26(4):357–64.
38. Izadiyan Z, Basri M, FardMasoumi HR, Abedi Karjiban R, Salim N, Kalantari K. Improvement of physicochemical properties of nanocolloidal carrier loaded with low water solubility drug for parenteral cancer treatment by Response Surface Methodology. Materials Science and Engineering C. 2019 Jan 1;94:841–9.
39. Artiga-Artigas M, Lanjari-Pérez Y, Martín-Belloso O. Curcumin-loaded nanoemulsions stability as affected by the nature and concentration of surfactant. Food Chem. 2018 Nov 15;266:466–74.
40. Kumar M, Bishnoi RS, Shukla AK, Jain CP. Techniques for Formulation of Nanoemulsion Drug Delivery System: A Review. PrevNutr Food Sci [Internet]. 2019 [cited 2025 Oct 9];24(3):225. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC6779084/
41. Yerramilli M, Ghosh S. Long-term stability of sodium caseinate-stabilized nanoemulsions. J Food Sci Technol. 2017 Jan 1;54(1):82–92.
42. Zhang Z, McClements DJ. Overview of Nanoemulsion Properties: Stability, Rheology, and Appearance. Nanoemulsions: Formulation, Applications, and Characterization [Internet]. 2018 Jan 1 [cited 2025 Oct 9];21–49. Available from: https://www.sciencedirect.com/science/article/abs/pii/B9780128118382000023
43. Bhanupriya C, Reddy MS, Vijetha KA. FORMULATION AND IN-VITRO EVALUATION OF NANO-EMULSION OF SERTRALINE *Corresponding Author. Certified Journal | 2011 WORLD JOURNAL OF PHARMACY AND PHARMACEUTICAL SCIENCES SJIF Impact Factor [Internet]. 2024 [cited 2025 Oct 9];13(11):2011–56. Available from: www.wjpps.com
44. Acosta E. Bioavailability of nanoparticles in nutrient and nutraceutical delivery. CurrOpin Colloid Interface Sci [Internet]. 2009 Feb [cited 2025 Oct 9];14(1):3–15. Available from: https://www.researchgate.net/publication/371721940_General_Formulation_of_Nanoemulsions_Using_High-Energy_and_Low-Energy_Principal_Methods_A_Brief_Review
45. Azmi NAN, Elgharbawy AAM, Motlagh SR, Samsudin N, Salleh HM. Nanoemulsions: Factory for Food, Pharmaceutical and Cosmetics. Processes 2019, Vol 7, Page 617 [Internet]. 2019 Sep 11 [cited 2025 Oct 9];7(9):617. Available from: https://www.mdpi.com/2227-9717/7/9/617/htm
46. Wang L, Dong J, Chen J, Eastoe J, Li X. Design and optimization of a new self-nanoemulsifying drug delivery system. J Colloid Interface Sci. 2009 Feb 15;330(2):443–8.
47. Aljabri NM, Shi N, Cavazos A. Nanoemulsion: An emerging technology for oilfield applications between limitations and potentials. J Pet Sci Eng [Internet]. 2022 Jan 1 [cited 2025 Oct 9];208:109306. Available from:

https://www.sciencedirect.com/science/article/abs/pii/S0920410521009591

48. Elsewedy HS, Al-Dhubiab BE, Mahdy MA, Elnahas HM. Basic concepts of nanoemulsion and its potential application in pharmaceutical, cosmeceutical and nutraceutical fields. Res J Pharm Technol. 2021 Jul 1;14(7):3938–46.
49. Aswathanarayan JB, Vittal RR. Nanoemulsions and Their Potential Applications in Food Industry. Front Sustain Food Syst [Internet]. 2019 Nov 13 [cited 2025 Oct 9];3:438537. Available from: www.frontiersin.org
50. Sabjan KB, Munawar SM, Rajendiran D, Vinoji SK, Kasinathan K. Nanoemulsion as Oral Drug Delivery - A Review. Curr Drug Res Rev [Internet]. 2020 Oct 28 [cited 2025 Oct 9];12(1):4–15. Available from: https://pubmed.ncbi.nlm.nih.gov/31774040/
51. Shikalgar S, Khule MA, Godse MA. International Journal of Current Science Research and Review A Review on Novel Drug Delivery System Nanoemulsion. [cited 2025 Oct 9]; Available from: www.ijcsrr.org
52. Kotta S, Khan AW, Pramod K, Ansari SH, Sharma RK, Ali J. Exploring oral nanoemulsions for bioavailability enhancement of poorly water-soluble drugs. Expert Opin Drug Deliv. 2012;9(5):585–98.
53. Bai X, Liu C, Yu S, Pan Y, Shafiq F, Qiao W. Lipase-Responsive Lignin Composite Nanoparticles for the Delivery of Insoluble Bioactives. Langmuir. 2024 Jun 4;40(22):11610–25.
54. Ahmadi M, Sharma MM, Pope GA, Torres DE, McCulley CA, Linnemeyer H. Chemical treatment to mitigate condensate and water blocking in gas wells in carbonate reservoirs. SPE Production and Operations. 2011;26(1):67–74.
55. Bouchemal K, Briançon S, Perrier E, Fessi H. Nano-emulsion formulation using spontaneous emulsification: Solvent, oil and surfactant optimisation. Int J Pharm. 2004 Aug 6;280(1–2):241–51.
56. Wani TA, Masoodi FA, Jafari SM, McClements DJ. Safety of Nanoemulsions and Their Regulatory Status. Nanoemulsions: Formulation, Applications, and Characterization [Internet]. 2018 Jan 1 [cited 2025 Oct 9];613–28. Available from: https://www.sciencedirect.com/science/article/abs/pii/B9780128118382000199
57. Allam OG, Ramadan MM, Ismail SA, Hebeish A. Preparation and application of lemon peel oil (Citrus aurantifolia) to improve microbial resistance of wool and viscose fabrics. Egypt J Chem. 2022 Aug 1;65(8):511–21.
58. Ali F, Neha K, Parveen S. Current regulatory landscape of nanomaterials and nanomedicines: A global perspective. J Drug Deliv Sci Technol [Internet]. 2023 Feb 1 [cited 2025 Oct 9];80:104118. Available from: https://www.sciencedirect.com/science/article/abs/pii/S1773224722010292
59. Hariri A, Mirian M, Zarepour A, Khosravi A, Iravani S, Zarrabi A. Lipid nanoparticles driving mRNA vaccine innovations: From concept to clinic. Appl Mater Today [Internet]. 2025 Jun 1 [cited 2025 Oct 9];44:102786. Available from: https://www.sciencedirect.com/science/article/abs/pii/S2352940725002057
60. Mrksich K, Padilla MS, Mitchell MJ. Breaking the final barrier: Evolution of cationic and ionizable lipid structure in lipid nanoparticles to escape the endosome. Adv Drug Deliv Rev [Internet]. 2024 Nov 1 [cited 2025 Oct 9];214:115446. Available from: https://www.sciencedirect.com/science/article/abs/pii/S0169409X24002680
61. Kumar R, Srivastava V, Baindara P, Ahmad A. Thermostable vaccines: an innovative concept in vaccine development. Expert Rev Vaccines [Internet]. 2022 [cited 2025 Oct 9];21(6):811–24. Available from: https://pubmed.ncbi.nlm.nih.gov/35285366/
62. Chakroborty S, Nath N, Mahal A, Barik A, Panda AR, Fahaduddin, et al. Stimuli-responsive nanogels: A smart material for biomedical applications. J Mol Liq [Internet]. 2024 Jun 1 [cited 2025 Oct 9];403:124828. Available from: https://www.sciencedirect.com/science/article/abs/pii/S0167732224008845
63. Pandian PD, Kaliyaperumal R. Global and Indian Regulatory Frameworks for Pharmaceutical Excipients, APIs, and Formulations: Challenges and Harmonization Strategies. Recent Adv Drug DelivFormul [Internet]. 2025 [cited 2025 Oct 9]; Available from: https://pubmed.ncbi.nlm.nih.gov/40530729/
64. Al-Sulaiti FK, Sahin S. Therapeutic potential and clinical translation of nanodrugs: A path forward-case studies from bench to bedside. J Drug Deliv Sci Technol [Internet]. 2025 Oct 1 [cited 2025 Oct 9];112:107252. Available from: https://www.sciencedirect.com/science/article/abs/pii/S1773224725006550
65. Su YY, Pan DW, Deng CF, Yang SH, Faraj Y, Xie R, et al. Facile and Scalable Rotation-Based Microfluidics for Controllable Production of Emulsions, Microparticles, and Microfibers. Ind Eng Chem Res [Internet]. 2023 Mar 15 [cited 2025 Oct 9];62(10):4373–87. Available from: https://pubs.acs.org/doi/abs/10.1021/acs.iecr.2c03622
66. Jacob S, Kather FS, Boddu SHS, Shah J, Nair AB. Innovations in Nanoemulsion Technology: Enhancing Drug Delivery for Oral, Parenteral, and Ophthalmic Applications. Pharmaceutics 2024, Vol 16, Page 1333 [Internet]. 2024 Oct 17 [cited 2025 Oct 9];16(10):1333. Available from: https://www.mdpi.com/1999-4923/16/10/1333/htm

67. Eslami F, Kamali R. Developing machine learning models with metaheuristic algorithms for droplet size prediction in a microfluidic microchannel. Swarm EvolComput [Internet]. 2024 Jun 1 [cited 2025 Oct 9];87:101583. Available from: https://www.sciencedirect.com/science/article/abs/pii/S2210650224001214
68. Farias CBB, Almeida FCG, Silva IA, Souza TC, Meira HM, Soares da Silva R de CF, et al. Production of green surfactants: Market prospects. Electronic Journal of Biotechnology [Internet]. 2021 May 1 [cited 2025 Oct 9];51:28–39. Available from: https://www.sciencedirect.com/science/article/pii/S0717345821000063
69. Suryavanshi S, Gade S, Bhonagle A, Devale R, Thorat A. Overview of Nanoemulsion. International Journal of Pharmaceutical Science Invention ISSN. 14:95–106.
70. Abou-Kassem JH, Farouq Ali SM. Modelling of emulsion flow in porous media. Journal of Canadian Petroleum Technology. 1995 Jun;34(6):30–8.
71. Moustafa H, Youssef AM, Darwish NA, Abou-Kandil AI. Eco-friendly polymer composites for green packaging: Future vision and challenges. Compos B Eng. 2019 Sep 1;172:16–25.
72. Rai VK, Mishra N, Yadav KS, Yadav NP. Nanoemulsion as pharmaceutical carrier for dermal and transdermal drug delivery: Formulation development, stability issues, basic considerations and applications. Journal of Controlled Release. 2018 Jan 28;270:203–25.
73. Comprehensive Guide to Surfactants: Structure, Uses, and Types | Stanford Chemicals [Internet]. [cited 2025 Oct 9]. Available from: https://www.stanfordchem.com/comprehensive-guide-to-surfactants-structure-uses-and-types.html
74. de Oliveira Filho JG, Miranda M, Ferreira MD, Plotto A. Nanoemulsions as Edible Coatings: A Potential Strategy for Fresh Fruits and Vegetables Preservation. Foods [Internet]. 2021 Oct 14 [cited 2025 Oct 29];10(10). Available from: http://www.ncbi.nlm.nih.gov/pubmed/34681488
75. Mushtaq A, MohdWani S, Malik AR, Gull A, Ramniwas S, Ahmad Nayik G, et al. Recent insights into Nanoemulsions: Their preparation, properties and applications. Food Chem X [Internet]. 2023 Jun 30 [cited 2025 Oct 9];18:100684. Available from: https://www.sciencedirect.com/science/article/pii/S2590157523001268
76. Boche M, Pokharkar V. Quetiapine Nanoemulsion for Intranasal Drug Delivery: Evaluation of Brain-Targeting Efficiency. AAPS PharmSciTech. 2017 Apr 1;18(3):686–96.
77. Manickam S, Sivakumar K, Pang CH. Investigations on the generation of oil-in-water (O/W) nanoemulsions through the combination of ultrasound and microchannel. UltrasonSonochem [Internet]. 2020 Dec 1 [cited 2025 Oct 9];69:105258. Available from: https://www.sciencedirect.com/science/article/pii/S1350417719318176
78. Niknam SM, Kashaninejad M, Escudero I, Sanz MT, Beltrán S, Benito JM. Preparation of Water-in-Oil Nanoemulsions Loaded with Phenolic-Rich Olive Cake Extract Using Response Surface Methodology Approach. Foods [Internet]. 2022 Feb 1 [cited 2025 Oct 9];11(3):279. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC8834604/
79. Patil H, Waghmare J. HARNESSING THE POTENTIAL OF MULTIPLE EMULSIONS: A COMPREHENSIVE REVIEW OF MANUFACTURING METHODS AND APPLICATIONS. Certified Journal | Harshal et al World Journal of Pharmaceutical and Medical Research [Internet]. 2025 [cited 2025 Oct 9];11(5). Available from: www.wjpmr.com
80. Gauthier G, Capron I. Pickering nanoemulsions: An overview of manufacturing processes, formulations, and applications. JCIS Open [Internet]. 2021 Dec 1 [cited 2025 Oct 9];4:100036. Available from: https://www.sciencedirect.com/science/article/pii/S2666934X21000350
81. Bisen VR, Mokaswad DD, Sikdar PA, Taksande JB, Umekar MJ. A COMPREHENSIVE REVIEW ON NANOEMULSION: FORMULATION, CHARACTERIZATION, AND APPLICATIONS. 2023 [cited 2025 Oct 9];10. Available from: www.jetir.org
82. McClements DJ. Nanoemulsion-based oral delivery systems for lipophilic bioactive components: Nutraceuticals and pharmaceuticals. TherDeliv. 2013;4(7):841–57.
83. Wilson RJ, Li Y, Yang G, Zhao CX. Nanoemulsions for drug delivery. Particuology [Internet]. 2022 May 1 [cited 2025 Oct 9];64:85–97. Available from: https://www.sciencedirect.com/science/article/pii/S1674200121001176
84. Alshehrei FM. Microbiological Quality Assessment of Skin and Body care Cosmetics by using Challenge test. Saudi J Biol Sci. 2024 Apr 1;31(4).
85. Mohan S, Kaur G, Panigrahi BK, David C, Amarendra G. Effect of Zr and Al addition on nanocluster formation in oxide dispersion strengthened steel - An ab initio study. J Alloys Compd [Internet]. 2018 Oct 30 [cited 2025 Oct 29];767:122–30. Available from: https://www.sciencedirect.com/science/article/abs/pii/S0925838818325477
86. Gupta R, Malik P, Rani R, Solanki R, Ameta RK, Malik V, et al. Recent progress on nanoemulsions mediated pesticides delivery: Insights for agricultural sustainability. Plant Nano Biology [Internet]. 2024 May 1 [cited 2025 Oct 9];8:100073. Available from:

https://www.sciencedirect.com/science/article/pii/S2773111124000160

87. Chavda VP, Balar PC, Bezbaruah R, Vaghela DA, Rynjah D, Bhattacharjee B, et al. Nanoemulsions: Summary of a Decade of Research and Recent Advances. Nanomedicine (Lond) [Internet]. 2024 [cited 2025 Oct 9];19(6):519–36. Available from: https://pubmed.ncbi.nlm.nih.gov/38293801/
88. Kaur G, Panigrahi C, Agarwal S, Khuntia A, Sahoo M. Recent trends and advancements in nanoemulsions: Production methods, functional properties, applications in food sector, safety and toxicological effects. Food Physics [Internet]. 2024 Sep 1 [cited 2025 Oct 9];1:100024. Available from: https://www.sciencedirect.com/science/article/pii/S2950069924000185
89. Deveci E. Nanoemulsions in cosmetics: Enhancing efficacy and stability. Journal of Dermatologic Science and Cosmetic Technology [Internet]. 2025 Sep 1 [cited 2025 Oct 9];2(3):100107. Available from: https://linkinghub.elsevier.com/retrieve/pii/S2950306X25000408
90. Håkansson A, Rayner M. General Principles of Nanoemulsion Formation by High-Energy Mechanical Methods. Nanoemulsions: Formulation, Applications, and Characterization [Internet]. 2018 Jan 1 [cited 2025 Oct 9];103–39. Available from: https://www.sciencedirect.com/science/article/abs/pii/B9780128118382000059
91. Safaya M, Rotliwala YC. Nanoemulsions: A review on low energy formulation methods, characterization, applications and optimization technique. Mater Today Proc [Internet]. 2020 Jan 1 [cited 2025 Oct 9];27:454–9. Available from: https://www.sciencedirect.com/science/article/abs/pii/S2214785319339537
92. Ahangaran F. Microencapsulation: Solvent evaporation. Principles of Biomaterials Encapsulation: Volume 1 [Internet]. 2023 Jan 1 [cited 2025 Oct 9];1:377–92. Available from: https://www.sciencedirect.com/science/article/abs/pii/B9780323859479000169
93. Ren G, Sun Z, Wang Z, Zheng X, Xu Z, Sun D. Nanoemulsion formation by the phase inversion temperature method using polyoxypropylene surfactants. J Colloid Interface Sci [Internet]. 2019 Mar 22 [cited 2025 Oct 9];540:177–84. Available from: https://www.sciencedirect.com/science/article/abs/pii/S0021979719300189
94. Cholakova D, Vinarov Z, Tcholakova S, Denkov ND. Self-emulsification in chemical and pharmaceutical technologies. CurrOpin Colloid Interface Sci [Internet]. 2022 Jun 1 [cited 2025 Oct 9];59:101576. Available from: https://www.sciencedirect.com/science/article/abs/pii/S1359029422000152
95. Dezhakam E, Kafili-Hajlari T, Naseri A. Sample homogenization. Comprehensive Sampling and Sample Preparation. 2025;71–97.
96. Villalobos-Castillejos F, Granillo-Guerrero VG, Leyva-Daniel DE, Alamilla-Beltrán L, Gutiérrez-López GF, Monroy-Villagrana A, et al. Fabrication of Nanoemulsions by Microfluidization. Nanoemulsions: Formulation, Applications, and Characterization [Internet]. 2018 Jan 1 [cited 2025 Oct 9];207–32. Available from: https://www.sciencedirect.com/science/article/abs/pii/B9780128118382000084
97. Kumar M, Bishnoi RS, Shukla AK, Jain CP. Techniques for Formulation of Nanoemulsion Drug Delivery System: A Review. PrevNutr Food Sci [Internet]. 2019 [cited 2025 Oct 29];24(3):225. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC6779084/
98. Ramos AC da S, Rolemberg MP, Moura LGM de, Zilio EL, Santos M de FP dos, González G. Determination of solubility parameters of oils and prediction of oil compatibility. J Pet Sci Eng [Internet]. 2013 Feb 1 [cited 2025 Oct 9];102:36–40. Available from: https://www.sciencedirect.com/science/article/pii/S0920410513000181
99. Iranzi J, Park YC, Son H. Coupling Effects of Surfactant-Induced Interfacial Tension Reduction and Wettability Alteration in CO2 Storage. Energy & Fuels [Internet]. 2024 Oct 17 [cited 2025 Oct 9];38(20):19715–26. Available from: /doi/pdf/10.1021/acs.energyfuels.4c03431?ref=article_openPDF
100. (PDF) Effects of surfactant mixture ratio and concentration on nanoemulsion physical stability [Internet]. [cited 2025 Oct 9]. Available from: https://www.researchgate.net/publication/305432724_Effects_of_surfactant_mixture_ratio_and_concentration_on_nanoemulsion_physical_stability
101. Iskandar B, Mei HC, Liu TW, Lin HM, Lee CK. Evaluating the effects of surfactant types on the properties and stability of oil-in-water Rhodiolaroseananoemulsion. Colloids Surf B Biointerfaces [Internet]. 2024 Feb 1 [cited 2025 Oct 9];234:113692. Available from: https://www.sciencedirect.com/science/article/pii/S0927776523005866
102. Al-Sakkaf MK, Onaizi SA. Effects of emulsification factors on the characteristics of crude oil emulsions stabilized by chemical and Biosurfactants: A review. Fuel. 2024 Apr 1;361.
103. G. Alharbi G, Abdulhamid MA. Optimization of water/oil emulsion preparation: Impact of time, speed, and homogenizer type on droplet size and dehydration efficiency. Chemosphere [Internet]. 2023

Sep 1 [cited 2025 Oct 9];335:139136. Available from: https://www.sciencedirect.com/science/article/abs/pii/S0045653523014030

104. Ravera F, Dziza K, Santini E, Cristofolini L, Liggieri L. Emulsification and emulsion stability: The role of the interfacial properties. Adv Colloid Interface Sci [Internet]. 2021 Feb 1 [cited 2025 Oct 9];288:102344. Available from: https://www.sciencedirect.com/science/article/abs/pii/S0001868620306138
105. Badruddoza AZM, Yeoh T, Shah JC, Walsh T. Assessing and Predicting Physical Stability of Emulsion-Based Topical Semisolid Products: A Review. J Pharm Sci [Internet]. 2023 Jul 1 [cited 2025 Oct 9];112(7):1772–93. Available from: https://jpharmsci.org/action/showFullText?pii=S0022354923001144
106. Danaei M, Dehghankhold M, Ataei S, HasanzadehDavarani F, Javanmard R, Dokhani A, et al. Impact of Particle Size and Polydispersity Index on the Clinical Applications of Lipidic Nanocarrier Systems. Pharmaceutics [Internet]. 2018 May 18 [cited 2025 Oct 9];10(2):57. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC6027495/
107. Magdy G, Aboelkassim E, Abd Elhaleem SM, Belal F. A comprehensive review on silver nanoparticles: Synthesis approaches, characterization techniques, and recent pharmaceutical, environmental, and antimicrobial applications. Microchemical Journal. 2024 Jan 1;196.
108. Inkson BJ. Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) for materials characterization. Materials Characterization Using Nondestructive Evaluation (NDE) Methods [Internet]. 2016 Jan 1 [cited 2025 Oct 9];17–43. Available from: https://www.sciencedirect.com/science/article/abs/pii/B978008100040300002X
109. Singh Y, Meher JG, Raval K, Khan FA, Chaurasia M, Jain NK, et al. Nanoemulsion: Concepts, development and applications in drug delivery. Journal of Controlled Release [Internet]. 2017 Apr 28 [cited 2025 Oct 9];252:28–49. Available from: https://www.sciencedirect.com/science/article/abs/pii/S0168365917301128
110. Chiarentin L, Cardoso C, Miranda M, Vitorino C. Rheology of Complex Topical Formulations: An Analytical Quality by Design Approach to Method Optimization and Validation. Pharmaceutics [Internet]. 2023 Jul 1 [cited 2025 Oct 9];15(7):1810. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC10385475/
111. Seddari S, Moulai-Mostefa N, Sabbache H. Effect of pH on the stability of W/O/W double emulsions prepared by the mixture of biopolymers using direct method. Mater Today Proc [Internet]. 2022 Jan 1 [cited 2025 Oct 9];49:1030–4. Available from: https://www.sciencedirect.com/science/article/abs/pii/S221478532105820X
112. Peng Z, Li S, Han X, Al-Youbi AO, Bashammakh AS, El-Shahawi MS, et al. Determination of the composition, encapsulation efficiency and loading capacity in protein drug delivery systems using circular dichroism spectroscopy. Anal Chim Acta [Internet]. 2016 Sep 21 [cited 2025 Oct 9];937:113–8. Available from: https://www.sciencedirect.com/science/article/abs/pii/S0003267016309382
113. Navarro-Pérez YM, Cedeño-Linares E, Norman-Montenegro O, Ruz-Sanjuan V, Mondeja-Rivera Y, Hernández-Monzón AM, et al. Prediction of the physical stability and quality of O/W cosmetic emulsions using full factorial design [Predicción de la estabilidadfísica y calidad de emulsionescosméticas O/W mediantediseño factorial completo]. © 2021 Journal of Pharmacy & Pharmacognosy Research [Internet]. 2021 [cited 2025 Oct 9];9(1):98–112. Available from: http://jppres.com/jppres
114. Kim Y, Park EJ, Kim TW, Na DH. Recent Progress in Drug Release Testing Methods of Biopolymeric Particulate System. Pharmaceutics [Internet]. 2021 Aug 1 [cited 2025 Oct 9];13(8):1313. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC8399039/
115. Steyn JD, Haasbroek-Pheiffer A, Pheiffer W, Weyers M, van Niekerk SE, Hamman JH, et al. Evaluation of Drug Permeation Enhancement by Using In Vitro and Ex Vivo Models. Pharmaceuticals [Internet]. 2025 Feb 1 [cited 2025 Oct 9];18(2):195. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC11859300/
116. Sukumaran A, K. Sweety V, Vikas B, Joseph B. Cytotoxicity and Cell Viability Assessment of Biomaterials. Cytotoxicity - Understanding Cellular Damage and Response [Internet]. 2023 Nov 15 [cited 2025 Oct 9]; Available from: https://www.researchgate.net/publication/371285599_Cytotoxicity_and_Cell_Viability_Assessment_of_Biomaterials
117. Nalezinková M. In vitro hemocompatibility testing of medical devices. Thromb Res [Internet]. 2020 Nov 1 [cited 2025 Oct 9];195:146–50. Available from: https://www.sciencedirect.com/science/article/abs/pii/S0049384820303182
118. Hossain TJ. Methods for screening and evaluation of antimicrobial activity: A review of protocols, advantages, and limitations. Eur J Microbiol Immunol (Bp) [Internet]. 2024 Apr 22 [cited 2025 Oct 9];14(2):97. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC11097785/
119. In vivo PK / Pharmacokinetic Studies - Sygnature Discovery [Internet]. [cited 2025 Oct 9]. Available from: https://www.sygnaturediscovery.com/publications/technical-notes/in-vivo-pk-pharmacokinetic-studies/

120. Fan W, Yu Z, Peng H, He H, Lu Y, Qi J, et al. Effect of particle size on the pharmacokinetics and biodistribution of parenteral nanoemulsions. Int J Pharm [Internet]. 2020 Aug 30 [cited 2025 Oct 9];586:119551. Available from: https://www.sciencedirect.com/science/article/abs/pii/S0378517320305354
121. Sanjay Shelar :-Suraj, Sanjay Pagar P, Wagh MK. Stability Studies in Pharmaceuticals: Guidelines and Recent Advances. International Journal of Scientific Development and Research [Internet]. 2025 [cited 2025 Oct 9];10. Available from: www.ijsdr.org
122. The pathway to process scale-up. Nature Chemical Engineering 2024 1:6 [Internet]. 2024 Jun 10 [cited 2025 Oct 9];1(6):387–8. Available from: https://www.nature.com/articles/s44286-024-00086-6
123. Kuppasani PR, Thomas A. Regulatory toxicology testing for pharmaceuticals. Targeted Therapy for the Central Nervous System: Formulation, Clinical Challenges, and Regulatory Strategies [Internet]. 2025 Jan 1 [cited 2025 Oct 9];475–500. Available from: https://www.sciencedirect.com/science/article/abs/pii/B9780443238413000212
124. Pereira LMS, Milan TM, Tapia-Blácido DR. Using Response Surface Methodology (RSM) to optimize 2G bioethanol production: A review. Biomass Bioenergy. 2021 Aug 1;151.
125. Truong TH, Alcantara KP, Bulatao BPI, Sorasitthiyanukarn FN, Muangnoi C, Nalinratana N, et al. Chitosan-coated nanostructured lipid carriers for transdermal delivery of tetrahydrocurcumin for breast cancer therapy. CarbohydrPolym. 2022 Jul 15;288.
126. Tavares Luiz M, Santos Rosa Viegas J, Palma Abriata J, Viegas F, Testa Moura de Carvalho Vicentini F, Lopes Badra Bentley MV, et al. Design of experiments (DoE) to develop and to optimize nanoparticles as drug delivery systems. European Journal of Pharmaceutics and Biopharmaceutics [Internet]. 2021 Aug 1 [cited 2025 Oct 9];165:127–48. Available from: https://www.sciencedirect.com/science/article/abs/pii/S0939641121001351
127. Luiz MT, Dutra JAP, Ribeiro T de C, Carvalho GC, Sábio RM, Marchetti JM, et al. Folic acid-modified curcumin-loaded liposomes for breast cancer therapy. Colloids Surf APhysicochemEng Asp. 2022 Jul 20;645.
128. Sandhu ZA, Raza MA, Farwa U, Nasr S, Yahia IS, Fatima S, et al. Response surface methodology: a powerful tool for optimizing the synthesis of metal sulfide nanoparticles for dye degradation. Mater Adv. 2023 Sep 8;4(21):5094–125.
129. Ruiz E, Orozco VH, Hoyos LM, Giraldo LF. Study of sonication parameters on PLA nanoparticles preparation by simple emulsion-evaporation solvent technique. Eur Polym J. 2022 Jun 15;173.
130. Xu Z, Song L, Ming S, Zhang C, Li Z, Wu Y, et al. Removal of starch granule associated proteins affects annealing of normal and waxy maize starches. Food Hydrocoll. 2022 Oct 1;131.
131. Tavares L, Zapata Noreña CP, Barros HL, Smaoui S, Lima PS, Marques de Oliveira M. Rheological and structural trends on encapsulation of bioactive compounds of essential oils: A global systematic review of recent research. Food Hydrocoll. 2022 Aug 1;129.
132. Sun L, Xu Z, Song L, Ma M, Zhang C, Chen X, et al. Removal of starch granule associated proteins alters the physicochemical properties of annealed rice starches. Int J BiolMacromol. 2021 Aug 31;185:412–8.
133. Wang Q, Shi A, Shah F. Rheology instruments for food quality evaluation. Evaluation Technologies for Food Quality [Internet]. 2019 Jan 1 [cited 2025 Oct 9];465–90. Available from: https://www.sciencedirect.com/science/article/abs/pii/B9780128142172000184
134. Preeti, Sambhakar S, Malik R, Bhatia S, Al Harrasi A, Rani C, et al. Nanoemulsion: An Emerging Novel Technology for Improving the Bioavailability of Drugs. Scientifica (Cairo) [Internet]. 2023 [cited 2025 Oct 9];2023:6640103. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC10625491/
135. Ferreira Soares DC, Domingues SC, Viana DB, Tebaldi ML. Polymer-hybrid nanoparticles: Current advances in biomedical applications. Biomedicine & Pharmacotherapy [Internet]. 2020 Nov 1 [cited 2025 Oct 9];131:110695. Available from: https://www.sciencedirect.com/science/article/pii/S0753322220308888X
136. Preeti, Sambhakar S, Malik R, Bhatia S, Al Harrasi A, Rani C, et al. Nanoemulsion: An Emerging Novel Technology for Improving the Bioavailability of Drugs. Scientifica (Cairo) [Internet]. 2023 [cited 2025 Oct 9];2023:6640103. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC10625491/
137. Tanuku S, Velisila D, Thatraju D, Vadaga A kumar. Nanoemulsion Formulation Strategies for Enhanced Drug Delivery. Journal of Pharma Insights and Research [Internet]. 2024 Aug 4 [cited 2025 Oct 9];2(4):125–38. Available from: https://www.researchgate.net/publication/383028269_Nanoemulsion_Formulation_Strategies_for_Enhanced_Drug_Delivery_Review_Article
138. Wells MJM, Chen JY, Bodycomb J, Wolgemuth D, Stretz HA, Zacheis GA, et al. Multi-laser nanoparticle tracking analysis (NTA): A unique method to visualize dynamic (shear) and dynamic (Brownian motion) light scattering and quantify nonliving natural organic matter (NNOM) in environmental water. Science of The Total

Environment [Internet]. 2024 Nov 1 [cited 2025 Oct 9];949:174985. Available from: https://www.sciencedirect.com/science/article/pii/S0048969724051350
139. Chen C, Wang J, Sun M, Li J, Wang HMD. Toward the next-generation phyto-nanomedicines: cell-derived nanovesicles (CDNs) for natural product delivery. Biomedicine and Pharmacotherapy. 2022 Jan 1;145.
140. Babick F. Dynamic light scattering (DLS). Characterization of Nanoparticles: Measurement Processes for Nanoparticles [Internet]. 2020 Jan 1 [cited 2025 Oct 9];137–72. Available from: https://www.sciencedirect.com/science/article/abs/pii/B9780128141823000109
141. Puccetti M, Pariano M, Schoubben A, Giovagnoli S, Ricci M. Biologics, theranostics, and personalized medicine in drug delivery systems. Pharmacol Res [Internet]. 2024 Mar 1 [cited 2025 Oct 9];201:107086. Available from: https://www.sciencedirect.com/science/article/pii/S1043661824000306
142. Shi YY, Li X, Li Z, Sun J, Gao T, Wei G, et al. Nano-formulations in disease therapy: designs, advances, challenges, and future directions. Journal of Nanobiotechnology [Internet]. 2025 Dec 1 [cited 2025 Oct 9];23(1):1–34. Available from: https://jnanobiotechnology.biomedcentral.com/articles/10.1186/s12951-025-03442-7
143. Zhu C, Mu J, Liang L. Nanocarriers for intracellular delivery of proteins in biomedical applications: strategies and recent advances. Journal of Nanobiotechnology [Internet]. 2024 Dec 1 [cited 2025 Oct 9];22(1):1–25. Available from: https://jnanobiotechnology.biomedcentral.com/articles/10.1186/s12951-024-02969-5