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Nanoemulsion and nanoencapsulation technologies in dairy systems: Advances in functional applications, oxidative stability and protein-based delivery

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Abstract

Nanoemulsion and nanoencapsulation technologies have gained considerable attention in dairy science due to their ability to enhance the stability, bioavailability, and controlled delivery of bioactive compounds. Conventional dairy matrices often suffer from oxidative instability and poor solubility of lipophilic components, which limits their functional efficacy. Nano-scale delivery systems overcome these challenges by improving physicochemical properties and protecting sensitive compounds from degradation. This review critically evaluates recent developments in nanoemulsion and nanoencapsulation technologies, focusing on preparation techniques, structural characteristics, and applications in dairy products. Special emphasis is placed on protein-based nano-carriers, oxidative stability, and functional food development. Additionally, safety considerations and future prospects are discussed to provide a comprehensive understanding of nanotechnology in dairy processing.

Keywords: Nanoemulsion, Nanoencapsulation, Dairy technology, Milk proteins, Functional foods, Bioavailability, Oxidative stability

1. Introduction

Dairy products constitute a fundamental component of human nutrition, supplying high-quality proteins, essential fatty acids, vitamins, and minerals that contribute significantly to growth, health maintenance, and disease prevention (Haug *et al.*, 2007) ^[12]. Milk and dairy-based foods are also widely recognized as effective carriers for functional ingredients due to their complex colloidal structure, which includes casein micelles, whey proteins, and milk fat globules (Walker *et al.*, 2015) ^[25]. However, the incorporation of bioactive compounds such as omega-3 polyunsaturated fatty acids (PUFAs), fat-soluble vitamins, carotenoids, and phenolic compounds into dairy matrices presents substantial technological challenges. These compounds are often highly susceptible to oxidative degradation, exhibit poor aqueous solubility, and may negatively affect sensory attributes, thereby limiting their stability, bioavailability, and overall efficacy in functional dairy products (Ozdal *et al.*, 2013) ^[19].

Lipid oxidation is a critical issue in fortified dairy systems, particularly when incorporating omega-3 fatty acids such as α -linolenic acid, which are prone to rapid oxidation due to their multiple double bonds (Shahidi & Ambigaipalan, 2015) ^[22]. Oxidative degradation not only reduces nutritional value but also leads to the formation of off-flavors and potentially harmful compounds, thereby compromising product quality and consumer acceptability (Jacobsen, 2010) ^[14]. Similarly, phenolic compounds, despite their strong antioxidant potential, often exhibit limited stability and interaction with milk proteins, which can influence both their functional performance and bioaccessibility (Ozdal *et al.*, 2013) ^[19].

In recent years, nanotechnology has emerged as a transformative tool in food science, offering innovative strategies to overcome these limitations. Nanoemulsion and nanoencapsulation systems have been extensively investigated for their ability to enhance the dispersion, stability, and controlled release of bioactive compounds in complex food matrices (Walker, 2015 & McClements *et al.*, 2020) ^[25, 16]. Nanoemulsions are fine oil-in-water or water-in-oil dispersions with droplet sizes typically ranging from 20 to 200 nm, characterized by high kinetic stability, large

interfacial surface area, and improved optical properties (Pateiro *et al.*, 2021 & Nile, 2020) ^[21, 18]. These systems facilitate the incorporation of lipophilic compounds into aqueous dairy products, thereby enhancing their bioavailability and functional performance (Öztürk, 2017) ^[20]. Nanoencapsulation, on the other hand, involves the entrapment of bioactive molecules within nanoscale carriers such as liposomes, biopolymeric nanoparticles, or protein-based matrices, providing protection against environmental stressors such as heat, light, and oxygen (Augustin & Sanguansri, 2015) ^[3]. This approach enables controlled release and targeted delivery of functional ingredients, making it particularly suitable for the development of next-generation dairy foods with enhanced nutritional and therapeutic properties (Walker, 2015) ^[25].

Milk proteins, particularly casein and whey proteins, play a crucial role in the development of nano-delivery systems due to their unique structural and functional properties. These proteins exhibit amphiphilic characteristics that allow them to adsorb at oil-water interfaces, forming viscoelastic interfacial layers that stabilize nanoemulsions and prevent droplet coalescence (Singh, 2011; Dickinson, 2011) ^[7, 24]. Furthermore, casein micelles possess an inherent ability to bind hydrophobic molecules, making them effective natural nanocarriers for bioactive compounds (Huppertz, 2025) ^[13].

An emerging area of interest is the interaction between milk proteins and phenolic compounds, which has been shown to enhance antioxidant activity and improve oxidative stability in dairy systems. Protein-polyphenol complexes are formed through non-covalent interactions such as hydrogen bonding, hydrophobic interactions, and electrostatic forces, leading to improved functional properties and stability of encapsulated compounds (Shahidi *et al.*, 2015) ^[22]. These complexes not only protect sensitive bioactives but also contribute to improved shelf life and nutritional quality of dairy products.

The application of nanoemulsion and nanoencapsulation technologies in dairy systems has expanded rapidly, with successful incorporation into products such as functional milk, yogurt, cheese, and ice cream. These technologies enable the development of dairy products with enhanced sensory attributes, improved nutrient delivery, and extended shelf life (Walker, 2015) ^[25]. Despite these advantages, challenges related to safety, regulatory approval, and consumer perception remain critical considerations for the widespread adoption of nanotechnology in the dairy industry (Siegrist *et al.*, 2020) ^[23].

In this context, the present review aims to provide a comprehensive overview of nanoemulsion and nanoencapsulation technologies in dairy products, with a focus on their physicochemical principles, preparation methods, functional applications, and future prospects. Emphasis is placed on the role of milk proteins as natural nano-carriers and the potential of these technologies to revolutionize the development of functional dairy foods.

2. Conceptual Framework of Nanoemulsion and Nanoencapsulation

2.1 Nanoemulsion Systems

Nanoemulsions are colloidal dispersions composed of immiscible phases (typically oil and water) stabilized by emulsifiers, with droplet sizes generally ranging from 20 to 200 nm. These systems are characterized by high kinetic stability, reduced gravitational separation, and enhanced optical clarity due to their nanoscale dimensions (McClements, 2020) ^[16]. The small droplet size significantly

increases the interfacial surface area, which facilitates improved digestion, absorption, and bioavailability of encapsulated lipophilic compounds (Siegrist, 2020) ^[23].

Nanoemulsions have gained considerable attention in dairy applications because of their ability to efficiently incorporate lipophilic bioactives such as fat-soluble vitamins (A, D, E, K), carotenoids, and omega-3 fatty acids into aqueous-based systems like milk and fermented products. This not only enhances the dispersion and stability of these compounds but also improves their functional performance and nutritional efficacy (McClement, 2020). Furthermore, nanoemulsions can be engineered using food-grade emulsifiers, including milk proteins and phospholipids, making them highly suitable for dairy systems (Singh, 2011) ^[24].

2.2 Nanoencapsulation Systems

Nanoencapsulation refers to the incorporation of bioactive compounds within nanoscale carrier systems such as liposomes, polymeric nanoparticles, solid lipid nanoparticles, and protein-based nanostructures (Table 1 & 2). These systems provide effective protection against environmental stressors including heat, light, oxygen, and enzymatic degradation, thereby enhancing the stability and shelf life of sensitive compounds (McClements, 2020) ^[16].

In addition to protection, nanoencapsulation enables controlled and targeted release of encapsulated bioactives, which can improve their bioaccessibility and bioavailability during gastrointestinal digestion. This property is particularly important for the development of functional dairy products enriched with nutraceuticals and bioactive ingredients (McClements, 2020; Pateiro *et al.*, 2021) ^[21, 16].

Milk proteins, especially casein and whey proteins, are widely utilized as natural encapsulating agents due to their excellent biocompatibility, biodegradability, and functional versatility. Casein micelles, in particular, possess an intrinsic ability to bind and transport hydrophobic molecules, making them effective nanocarriers for bioactive delivery in dairy systems (Huppertz, 2025; Singh, 2011) ^[13, 24]. These protein-based delivery systems also exhibit good emulsifying properties and can form stable structures that enhance the protection and controlled release of encapsulated compounds (Dickinson, 2010) ^[6].

Table 1: Comparative Characteristics of Nanoemulsion and Nanoencapsulation

Parameter	Nanoemulsion	Nanoencapsulation
Structure	Dispersed droplets	Core-shell system
Size range	20-200 nm	10-500 nm
Function	Stability and dispersion	Protection and delivery
Application	Beverages, milk systems	Functional and nutraceutical foods

3. Preparation Techniques

Nanoemulsions can be prepared using high-energy and low-energy methods. High-energy methods such as high-pressure homogenization and ultrasonication are widely used in dairy systems due to their ability to produce fine and uniform droplets. Microfluidization is another effective technique that ensures consistent droplet size distribution.

Low-energy methods, including phase inversion temperature and spontaneous emulsification, rely on physicochemical properties such as interfacial tension and are more energy-efficient (Walker, 2015) ^[25].

Milk proteins such as sodium caseinate and whey protein concentrate act as effective emulsifiers by forming

viscoelastic interfacial layers that prevent droplet coalescence (Singh, 2011; El-Salam *et al.*, 2025) ^[1, 24].

4. Role of Milk Proteins in Nano Systems

Milk proteins play a critical role in stabilizing nanoemulsions and enhancing encapsulation efficiency. Casein micelles and whey proteins possess amphiphilic characteristics that allow them to adsorb at oil-water interfaces and reduce interfacial tension (Singh, 2011) ^[24].

Furthermore, protein-polyphenol interactions contribute to improved antioxidant properties and oxidative stability. Studies have shown that complexes formed between milk proteins and phenolic acids exhibit enhanced radical scavenging activity and reduced lipid oxidation (El-Salam *et al.*, 2025) ^[1].

Electrostatic and hydrophobic interactions are the primary mechanisms responsible for the formation of these complexes, which ultimately improve the functional properties of dairy nano-systems (Öztürk *et al.*, 2017) ^[23].

5. Applications of Nanoemulsion and Nanoencapsulation in Dairy Products

Nanoemulsion and nanoencapsulation technologies have demonstrated substantial potential in enhancing the functional, nutritional, and sensory attributes of dairy products. These nano-delivery systems enable efficient incorporation of bioactive compounds while improving their

stability, solubility, and controlled release within complex dairy matrices (Walker, 2015) ^[25].

5.1 Functional Milk

Functional milk serves as an ideal vehicle for the delivery of bioactive compounds due to its widespread consumption and balanced nutritional profile. However, the incorporation of lipophilic bioactives such as omega-3 fatty acids, vitamin D, carotenoids, and coenzyme Q10 into milk systems is challenging due to their poor solubility and susceptibility to oxidation (Walker, 2015 & Gao, 2021) ^[25].

Nanoemulsion systems have been extensively utilized to address these challenges by reducing droplet size and increasing surface area, thereby enhancing the dispersion and bioavailability of lipophilic compounds. For instance, omega-3 fatty acids encapsulated in nanoemulsions exhibit significantly improved oxidative stability and reduced development of off-flavors compared to conventional emulsions (Jacobsen, 2015) ^[15].

Milk proteins such as casein and whey proteins act as natural emulsifiers, forming stable interfacial layers that protect encapsulated lipids from oxidation (Singh, 2011) ^[24]. Additionally, nanoencapsulation techniques facilitate controlled release and improved gastrointestinal absorption of bioactive compounds, thereby enhancing their nutritional efficacy (Walker, 2015) ^[25].

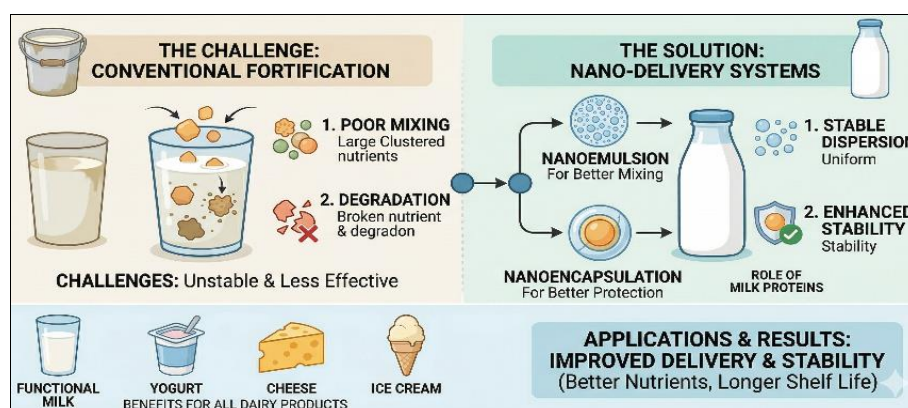


Fig 1: Comparison of conventional fortification challenges and nanotechnology-based delivery solutions in dairy matrices.

5.2 Yogurt

Yogurt is a widely consumed fermented dairy product and an excellent carrier for probiotics and functional ingredients. However, maintaining the viability of probiotic microorganisms during processing, storage, and gastrointestinal transit remains a major challenge (Champagne *et al.*, 2018).

Nanoencapsulation has been shown to significantly enhance the survival of probiotic bacteria by protecting them from adverse environmental conditions such as low pH, oxygen exposure, and thermal stress (Gbassi & Vandamme, 2012). Encapsulation matrices based on proteins, polysaccharides, and lipids provide a protective barrier, ensuring the delivery of viable cells to the intestine.

In addition to probiotic delivery, nanoemulsion systems improve the incorporation of bioactive compounds such as polyphenols and vitamins into yogurt without adversely affecting its sensory properties (Ozturk *et al.*, 2015). Furthermore, nano-scale droplets contribute to improved texture, viscosity, and mouthfeel by influencing the microstructure of the yogurt gel network (Walker, 2015) ^[25].

5.3 Cheese

Cheese is a complex dairy matrix where nanoencapsulation technologies can be applied to improve flavor, texture, and nutritional value. The encapsulation of flavor compounds in nano-systems enables their controlled release during ripening, resulting in enhanced flavor development and consistency (Walker, 2015) ^[25].

Nanoencapsulation also allows the incorporation of bioactive compounds such as antioxidants, vitamins, and antimicrobial agents into cheese without compromising its structural integrity. For example, encapsulated essential oils and phenolic compounds can be used to improve the shelf life and microbial safety of cheese products (Donsì *et al.*, 2011).

Additionally, nanoemulsion-based delivery systems facilitate uniform distribution of lipophilic compounds within the cheese matrix, thereby improving their stability and functional performance (Ozturk, 2017). The use of protein-based nanocarriers further enhances compatibility with the dairy matrix and minimizes undesirable interactions.

5.4 Ice Cream

Ice cream is a multiphase system consisting of air, ice crystals, fat globules, and an unfrozen aqueous phase, making it highly suitable for the application of nanoemulsion technology. The incorporation of nanoemulsions in ice cream formulations leads to improved fat dispersion and stabilization, resulting in enhanced creaminess and smoother texture (Goff & Hartel, 2013).

Nanoemulsions reduce fat globule size and promote a more uniform distribution, which improves the partial coalescence of fat during freezing and contributes to desirable rheological properties (Ozturk, 2017). This results in improved mouthfeel, reduced iciness, and enhanced sensory quality.

Furthermore, nanoencapsulation enables the incorporation of functional ingredients such as vitamins, antioxidants, and flavor compounds into ice cream without negatively affecting its stability or sensory attributes (Walker, 2015) ^[25]. Encapsulated bioactives are protected from degradation during freezing and storage, ensuring their functional efficacy.

The use of nanoemulsions also allows for the development of low-fat or reduced-calorie ice cream formulations by mimicking the textural properties of fat through nano-scale structuring.

Table 2: Summary of Nano-Applications in Dairy Products

Dairy Product	Nano-Technology Used	Key Functional Benefit	Supporting Reference
Functional Milk	Nanoemulsion	Enhanced bioavailability of omega-3	McClementset <i>et al.</i> , 2015 ^[16]
Yogurt	Nanoencapsulation	Improved probiotic survival	Champagne <i>et al.</i> , 2018
Cheese	Nanoencapsulation	Controlled flavor release	Walker, 2015 ^[25]
Ice Cream	Nanoemulsion	Improved texture & creaminess	Ozturk, 2017

6. Oxidative Stability and Functional Enhancement

Lipid oxidation represents a critical limitation in dairy products, particularly in systems enriched with polyunsaturated fatty acids (PUFAs) such as omega-3 lipids, which are highly susceptible to oxidative deterioration due to the presence of multiple double bonds (Shahidi & Ambigaipalan, 2015) ^[22]. Oxidation leads to the formation of hydroperoxides and secondary volatile compounds, resulting in off-flavors, reduced nutritional value, and compromised product quality (Jacobsen, 2015) ^[15]. Therefore, improving oxidative stability is a major objective in the development of functional dairy products.

Nanoemulsion systems have been widely reported to enhance oxidative stability by modifying the physical structure of lipid dispersions. The reduced droplet size (typically <200 nm) increases the surface area but simultaneously allows the formation of a more uniform and compact interfacial layer around lipid droplets, which acts as a barrier against pro-oxidants such as oxygen, metal ions, and free radicals (Walker, 2015) ^[25]. The choice of emulsifier plays a crucial role in this context, as proteins and biopolymers can form viscoelastic interfacial films that inhibit lipid oxidation by limiting the diffusion of reactive species.

Milk proteins, particularly casein and whey proteins, contribute significantly to oxidative stability due to their ability to bind pro-oxidant metal ions and scavenge free radicals (Singh, 2006). Furthermore, the incorporation of protein-polyphenol complexes has been shown to synergistically enhance antioxidant activity. Polyphenols, such as caffeic acid and gallic acid, exhibit strong radical-scavenging properties, while their interaction with milk proteins improves their stability and retention within the nanoemulsion system (Ozidal *et al.*, 2013; El-Salam *et al.*, 2025) ^[1, 19].

These complexes are primarily stabilized through non-covalent interactions, including hydrogen bonding and hydrophobic interactions, which facilitate the formation of stable conjugates capable of protecting lipids from oxidative degradation. Studies have demonstrated that nanoemulsions stabilized with protein-polyphenol complexes exhibit significantly lower peroxide values and thiobarbituric acid reactive substances (TBARS), indicating reduced lipid oxidation and improved shelf life (El-Salam *et al.*, 2025) ^[1].

In addition to enhancing oxidative stability, nanoemulsion and nanoencapsulation systems improve the functional performance of dairy products by enabling controlled release and targeted delivery of bioactive compounds. This results in improved bioavailability and sustained antioxidant activity during digestion (Walker, 2015) ^[25]. Consequently, these technologies not only extend shelf life but also enhance the nutritional and functional quality of dairy products.

7. Safety and Regulatory Considerations

Although nanoemulsion and nanoencapsulation technologies offer significant advantages in improving the functionality and stability of dairy products, their application raises important safety and regulatory concerns that must be carefully addressed. One of the primary issues relates to the potential toxicity and long-term health effects of engineered nanomaterials when ingested through food systems. Due to their extremely small size and high surface area, nanoparticles may exhibit altered physicochemical properties compared to their bulk counterparts, which can influence their absorption, distribution, metabolism, and excretion within the human body (Chaudhry *et al.*, 2008).

Studies have suggested that certain nanomaterials may cross biological barriers, including the gastrointestinal epithelium, and interact with cellular components, potentially leading to oxidative stress or inflammatory responses under specific conditions (Ngo *et al.*, 2008). However, it is important to note that most nanoemulsion systems used in dairy applications are formulated using food-grade, Generally Recognized as Safe (GRAS) materials such as milk proteins, phospholipids, and polysaccharides, which significantly reduces potential health risks (Walker, 2015) ^[25]. Nevertheless, comprehensive toxicological evaluation and risk assessment remain essential before large-scale commercialization.

Another critical aspect influencing the adoption of nanotechnology in dairy products is consumer perception and acceptance. Public concerns regarding the safety, transparency, and labeling of nano-enabled foods can significantly impact market acceptance (Siegrist *et al.*, 2020) ^[23]. Studies indicate that consumer acceptance is strongly influenced by perceived benefits, trust in regulatory authorities, and clear communication regarding safety and functionality. Therefore, transparent risk communication and proper labeling are essential to enhance consumer confidence

and facilitate the successful integration of nanotechnology into the dairy industry.

Overall, while nanoemulsion and nanoencapsulation technologies hold considerable promise, their sustainable application in dairy systems depends on rigorous safety evaluation, clear regulatory frameworks, and improved consumer awareness.

8. Future Perspectives

The application of nanoemulsion and nanoencapsulation technologies in dairy systems is still evolving, and future research is expected to focus on the development of more efficient, safe, and sustainable nano-delivery platforms. One of the key areas of advancement is the design of smart nano-delivery systems capable of responding to environmental or physiological triggers such as pH, temperature, or enzymatic activity. These systems can enable targeted and controlled release of bioactive compounds during digestion, thereby improving their bioavailability and functional efficacy (Walker, 2015)^[25].

Another promising direction is the integration of nanotechnology with precision dairy processing, including real-time monitoring and control of processing parameters using advanced sensors and data-driven technologies. The combination of nanotechnology with precision processing can improve product consistency, optimize nutrient delivery, and enhance overall process efficiency (McClements *et al.*, 2020)^[16]. This interdisciplinary approach aligns with the broader concept of smart and digitalized dairy manufacturing systems. Sustainability is also emerging as a critical consideration in the development of nano-enabled dairy products. Future research should prioritize the use of biodegradable and food-grade nanomaterials, such as protein-based nanoparticles, polysaccharides, and lipid-based carriers, to minimize environmental impact and ensure consumer safety (Augustin & Sanguansri, 2015)^[3]. The shift toward green nanotechnology will be essential for meeting regulatory requirements and improving public acceptance.

In addition, nanoencapsulation technologies hold significant potential in the field of personalized nutrition, where dairy products can be tailored to deliver specific nutrients or bioactive compounds based on individual health needs, age, or metabolic conditions. Such customized functional foods could play a vital role in preventive healthcare and targeted dietary interventions (Walker, 2015)^[25].

Overall, continued advancements in nanotechnology, combined with a strong focus on safety, sustainability, and consumer acceptance, are expected to drive the development of next-generation dairy products with enhanced nutritional, functional, and therapeutic properties (McClements *et al.*, 2020)^[16].

9. Conclusion

Nanoemulsion and nanoencapsulation technologies represent advanced strategies for improving the stability, bioavailability, and functional performance of bioactive compounds in dairy systems. Their application enables effective incorporation of lipophilic and oxidation-sensitive nutrients, while milk proteins serve as efficient natural carriers that enhance system stability and compatibility. These technologies have demonstrated significant potential across various dairy products, contributing to improved quality, shelf life, and development of functional foods.

However, challenges related to safety evaluation, regulatory compliance, and consumer acceptance must be addressed to

ensure their wider adoption. Future advancements integrating smart delivery systems, sustainable materials, and precision processing are expected to further expand their applications. Overall, nanotechnology offers a promising pathway for the development of next-generation, health-oriented dairy products.

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