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NANOEMULSIONS: A VERSATILE PLATFORM FOR ENHANCED DRUG DELIVERY SYSTEMS

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ABSTRACT
Nanoemulsions have emerged as a promising vehicle for drug delivery, offering significant advantages over traditional delivery systems. Characterized by their nanometer-sized droplets, nanoemulsions exhibit unique properties such as high solubilization capacity, improved stability, and enhanced bioavailability, making them ideal for delivering poorly soluble drugs. This review explores the composition, types, and preparation methods of nanoemulsions, highlighting their role in various drug delivery applications, including oral, topical, parenteral, and pulmonary routes. The potential of nanoemulsions in targeted drug delivery, controlled release, and combination therapies is also discussed, alongside the challenges of stability, scalability, and regulatory considerations. Recent advancements in functionalization and innovations in gene therapy further demonstrate the transformative potential of nanoemulsions in personalized medicine. This comprehensive review aims to provide a deeper understanding of nanoemulsions as a versatile platform for drug delivery, emphasizing their future impact on the healthcare industry.

KEYWORDS: Nanoemulsion, Drug Delivery Systems, Bioavailability, Targeted Therapy, Controlled Release.

INTRODUCTION

Background on Drug Delivery Systems

Drug delivery systems (DDS) manage drug distribution to the target site. Oral, intravenous, and topical medication delivery have pros and cons. The most popular method is oral owing to ease and patient cooperation. Poor bioavailability, first-pass metabolism, and absorption variability are common concerns. Intravenous and intramuscular injections are intrusive, unpleasant, and inconvenient for prolonged therapy, but they deliver drugs quickly and completely. Topical treatments are useful for targeted treatment, however the skin's barrier qualities limit medication penetration. Conventional drug delivery systems struggle to distribute poorly water-soluble medicines, which make up a large share of new drug candidates. Due to low oral bioavailability, many medicines require greater dosages to reach therapeutic levels, which might cause toxicity and side effects. Conventional techniques also fail to target specific tissues or cells, resulting in body-wide dissemination. Drug non-specificity decreases therapeutic efficacy and raises systemic side effects. Due to rapid bloodstream medication clearance, frequent dosing might diminish patient compliance and raise healthcare expenses. Given these constraints, there is significant interest in developing improved drug delivery systems that can overcome existing approaches. Due to their unique features and varied drug delivery applications, nanoemulsions have garnered interest. (Allen, 2004; Torchilin, 2006)

Nanoemulsions

Nanoemulsions are nanoscale emulsions composed of oil, water, and surfactants, with droplet sizes typically ranging from 20 to 200 nanometres. (McClements, 2012) Unlike conventional emulsions, which are thermodynamically unstable and tend to phase-separate over time, nanoemulsions are kinetically stable, meaning they can remain in a stable state for extended periods without significant phase separation. (Jaiswal, 2015) This stability, combined with their small droplet size, gives nanoemulsions unique properties that make them highly effective as drug delivery systems.

The basic concept of nanoemulsions revolves around the dispersion of one immiscible liquid into another, stabilized by surfactants that reduce the interfacial tension between the two phases. The small droplet size of nanoemulsions results in a large surface area, which enhances the solubilization of hydrophobic drugs and facilitates their absorption across biological membranes. (Solans, 2012) Nanoemulsions can be formulated in various forms, including oil-in-water (O/W), water-in-oil (W/O), and bicontinuous structures, depending on the

nature of the drug and the intended route of administration. (Mason, 2007).

The historical development of nanoemulsions dates back to the early 20th century, with the first reports of emulsions in the pharmaceutical field. However, it was not until the advancement of nanotechnology in the late 20th and early 21st centuries that nanoemulsions began to be extensively explored as drug delivery vehicles. The ability to precisely control the size and composition of nanoemulsions, coupled with their potential for encapsulating both hydrophobic and hydrophilic drugs, has led to their widespread application in various fields, including pharmaceuticals, cosmetics, and food industries. (Solans, 2005)

In drug delivery, nanoemulsions offer several advantages over conventional delivery systems. Their small size allows for enhanced penetration through biological barriers, such as the gastrointestinal tract, skin, and blood-brain barrier, enabling more effective delivery of therapeutic agents to target sites. (Jaiswal, 2015) Additionally, nanoemulsions can be engineered to provide controlled and sustained release of drugs, reducing the frequency of dosing and improving patient compliance. The ability to incorporate both lipophilic and hydrophilic drugs within the same system further broadens the scope of nanoemulsions in delivering a wide range of therapeutic agents. (Gupta, 2016)

Given these advantages, nanoemulsions are being increasingly recognized as a versatile and promising platform for drug delivery, with potential applications in various therapeutic areas. This review will explore the composition, preparation methods, advantages, and applications of nanoemulsions in drug delivery, as well as the challenges and future prospects of this innovative technology.

COMPOSITION AND TYPES OF NANOEMULSIONS

Nanoemulsions are colloidal dispersions composed of at least two immiscible liquids—typically oil and water-stabilized by an interfacial film of surfactants and often co-surfactants. The small droplet size, usually in the range of 20 to 200 nanometres, imparts unique properties to nanoemulsions, making them highly effective for drug delivery applications. (McClements, 2012) This section details the components, types, and preparation methods of nanoemulsions. Figure 1 indicates the general composition of nanoemulsion.

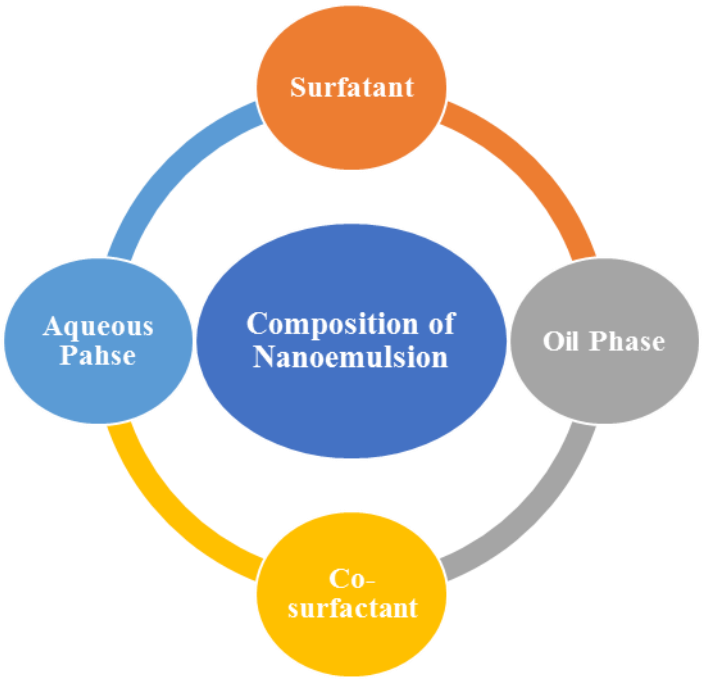

Fig. 1: Composition of Nanoemulsion.

COMPONENTS OF NANOEMULSIONS

The formulation of a nanoemulsion typically involves four key components: the oil phase, the aqueous phase, surfactants, and co-surfactants. (Ghosh, 2006; Mason, 2006; Izquierdo, 2002)

a. Oil Phase: The oil phase plays a crucial role in solubilizing lipophilic drugs, which are otherwise poorly soluble in water. Commonly used oils include medium-chain triglycerides (e.g., caprylic/capric triglycerides), long-chain triglycerides (e.g., soybean oil), and non-ionic surfactant oils (e.g., isopropyl myristate). The choice of oil depends on the drug's solubility, the desired release profile, and the application route. The oil phase not only influences the droplet size and stability of the nanoemulsion but also affects the drug loading capacity and release kinetics. (Pérez, 2007)

b. Aqueous Phase: The aqueous phase generally comprises purified water, which serves as the continuous phase in oil-in-water (O/W) nanoemulsions or the dispersed phase in water-in-oil (W/O) nanoemulsions. In some formulations, buffers or electrolytes may be included in the aqueous phase to maintain pH stability and osmolarity, which is particularly important for parenteral and ophthalmic applications. The composition of the aqueous phase can significantly affect the droplet formation and stability of the nanoemulsion. (Binks, 2000; Aroa, 2004)

c. Surfactants: Surfactants are amphiphilic molecules that reduce the interfacial tension between the oil and water phases, thereby stabilizing the nanoemulsion. Common surfactants used in nanoemulsion formulations include non-ionic surfactants like polysorbates (e.g., Tween 80) and sorbitan esters (e.g., Span 80), as well as ionic surfactants like sodium dodecyl sulfate (SDS). The choice of surfactant affects the droplet size, stability, and toxicity of the nanoemulsion. Non-ionic surfactants are often preferred due to their lower toxicity and irritation potential compared to ionic surfactants. (Pardeshi, 2012; Moghimipour, 2013)

d. Co-surfactants: Co-surfactants, such as alcohols (e.g., ethanol, propylene glycol) or glycols (e.g., polyethylene glycol), are often added to enhance the flexibility of the interfacial film and further reduce interfacial tension. This allows for the formation of smaller droplets and stabilizes the nanoemulsion. Co-surfactants can also modulate the viscosity of the formulation, which is critical for topical and transdermal applications. (Jadhav, 2021) The ratio of surfactant to co-surfactant, along with the HLB (hydrophilic-lipophilic balance) value, plays a significant role in determining the type and stability of the nanoemulsion. (Rao, 2012; Pouton, 2000)

TYPES OF NANOEMULSIONS

Nanoemulsions can be classified into three main types based on the nature of the dispersed and continuous phases. (Mason, 2006; Kawakatsu, 2001; Sagalowicz, 2010)

a. Oil-in-Water (O/W) Nanoemulsions

In O/W nanoemulsions, the oil phase is dispersed as small droplets within the continuous aqueous phase. These formulations are particularly useful for delivering lipophilic drugs orally, parenterally, or topically. O/W nanoemulsions improve the solubility and bioavailability of poorly water-soluble drugs, enhance absorption, and can provide a controlled release profile. They are widely used in pharmaceutical, cosmetic, and food industries due to their stability and ease of formulation.

b. Water-in-Oil (W/O) Nanoemulsions

W/O nanoemulsions consist of water droplets dispersed in a continuous oil phase. These are less common but are valuable for delivering hydrophilic drugs through topical or transdermal routes, where the oil phase can act as a barrier to control drug release. W/O nanoemulsions are particularly beneficial in enhancing the penetration of active ingredients through the skin by disrupting the stratum corneum and providing a reservoir effect. However, they are generally less stable than O/W nanoemulsions and may require careful selection of surfactants to maintain stability.

c. Bicontinuous Nanoemulsions

In bicontinuous nanoemulsions, both the oil and water phases are interspersed in a continuous network, without distinct droplets. These complex structures are stabilized by a combination of surfactants and co-surfactants and can be used for delivering both hydrophilic and lipophilic drugs simultaneously. Bicontinuous nanoemulsions are particularly interesting for their potential in controlled drug release and targeted delivery, as they can be engineered to respond to environmental triggers such as pH or temperature. However, their formulation and stability are more challenging compared to O/W and W/O nanoemulsions.

PREPARATION METHODS

The preparation of nanoemulsions requires techniques that can produce small and uniform droplets, ensuring stability and optimal drug delivery. The methods used can be broadly classified into high-energy and low-energy approaches.

HIGH-ENERGY METHODS

These methods use external energy sources to break down larger droplets into nano-sized ones.

a. High-Pressure Homogenization

This is one of the most commonly used techniques, where the emulsion is forced through a narrow orifice under high pressure, leading to the formation of small droplets due to shear forces, cavitation, and turbulence. High-pressure homogenizers can achieve droplet sizes in the range of 50 to 200 nm and are widely used in both laboratory and industrial-scale production of nanoemulsions. This method is particularly effective for producing stable O/W nanoemulsions for oral and parenteral drug delivery. (Salvia-Trujillo, 2013; Qian, 2011)

b. Ultrasonication

In this method, high-frequency sound waves are applied to the emulsion, causing cavitation and the subsequent breakup of droplets into nanoscale sizes. Ultrasonication is effective in producing nanoemulsions with narrow size distributions, and it is often used for small-scale formulations. However, it may not be as scalable as high-pressure homogenization and can lead to degradation of sensitive drugs due to the heat generated during the process. (Gaikwad, 2008; Abismaïl, 1999)

c. Microfluidization

This technique involves the use of a microfluidizer, where the emulsion is passed through microchannels at high velocities, resulting in the formation of fine droplets

due to shear and impact forces. Microfluidization produces nanoemulsions with uniform droplet sizes and is suitable for both laboratory and industrial production. It is particularly advantageous for producing stable nanoemulsions with high drug loading capacities. (Patel, 2011; Jafari, 2007)

LOW-ENERGY METHODS

These methods rely on the physicochemical properties of the system, such as phase transitions, to form nanoemulsions without the need for external energy input.

a. Phase Inversion Temperature (PIT) Method

This method involves heating the emulsion system to a temperature at which the surfactant's affinity for the oil and water phases changes, leading to phase inversion and the formation of nano-sized droplets. Upon cooling, a stable nanoemulsion is formed. The PIT method is advantageous because it requires less energy than high-energy methods and can produce nanoemulsions with very small droplet sizes. However, it is highly sensitive to the type and concentration of surfactants used, and achieving consistent results can be challenging. (Tadros, 2004; Anton, 2013)

b. Spontaneous Emulsification

This technique involves the rapid mixing of the oil phase, containing a water-miscible solvent and surfactant, with the aqueous phase. The rapid diffusion of the solvent into the aqueous phase leads to the spontaneous formation of nano-sized droplets. Spontaneous emulsification is simple and does not require complex equipment, making it suitable for lab-scale formulations. However, the process may not be easily scalable, and the resulting nanoemulsions may have broader size distributions compared to those produced by high-energy methods. (Forgiarini, 2001; Solè, 2010)

ADVANTAGES OF NANOEMULSIONS IN DRUG DELIVERY

Nanoemulsions offer several significant advantages in drug delivery, which enhance the therapeutic efficacy and safety of various drugs. This section explores these advantages in detail, highlighting the benefits of nanoemulsions in terms of bioavailability, controlled release, drug protection, and patient compliance.

a. Enhanced Bioavailability

One of the most notable advantages of nanoemulsions is their ability to improve the bioavailability of poorly soluble drugs. Nanoemulsions enhance the solubility of lipophilic drugs by dispersing them in a nanometer-sized aqueous phase. The reduced droplet size increases the surface area available for dissolution, which significantly enhances the rate and extent of drug absorption. (Kohli, 2010; Gupta, 2008) For instance, drugs like paclitaxel, which have poor water solubility, have shown improved bioavailability when formulated as nanoemulsions (Deng, 2003; Sastry, 2007). The high surface area to volume ratio of nanoemulsion droplets facilitates the faster dissolution and absorption of these drugs in the gastrointestinal tract, leading to improved therapeutic outcomes. (Khan, 2015) By enhancing solubility and bioavailability, nanoemulsions often allow for lower doses of the drug to be used, which can reduce the risk of toxicity and side effects. This is particularly beneficial for drugs with narrow therapeutic windows or those that have significant adverse effects at higher doses. (Hassan, 2014) Additionally, the improved bioavailability can help in achieving effective therapeutic levels of the drug with reduced dosing frequency, which contributes to better patient adherence.

b. Controlled and Targeted Drug Release

Nanoemulsions provide mechanisms for controlling and targeting drug release, which can enhance therapeutic efficacy and reduce side effects. Nanoemulsions can be engineered to release their active ingredients in a controlled manner. This is achieved through the manipulation of formulation parameters such as surfactant concentration, droplet size, and the type of oil used. (Tadros, 2013) Controlled release can be achieved through several mechanisms, including diffusion of the drug through the emulsion matrix, degradation of the emulsion over time, or changes in environmental conditions (e.g., pH or temperature). (Bambang, 2014; Santos, 2017) For example, nanoemulsions can be designed to provide sustained drug release over extended periods, which is beneficial for chronic conditions that require long-term medication. Nanoemulsions can also be modified to target specific tissues or cells, improving the efficacy of the drug while minimizing systemic side effects. This can be achieved by incorporating targeting ligands or modifying the surface properties of the nanoemulsion droplets to enhance their interaction with specific cellular receptors or tissues. (Moghimi, 2001; Gao, 2012) Targeted nanoemulsions have shown promise in oncology for delivering chemotherapeutic agents directly to tumor cells, thus sparing healthy tissues and reducing the overall toxicity.

c. Protection of Encapsulated Drugs

The protection of active pharmaceutical ingredients (APIs) is another key advantage of nanoemulsions. Nanoemulsions can protect sensitive drugs from hydrolysis and enzymatic degradation. The nano-sized droplets create a barrier that can shield the drug from environmental factors that might otherwise lead to degradation. (Bhosale, 2015; Choi, 2013) For example, drugs susceptible to oxidative degradation can be effectively protected within the oil phase of a nanoemulsion, thereby extending their shelf life and maintaining their potency. (Yao, 2014; Wang, 2016) This is particularly valuable for biologics and other drugs that are prone to instability under standard storage conditions. By encapsulating the drug within a nanoemulsion, it can be shielded from external factors such as light, heat, and moisture, which can contribute to chemical instability. This added protection helps in maintaining the drug's efficacy throughout its shelf life.

Moreover, nanoemulsions can be designed to release the drug gradually, reducing the risk of sudden degradation that can occur with rapid release systems.

d. Improved Patient Compliance

Nanoemulsions also offer benefits in terms of patient compliance, making them a preferred choice for various drug delivery applications. Nanoemulsions are often easier to administer compared to conventional formulations. They can be formulated into a variety of dosage forms, including oral liquids, topical gels, and injectable solutions, which can be tailored to the needs of different patients. (Shakeel, 2012; Gupta, 2016) The small droplet size of nanoemulsions often results in a more aesthetically pleasing formulation that is easier to ingest or apply, enhancing patient acceptance. The controlled release properties of nanoemulsions often allow for extended dosing intervals. This means patients may need to take their medication less frequently, which can significantly improve adherence to treatment regimens. (Salvia-Trujillo, 2013) Reduced dosing frequency is particularly beneficial for patients with chronic conditions who require long-term therapy, as it minimizes the burden of frequent medication intake and helps in maintaining consistent drug levels.

APPLICATIONS OF NANOEMULSIONS IN DRUG DELIVERY

Nanoemulsions have emerged as versatile carriers in drug delivery systems, with applications across various routes of administration. Their unique properties, including small droplet size and enhanced stability, make them suitable for a range of therapeutic applications.

a. Oral Drug Delivery

Nanoemulsions are particularly beneficial for oral drug delivery, especially for drugs with poor water solubility. Numerous studies have demonstrated the efficacy of nanoemulsions in improving the bioavailability of oral medications. For example, nanoemulsion formulations of poorly soluble drugs like curcumin and celecoxib have shown significant enhancement in oral bioavailability and therapeutic effectiveness. (Yadav, 2016; Pouton, 2016) Clinical trials have reported improved absorption and faster onset of action for these formulations compared to conventional oral dosage forms. Nanoemulsions can also be used to mask the taste of unpleasant drugs, making oral administration more palatable. Their ability to increase solubility and facilitate absorption is particularly valuable in treating conditions that require high doses of lipophilic drugs, such as cancer or chronic inflammation. The nanoemulsion formulation of the anti-inflammatory drug diclofenac has been used in clinical trials, showing improved absorption and reduced gastrointestinal irritation compared to standard formulations. (Jadhav, 2023; Bhatt, 2011) Another example is the use of nanoemulsions for the delivery of antifungal drugs like itraconazole, where the nanoemulsion has demonstrated enhanced efficacy in treating fungal infections. (Patel, 2010; Kassem, 2014)

b. Topical Drug Delivery

Topical drug delivery benefits significantly from the use of nanoemulsions due to their ability to enhance skin permeation and drug efficacy. Nanoemulsions can improve the penetration of active ingredients through the skin by disrupting the stratum corneum and increasing the drug's solubility in the lipid-rich layers of the skin. (Kaur, 2004) This enhanced permeation can lead to more effective treatments for dermatological conditions such as acne, eczema, and psoriasis. Studies have shown that nanoemulsions of anti-inflammatory drugs, such as hydrocortisone, can provide better therapeutic outcomes with reduced side effects compared to conventional topical formulations. Nanoemulsions of anti-aging agents, such as retinoids, have been developed to improve skin penetration and efficacy while minimizing irritation. (Patel, 2016)

c. Parenteral Drug Delivery

Nanoemulsions are also used in parenteral drug delivery, including intravenous (IV) and intramuscular (IM) routes. Nanoemulsions can be utilized to deliver drugs via IV and IM routes, where their small droplet size and enhanced stability provide several benefits via prefilled syringes (Jadhav, 2020). For intravenous delivery, nanoemulsions can improve the solubility of drugs like paclitaxel, which is used in chemotherapy. (Shakhwar, 2020; Nikam, 2013) The ability of nanoemulsions to encapsulate and stabilize these drugs ensures that they remain effective throughout the infusion period. Intramuscular injections of nanoemulsions can also enhance the release profile of the drug, providing sustained and controlled release that can reduce the frequency of injections. Nanoemulsion formulations of antibiotics, such as vancomycin, have been used to achieve higher plasma concentrations with fewer side effects. (Zong, 2022)

d. Pulmonary and Nasal Delivery

Nanoemulsions are increasingly being explored for pulmonary and nasal drug delivery, where their small size and ability to form fine aerosols make them suitable for inhalation and nasal sprays. For pulmonary delivery, nanoemulsions can be aerosolized to deliver drugs directly to the lungs, which is beneficial for treating respiratory conditions such as asthma and chronic obstructive pulmonary disease (COPD). (Kim, 2015; Jadhav, 2021) Nanoemulsions used in nasal sprays can enhance drug absorption through the nasal mucosa, providing effective treatment for conditions like rhinitis or migraine. The high surface area and small droplet size of nanoemulsions improve drug deposition and absorption in the lungs and nasal cavity. Nanoemulsion-based inhalation therapies for corticosteroids have shown improved delivery and therapeutic effects in asthma management. (Raja, 2014) Nasal nanoemulsion sprays for analgesics and anti-inflammatory agents are being developed to provide rapid onset of action and improved patient compliance.

CHALLENGES AND LIMITATIONS

Despite their advantages, nanoemulsions face several challenges and limitations that need to be addressed for their successful implementation in drug delivery systems.

a. Stability Issues

Nanoemulsions are susceptible to physical instability, including phase separation, flocculation, and coalescence. The small droplet size and high surface area of nanoemulsions make them prone to destabilization over time. (Tayeb, 2021) Chemical stability can also be a concern, particularly for sensitive drugs that may undergo hydrolysis or oxidation within the emulsion. Ensuring long-term stability requires careful formulation and the use of stabilizers that can prevent these issues.

b. Scalability and Manufacturing

Scaling up the production of nanoemulsions from laboratory to industrial scale can be challenging due to the need for precise control over formulation parameters and manufacturing conditions. High-energy methods, such as high-pressure homogenization, are often used in production but can be costly and require specialized equipment. Low-energy methods, while simpler, may face difficulties in achieving consistent quality on a larger scale. The transition from bench-scale to pilot-scale production of nanoemulsions often requires extensive optimization to ensure that the quality and performance of the nanoemulsion are maintained.

RECENT ADVANCES AND INNOVATIONS

Recent advancements in nanoemulsion technology have opened new possibilities for drug delivery, including functionalization, combination therapies, and gene therapy.

a. Functionalization of Nanoemulsions

Recent innovations include the functionalization of nanoemulsions to enhance their targeting capabilities and therapeutic efficacy. Surface modification techniques involve attaching targeting ligands or antibodies to the nanoemulsion particles to selectively deliver drugs to specific cells or tissues. This targeted approach improves the precision of drug delivery and reduces off-target effects.

b. Combination Therapies

Nanoemulsions are being explored for combination therapies, where multiple drugs are delivered simultaneously to achieve synergistic effects. This approach can improve therapeutic outcomes for complex diseases by providing a comprehensive treatment strategy. Nanoemulsions can encapsulate different drugs in a single formulation, allowing for coordinated delivery and enhanced efficacy.

c. Nanoemulsions in Gene Therapy

Nanoemulsions are also being investigated for gene therapy applications, where they can be used to deliver nucleic acids such as DNA, RNA, or siRNA. The small size and stability of nanoemulsions facilitate the delivery of genetic material to target cells, which is crucial for the success of gene therapy.

RECENT ADVANCES AND INNOVATIONS

Recent advancements in nanoemulsion technology have significantly expanded their potential applications and improved their performance in drug delivery systems. Key areas of progress include functionalization, combination therapies, and gene therapy applications.

a. Functionalization of Nanoemulsions

Functionalization refers to the modification of nanoemulsion surfaces to enhance their targeting capabilities and therapeutic efficacy. Surface modification of nanoemulsions can be achieved through the incorporation of targeting ligands, such as antibodies, peptides, or small molecules, which can bind specifically to certain cell types or receptors. This approach enhances the selective delivery of drugs to targeted tissues or cells, improving therapeutic outcomes while minimizing side effects. Functionalized nanoemulsions have shown promise in targeting cancer cells, where they can deliver chemotherapeutic agents directly to tumor sites. Additionally, surface modification can be used to improve the stability of nanoemulsions and control the release of encapsulated drugs.

b. Combination Therapies

Combination therapies involve the simultaneous delivery of multiple drugs or therapeutic agents to achieve synergistic effects and improved treatment outcomes. Nanoemulsions are increasingly used in combination therapies, where they can encapsulate and deliver multiple drugs within a single formulation. This approach allows for coordinated delivery and synergistic effects, which can enhance therapeutic efficacy and reduce the risk of drug resistance.

c. Nanoemulsions in Gene Therapy

Gene therapy aims to treat or prevent diseases by introducing genetic material into a patient's cells. Nanoemulsions are being explored as carriers for gene therapy applications due to their ability to encapsulate and protect nucleic acids, such as DNA, RNA, and siRNA, from degradation. (Morales-Becerril, 2022)

FUTURE PERSPECTIVES

The future of nanoemulsions in drug delivery looks promising, with ongoing research highlighting their potential in personalized medicine. Nanoemulsions are expected to enable customized treatments tailored to individual patients' genetic, environmental, and lifestyle factors, improving drug efficacy and minimizing side effects. Advances in nanotechnology and biomaterials are paving the way for these tailored formulations. Nanoemulsions could transform healthcare by enhancing drug solubility, stability, and targeting, leading to better treatments for diseases like cancer, neurological disorders, and infections. However, challenges remain, including issues with stability, scalability, regulatory compliance, and safety. Future research needs to focus

on developing robust manufacturing processes, improving long-term stability, and addressing regulatory and safety concerns while exploring new applications to expand their use in drug delivery.

CONCLUSION

The potential of nanoemulsions as advanced drug delivery systems is vast, with ongoing research and innovations continually expanding their applications and benefits. Nanoemulsions offer numerous advantages in drug delivery, including enhanced bioavailability, controlled and targeted release, protection of encapsulated drugs, and improved patient compliance. Their applications span various routes of administration, including oral, topical, parenteral, and pulmonary delivery, making them versatile and effective carriers for a wide range of therapeutic agents. Recent advancements in functionalization, combination therapies, and gene therapy further highlight the potential of nanoemulsions to address complex medical challenges and improve treatment outcomes. The future of nanoemulsions in drug delivery looks promising, with ongoing research driving innovations and expanding their potential applications. As technology advances and new challenges are addressed, nanoemulsions are expected to play a crucial role in shaping the future of drug delivery and personalized medicine. Continued exploration and development will be essential to realizing the full potential of nanoemulsions and transforming healthcare.

Conflict of interest

The author declares no conflict of interest. The manuscript has not been submitted for publication in another journal.

Ethics approval

Not applicable.

Competing Interests

The author declares no conflict of interest. The manuscript has not been submitted for publication in another journal.

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