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Use of Nanoemulsion Technology in Dairy Industry

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A B S T R A C T

Nanoemulsions, characterized by droplet sizes below 100 nm, are increasingly recognized for their applications in dairy technology. They are typically created using high-energy or low-energy methods and enable the encapsulation of functional food ingredients within droplets or at the interface, thereby increasing nutrient bioavailability and physical stability. The demand for nanoemulsions is increasing due to their applications in functional beverages and foods. In dairy-based products such as yogurt, cheese, and ice cream, nanoemulsions play multiple roles by stabilizing them and providing health benefits. They increase the physical stability of milk-based products, extend their shelf life, and improve sensory properties. Nanoemulsions also act as carriers for bioactive compounds, vitamins, and flavors, enriching the nutritional profile and consumer appeal of dairy products. Research on nanoemulsions is advancing due to their superior properties such as improved solubility, enhanced nutrient absorption, and controlled release capabilities. They are used in functional milk drinks, fortified milks, and milk-based supplements, contributing to the physical stability of products and offering health and nutritional benefits. Dairy products can be enriched with various functional ingredients by adding nanoemulsions. This review focuses on nanoemulsion formation and applications of nanoemulsion technology applied to dairy products within the scope of innovative approaches in the dairy industry and includes studies and results on this subject.

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Introduction

Nanoemulsions have brought about a significant shift in the development of functional foods, introducing a novel approach to food encapsulation (Kumar et al., 2018). They are viewed as one of the most promising applications of nanotechnology in the food sector, given their capacity to encapsulate, safeguard, and deliver bioactive compounds (Guttoff et al., 2015). In particular, the dairy industry has found nanoemulsion technology to be of immense value, yielding multiple benefits. The incorporation of nanoemulsions in dairy products has been associated with several improvements, including enhanced product stability, increased bioavailability of bioactive elements, and improved product functionality (McClements and Rao, 2011).

In dairy products containing fat, nanoemulsions can reduce the fat content while maintaining the creamy texture and mouthfeel. This enables the production of low-fat or fat-free dairy products that still provide consumers with the desired flavor experience. Additionally, nanoemulsions enable the encapsulation of bioactive ingredients such as vitamins, antioxidants, and probiotics into dairy products, increasing the stability and bioavailability of these components. This enhancement in nutritional value offers greater health benefits to consumers. Nanoemulsions also help in encapsulating flavor and aroma components in dairy products, preventing their loss during processing and storage. This preservation of the desired taste profile throughout the product's shelf life enhances consumer satisfaction (Panghal et al., 2019). Moreover, the technology allows manufacturers to modify the texture and viscosity of dairy products, facilitating the production of items with desired rheological properties. This capability enables the creation of dairy products with a creamy and smooth texture, improving spreadability and mouthfeel. Furthermore, nanoemulsions increase the stability and shelf life of dairy products by preventing phase separation, microbial spoilage, and oxidation. This prolongs the freshness and quality of the product, reduces food waste, and enhances product integrity. In conclusion, the application of nanoemulsion technology in the dairy industry presents numerous opportunities for innovation, product diversification, and the development of healthier and more appealing dairy products.

In this review, nanoemulsion formation and applications of nanoemulsion technology applied to dairy products are discussed within the scope of innovative approaches in the dairy industry, and studies and results on this subject are included.

Nanoemulsion

Nanoemulsions are optically isotropic and thermodynamically stable systems consisting of two immiscible liquids (usually water, oil, and surfactants), in which one liquid is dispersed in droplets within the other (Figure 1). Emulsions with nanoscopic droplet sizes (generally in the range of 0.01–100 µm) are typically referred to as nanoemulsions (Tan and McClements, 2021). Emulsions, based on their stability and droplet size, can be categorized into nanoemulsions, microemulsions, macroemulsions, or coarse emulsions (Jose et al., 2022). The smaller droplet sizes offer distinct properties such as high surface area, excellent physical stability, quick digestibility, and increased bioavailability. Nanoemulsions are primarily classified into oil-in-water (O/W) and water-in-oil (W/O) types. In a water-in-oil emulsion, water droplets are dispersed in oil, whereas in an oil-in-water emulsion, oil particles are dispersed in water (Naseema et al., 2020). O/W nanoemulsions, which consist of oil droplets dispersed in water (Jafari et al., 2017), are ideal for creating edible coatings as they can incorporate various lipophilic compounds with antimicrobial and antioxidant properties into a hydrophilic polymeric system (Zambrano-Zaragoza et al., 2018). Conversely, W/O nanoemulsions, like butter and cold cream (Panchal et al., 2021), contain small water droplets dispersed in oil. Besides these two types, binary emulsions such as W/O/W and O/W/O also exist but are less frequently used (Sheth et al., 2020).

Delivery systems based on nanoemulsions can enhance the water dispersibility, stability, and bioavailability of hydrophobic bioactive substances. Nevertheless, careful formulation is required to attain the desired functional attributes. Factors such as the concentration, size, charge, and physical characteristics of the nanodroplets need to be tailored for each unique application. Prior to introducing a nanoscale product, it's crucial to ascertain the physicochemical attributes of the nanoparticles and assess potential health and environmental risks. Furthermore, legal considerations, consumer perspectives, and economic implications should be factored into the development of these systems.

Components of Nanoemulsion

The components of nanoemulsions include emulsifiers, stabilizers, and texture regulators, which enhance the kinetic stability of nanoemulsions (Gupta et al., 2016; Wilson et al., 2021).

The oil phase plays a critical role in nanoemulsions. Lipophilic core materials consist of tri-, di-, or mono-acylglycerols, free fatty acids, essential oils, and waxes (Umaraw and Verma, 2017). Sunflower oil, corn germ oil, and soybean oil are commonly used due to their low cost, non-toxicity, and abundance in nature (Sridhar et al., 2021).

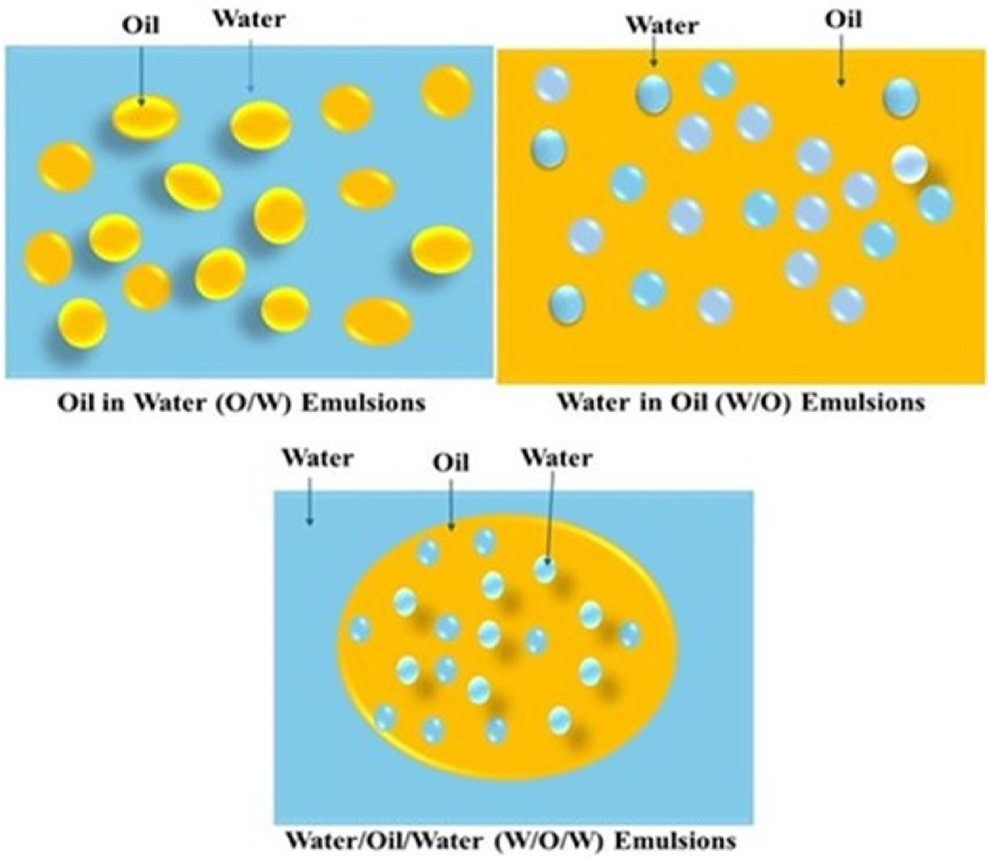

Figure 1. Different emulsion-based delivery systems (Source: Teo et al. (2022)

The aqueous phase in nanoemulsions contains various polysaccharides, co-solvents, salts, proteins, and core compounds. These components alter the physicochemical properties of nanoemulsions by affecting the pH, ionic strength, viscosity, polarity, phase behavior, and interfacial tension of the water phase.

Polysaccharides play a significant role in enhancing the stability of nanoemulsions. Amphiphilic polysaccharides such as modified celluloses, modified alginates, galactomannans, modified starches, pectins, and gum arabic are often used as emulsifiers to provide stability by increasing viscosity (Versino et al., 2016). These polysaccharides are low-cost and abundant in nature. When dissolved in water, they form strong hydrogen bonds and have minimal effects on the taste or appearance of food. However, their high water vapor permeability and solubility may limit their use in nanoemulsions.

Emulsifiers reduce the interfacial tension between oil and water, enhancing droplet formation and stability. Phospholipids, polysaccharides, synthetic small molecule surfactants, and proteins are commonly used. Proteins interact with both the water and oil phases, acting like surfactants and increasing the stability of nanoemulsions. Natural emulsifiers are preferred for food safety and cost considerations (Azrini et al., 2019; Cassiday, 2016; Flores-López et al., 2016; Guttoff et al., 2015).

Surfactants adsorb at the oil-water interface, providing stability to nanoemulsions. Lecithin, a commonly used surfactant, prevents droplet aggregation. Co-surfactants help form smaller droplets by reducing surface tension. However, they are not sufficient for stability on their own, so co-surfactants are added. Commonly used co-surfactants include medium or short-chain alcohols and polyols similar to ethanol (Jin et al., 2016). Additionally, long-chain triacylglycerols, mineral oils, ester waxes, alcohols, and polyols can enhance the properties of nanoemulsions, though they are not essential for their formation (Jin et al., 2016).

Methods of Nanoemulsion Formation

Nanoemulsions can be prepared using either high-energy or low-energy methods (Salem et al., 2019). The preparation methods influence characteristics such as droplet size and the stability of the emulsion. There is no difference in the properties of the final dispersion between nanoemulsions prepared using high shear (external energy, dispersion methods) or stored chemical energy within the system (condensation methods) (Gutierrez et al., 2008). Droplet size varies depending on the components, operating conditions, and preparation methods. The emulsification process involves the breaking down of droplets into smaller fragments, the adsorption of surfactants, and the collision of droplets. The kinetics of adsorption also affect the stability and droplet size of nanoemulsions (Silva et al., 2015). Some commonly used high-energy or low-energy nanoemulsion methods and their applications are summarized in Table 1.

Table 1. High-energy or low-energy nanoemulsion methods and their applications

Preparation Method	Oil Phase	Surfactant/Co-surfactant	Bioactive Component	References
Membrane Emulsification	Methylene chloride	Tween-20/ Tween®80/Polivinil Alkol	Flurbiprofen	Oh et al. (2011)
Membrane Emulsification	Medium-Chain Triglycerides	Tween-80	Vitamin E	Laouini et al. (2012)
High-pressure homogenization	Corn oil	Tween-20, SD-S, sodium caseinate, and β-lactoglobulin		Qian and McClements (2011)
Phase Inversion Temperature	Orange oil	Tween-20	β-Carotene	Qian and McClements (2011)
Ultrasonic Emulsification	Basil oil	Tween-80A	Basil oil	Ghosh et al. (2013)
Ultrasonic Emulsification	Sunflower oil	Tween-80	Protein (β-lactoglobulin) and Anionic Polysaccharide (Apricot Gum)	Shamsara et al. (2015)
High-Pressure Homogenization	Oil-in-Water	Tween-20 gum arabic, sodium caseinate	*Nigella sativa* oil	Mohammed et al. (2020)
Spontaneous Emulsification Method	Lemon oil	Tween-80	Polyunsaturated (ω-3) oils	Gulotta et al. (2014)
Spontaneous Emulsification	Medium chain Triglycerides	Tween-80	Vitamin D	Guttoff et al. (2015)
Nanoemulsion	Sunflower oil	Tween-80	Vitamin D3	Hendy (2023)
Spontaneous Emulsification	Medium-chain Triglycerides	Tween-20, 40, 60, 80	Vitamin E	Saberi et al. (2013)
Spontaneous Emulsification	Coconut oil	Tween-80	Cinnamon oil	Yıldırm et al. (2017)
Spontaneous Nanoemulsification	Water	Tween-20,	Cinnamon essential oils	Arul Raj et al. (2024)
Phase inversion composition	Hydrogenated polyisobutane	Polietilen Glikol-400 Monoizostearat	_	Sonneville-Aubrun et al. (2009)
Phase inversion composition	n-Dodecane	Hexanol or Sodium dodecyl sulfate	_	Solè et al. (2010)
Ultrasonic Emulsification	Sodium Alginate	Tween-80	*Myrtus communis L*	Polat Yemiş et al. (2022)

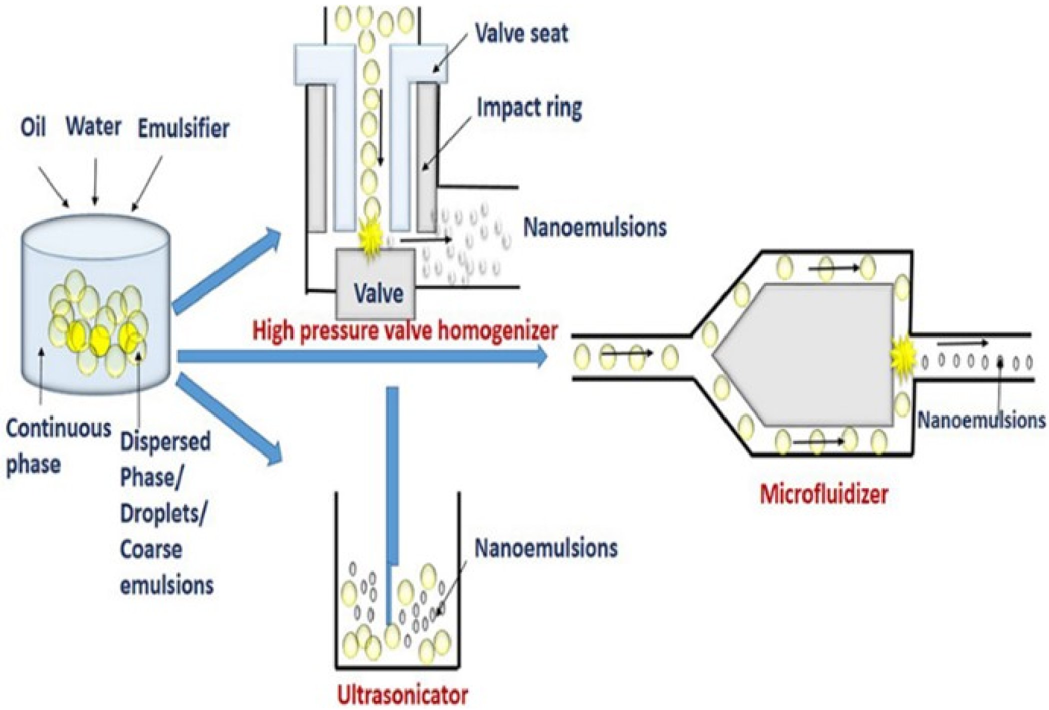

Figure 2. High-Pressure Homogenization (HPH), Microfluidization, and Ultrasonication Methods (Source: Aswathanarayan & Vittal 2019).

High-Energy Approaches

High-energy methods involve the use of mechanical devices such as high-pressure valve homogenizers, microfluidizers, and ultrasonicators (Figure 2). These devices are utilized to disperse macroemulsions into small droplets by generating powerful disruptive forces (Maali & Hamed Mosavian, 2013).

High-Pressure Homogenization Method

High-pressure homogenizers are frequently utilized in the creation of nanoemulsions. These traditional devices typically function at pressures between 50 and 100 MPa (Solans et al., 2005). The process of high-pressure homogenization involves subjecting a liquid product to high shear stress, which results in the formation of extremely fine emulsion droplets. This shear stress is produced by the sudden constriction of the flow under high pressure through valves (Augustin & Sanguansri, 2006; Saffarionpour, 2019). This method has been used to produce nanoemulsions of various, including carvacrol, tangerine, bergamot, and lemon.

Ultrasonication

Ultrasonication employs high-intensity and high-frequency ultrasonic waves to mix and disrupt oil and water phases, creating nanoemulsions with small droplets (Sanguansri & Augustin, 2006; Leong et al., 2009). Desktop ultrasonic devices, containing a probe with piezoelectric crystals, convert electrical voltage into mechanical vibrations, generating sound waves that produce intense disruptive forces through cavitation, turbulence, and surface waves (Kentish et al., 2008). This process operates on two main mechanisms: dispersing the oil phase into droplets and collapsing microbubbles, resulting in sub-micron-sized droplets exposed to high shear rates (Shamsara et al., 2015).

Nanoemulsions produced by ultrasonication typically have broad and bimodal size distributions (Jafari et al., 2017). Ultrasonication has been successfully used for eugenol-loaded nanoemulsions for wound treatment (Ahmad et al., 2018) and anise oil nanoemulsions with antimicrobial properties (Ghazy et al., 2021). Studies have shown that increasing ultrasonication time reduces droplet diameter in celery oil nanoemulsions, enhancing their anticancer activity (Nirmala et al., 2020). Significant variables in the nanoemulsification process include the concentration of dissolved gas, hydrostatic pressure, apparatus configuration, and temperature. Commercial homogenizers have been developed for large-scale applications (Singh et al., 2017). Although ultrasonication uses less energy compared to other high-energy techniques, probe contamination remains a significant disadvantage.

Microfluidization

Microfluidization distinguishes itself from high-pressure homogenization through the use of a microchannel that provides optimal cavitation, shear, and impact forces for dispersion, size reduction, and emulsion production (Sanguansri & Augustin, 2006). Microfluidization (colloid mill) processes and similar fluid-based technologies benefit from the flow-induced shear of liquids, hot melts, and other soft aggregates (Fig 2). This process achieves the dispersion of processed materials at the nanoscale (Acosta, 2009). Prior to homogenization with a microfluidizer, the aqueous phase and oil phase are typically combined using a high-speed homogenizer to form a coarse emulsion. This coarse emulsion is then passed through the microfluidizer to obtain a stable nanoemulsion (Koroleva & Yurtov, 2012). Nanoemulsions of black seed oil O/W (Foo et al., 2022) and limonene O/W (Hidajat et al., 2020) have been successfully processed using microfluidization.

Low-Energy (LE) Methods

Low-energy (LE) methods rely on the spontaneous formation of small oil droplets from incompatible oil/water/emulsifier mixtures through controlled changes. LE methods are characterized by changes in the physicochemical factors of the mixture composition, such as temperature, solubility, and environmental conditions. These factors significantly influence the formation of nanodroplets in mixed systems containing oil, water, and surfactants (Salvia-Trujillo et al., 2017). Commonly, three fundamental low-energy methods are used in nanoemulsion synthesis: Phase Inversion Temperature (PIT), Phase Inversion Composition (PIC), and Spontaneous Emulsification Method (Figure 3). Mehrnia et al. (2015) reported two main methods in the development of nanoemulsions with LE methods: phase inversion and spontaneous emulsification. These methods use very little energy, thus preserving heat-sensitive substances without degradation (Anton & Vandamme, 2009). The interest in adopting LE methods in production and application stems from their affordability, simple applicability, non-destructive characteristics, and energy efficiency (Gulotta et al., 2014; Komaiko & McClements, 2016;).

Phase Inversion Temperature (PIT)

The PIT method involves manipulating the temperature to induce phase inversion, resulting in the formation of stable nanoemulsions (Figure 3). While some researchers do not consider this method valid for the production of nanoemulsions, others have adopted it. The method is based on the changes in solubility of polyoxyethylene type non-ionic surfactants with temperature (Izquierdo et al., 2002). The dehydration of the polymer chain causes these surfactants to become more lipophilic as the temperature increases (Solans et al., 2005). However, this technique is extremely expensive and therefore not suitable for industrial use (Santana et al., 2013).

Phase Inversion Composition (PIC)

Similar to PIT, the PIC method focuses on altering the composition of the emulsion system to achieve phase inversion. This method involves a gradual dilution with water or oil, and this composition is optimized at a certain temperature (Figure 3). This phase change is driven by the Gibbs free energy of the emulsion, resulting in the spontaneous inversion of the curvature of the surfactant from positive to negative (Sonneville-Aubrun et al., 2009). This method is inexpensive, does not require the application of organic solvents, and is therefore thermodynamically stable. Using the phase inversion composition technique, safe-to-consume nanoemulsions have been prepared, supported with Vitamin E acetate, with a standard particle size of 40 nanometers. This process has been proven to be more effective than microfluidization in producing nanoemulsions with high surfactant concentrations (Shakeel et al., 2009).

Spontaneous Emulsification (Self-Emulsification)

Spontaneous emulsification, also known as solvent diffusion emulsification, facilitates emulsion formation through diffusion driven by a chemical potential gradient (Espitia et al., 2019; Solans et al., 2016). Typically, oil-in-water nanoemulsions are formed by gradually adding water to a solution of oil and surfactant (Kelmann et al., 2007; Saberi et al., 2013). This method is employed in distributing bioactive food components, beginning with the combination of the organic phase (oil and surfactant) with the aqueous phase (co-surfactant and water) (Kheawfu et al., 2018). As the microemulsion phases break down, fine oil droplets form spontaneously (Anton et al., 2008). Solvents can accelerate this process, even without surfactants (Komaiko & McClements, 2016).

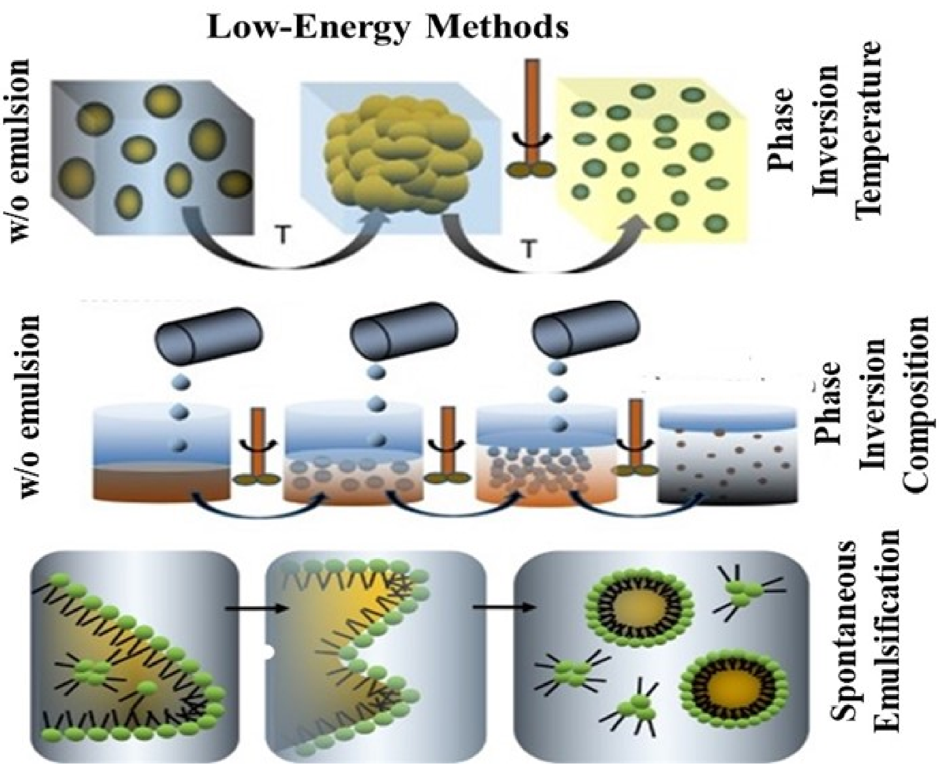

Figure 3. Phase Inversion Temperature, Phase Inversion Composition, and Spontaneous Emulsification (Source: Rai et al., 2018)

This method can produce nano or microemulsions without regard to kinetics and is advantageous because it does not require special equipment, allowing for nanoemulsion development under ambient conditions (Chen et al., 2016). However, the presence of solvents and the limited amount of the oil phase are notable disadvantages (Maali & Mosavian, 2013; Subasi et al., 2017). Studies have demonstrated the advantages of nanoemulsions containing vitamin E acetate, vitamin D, and omega-3 fish oil, which maintain structural stability at approximately 37 °C and oxidative stability for 14 days at 55 °C (Guttoff et al., 2015; Walker et al., 2015). Despite being a relatively new industrial application, spontaneous emulsification shows potential as an economical approach to nanoemulsion production.

An Overview of the Methods

Each method has its own advantages and disadvantages, and the choice of method will depend on the specific requirements of the application. When choosing a method it is important to consider factors such as cost, energy efficiency and the nature of the materials being processed. The high pressure homogenization method creates extremely fine emulsion droplets by subjecting a liquid product to high shear stress. Its main advantage is the ability to form fine emulsions, but this can be energy intensive. While the ultrasonication method uses less energy than other high-energy techniques, a significant disadvantage is the risk of probe contamination. The microfluidization process enables the dispersion of engineered materials at the nanoscale, which can be advantageous in some applications. It is useful in protecting heat-sensitive materials from deterioration in low energy methods. They are affordable, easy to apply, non-destructive and energy efficient. Despite the effectiveness of the phase ınversion temperature method, this technique is extremely expensive and therefore not suitable for industrial use. The phase ınversion compounding method has proven to be more effective than microfluidization in producing nanoemulsions with high surfactant concentrations. Although self-emulsification is a relatively new industrial application, it shows potential as an economical approach to nanoemulsion production.

Applications of Nanoemulsions in the Dairy Industry

Nanoemulsions have significant potential to meet the vast market demand through their possible applications in the beverage, confectionery, and food packaging industries (Dasgupta & Ranjan 2018). Similarly, nanoemulsion technology offers a variety of applications in the dairy industry. It provides several advantages, such as enhanced stability of dairy products, improved bioavailability, and increased functionality. The applications of nanoemulsion technology in the dairy industry include:

Fat Reduction: Nanoemulsions can maintain the creamy texture and mouthfeel of dairy products like milk, cheese, yogurt, and ice cream while reducing their fat content (Martins et al., 2007; Unilever, 2011). Fat droplets can be encapsulated at the nanoscale, allowing for the creation of low-fat or fat-free products.

Enhanced Nutrient Delivery: Nanoemulsions can encapsulate bioactive compounds such as vitamins, antioxidants, and probiotics. This enhances their stability and bioavailability in dairy products, enriching the products and offering greater health benefits to consumers.

Improved Flavor Encapsulation: Nanoemulsions can encapsulate flavors and aromas, preventing their degradation and loss during the processing and storage of dairy products. This ensures the preservation of the desired flavor profile throughout the product's shelf life, increasing consumer satisfaction.

Texture Modification: Nanoemulsions can be used to alter the texture and viscosity of dairy products. This facilitates the creation of products with creamy and smooth textures.

Extended Shelf Life: Nanoemulsions can increase product stability and shelf life by preventing phase separation, microbial spoilage, and oxidation. This reduces food waste and maintains product quality.

Functional Content Delivery: Nanoemulsions can enable targeted delivery and release of functional components such as omega-3, prebiotics, and bioactive peptides. This facilitates the development of dairy products with enhanced functional properties that promote health.

Reduced Ingredient Usage: Nanoemulsions allow for the reduction of components such as stabilizers and emulsifiers in dairy product formulations, leading to cleaner labels and potentially lowering production costs.

In conclusion, nanoemulsion technology presents significant opportunities in the dairy industry for fat reduction, nutrient distribution, flavor encapsulation, texture modification, shelf life extension, functional content delivery, and reduction of production costs.

Nanoemulsion Application in Dairy Products

Dairy products are a significant part of the food industry. Nanoemulsion technology is effectively applied in various areas, such as extending the shelf life of dairy products, enhancing nutritional value, improving bioavailability, carrying functional components, and developing new products (Table 2). This technology offers a versatile and effective method to enhance the quality, stability, and functionality of milk and dairy products, representing a significant advancement in the dairy industry.

Milk

The potential of milk and dairy products to increase micronutrient content and strengthen resistance to diseases is supported by various studies. Lipid-based nanoemulsions can improve the integration of essential micronutrients such as vitamins A, D, and E into foods by increasing the solubility and bioavailability of lipophilic vitamins. Milk, especially when containing vitamin D3 and calcium, has positive effects on aging and bone health, while fat-soluble vitamin D supports calcium absorption and bone formation. However, because vitamin D is not water-soluble, low-fat milk and dairy products do not naturally contain this vitamin. Therefore, lipid nanoparticles may increase the nutritional value of dairy products by facilitating the transport of substances such as vitamin D.

Table 2. Application of nanoemulsion technology in milk and dairy products

Dairy Product	Nanoemulsion Methods	Delivery Systems	Bioactive Component	Effect on the Product	References
Skim milk, Semi fat milk (%2 fat) Full fat milk (%4 fat)	Microprocessor homogenizer	Oil-in-Water nanoemulsion	*Thymus capitatus* essential oil	Inactivation of *L. monocytogenes*	Xue et al. (2013)
Driking milk	High-pressure homogenizer	Oil-in-Water nanoemulsion	Curcumin	Lower lipid oxidation Effective oxygen scavenging activity	Joung et al. (2016).
Pasteurized and raw milk	High pressure microfluidizer	Oil-in-Water nanoemulsion	*Thymus capitatus* essential oil	Protective effect of against pathogenic bacteria	Ben Jemaa et al. (2017)
Skim Full fat milk	Microprocessor homogenizer	Solid-in-oil-in-water (S/O/W) emulsions	Spray dried lactase powder	Potential to carrier lactase in milk for lactose-intolerant consumers	Zhang and Zhong (2017)
Pineapple ice cream	Emulsion inversion point	Oil-in-water	Curcumin	A suitable alternative to reduce the use of artificial dyes.	Borrin et al. (2018)
Ice-cream	High-pressure homogenizer	Oil-in-Water nanoemulsion	*Nigella sativa* oil	Improved the ice-cream physical properties and consumer acceptability	Mohammed et al. (2020)
Ice-cream	Ultrasonication	Oil-in-water	Moringa seed oil (omega-3 content)	Enhanced antioxidan	Abdelraouf et al.(2023)
Gelato-type ice cream	High pressure homogenization	Oil-in-water	β-carotene	Increasing yield by increasing volume.	Borba et al. (2023)
Frozen yogurt	Ultrasonication	Oil-in-water	γ-oryzanol	Natural antioxidant content	Alfaro et al. (2015)
Yogurt	Low-energy emulsification	Oil-in-water	γ-oryzanol	Maximum retention of docosahexaenoic acid and eicosapentaenoic acid	Zhong et al. (2018)
Low-fat set yogurts	High-pressure homogenizer	Water -in-oil	Docosahexaenoic acid and Eicosapentaenoic acid	Significant effect on the retention of docosahexaenoic acid and eicosapentaenoic acid	Bakry et al. (2019)
Stirred yogurt	Low energy spontaneous emulsification	Water -in-oil	Essential oil (Lemongrass, Spearmint, Cloves and, Cinnamon)	Naturally flavored yogurt	Salama et al. (2022)
Stirred yogurt	Ultrasonication	Water -in-oil	Virgin olive oil	a good carrier for synbiotic bacteria and antioxidant	El-Sayed et al. (2022a)
Yogurt	Ultrasonication	Oil-in-water	Rosehip oil (Omega-3 fatty acids)	Potential for preserving linoleic acids, increasing the stability of omega-3 fatty acids and masking yoghurt sourness.	Rao et al. (2023)
Lab-manufactured yogurt	High-pressure homogenizatio	Oil-in-water	Cinnamaldehyde	anti-*H. pylori* activity	Abdelhamid et al. (2023)
Yogurt	High-pressure homogenizatio	Oil-in-water	*Oleoresin capsicum* (Capsaicin)	With its increasing health benefits, capsaicin has the potential to be used as a commercial product.	Ko et al. (2024)
Minas Padrão cheese	Phase inversion temperature	Oil-in-water	Essential oil of oregano	Antifungal effect (*Cladosporium* sp., *Fusarium* sp *Penicillium* sp)	Bedoya-Serna et al. (2018)
White soft cheese	High-pressure homogenizatio	Oil-in-water	Cumin essential oil	Antimicrobial activity *(S. aureus*, *B. cereus*, *L. monocytogenes*, *E. coli*, *S.typhimurium*, *P.aeruginosa*, *Y. enterocolitica*, *A. niger*, *A. flavus)*	El-Sayed and El-Sayed (2021)
Herbal soft cheese	Low energy spontaneous emulsification	Water -in-oil	*Coriandrum sativum* L. seed extract	Bacteriostatic action against *S. aureus*, *E. coli*, *A. flavus*	El-Sayed et al. (2022)
Fresh Kasar cheese	Ultrasonication	Water -in-oil	*Myrtus communis* essential oil	Antibacterial activity against *L. monocytogenes*	Polat Yemiş et al. (2022)
Soft Cheese	Ultrasonication	Oil-in-water	Curcumin	Improved sensory properties, Antibacterial activity (*S. aureus, E. coli)*	Bagale et al. (2023)
Karish cheese	Ultrasonication	Oil-in-water	VD3	Cheese fortified with VD3	Hendy, (2023)
Processed cheeses	Low energy spontaneous emulsification	Water -in-oil	*Laurus nobilis L* extract	Enrichment of cheese with agents that provide protection against hyperhomocysteinemia in Ehrlich ascites carcinoma.	Hussein et al. (2023)
Grated mozzarella cheese	Microfluidizer	Oil-in-water	Cinnamaldehyde	*A. niger,* *Penicillium commune,* *Paecilomycess spp.,* *Penicillium citrinum* *Penicillium crustosum*	Ghada et al. (2024).

Gruenwald (2009) stated that skim milk is a poor source of vitamins, and fortifying it with vitamin D3 increases calcium absorption in humans. In one study, patients with vitamin D deficiency were administered a diet program in which they were given vitamin D-enriched milk with different lipid distributions for 6 weeks. At the end of the research, it was observed that olive oil significantly increased the vitamin D content in the patients' serum. This study supports the use of olive oil as a lipid component in vitamin D-fortified milk beverages (McCourt et al., 2021). In a study in which the essential oil obtained from the *Thymus capitatus* (thyme) plant (main component 76.1% carvacrol) by hydrodistillation was added to pasteurized and raw milk (Ben Jemaa et al., 2017), it was determined that thyme essential oil was effective in preventing spoilage. Additionally, adding thyme essential oil to raw milk extended the shelf life of milk by delaying the development of contaminating pathogenic bacteria and the oxidation of milk fat. In a study examining the antimicrobial activity of thymol, Xue et al. (2013) observed that the nanoemulsion form of thymol was more effective than free thymol and significantly reduced *Listeria monocytogenes* (*L. monocytogenes*), especially in 2% fat and whole milk. Additionally, nanoemulsions in skim milk were found to reduce *Escherichia coli* (*E. coli*) below the limit of detection. Stable curcumin nanoemulsions were synthesized by high-pressure homogenization and added to commercial milk samples. These nanoemulsions have been reported to show effective oxygen scavenging properties in commercial milk samples and remain stable for up to one month at room temperature (Joung et al., 2016). The potential of nanoemulsion technology for controlled lactose hydrolysis in milk was investigated. Freeze-dried capsules from lactase-containing S/O/W emulsions demonstrated gradual release of lactase into dairy products and achieved controlled lactose hydrolysis over a three-week storage period (Zhang & Zhong, 2017). These findings highlight the promise of nanoemulsion techniques in enhancing the quality, stability, and utility of milk-based and dairy items. Nanoemulsions could augment the nutritional content of dairy goods, possibly exert beneficial effects on human wellness, and bolster disease resistance. This technology is seen as an important tool for innovative applications in the dairy industry sector.

Ice Cream

Ice cream is defined as a dairy product obtained by processing a mixture of sweeteners, stabilizers, emulsifiers, colorants, flavors, and taste substances with air in special equipment called freezers. Typically, the size of ice crystals and air bubbles varies between 20 and 50 µm. While fat globules usually form a coating around air bubbles, proteins or emulsifiers form a coating around fat globules. Different equipment and techniques are used to develop nanoemulsions in ice cream production. Curcumin is a polyphenolic compound with various health benefits; these include antioxidant, anti-inflammatory, antitumorigenic, anticoagulant, antibacterial, and anticarcinogenic effects. However, the use of curcumin as a functional component is limited because it shows a tendency to degrade in the presence of water solubility, biological availability, absorption in the gastrointestinal system, alkaline pH, high temperature, and light (Aditya et al., 2014). This problem can be resolved by including curcumin in the nanoemulsion formulation and using it as a carrier. Ice cream is a product loved by almost every age group and season; therefore, it could be a suitable carrier for encapsulated curcumin. Nestle and Unilever have developed nanoemulsions in ice creams to reduce the fat content from 16% to 1% (Martins et al., 2007; Unilever, 2011). Nanoemulsions have also been utilized to improve the consistency and texture of ice cream. It has been indicated that nanoemulsions prepared using antioxidant-rich moringa seed oil and whey proteins have been successful in ice cream production and provided functional properties enriched with omega-3 content (Abdelraouf et al., 2023). The addition of β-carotene and corn oil nanoemulsions to gelato-type ice cream has been found to increase volume expansion, thereby enhancing gelato yield (Borba et al., 2023).

A research study focused on creating ice cream enriched with *Nigella sativa oil* (NSO) nanoemulsion at different ratios (0% control, 3%, 5%, and 10%), it was stated that when the NSO nanoemulsion was stabilized with gum arabic, sodium caseinate, and Tween-20, the 10% nanoemulsion showed the highest stability in ice cream (Mohammed et al., 2020).

Yogurt

Yogurt is a fermented dairy product that includes sweeteners, flavors, and starter bacterial cultures. Due to its extensive health benefits, yogurt is frequently incorporated into daily diets. Dairy products, particularly yogurt, are considered an ideal medium for functional ingredients such as essential oils and probiotic bacteria. Nanoemulsion technology enhances the solubility of lipophilic bioactive compounds and oils in water, thereby increasing their effectiveness. Accepted as the most advanced encapsulation method for lipids, nanoemulsion technology is employed to improve quality maintenance and bioavailability in food systems. High-energy methods like sonication and high-pressure optimization are commonly used in the preparation of oil nanoemulsions. The introduction of γ-oryzanol and fish oil-enriched nanoemulsions into yogurt has been shown to reduce peroxide value, syneresis, and acidity gradually while maintaining higher levels of docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA) (Zhong et al., 2018). This nanoemulsion preserves the antioxidant properties of γ-oryzanol, contributing to yogurt's health benefits. Adding nanoemulsion rice bran oil—a natural antioxidant source containing α-tocopherol, tocotrienol, and γ-oryzanol—to frozen yogurts significantly increases the natural antioxidant content, enhancing the product's nutritional profile (Alfaro et al., 2015). Salama et al. (2022) developed functional yogurt using nanoemulsions of peppermint, lemongrass, clove, and cinnamon essential oils with lactic acid bacteria. A study reported that adding extra virgin olive oil nanoemulsion and symbiotic bacteria (*Lactobacillus acidophilus and Bifidobacterium bifidum*) encapsulated in maltodextrin microcapsules to yogurt increased the viability of probiotics and provided high antioxidant activity (El-Sayed et al., 2022a). In low-fat set yogurt enriched with tuna and peppermint oil microemulsions, peppermint oil was found to enhance oxidative stability, mask the fish odor, and improve sensory properties. The microemulsions also maintained the stability of DHA and EPA (Bakry et al., 2019). A rose oil nanoemulsion prepared by ultrasonication has been effective in masking the sour taste in yogurt by preserving linoleic acid and enhancing the stability of omega-3 fatty acids (Rao et al., 2023). In research testing the most effective probiotic strains and nanoemulsions against *Helicobacter pylori*, the combination reduced the count of *H. pylori* by 3.9 log and showed a low inhibitory effect on other microorganisms (Abdelhamid et al., 2023). When a nanoemulsion, created to increase the stability of capsaicin and mask its strong taste and odor, was used in the production of capsaicin-enriched yogurts, this method demonstrated its potential in the production of yogurt as a new nutritionally enriched food (Ko et al ., 2024).

Cheese

Recent developments in dairy technology have centered on improving the nutritional value and extending the shelf life of cheese through the integration of nanoemulsions. These nanoemulsions act as carriers for essential nutrients, such as Vitamin D3, which can be synthesized from exposure to sunlight or added to foods as a fortification. The addition of emulsifying agents such as vitamin D3 and milk proteins during the water-in-oil emulsion phase has been shown to improve vitamin retention in cheese. For example, Karish cheese fortified with Vitamin D3 nanoemulsion has been identified as an effective approach to addressing vitamin D deficiency, with the application method, particularly the spraying technique, significantly increasing vitamin retention and improving the cheese's overall quality (Hendy, 2023). Minas Padrão cheese was studied for its antifungal properties when enriched with nanoemulsion-encapsulated *Origanum vulgare* (oregano) essential oil. The nanoencapsulation was found to have inhibitory effects against fungi such as *Cladosporium* sp., *Fusarium* sp., and *Penicillium* sp., with result varying based on the encapsulation (Bedoya-Serna et al., 2018).

The use of antifungal nanoemulsions containing natural essences encapsulated with whey protein isolate and maltodextrin has been effective in extending the shelf life of grated mozzarella cheese. This promising approach could provide an antifungal preservation method for cheese and offer an alternative to traditional preservatives like natamycin (Ghada et al., 2024).

Nanoemulsion-based coatings incorporating oregano essential oil have been employed to prolong the shelf life of low-fat sliced cheese by reducing *Staphylococcus aureus* (*S. aureus*) populations and inhibiting the growth of psychrophilic bacteria, yeast, and mold during storage. The coatings' composition, including sodium alginate and mandarin fiber, preserved the cheese's nutritional properties and improved its appearance (Artiga-Artigas et al., 2017).

El-Sayed and El-Sayed (2021) reported that the nanoemulsion of cumin essential oil (CEO) added to white soft cheese exhibited antimicrobial activity against *S. aureus*, *Bacillus cereus*, *L. monocytogenes*, *E. coli*, *Salmonella typhimurium*, *Pseudomonas aeruginosa*, *Yersinia enterocolitica*, *Aspergillus niger*, and *Aspergillus flavus* (*A. flavus*).

Active films containing marjoram essential oil have been effective in controlling microbial spoilage (Mohammadi Jarchelo et al., 2022). Polat Yemiş et al. (2022) have demonstrated that the application of nanoemulsion coatings, which incorporate myrtle essential oil, are successful in suppressing the proliferation of *L. monocytogenes* and found to maintain the physicochemical characteristics of the cheese, indicating their potential utility in food preservation.

Application of the nanoemulsion form of coriander seed ethanolic extract showed bacteriostatic effects against *S. aureus*, *E. coli*, and *A. flavus*, delayed the growth of yeast and mold, and also positively affected the microbiological, chemical, and sensory properties of soft cheese (El-Sayed et al., 2022). The impact of stabilized curcumin nanoemulsions (CUNE) on cheese was evaluated, revealing that CUNE addition improved sensory properties by 150% and extended shelf life without altering the cheese's uniform porosity distribution, thus adding value to the dairy industry (Bagale et al., 2023).

The protective effect of cheese enriched with Laurus nobilis L. extract nanoemulsion against hyperhomocysteinemia in an Ehrlich acid carcinoma model was also assessed. The enriched cheese reduced serum levels of Hcy, TNF-α, TBARS, and MMP-9 while increasing SOD activity and Bcl-2 levels, thereby mitigating oxidative stress, inflammation, and apoptosis (Hussein et al., 2023). In another study, cheese safety was enhanced using probiotic cell pellets (LCP) or cell-free extracts (CFS) to improve cheese characteristics. Six CFS probiotics were evaluated for their antifungal properties against toxigenic fungi, and the most effective CFS was selected for nanoemulsion coating. *Lactobacillus rhamnosus* (*L. rhamnosus*) CFS demonstrated potential for reducing aflatoxins. Uncoated cheese showed higher yeast and mold counts compared to processed cheeses. No *Aspergillus* growth was observed in LCP-CFS-coated cheese for up to 40 days. Coating cheese with *L. rhamnosus* nanoemulsion provided antifungal and antiaflatoxigenic properties that could extend the cheese's shelf life (Ibrahim et al., 2023). Innovative biocomposite materials based on Moringa nanoemulsion and chitosan/whey protein concentrate were developed for coating Ras cheese (Adel et al., 2023).

Overall, these studies highlight the potential of nanoemulsions as natural food preservatives and functional food ingredients, capable of enhancing the safety, nutritional value, and sensory qualities of cheese while also offering health benefits and extending shelf life. The use of nanoemulsions in cheese fortification represents a promising direction for the dairy industry, aiming to meet consumer demands for healthier and longer-lasting dairy products.

Advantages and Disadvantages of Nanoemulsion Technology Applications in the Dairy Industry

Advantages

Nanoemulsion technology represents one of the significant advantages in the dairy industry. It increases the stability of bioactive components added to dairy products, enhances bioavailability, and facilitates their absorption by the body. It helps preserve the nutritional value of products by protecting sensitive components, especially omega-3 fatty acids, from oxidation. Additionally, nanoemulsions extend the shelf life of dairy products and reduce microbial spoilage. Nanosized emulsion droplets can inhibit microbial growth and slow oxidative degradation. This improves food safety because the active antimicrobial substances in the emulsion droplets can inhibit the growth of pathogenic microorganisms and thus help prevent foodborne diseases. Nanoemulsions also improve the taste, aroma, and texture of dairy products, making them more attractive to consumers and potentially increasing market share. Although some bioactive ingredients are insoluble in water, nanoemulsion technology can provide a homogeneous distribution by increasing their solubility and distribution in dairy products. Nanoemulsions facilitate the development of new products and aid in the production of functional foods..

Disadvantages

Nanoemulsions present potential opportunities in the food industry, including dairy products. However, to fully exploit their advantages, various disadvantages must be considered. The preparation of nanoemulsions necessitates specific methods, leading to high energy consumption and significant costs. This requirement for specialized equipment, such as high-pressure homogenizers, may restrict their broad application. Ostwald ripening is also a fundamental stability issue (Ayata, 2010). The lack of comprehensive research on the potential health risks associated with nanoparticles contributes to consumer hesitation and distrust towards this technology.

The production of nanoemulsions involves intricate processes that demand high pressure and energy, which can complicate the management of the production process. Environmental concerns stem from the not-yet-fully understood impacts of nanoparticles on the environment. Incomplete legal and regulatory frameworks for nanoemulsions generate uncertainty for producers, potentially delaying their introduction to the market. Addressing these disadvantages and advancing further research and development are crucial to harnessing the full potential of nanoemulsion technology. It is important to present this information clearly and professionally, maintaining the use of the present tense throughout the passage for consistency.

Conclusion

In conclusion, findings from various studies highlight the significant potential of nanoemulsion technology in the dairy industry.

These innovative approach methods in the dairy industry can offer consumers both healthier and more nutritious products by increasing the bioavailability of nutrients.

The increased stability and extended shelf life facilitated by this technology could expand the reach of dairy products and allow a broader demographic group to benefit from these healthy alternatives. Researchers are constantly developing new strategies to reduce the production costs of nanoemulsions and reduce their environmental impact. The use of emulsifiers and stabilizers derived from renewable sources marks an important step towards making this technology more sustainable and environmentally friendly. Additionally, extensive research on the safety and effectiveness of nanoemulsions will increase consumer confidence and accelerate industrial adoption. Looking ahead, nanoemulsion technology can offer innovative solutions that extend beyond the dairy industry to personal care, pharmaceuticals and many other sectors, thereby improving various aspects of our lives. Implementation of this technology in accordance with sustainability and safety norms can mark a new era in healthy living and promise significant advances.

Declarations

Conflict of Interest

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this review.

Ethics Committee Approval

Ethics committee approval is not required.

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References

Abdelhamid, S. M., Edris, A. E., & Sadek, Z. (2023). Novel approach for the inhibition of Helicobacter pylori contamination in yogurt using selected probiotics combined with eugenol and cinnamaldehyde nanoemulsions. Food Chemistry, 417, 135877. https://doi.org/10.1016/j.foodchem.2023.135877

Abdelraouf, W., Mattr, A., El-Desouky, S., & Elrefaey, A. (2023). Preparation and characterization nanoemulsion moringa oil by whey protein and application in ice cream as a food model. *Egyptian Journal of Dairy Science*, *0*(0). https://doi.org/10.21608/ejds.2023.207208.1012

Acosta, E. (2009). Bioavailability of nanoparticles in nutrient and nutraceutical delivery. *Current Opinion in Colloid & Interface Science*, *14*(3-15). https://doi.org/10.1016/j.cocis.2008.01.002

Adel, K., Youssef, A., Awad, R., & Gamal El Din, A. (2023). Development of CS/WPC/MO-NE bionanocomposites for coating Ras cheese based on Moringa essential oil nanoemulsion. *Al-Azhar Journal of Agricultural Research*. https://doi.org/10.21608/ajar.2022.177011.1104

Aditya, N. P., Macedo, A. S., Doktorovova, S., Souto, E. B., Kim, S., Chang, P. S., & Ko, S. (2014). Development and evaluation of lipid nanocarriers for quercetin delivery: A comparative study of solid lipid nanoparticles (SLN), nanostructured lipid carriers (NLC), and lipid nanoemulsions (LNE). *LWT - Food Science and Technology*, *59*(1), 115-121.

Ahmad, N., Alam, M. A., Ahmad, F. J., Sarafroz, M., Ansari, K., Sharma, S., & Amir, M. (2018). Ultrasonication techniques used for the preparation of novel Eugenol Nanoemulsion in the treatment of wounds healings and anti-inflammatory. *Journal of Drug Delivery Science and Technology*, *46*, 461–473. https://doi.org/10.1016/j.jddst.2018.06.003

Alfaro, L., Hayes, D., Boeneke, C., Xu, Z., Bankston, D., Bechtel, P. J., & Sathivel, S. (2015). Physical properties of a frozen yogurt fortified with a nano-emulsion containing purple rice bran oil. *LWT - Food Science and Technology*, *62*(2). https://doi.org/10.1016/j.lwt.2015.01.055

Anton, N., Benoit, J.-P., & Saulnier, P. (2008). Design and production of nanoparticles formulated from nano-emulsion templates—A review. *Journal of Controlled Release*, *128*(2), 185–199.

Anton, N., & Vandamme, T. F. (2009). The universality of low-energy nano-emulsification. *International Journal of Pharmaceutics*, *377*(1-2), 142–147.

Arul Raj, J., Suriya, J., Aliyas, S., Arul Soundara Rajan, Y. A. P., Murugan, K., Karuppiah, P., Arumugam, N., Almansour, A. I., & Karthikeyan, P. (2024). Spontaneous Nanoemulsification of Cinnamon Essential Oil: Formulation, Characterization, and Antibacterial and Antibiofilm Activity against Fish Spoilage Caused by Serratia Rubidaea BFMO8. Biotechnology and Applied Biochemistry. https://doi.org/10.1002/bab.2555.

Artiga-Artigas, M., Acevedo-Fani, A., & Martín-Belloso, O. (2017). Improving the shelf life of low-fat cut cheese using nanoemulsion-based edible coatings containing oregano essential oil and mandarin fiber. *Food Control*, *76*, 1-12.

Aswathanarayan, J. B., & Vittal, R. R. (2019). Nanoemulsions and their potential applications in food industry. *Frontiers in Sustainable Food Systems*, *3*.:95. https://doi.org/10.3389/fsufs.2019.00095

Azrini, N., Azmi, N., Elgharbawy, A. A. M., Motlagh, S. R., & Samsudin, N. (2019). Nanoemulsions: Factory for food, pharmaceutical and cosmetics. *Processes*, *7*, 1–34.

Bagale, U., Kadi, A., Abotaleb, M., & Potoroko, I., Sonawane, S. H. (2023). Prospect of bioactive curcumin nanoemulsion as effective agency to improve milk based soft cheese by using ultrasound encapsulation approach. *International Journal of Molecular Sciences*, *24*(3), 2663. https://doi.org/10.3390/ijms24032663

Bakry, M., Chen, Q., & Liang, L. (2019). Developing a mint yogurt enriched with omega-3 oil: Physiochemical, microbiological, rheological, and sensorial characteristics. *Journal of Food Processing and Preservation*, *43*(12). https://doi.org/10.1111/jfpp.14287

Bedoya-Serna, C. M., Dacanal, G. C., Fernandes, A. M., & Pinho, S. C. (2018). Antifungal activity of nanoemulsions encapsulating oregano (Origanum vulgare) essential oil: In vitro study and application in Minas Padrão cheese. *Brazilian Journal of Microbiology*, *49*(4). https://doi.org/10.1016/j.bjm.2018.05.004

Ben Jemaa, M., Falleh, H., Neves, M. A., Isoda, H., Nakajima, M., & Ksouri, R. (2017). Quality preservation of deliberately contaminated milk using thyme free and nanoemulsified essential oils. *Food Chemistry*, 217, 726–734. https://doi.org/10.1016/j.foodchem.2016.09.030

Bénichou, A., Aserin, A., & Garti, N. (2004). Double emulsions stabilized with hybrids of natural polymers for entrapment and slow release of active matters. *Advances in Colloid and Interface Science*. https://doi.org/10.1016/j.cis.2003.10.013

Borba, C. M., Araújo, G. M. S., Contessa, C. R., Dora, C. L., & Burkert, J. F. M. (2023). Influence of β-carotene nanoemulsions on technological parameters and stability in food matrices. *Food and Bioprocess Technology*, *16*(11). https://doi.org/10.1007/s11947-023-03060-x

Borrin, T.R., Georges, E.L., Brito-Oliveira, T.C., Moraes, I.C.F. & Pinho, S.C. (2018), Technological and sensory evaluation of pineapple ice creams incorporating curcumin-loaded nanoemulsions obtained by the emulsion inversion point method. *Intenational Journal Dairy Technology, 71*: 491-500. https://doi.org/10.1111/1471-0307.12451

Cassiday, L. (2016). Food emulsifier fundamentals. *International News on Fats, Oils and Related Materials*, *27*, 10–6. https://doi.org/10.21748/inform.11.2016.10

Chen, H., Hu, X., Chen, E., Wu, S., McClements, D. J., Liu, S., Li, B., & Li, Y. (2016). Preparation, characterization, and properties of chitosan films with cinnamaldehyde nanoemulsions. *Food Hydrocolloids*, *61*. https://doi.org/10.1016/j.foodhyd.2016.06.034

Dasgupta, N., & Ranjan, S. (2018). Food nanoemulsions: Stability, benefits, and applications. In: An Introduction to Food Grade Nanoemulsions. Environmental Chemistry for a Sustainable World. Springer, Singapore. https://doi.org/10.1007/978-981-10-6986-4_2

El-Sayed, H. S., & El-Sayed, S. M. (2021). A modern trend to preserve white soft cheese using nano-emulsified solutions containing cumin essential oil. *Environmental Nanotechnology, Monitoring and Management*, *16*. https://doi.org/10.1016/j.enmm.2021.100499

El-Sayed, H. S., Youssef, K., & Hashim, A. F. (2022a). Stirred yogurt as a delivery matrix for freeze-dried microcapsules of synbiotic EVOO nanoemulsion and nanocomposite. *Frontiers in Microbiology*, *13*. https://doi.org/10.3389/fmicb.2022.893053

El-Sayed, H. S., Fouad, M. T., & El-Sayed, S. M. (2022b). Enhanced microbial, functional and sensory properties of herbal soft cheese with coriander seeds extract nanoemulsion. *Biocatalysis and Agricultural Biotechnology*, *45*. https://doi.org/10.1016/j.bcab.2022.102495

Espitia, P. J. P., Fuenmayor, C. A., & Otoni, C. G. (2019). Nanoemulsions: Synthesis, characterization, and application in bio-based active food packaging. *Comprehensive Reviews in Food Science and Food Safety*, *18*(1), 264–285. https://doi.org/10.1111/1541-4337.12405

Flores-López, M. L., Cerqueira, M. A., de Rodríguez, D. J., & Vicente, A. A. (2016). Perspectives on utilization of edible coatings and nano-laminate coatings for extension of postharvest storage of fruits and vegetables. *Food Engineering Reviews*, *8*(292-305). https://doi.org/10.1007/s12393-015-9135-x

Foo, M. L., Ooi, C. W., Tan, K. W., & Chew, I. M. L. (2022). Preparation of black cumin seed oil Pickering nanoemulsion with enhanced stability and antioxidant potential using nanocrystalline cellulose from oil palm empty fruit bunch. *Chemosphere, 287*, 132108. https://doi.org/10.1016/j.chemosphere.2021.132108

Sassi, G., Shankar, S., Jaiswal, L., Salmieri, S., Karboune, S., & Lacroix, M. (2024). Nanoemulsion-based spray-dried formulation of essential oils, whey protein isolate, and maltodextrin: An approach for antifungal preservation of grated mozzarella cheese. *International Dairy Journal, 154*, 105919. https://doi.org/10.1016/j.idairyj.2024.105919

Ghazy, O. A., Fouad, M. T., Saleh, H. H., Kholif, A. E., & Morsy, T. A. (2021). Ultrasound-assisted preparation of anise extract nanoemulsion and its bioactivity against different pathogenic bacteria. *Food Chemistry, 341*, 128259. https://doi.org/10.1016/j.foodchem.2020.128259

Ghosh, V., Mukherjee, A., & Chandrasekaran, N. (2013). Ultrasonic emulsification of food-grade nanoemulsion formulation and evaluation of its bactericidal activity. *Ultrasonics Sonochemistry, 20*(1), 338-344. https://doi.org/10.1016/j.ultsonch.2012.08.010

Gruenwald, J. (2009). Novel botanical ingredients for beverages. *Clinics in Dermatology, 27*(2), 210-216. https://doi.org/10.1016/j.clindermatol.2008.11.003

Gupta, A., Eral, H. B., Hatton, T. A., & Doyle, P. S. (2016). Nanoemulsions: Formation, properties, and applications. *Soft Matter, 12*(11), 2826-2841. https://doi.org/10.1039/C5SM02958A

Gulotta, A., Saberi, A. H., Nicoli, M. C., & McClements, D. J. (2014). Nanoemulsion-based delivery systems for polyunsaturated (ω-3) oils: Formation using a spontaneous emulsification method. *Journal of Agricultural and Food Chemistry, 62*(7), 1720-1725. https://doi.org/10.1021/jf4054808

Gutiérrez, J. M., González, C., Maestro, A., Solè, I., Pey, C. M., & Nolla, J. (2008). Nano-emulsions: New applications and optimization of their preparation. *Current Opinion in Colloid & Interface Science, 13*(4), 245-251. https://doi.org/10.1016/j.cocis.2008.01.005

Guttoff, M., Saberi, A. H., & McClements, D. J. (2015). Formation of vitamin D nanoemulsion-based delivery systems by spontaneous emulsification: Factors affecting particle size and stability. *Food Chemistry, 171*, 117-122. https://doi.org/10.1016/j.foodchem.2014.08.087

Hendy, S. A. (2023). Production of functional Karish cheese fortified with vitamin D3 in nanoemulsion. *Al-Azhar Journal of Agricultural Research, 48*(1). https://doi.org/10.21608/ajar.2023.316054

Hidajat, M. J., Jo, W., Kim, H., & Noh, J. (2020). Effective droplet size reduction and excellent stability of limonene nanoemulsion formed by high-pressure homogenizer. *Colloids and Interfaces, 4*(1). https://doi.org/10.3390/colloids4010005

Hussein, J., El-Bana, M., Abdel Latif, Y., El-Sayed, S., Youssef, A., Elnaggar, M., & Medhat, D. (2023). Processed cheeses fortified by Laurus nobilis L. extract nanoemulsion ameliorate hyperhomocysteinemia in Ehrlich ascites carcinoma model. *Egyptian Journal of Chemistry, 66*(2), 199-211. https://doi.org/10.21608/ejchem.2022.135198.5944

Ibrahim, R. A., Abd El-Salam, B. A., Alsulami, T., Ali, H. S., Hoppe, K., & Badr, A. N. (2023). Neoteric biofilms applied to enhance the safety characteristics of Ras cheese during ripening. *Foods, 12*(19). https://doi.org/10.3390/foods12193548

Izquierdo, P., Esquena, J., Tadros, T. F., Dederen, C., Garcia, M. J., Azemar, N., & Solans, C. (2002). Formation and stability of nano-emulsions prepared using the phase inversion temperature method. *Langmuir, 18*(1), 26-30. https://doi.org/10.1021/la0108011

Jafari, S. M., & McClements, D. J. (2017). Nanotechnology approaches for increasing nutrient bioavailability. In F. Toldrá (Ed.), *Advances in Food and Nutrition Research* (Vol. 81, pp. 1-30). Academic Press. https://doi.org/10.1016/bs.afnr.2016.11.002

Jin, W., Xu, W., Liang, H., Li, Y., Liu, S., & Li, B. (2016). Nanoemulsions for food: Properties, production, characterization, and applications. In D. Julian McClements & L. J. Decker (Eds.), *Emulsions* (pp. 1-36). Academic Press. https://doi.org/10.1016/B978-0-12-804306-6.00001-5

Jintapattanakit, A. (2018). Preparation of nanoemulsions by phase inversion temperature (PIT) method. *Pharmaceutical Sciences Asia, 45*(1), 1-12. https://doi.org/10.29090/psa.2018.01.017.0037

Jose, D., Muenmuang, C., Kitiborwornkul, N., Yasurin, P., Asavasanti, S., Tantayotai, P., & Sriariyanun, M. (2022). Effect of surfactants and co-surfactants in formulation of noni fruit extract in virgin coconut oil-based emulsion. *Journal of the Indian Chemical Society, 99*(10), 100729. https://doi.org/10.1016/j.jics.2022.100729

Joung, H. J., Choi, M. J., Kim, J. T., Park, S., Park, H., & Shin, G. (2016). Development of food-grade curcumin nanoemulsion and its potential application to food beverage system: Antioxidant property and in vitro digestion. *Journal of Food Science, 81*(6), N1427-N1436. https://doi.org/10.1111/1750-3841.13224

Kelmann, R. G., Kuminek, G., Teixeira, H. F., & Koester, L. S. (2007). Carbamazepine parenteral nanoemulsions prepared by spontaneous emulsification process. *International Journal of Pharmaceutics, 342*(1-2), 231-239. https://doi.org/10.1016/j.ijpharm.2007.05.030

Kentish, S., Wooster, T. J., Ashokkumar, M., Balachandran, S., Mawson, R., & Simons, L. (2008). The use of ultrasonics for nanoemulsion preparation. *Innovative Food Science & Emerging Technologies, 9*(2), 170-175. https://doi.org/10.1016/j.ifset.2007.07.005

Kheawfu, K., Pikulkaew, S., Rades, T., Müllertz, A., & Okonogi, S. (2018). Development and characterization of clove oil nanoemulsions and self-microemulsifying drug delivery systems. *Journal of Drug Delivery Science and Technology, 46*, 330-338. https://doi.org/10.1016/j.jddst.2018.05.018

Ko, J. A., Kim, J., Doh, H., & Park, H. J. (2024). Quality evaluation and storage test for capsaicin-fortified yogurt based on the multilayer nanoemulsion system. *Food Science and Biotechnology, 33*(2), 441-451. https://doi.org/10.1007/s10068-023-01386-y

Komaiko, J. S., & McClements, D. J. (2016). Formation of food-grade nanoemulsions using low-energy preparation methods: A review of available methods. *Comprehensive Reviews in Food Science and Food Safety, 15*(2), 331-352. https://doi.org/10.1111/1541-4337.12189

Koroleva, M. Y., & Yurtov, E. V. (2012). Nanoemulsions: The properties, methods of preparation and promising applications. *Russian Chemical Reviews, 81*(1), 21-43. https://doi.org/10.1070/RC2012v081n01ABEH004239

Kumar, D. L., & Sarkar, P. (2018). Encapsulation of bioactive compounds using nanoemulsions. *Environmental Chemistry Letters, 16*(1), 59-70. https://doi.org/10.1007/s10311-017-0663-x

Laouini, A., Fessi, H., & Charcosset, C. (2012). Membrane emulsification: A promising alternative for vitamin E encapsulation within nano-emulsion. *Journal of Membrane Science, 423*, 85-96. https://doi.org/10.1016/j.memsci.2012.07.013

Leong, T. S. H., Wooster, T. J., Kentish, S. E., & Ashokkumar, M. (2009). Minimising oil droplet size using ultrasonic emulsification. *Ultrasonics Sonochemistry, 16*(6), 721-727. https://doi.org/10.1016/j.ultsonch.2009.02.005

Maali, A., & Hamed Mosavian, M. T. (2013). Preparation and application of nanoemulsions in the last decade (2000–2010). *Journal of Dispersion Science and Technology, 34*(1), 92-105. https://doi.org/10.1080/01932691.2011.648498

McClements, D. J., & Rao, J. J. (2011). Food-grade microemulsions, nanoemulsions and emulsions: Fabrication from sucrose monopalmitate & lemon oil. *Food Hydrocolloids, 25*(6), 1413-1423. https://doi.org/10.1016/j.foodhyd.2010.12.007

McClements, D. J. (2012). Nanoemulsions versus microemulsions: Terminology, differences, and similarities. *Soft Matter, 8*(6), 1719-1729. https://doi.org/10.1039/C2SM06903B

McCourt, A. F., Mulrooney, S. L., & O'Neill, G. J., et al. (2021). Postprandial 25-hydroxyvitamin D response varies according to the lipid composition of a vitamin D3 fortified dairy drink. *International Journal of Food Sciences and Nutrition, 72*(2), 198-210. https://doi.org/10.1080/09637486.2021.1984400

Mehrnia, M., Jafari, S. M., Makhmal-Zadeh, B. S., & Maghsoudlou, Y. (2015). Crocin loaded nano-emulsions: Factors affecting emulsion properties in spontaneous emulsification. *International Journal of Biological Macromolecules, 84*, 261-267. https://doi.org/10.1016/j.ijbiomac.2015.11.002

Mohammadi Jarchelo, H., Hosseini Ghaboos, S. H., & Almasi, H. (2022). Investigation of the physical properties of gluten-based active film containing free and encapsulated marjoram (Origanum majorana L.) essential oil and evaluation of its performance in the control of microbial spoilage in UF cheese and red meat. *Journal of Food Science and Technology (Iran), 19*(130), 121-133. https://doi.org/10.22034/FSCT.19.130.121

Mohammed, N. K., Muhialdin, B. J., & Meor Hussin, A. S. (2020). Characterization of nanoemulsion of *Nigella sativa* oil and its application in ice cream. *Food Science and Nutrition, 8*(6), 2608-2618. https://doi.org/10.1002/fsn3.1500

Naseema, A., Kovooru, L., Behera, A. K., Kumar, K. P., & Srivastava, P. (2020). A critical review of synthesis procedures, applications and future potential of nanoemulsions. *Advances in Colloid and Interface Science, 102318*. https://doi.org/10.1016/j.cis.2020.102318

Oh, D. H., Balakrishnan, P., Oh, Y. K., Kim, D. D., Yong, C. S., & Choi, H. G. (2011). Effect of process parameters on nanoemulsion droplet size and distribution in SPG membrane emulsification. *International Journal of Pharmaceutics, 404*(1-2), 191-197. https://doi.org/10.1016/j.ijpharm.2010.11.029

Panchal, B., Truong, T., Prakash, S., Bansal, N., & Bhandari, B. (2021). Influence of fat globule size, emulsifiers, and cream-aging on microstructure and physical properties of butter. *International Dairy Journal, 117*, 105003. https://doi.org/10.1016/j.idairyj.2021.105003

Panghal, A., Chhikara, N., Anshid, V., Charan, M. V. S. C., Surendran, V., Malik, A., & Dhull, S. B. (2019). Nanoemulsions: A promising tool for dairy sector. In *Nanotechnology in the Life Sciences*. Springer. https://doi.org/10.1007/978-3-030-16522-2_8

Polat Yemiş, G., Sezer, E., & Sıçramaz, H. (2022). Inhibitory effect of sodium alginate nanoemulsion coating containing myrtle essential oil (*Myrtus communis L.*) on *Listeria monocytogenes* in Kasar cheese. *Molecules, 27*(21), 7298. https://doi.org/10.3390/molecules27217298

Qian, C., & McClements, D. J. (2011). Formation of nanoemulsions stabilized by model food-grade emulsifiers using high-pressure homogenization: Factors affecting particle size. *Food Hydrocolloids, 25*(5), 1000-1008. https://doi.org/10.1016/j.foodhyd.2010.09.017

Rai, V. K., Mishra, N., Yadav, K. S., & Yadav, N. P. (2018). Nanoemulsion as pharmaceutical carrier for dermal and transdermal drug delivery: Formulation development, stability issues, basic considerations and applications. *Journal of Controlled Release, 270*, 203-225. https://doi.org/10.1016/j.jconrel.2017.11.049

Rao, S., Radhakrishnan, P., Valiathan, S., & M, S. (2023). Rosehip oil nanoemulsion as a stable delivery system for omega-3 fatty acids to enhance the nutritional value of yogurt. *Food Chemistry Advances, 3*, 100545. https://doi.org/10.1016/j.focha.2023.100545

Saberi, A. H., Fang, Y., & McClements, D. J. (2013). Fabrication of vitamin E-enriched nanoemulsions by spontaneous emulsification: Effect of propylene glycol and ethanol on formation, stability, and properties. *Food Research International, 54*(1), 812-820. https://doi.org/10.1016/j.foodres.2013.08.013

Saffarionpour, S. (2019). Preparation of food flavor nanoemulsions by high- and low-energy emulsification approaches. In *Food Engineering Reviews, 11*(4), 259-289. https://doi.org/10.1007/s12393-019-09197-0

Salama, H. H., El-Sayed, H. S., Kholif, A. M. M., & Edris, A. E. (2022). Essential oils nanoemulsion for the flavoring of functional stirred yogurt: Manufacturing, physicochemical, microbiological, and sensorial investigation. *Journal of the Saudi Society of Agricultural Sciences, 21*(6). https://doi.org/10.1016/j.jssas.2021.10.001

Salem, M. A., & Ezzat, S. M. (2019). Nanoemulsions in food industry. *Some New Aspects of Colloid Systems in Foods,* IntechOpen 2(12) 238–267.https://doi.org/10.5772/intechopen.79447.

Salvia-Trujillo, L., Soliva-Fortuny, R., Rojas-Graü, M. A., McClements, D. J., & Martín-Belloso, O. (2017). Edible nanoemulsions as carriers of active ingredients: A review. *Annual Review of Food Science and Technology, 8*, 439–466. DOI:10.1146/annurev-food-030216-025908

Sanguansri, P., & Augustin, M. A. (2006). Nanoscale materials development – a food industry perspective. *Trends in Food Science & Technology, 17*, 547-556. https://doi.org/10.1016/j.tifs.2006.04.010

Santana, R. C., Perrechil, F. A., & Cunha, R. L. (2013). High- and low-energy emulsifications for food applications: A focus on process parameters. *Food Engineering Reviews, 5*(2), 107–122. https://doi.org/10.1007/s12393-013-9065-4

Shamsara, O., Muhidinov, Z. K., Jafari, S. M., Bobokalonov, J., Jonmurodov, A., Taghvaei, M., & Kumpugdee-Vollrath, M. (2015). Effect of ultrasonication, pH, and heating on stability of apricot gum-lactoglobuline two layer nanoemulsions. *International Journal of Biological Macromolecules, 81*, 1019–1025. https://doi.org/10.1016/j.ijbiomac.2015.09.056

Sheth, T., Seshadri, S., Prileszky, T., & Helgeson, M. E. (2020). Multiple nanoemulsions. *Nature Reviews Materials, 5*, 214–228. https://doi.org/10.1038/s41578-019-0161-9

Shakeel, F., Baboota, S., Ahuja, A., Ali, J., & Shafiq, S. (2009). Celecoxib Nanoemulsion for Transdermal Drug Delivery: Characterization and in Vitro Evaluation." *Journal of Dispersion Science and Technology* 30(6) 834–842. https://doi.org/10.1080/01932690802644012

Silva, H. D., Cerqueira, M. A., & Vicente, A. (2012). Nanoemulsions for food applications: Development and characterization. *Food and Bioprocess Technology, 5*, 854–867. https://doi.org/10.1007/s11947-011-0683-7

Silva, H. D., Cerqueira, M. A., & Vicente, A. A. (2015). Influence of surfactant and processing conditions in the stability of oil-in-water nanoemulsions. *Journal of Food Engineering, 167*, 89–98. https://doi.org/10.1016/j.jfoodeng.2015.07.037

Solans, C., Izquierdo, P., Nolla, J., Azemar, N., & Garcia-Celma, M. J. (2005). Nanoemulsions. *Current Opinion in Colloid & Interface Science, 10*(3), 102–110. https://doi.org/10.1016/j.cocis.2005.06.004

Solans, C., Morales, D., & Homs, M. (2016). Spontaneous emulsification. *Current Opinion in Colloid & Interface Science, 22*, 88–93.

Solè, I., Pey, C. M., Maestro, A., González, C., Porras, M., Solans, C., & Gutiérrez, J. M. (2010). Nano-emulsions prepared by the phase inversion composition method: Preparation variables and scale-up. *Journal of Colloid and Interface Science, 344*(2), 417–423.

Sonneville-Aubrun, O., Babayan, D., Bordeaux, D., Lindner, P., Rata, G., & Cabane, B. (2009). Phase transition pathways for the production of 100 nm oil-in-water emulsions. *Physical Chemistry Chemical Physics, 11*(1), 101–110.

Sridhar, A., Ponnuchamy, M., Kumar, P. S., & Kapoor, A. (2021). Food preservation techniques and nanotechnology for increased shelf life of fruits, vegetables, beverages and spices: A review. *Environmental Chemistry Letters, 19*, 1715–1735. https://doi.org/10.1007/s10311-020-01126-2

Subasi, A., Alickovic, E., & Kevric, J. (2017). Diagnosis of chronic kidney disease by using random forest. In *CMBEBIH 2017* (pp. 589–594). Singapore: Springer.

Sugumar, S., Singh, S., Mukherjee, A., & Chandrasekaran, N. (2015). Nanoemulsion of orange oil with non-ionic surfactant produced emulsion using ultrasonication technique: Evaluating against food spoilage yeast. *Applied Nanoscience, 6*, 113–120. https://doi.org/10.1007/s13204-015-0412-z

Tan, C., & McClements, D. J. (2021). Application of advanced emulsion technology in the food industry: A review and critical evaluation. *Foods, 10*(4), 812. https://doi.org/10.3390/foods10040812

Teo, S. H., Chee, C. Y., Fahmi, M. Z., Wibawa Sakti, S. C., & Lee, H. V. (2022). Review of Functional Aspects of Nanocellulose-Based Pickering Emulsifier for Non-Toxic Application and Its Colloid Stabilization Mechanism. *Molecules, 27*(21), 7170. https://doi.org/10.3390/molecules27217170

Umaraw, P., & Verma, A. K. (2017). Comprehensive review on application of edible film on meat and meat products: An eco-friendly approach. *Critical Reviews in Food Science and Nutrition, 57*(6), 1270–1279. https://doi.org/10.1080/10408398.2014.986563

Unilever. (2011). Available online at: http://www.unilever.com/innovation/productinnovations/coolicecreaminnovations/?WT.LHNAV=Cool_ice_cream_innovations (accessed April 13, 2011).

Versino, F., Lopez, O. V., Garcia, M. A., & Zaritzky, N. E. (2016). Starch-based films and food coatings: An overview. *Starch - Stärke, 68*, 1026–1037. https://doi.org/10.1002/star.201600095

Walker, R. M., Decker, E. A., & McClements, D. J. (2015). Physical and oxidative stability of fish oil nanoemulsions produced by spontaneous emulsification: Effect of surfactant concentration and particle size. *Journal of Food Engineering, 164*, 10–20. https://doi.org/10.1016/j.jfoodeng.2015.04.028

Xue, J., Davidson, P. M., & Zhong, Q. (2013). Thymol nanoemulsified by whey protein-maltodextrin conjugates: The enhanced emulsifying capacity and antilisterial properties in milk by propylene glycol. *Journal of Agricultural and Food Chemistry, 61*(51), 12720-12726. https://doi.org/10.1021/jf4043437

Zambrano-Zaragoza, M. L., González-Reza, R., Mendoza-Muñoz, N., Miranda-Linares, V., Bernal-Couoh, T. F., Mendoza-Elvira, S., & Quintanar-Guerrero, D. (2018). Nanosystems in edible coatings: A novel strategy for food preservation. *International Journal of Molecular Sciences, 19*(3), 705. https://doi.org/10.3390/ijms19030705

Zhang, Y., & Zhong, Q. (2017). Solid-in-oil-in-water emulsions for delivery of lactase to control in vitro hydrolysis of lactose in milk. *Journal of Agricultural and Food Chemistry*. https://doi.org/10.1021/acs.jafc.7b03787.s001

Zhong, J., Yang, R., Cao, X., Liu, X., & Qin, X. (2018). Improved physicochemical properties of yogurt fortified with fish oil/γ-oryzanol by nanoemulsion technology. *Molecules*, *23*(1), 56. https://doi.org/10.3390/molecules23010056