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Review

Techniques for nanoemulsion in milk and its application: A review

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Abstract

The present review provides a comprehensive overview of nanoemulsion preparation techniques and their impact on dairy milk and milk foam properties. It highlights high-energy methods utilising mechanical forces to produce nanoscale droplets, thus enhancing emulsion stability, and allowing precise control over droplet size. While effective for various production scales, these methods require significant energy and sophisticated equipment, with potential heat generation affecting sensitive compounds. Conversely, low-energy methods rely on thermodynamic changes, offering cost-effective solutions for heat-sensitive compounds, despite facing challenges in scalability and formulation specificity. The incorporation of nanometre-sized droplets into dairy milk significantly influences foaming behaviour and texture modulation, improving foam stability and foamability. Smaller fat globule sizes promote long-term physical stability, addressing common issues like foam destabilisation and coalescence. Understanding the interactions between milk quality, fat content, and processing conditions reveals opportunities for enhancing dairy product quality. The present review underscores the potential of nanoemulsions into optimising dairy milk properties, ultimately revolutionising dairy processing, and providing manufacturers with innovative tools to meet consumer demand for superior texture and stability in milk-based products.

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Introduction

Nanotechnology has gained prominence in various sectors, particularly food and health over the past few decades, primarily for delivering bioactive compounds such as flavours and fatty acids. Nanoemulsions, which are small droplets ranging from 10 to 1,000 nm in size, have been widely studied for their stability and potential applications in the food industry (Wilson *et al*., 2022). They form when two immiscible liquids combine into a stable mixture with the aid of emulsifying agents and energy. Compared to conventional emulsions, nanoemulsions exhibit smaller droplet sizes and enhanced long-term stability. These nanoemulsions are typically classified into three types: oil-in-water (O/W), water-in-oil (W/O), and bicontinuous phase emulsions, and can take the form of inflated micelles or bicontinuous structures (Azmi *et al*., 2019).

The production of nanoemulsions is influenced by factors such as the oleaginous phase, surfactant selection, and system composition. Methods for nanoemulsion preparation are broadly categorised into low- and high-energy techniques, depending on the source and amount of energy applied. Advances in food processing technologies aim to create food products that are flavourful, nutritious, safe, and minimally processed. This has led to a focus on novel

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non-thermal techniques that preserve the nutritional content and flavour of food products, with nanoemulsion technology gaining increasing interest for its ability to enhance the delivery of nutrients and improve product stability.

In the dairy industry, nanoemulsions are being explored for their potential to improve the quality of milk products, particularly by enhancing the stability and sensory properties of milk and milk foams. Milk is a natural O/W emulsion but is thermodynamically unstable, which can lead to destabilisation over time through mechanisms such as gravitational separation, coalescence, flocculation, and partial coalescence. Nanoemulsion technology, *via* the reduction of fat globule size to nanoscale, offers a solution to these challenges. Recent studies have demonstrated that reducing fat globule size in milk can improve physical stability, enhance foamability, and prolong shelf life (Aswathanarayan and Vittal, 2019; Maklin *et al*., 2025).

According to recent market reports, the global nanoemulsion market in foods and beverages is expected to grow significantly, reaching an estimated value of USD 16.05 billion by 2032, growing at a CAGR of 8.4% (Reports and Data, 2023). The dairy sector is expected to account for a substantial portion of this growth due to the increasing demand for functional foods, such as fortified dairy products. Nanoemulsions are being used to enhance the bioavailability of nutrients, flavours, and bioactive compounds, making them a valuable technology for improving the nutritional and sensory quality of dairy products (Kaur *et al*., 2024). This trend reflects the growing consumer preference for healthier, more functional dairy products, aligning with advancements in food processing technologies like ultrasonication and high-pressure homogenisation.

Nanoemulsions are being used to enhance the properties of milk foam in beverages such as cappuccinos, ice creams, and whipped creams, as small droplet sizes contribute to improved texture, smoothness, and foam stability (Khezri *et al*., 2017; Maklin *et al*., 2025). This growth in demand for functional dairy products is further supported by the application of nanoemulsions in extending shelf life, and improving the bioavailability of lipophilic compounds, such as omega-3s and vitamins.

The formation and stabilisation of milk foam are influenced by factors such as fat content, protein composition, and processing methods. While milk foam is a desirable feature in many dairy products, maintaining foam stability can be challenging. Large fat globules in milk tend to destabilise foam by causing bubbles to collapse under their weight. On the other hand, reducing fat globule size, for example through homogenisation or nanoemulsion technology, enhances foam stability. The present review explores the role of nanoemulsion techniques in reducing milk fat globule size, and examines their impact on foam formation, stability, and overall milk quality, aiming to offer insights into innovative approaches for improving the sensory and functional properties of milk-based beverages.

Nanoemulsion in milk

The primary components of nanoemulsion are oil, emulsifying agents, and aqueous phases, and the right combination of these components influences the emulsion's stability and properties (Dasgupta *et al*., 2019). Nanoemulsions are created through the blending of two immiscible liquids, with the addition of an emulsifying agent. The immiscible liquids come in various varieties, with one being oil-based (oleaginous) and the other being water-based (aqueous). This combination allows for the formation of stable nanoemulsions, which find applications in various industries due to their unique properties.

Oleaginous phase

The oleaginous phase of a nanoemulsion is composed of various lipophilic components, including triacylglycerols, diacylglycerols, monoacylglycerols, and free fatty acids. Additionally, non-polar essential oils, mineral oils, lipid substitutes, waxes, weighing agents, oil-soluble vitamins, and other hydrophobic substances contribute to the oleaginous phase. The viscosity, refractive index, density, phase behaviour, and interfacial tension of these components significantly affect nanoemulsion formation, stability, and functional properties (Aswathanarayan and Vittal, 2019). In milk nanoemulsions, the interaction of the oleaginous phase with milk components, particularly fat globules and milk proteins, is critical in determining the behaviour of milk foams. Fat globules within the oleaginous phase adsorb onto the air-liquid interface of the milk foam, influencing both foam formation and stability. These interactions between the oleaginous phase components and milk proteins, such as casein and whey, are crucial in stabilising the nanoemulsion and enhancing the quality of milk foam.

Long-chain triacylglycerols, on the other hand, are preferred for nanoemulsion formulation due to their cheap cost, availability, functionality, and nutritional qualities (Mushtaq *et al*., 2023). Long-chain triacylglycerols also play a vital role in milk foaming by reducing the coalescence of fat droplets, and enhancing foam structure. Their hydrophobic nature promotes the formation of a stable lipid-protein interface, where casein micelles and whey proteins interact with the oil droplets, forming a viscoelastic film that stabilises foam bubbles. This results in improved foamability and prolonged foam stability, critical for applications like lattes and milk-based beverages. Research by Mohd Yaakub *et al*. (2024) focused on optimizing the ultrasonication process for fresh cow's milk to understand its effect on various nutritional components. The researchers tested different factors, such as fat content, ultrasound amplitude, and sonication time. In the same report, it showed that ultrasonication significantly influenced components like fat, free fatty acids, protein, solids, lactose, and casein. The findings helped identify the ideal processing conditions for maximizing fat content while minimizing the generation of free fatty acids (Mohd Yaakub *et al*., 2024).

In fortified dairy products, long-chain triglycerides are often employed to encapsulate fat-soluble vitamins such as A, D, and E, improving nutrient delivery while contributing to the structural integrity of milk foam (Zhang *et al*., 2022). The encapsulation process allows the oil-soluble vitamins to remain suspended within the nanoemulsion, ensuring even distribution within the milk. Moreover, these encapsulated nutrients interact with milk proteins, contributing to the overall texture and stability of the foam by modifying the interfacial properties between the oleaginous and aqueous phases. By stabilising the fat-protein interface and contributing to nutrient encapsulation, the oleaginous phase not only supports the formation of nanoemulsions, but also improves the functional and sensory attributes of milk foams in various dairy applications (Zhang *et al*., 2022).

Aqueous phase

The aqueous component within a nanoemulsion consists of a polar solvent alongside a co-solvent, both of which are crucial in determining the polarity, rheological properties, phase behaviour, interfacial tension, and ionic concentration of the system. Water is the most common polar solvent, while co-solvents can include carbohydrates, alcohols, proteins, and polyols (Gazi *et al*., 2023). In milk-based nanoemulsions, the aqueous phase interacts directly with milk proteins, such as casein and whey, influencing foaming properties by stabilising the air-liquid interface. Milk proteins, when dissolved in the aqueous phase, adsorb onto fat globule surfaces and air bubbles, reducing surface tension and stabilising foam structures.

Phase separation between the aqueous and oleaginous phases in nanoemulsions can result from processes such as Ostwald ripening, where smaller droplets dissolve and redeposit onto larger ones, leading to an overall increase in droplet size over time (Maphosa and Jideani, 2018). Other processes, like coalescence, flocculation, and gravitational separation, also contribute to phase segregation. To counteract these phenomena, stabilising agents such as emulsifiers, ripening inhibitors, density modifiers, and texture enhancers are introduced.

The aqueous phase in nanoemulsions plays a key role in interacting with milk components, particularly in foaming applications. The interaction between the aqueous phase and milk proteins, for example, promotes the adsorption of proteins at the oil-water interface in nanoemulsions, stabilising fat globules and foam bubbles. This stabilisation is critical in milk foaming, where proteins form a viscoelastic film around air bubbles, enhancing foam stability and preventing coalescence. In systems where carbohydrates or polyols are used as co-solvents, these molecules can further contribute to the viscosity of the aqueous phase, improving foam texture by increasing resistance to foam collapse.

In milk foams, stabilising agents, such as proteins and carbohydrates dissolved in the aqueous phase, prevent phase separation, and improve foamability. For example, stabilisers used in yogurt formulations maintain nanoemulsion stability during processing and storage by inhibiting phase separation, and ensuring a smooth and consistent texture (Aliabbasi and Emam-Djomeh, 2024). Additionally, the aqueous phase modifies the physicochemical environment, which can influence the size of the air bubbles within milk foams, thus contributing to the texture and mouthfeel of dairy products. The interaction of the aqueous phase with milk proteins also enhances the mechanical properties of the foam, improving its resistance to gravitational separation and coalescence over time.

Emulsifying agents

Emulsifying agents are surface-active molecules that stabilise nanoemulsions by reducing interfacial tension between immiscible liquids, such as oil and water, allowing the formation of stable, small-sized droplets. These agents prevent droplet coalescence and aggregation, thus enhancing the stability and lifespan of nanoemulsions (Xiong *et al.*, 2023). Common emulsifiers include cationic, anionic, non-ionic, and zwitterionic types, with surfactants, phospholipids, proteins, and polysaccharides being widely used (Pal *et al.*, 2021). Polymers like polyvinyl alcohol are also employed for their stabilising properties.

Emulsifiers stabilise nanoemulsions by adsorbing onto the surface of oil droplets, and forming a protective barrier. In milk, emulsifiers interact with both fat globules and proteins to enhance foam formation and stability. Proteins like casein and whey protein in milk can act as natural emulsifiers, contributing to foam formation by reducing surface tension, and providing structural integrity to the air-liquid interface in foams. Surfactants, particularly non-ionic surfactants, stabilise nanoemulsions by forming a steric barrier around fat globules, preventing coalescence through steric hindrance and hydration. These surfactants also interact with milk proteins, leading to enhanced foamability by stabilising the interface between air bubbles and the liquid phase. Charged surfactants, on the other hand, provide stability through electrostatic repulsion, which prevents fat globule aggregation by generating repulsive forces between droplets (Marhamati *et al.*, 2021).

Phospholipids, such as lecithin, are commonly used as emulsifiers in milk foams. They align at the air-liquid interface, helping to stabilise foam by reducing surface tension and preventing air bubble coalescence. The amphiphilic nature of phospholipids allows them to interact with both the hydrophilic (water) and hydrophobic (fat) phases of milk, forming a stable emulsion that enhances the foam's resilience and texture. Lecithin also interacts with milk proteins, creating a more stable matrix that supports longer-lasting foams.

In O/W nanoemulsions, a hydrophilic-lipophilic balance (HLB) greater than 10 guides the selection of emulsifying agents. Proteins that do not dissolve in oils are often used as emulsifiers, particularly in food-grade applications. The combination of multiple emulsifiers, such as hydrophilic and lipophilic surfactants, reduces surface tension synergistically and improves emulsion stability. For example, block copolymers can effectively lower surface tension and stabilise nanoemulsions, further enhancing foam stability (Opdam *et al.*, 2022).

The interactions within nanoemulsions affect the structure and properties of milk foams. Smaller droplet sizes in nanoemulsions increase surface area, allowing more emulsifier molecules to stabilise air bubbles in the foam, leading to improved foamability and stability. This can prevent common issues like foam destabilisation, coalescence, and gravitational separation. Furthermore, using lecithin or other natural emulsifiers aligns with food safety standards and consumer preferences, particularly for clean-label dairy products.

In conclusion, emulsifying agents play a vital role in the stabilisation of nanoemulsions and their subsequent impact on milk foaming properties. Through molecular interactions with fat globules and proteins, emulsifiers enhance foamability, texture, and stability in dairy products, contributing to improved quality and consumer appeal.

Nanoemulsion applications in dairy products

Nanoemulsions are gaining traction in the dairy industry, particularly in the production of functional dairy products with enhanced nutritional profiles and improved stability. Their application in dairy products, such as milk, yogurt, and creamers, leverages their small droplet size, typically in the range of 10 - 200 nm (Wilson *et al.*, 2022), which offers improved bioavailability of nutrients and bioactive compounds, better texture, and prolonged stability. However, despite these benefits, recent research highlights both opportunities and challenges in fully integrating nanoemulsions into commercial dairy products.

Fortification of dairy products

One prominent application of nanoemulsions in dairy is the fortification of milk with fat-soluble vitamins (A, D, E, and K) and omega-3 fatty acids. Nanoemulsions allow for the efficient encapsulation and delivery of these bioactive compounds, which are critical for human health. While fortified milk products often use nanoemulsion technology to improve the bioavailability of poorly soluble compounds like vitamins A and D (Mushtaq *et al.*, 2023), new developments in encapsulation techniques are enhancing the precision of nutrient release. Advanced surfactant systems, such as plant-based emulsifiers, offer both functional and clean-label solutions, allowing for wider adoption in the growing market of plant-based dairy alternatives. The nano-sized droplets help disperse these compounds evenly throughout the product, preventing aggregation, and enhancing nutrient absorption during digestion.

In yogurt, nanoemulsions are used to encapsulate probiotics and other heat-sensitive nutrients, ensuring their protection during processing, and enhancing their bioavailability when consumed. Nanoemulsions improve the shelf life and stability of functional components in yogurt, allowing for long-term preservation without degradation of nutritional quality (Aliabbasi and Emam-Djomeh, 2024).

Texture and stability enhancement

Nanoemulsions play a significant role in improving the texture and stability of dairy products, particularly in creamers and yogurt. Due to their small particle size, nanoemulsions help create a smooth, creamy texture without the need for excessive stabilisers or thickeners. This is particularly beneficial in low-fat or non-fat dairy products where achieving the desired mouthfeel can be challenging. Recent advancements in emulsification technology, such as high-pressure homogenisation and ultrasonic emulsification, have further refined droplet size control, which leads to more consistent textures in reduced-fat formulations (Zhou *et al*., 2021). However, practical challenges remain, particularly in scaling up these processes for industrial applications without compromising droplet uniformity or stability.

In yogurt, nanoemulsions improve consistency by preventing phase separation, and ensuring a homogeneous distribution of fat throughout the product. Stabilisers such as lecithin or proteins are used as emulsifiers to maintain the stability of nanoemulsions in yogurt, keeping the product stable during storage and preventing coalescence or creaming (Marhamati *et al*., 2021).

Nutrient delivery systems

The potential for nanoemulsions to function as nutrient delivery systems is one of their most promising applications in dairy products. Nanoemulsions can encapsulate bioactive compounds such as antioxidants, peptides, and plant extracts, improving their stability in the product, and enhancing their absorption in the gastrointestinal tract (Pateiro *et al*., 2021). For instance, omega-3 fatty acids, which are prone to oxidation, can be effectively delivered in dairy products using nanoemulsions to protect them from degradation, and improve their bioavailability (Aswathanarayan and Vittal, 2019). Recent studies are focusing on optimising droplet composition to further enhance absorption in the gastrointestinal tract (Choi and McClements, 2020; Kaur *et al*., 2024). However, one critical challenge is the interaction of nanoemulsions with other components in dairy systems, such as proteins and polysaccharides, which can affect both nutrient release and product stability. These interactions need to be better understood to tailor nanoemulsion formulations for specific dairy products.

Moreover, the use of nanoemulsions allows for the delivery of functional compounds at much lower concentrations while still achieving the desired health benefits, thereby reducing the cost of fortification on manufacturers, and making functional dairy products more accessible to consumers.

Regulatory challenges and consumer perception

Despite the advantages of nanoemulsions in dairy products, there are notable regulatory and consumer perception challenges that must be addressed. Regulatory bodies such as the U.S. Food and Drug Administration (FDA) and the European Food Safety Authority (EFSA) require nanoemulsion-based products to undergo extensive safety testing. Nano-sized particles are scrutinised for their potential toxicity, bioaccumulation, and interaction with biological systems, which could lead to delays in product approval and commercialisation (Gupta and Xie, 2018).

Furthermore, labelling requirements for nanoemulsion-based products have raised concerns about transparency. Consumers are increasingly aware of the presence of nanotechnology in food, and many associate the term "nano" with synthetic or artificial processes. This scepticism can deter some consumers from purchasing nanoemulsion-enhanced dairy products, especially in markets where "natural" and "organic" labels are highly valued (Varzakas and Antoniadou, 2024). Therefore, educating consumers about the safety and benefits of nanoemulsions is crucial for overcoming these barriers. Companies must emphasise that nanoemulsions enhance the bioavailability of essential nutrients, and contribute to product stability, improving both the quality and nutritional value of the product.

As consumer awareness of the benefits of functional foods grows, the demand for nanoemulsion-based dairy products is expected to rise. Innovations in emulsification technology, such as the development of surfactant-free nanoemulsions, offer new opportunities for creating dairy products that meet consumer demand for clean-label and additive-free foods (Chen *et al*., 2018). Researchers are also exploring plant-based nanoemulsion systems to align with the growing demand for plant-based dairy alternatives, further expanding the market potential for nanoemulsions in the dairy industry.

Preparation of nanoemulsion

In preparing nanoemulsions, it is vital to consider various factors, including the intended application and processing requirements. This necessitates a careful selection of ingredients to achieve specific functions within the formulation. These functions can encompass stabilising food emulsions, enhancing texture in products like ice cream and cheese, homogenising colour, improving nutrient bioavailability, and controlling enzymatic, oxidative, or respiratory processes in minimally processed goods (Table 1).

High energy method

High-energy methods of emulsification are distinguished by their use of powerful mechanical devices to create nanoemulsions that possess significant kinetic energy (Mushtaq *et al*., 2023). These methods employ advanced mechanical instruments capable of generating intense disruptive forces, which effectively fragment the oleaginous and aqueous phases into nanoscale droplets. Commonly utilised equipment includes ultrasonicators, microfluidisers, and high-pressure homogenisers.

The resulting particle size of nanoemulsions produced *via* high-energy methods is influenced by several factors, including the type of equipment employed, operational parameters such as processing time and temperature, and the specific characteristics and composition of the sample being emulsified (Nantarat *et al*., 2015). These factors must be carefully controlled to achieve the desired droplet size and emulsion stability. High-energy emulsification techniques are versatile, and can generate both O/W and W/O nanoemulsions. High-pressure homogenisation and microfluidisation are particularly effective for producing nanoemulsions on both laboratory and industrial scales, while ultrasonic emulsification is primarily utilised within laboratory settings (Liu *et al*., 2021). It is important to acknowledge that high-energy emulsification methods necessitate sophisticated instrumentation and substantial energy input, which can significantly increase the overall cost of nanoemulsion production (Abliz *et al*., 2021). Consequently, while these methods offer effective solutions for producing nanoemulsions, considerations regarding cost and energy consumption must be factored in during the decision-making process for their implementation (Figure 1).

Ultrasonic method

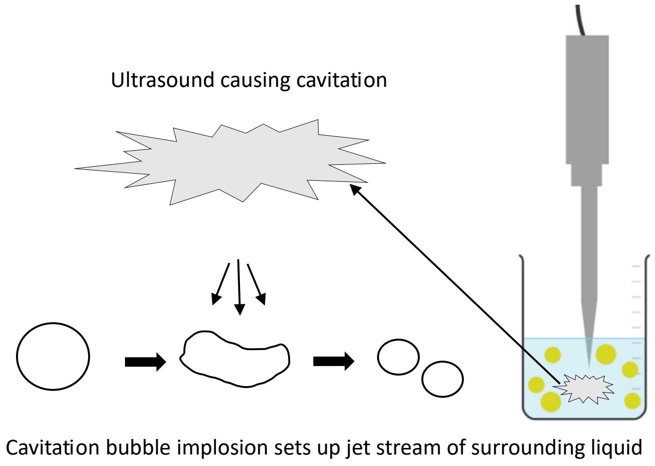
Ultrasound (US) is defined as sound waves with frequencies exceeding the human hearing threshold of 20 kHz. It can be classified into two categories based on intensity and frequency: high intensity-low frequency (I = 10 - 1000 W/cm^2 and F = 20 - 100 kHz) and low intensity-high frequency (I = 1 W/cm^2 and F > 1 MHz) (Tiwari and Mason, 2012). The ultrasonication process is a widely employed technique for standardising droplet size in emulsions (Sandhya *et al*., 2021). It involves utilising an ultrasonic wave-emitting probe to disrupt macroemulsions through cavitation forces (Truong *et al*., 2016), as illustrated in Figure 1(a). The electric probe generates sound energy, which causes size reduction due to the growth of unstable cavitation bubbles. During sonication, larger emulsion droplets disintegrate because of the pressure differential that arises during bubble collapse (Zhou *et al*., 2021).

The phenomenon of cavitation leads to the formation of bubbles that generate extremely high temperatures (up to 5000 K) and pressures (approximately 500 atm), resulting in powerful shear forces (Pollet and Ashokkumar, 2019). The abrupt collapse of these bubbles produces a variety of physical and chemical effects within the liquid medium, including microstreaming, turbulence, shock waves, radical formation, and sonoluminescence (Pollet and Ashokkumar, 2019). The chemical reactions in this environment produce highly reactive radical species; for instance, the sonication of argon-saturated water generates H and OH radicals, with the former acting as reducing agents, and the latter as oxidising agents (Bhangu and Ashokkumar, 2016).

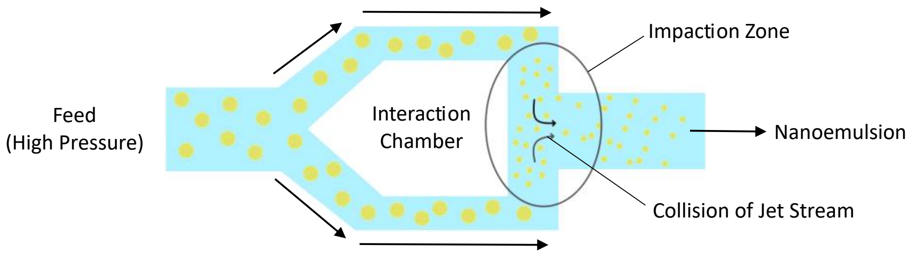
Table 1. Comparison of nanoemulsion preparation techniques: High- *vs*. low-energy methods.

Type	**Method**	**Principle**	**Advantage**	**Disadvantage**	**Reference**
High-energy	Ultrasonication	Uses ultrasonic waves to generate cavitation, breaking droplets into nanosized	Short processing time, produces uniform droplets	Equipment cost, heat generation may degrade sensitive compounds	Aswathanarayan and Vittal (2019)
			Effective for small batch sizes	Requires cooling during processing	Mushtaq *et al*. (2023)
	Microfluidisation	Forces liquid through a small chamber at high pressure, creating shear forces	Produces stable nanoemulsions, high reproducibility	High equipment cost, multiple passes needed for uniform size	Kumar *et al*. (2022)
			Effective for large scale	Possible clogging of chambers	Yurdacan and Murat Sari (2021)
	High-Pressure Valve Homogenisation	Forces liquid through a valve under high pressure, creating shear and turbulence	Suitable for large-scale production, cost-effective	Requires high pressure, can cause droplet coalescence	Lammari *et al*. (2021)
			Produces fine and stable emulsions	Heat generation	Malik *et al*. (2023)
Low-energy	Phase Inversion Temperature	Emulsion is formed by temperature-induced changes in the solubility of surfactants	No need for high-energy input, good for heat-sensitive compounds, simple and easy to scale up	Sensitive to temperature, limited to specific surfactants, phase inversion may lead to instability	Friberg *et al*. (2011)
	Phase Inversion Composition	Emulsion is formed by altering the oil/water ratio or surfactant concentration	No energy input required, cost-effective, suitable for large batches	Limited to specific formulation, poor reproducibility, low flexibility in emulsion composition	Perazzo *et al*. (2015)
	Spontaneous Emulsification	Emulsion is formed through rapid mixing of oil, water, and surfactant	Simple process, no energy required	Limited to specific formulation, stability issues	Al-Sakkaf and Onaizi (2024)
			Good for encapsulating heat-sensitive compounds	May require high surfactant concentration	Komaiko and McClements (2016)

a) Ultrasonication Method



b) Microfluidization Method



c) High-Pressure Homogenization Method

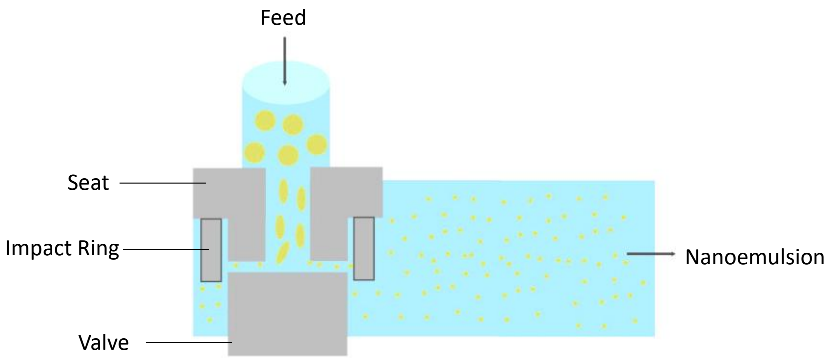


Figure 1. High-energy methods for nanoemulsion formulation.

Recent advancements in ultrasound technology suggest that employing lower acoustic power over extended periods can effectively reduce droplet size without adversely affecting the flavour profile of dairy products (Carrillo-Lopez *et al.*, 2021). Studies have demonstrated that droplet sizes as small as 0.73 µm can be achieved in whole milk through 10 min of sonication at 450 W (Al-Hilphy *et al.*, 2013). Furthermore, it was observed that the yield of radicals tended to increase with increasing frequency until a maximum point was reached, after which it decreased with further increases in frequency. This phenomenon indicated that optimal cavitation effects occurred between 200 and 800 kHz, where the production of sonochemical radicals was maximised (Bhangu and Ashokkumar, 2016).

The efficacy of the ultrasonication process in achieving homogenisation is contingent upon several factors, including processing time, acoustic power, and operating temperature. Extended processing times at high acoustic power and elevated temperatures can facilitate the attainment of smaller fat globule sizes (Carrillo-Lopez *et al.*, 2021). According to Al-Hilphy *et al.* (2013), fat globule sizes of 3.22 and 0.73 μm can be achieved in whole milk using 10 min sonication treatments at 180 and 450 W, respectively.

However, the application of High-Intensity Ultrasound (HIU) in milk processing has been reported to alter the colour of milk, leading to a less vibrant appearance (Carrillo-Lopez *et al*., 2021). It has also been documented that HIU could cause denaturation of proteins in pasteurised milk (Gregersen *et al*., 2019). The colour of milk is influenced by various factors, including the animal's diet, breed, and overall health (Azmi *et al*., 2019). Processing methods such as thermo-sonication can further affect milk colour by altering its physical structure, fat concentration, and light interaction properties (Mushtaq *et al*., 2023). During processing, cavitation may release compounds that impact the colour and overall characteristics of the milk product.

While HIU has demonstrated potential in maintaining the taste of milk by mitigating typical changes associated with pasteurisation, its acceptance in the dairy industry remains limited. There are concerns regarding the effects of HIU on enzymes and the overall sensory quality of milk (Van Hekken *et al*., 2019). It is noteworthy that over a decade ago, it was established that ultrasonication did not enhance the shelf life of milk products, a finding that remains relevant today (Carrillo-Lopez *et al*., 2021). Additionally, reports have indicated the emergence of off-flavours in milk processed with HIU, which some attribute to changes in protein structure (Nguyen and Anema, 2017). Others suggest that these unusual tastes may arise from alterations in physical properties, degradation of components due to cavitation-induced heating, and the oxidation of compounds such as polyunsaturated fatty acid (PUFA) hydroperoxides, leading to the formation of volatile substances in sonicated milk (Majid *et al*., 2015).

Microfluidisation method

Nanoemulsions are utilised as delivery systems due to their clear visibility, long-term stability, and improved absorption, which stem from their small particle size and high surface-to-volume ratio (Bai and McClements, 2016). Microfluidisation requires the use of specialised equipment that generates strong disruptive forces to blend substances on a larger scale (Abbas Syed, 2018). Nonetheless, microfluidisation has gained popularity in the food industry due to its flexibility and efficiency in producing nanoemulsions. With its powerful impact, it can produce small and uniform droplets, in contrast to low-energy approaches, which necessitate the use of additional surfactants, and may raise concerns regarding taste and health implications (Bai and McClements, 2016). Furthermore, microfluidisation is particularly advantageous in the beverage industry, where it addresses cloudiness issues while preserving essential compounds and nutrients (Abliz *et al*., 2021).

Some investigations have observed that particle size reduction occurred only at pressures below 100 MPa, whereas others have indicated that the reduction persisted even at pressures up to 150 MPa. A study by Sinaga *et al*. (2018) further investigated functions to predict the average diameter and size distribution of microfluidised fat globules in dairy model emulsions. They reported that particle sizes of 0.246 to 0.239 μm were achieved at set pressures of 12, 14, 16, and 18 kpsi (83, 97, 112, and 126 MPa) for a single cycle. The remaining sample from the first cycle was then subjected to additional passes in the second, third, and fourth cycles at 83, 97, and 126 MPa.

As illustrated in Figure 1(b), microfluidisation entails the collision of two rapidly moving microstreams, resulting in the fragmentation of larger particles into smaller ones, typically reducing them to nanoscale dimensions (Truong *et al*., 2016). This method employs a high-pressure positive displacement pump operating at very high pressures (up to 20,000 psi). Within this procedure, the pump plays a pivotal role in propelling macroemulsion droplets through an interaction chamber, meticulously constructed with a series of microchannels. As these macroemulsion droplets traverse these microchannels, they undergo rapid, high-velocity collisions within an impingement area, culminating in the creation of exceedingly fine nanoemulsions. The flexibility of this method allows for the achievement of a desired size range, and dispersion pattern by modulating operating pressure and the number of passes through the interaction chambers, akin to principles used in high-pressure homogenisation techniques.

Microfluidisation employs fundamental stages, including cavitation, shearing, and turbulence, like homogenisation. Nevertheless, its capacity to achieve consistent size under constant pressure proves notably efficient, surpassing high-pressure homogenisation (Hidajat *et al*., 2020). The effectiveness of this technique is significantly influenced by various factors, including operational pressure, fat content in the final product, and the quantity of emulsifier (Villalobos-Castillejos *et al.*, 2018). Consequently, it becomes imperative to identify the optimal conditions tailored to the specific operational environment to enhance overall performance.

High-pressure valve homogenisation method

High-Pressure Homogenisation (HPH) developing technologies are regularly investigated as potential replacements for established techniques of reducing the impact of heat on food components. The purpose is to ensure microbiological safety, preserve nutrients, retain sensory features, and, in certain situations, improve techno-functional aspects (Alves Filho *et al.*, 2020). This evolving landscape underscores the increasing relevance of HPH as a promising non-thermal technique with significant industrial applicability (Malik *et al.*, 2023). Recent advancements in HPH technology have focused on expanding its applications in food processing, including the ability to create larger emulsions, and adjust not only macromolecular aggregates, but also specific food ingredients (Mushtaq *et al.*, 2023).

HPH offers compelling opportunities for reorganising dietary proteins, thereby influencing protein structure and resulting in denaturation, gelation, or aggregation. This process ultimately contributes to the development of novel products with enhanced textures (Jiang *et al.*, 2022). As illustrated in Figure 1(c), high-pressure homogenisation is the most utilised method for fabricating nanoemulsions, particularly within the dairy sector. The transformation of large milk fat globules into smaller ones is achieved through the application of shear forces. During the high-pressure homogenisation process, the macroemulsion is forced through a small aperture at operational pressures ranging from 500 to 5,000 psi. Numerous forces act during this procedure, including hydraulic shear, vigorous turbulence, and cavitation, all of which synergistically contribute to producing nanoemulsions with exceedingly small droplet sizes.

Moreover, the efficiency of HPH in achieving desired droplet sizes is contingent upon several operational parameters, including pressure, number of passes, and temperature during processing. For instance, Ren *et al.* (2020) reported that after homogenisation at pressures of 20, 30, and 40 MPa, the particle size distribution of milk was reduced to between 0.4 μm and below 0.1 μm. Furthermore, should it be necessary, the processed product can undergo multiple rounds of high-pressure homogenisation until the desired droplet size is attained, thus enhancing the versatility of this method in food formulation.

High-pressure homogenisation is a relatively recent innovation that has gained widespread traction in the food industry. It possesses the ability to pasteurise, sterilise, and modify the structure of various dietary components, offering a multifunctional approach to food processing. Initially employed to improve the emulsification of products such as milk, HPH has seen significant advancements that extend its applicability across different food matrices. Emerging research continues to explore the potential of HPH in producing high-quality food products that retain nutritional and sensory attributes akin to those of fresh ingredients, thereby emphasising the need for further investigation into its long-term benefits and applications in food technology.

Low energy method

Nanoemulsions are defined as emulsions characterised by droplet sizes ranging from 20 to 500 nm (Azmi *et al.*, 2019). Due to their small droplet sizes, nanoemulsions exhibit remarkable stability against certain phenomena such as creaming or sedimentation. This inherent stability renders them particularly advantageous in various sectors, including beverages, cosmetics, agrochemicals, and pharmaceuticals, where they provide several benefits such as reduced production costs, enhanced stability, and improved product quality (Abliz *et al.*, 2021).

However, it is important to recognise that nanoemulsions function as nonequilibrium systems, necessitating an input of energy for their formation. Both high- and low-energy emulsification techniques may be employed in the production of nanoemulsions (Nantarat *et al.*, 2015). High-energy emulsification techniques, including high-pressure homogenisation and ultrasonication, utilise mechanical technologies that generate substantial disruptive forces, facilitating the dispersion of one phase into another as fine droplets (Ren *et al.*, 2020).

Recent advances in low-energy emulsification have introduced methods like phase inversion temperature (PIT) and spontaneous emulsification that improve how emulsions are made. The PIT method adjusts the temperature during emulsification, which changes the types of emulsions, and helps create smaller and more stable droplets (Abliz *et al*., 2021). Co-surfactants also help in this process by lowering the tension between oil and water, making it easier to form smaller droplets. This is especially useful for enhancing the effectiveness of ingredients in food and pharmaceutical products (Ozturk and Turasan, 2021). Using ionic liquids as surfactants is another promising development. They have low volatility and adjustable solubility, which help stabilise emulsions and are better for the environment (Chen *et al*., 2018). This could lead to more sustainable ways to produce nanoemulsions.

In conclusion, low-energy emulsification methods provide a cost-effective option compared to high-energy methods, allowing for better control over droplet size and stability. Ongoing research into these methods highlights their potential for improving the production of nanoemulsions for various uses (Figure 2).

Phase inversion temperature method

The Phase Inversion Temperature (PIT) method utilises the molecular phase penetration characteristics of surfactants, wherein the hydrophilic or lipophilic nature of the emulsifier changes in response to temperature fluctuations at a specific composition, as illustrated in Figure 2(a). At low temperatures, an O/W emulsion is formed, and the emulsifier's solubility in water diminishes as the temperature increases. In recent decades, the PIT

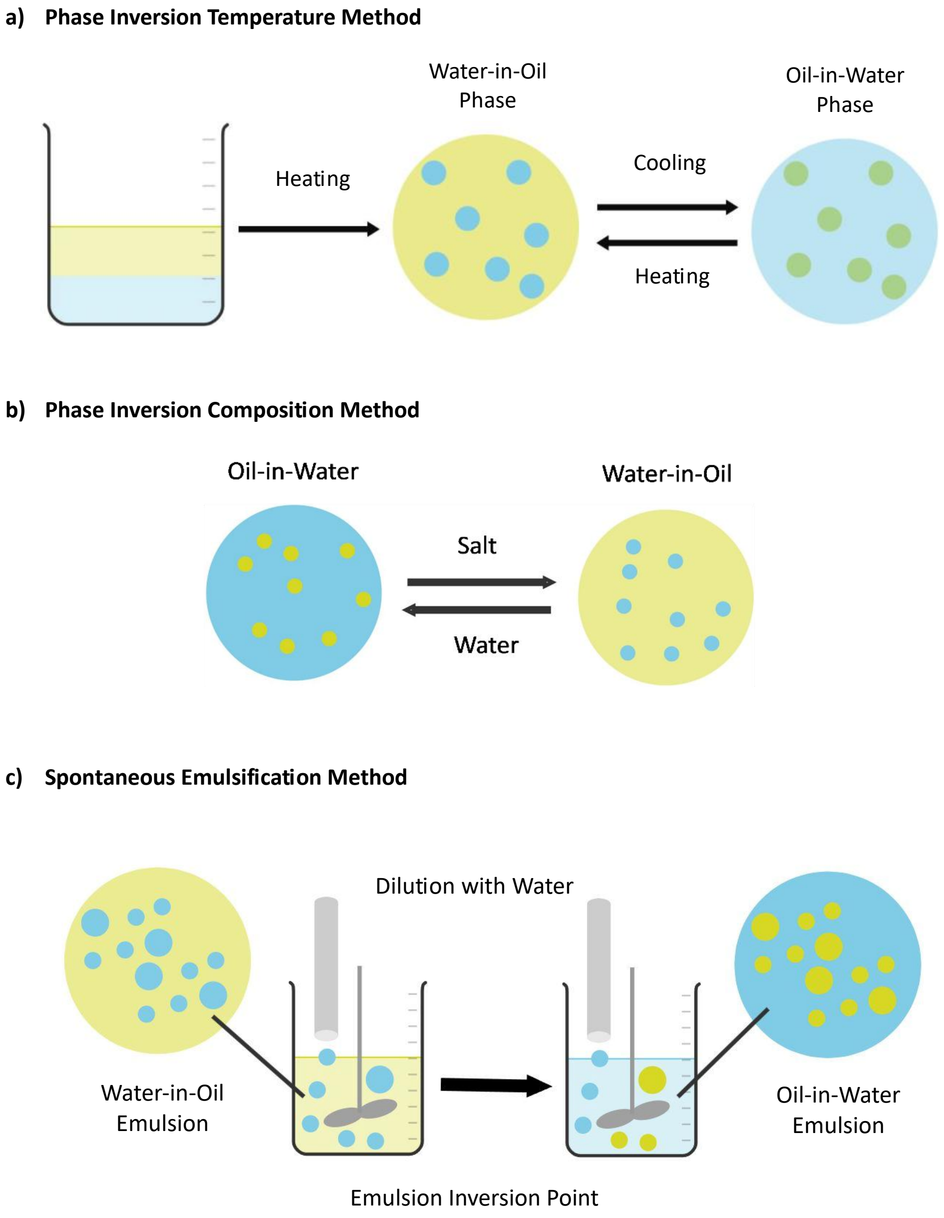


Figure 2. Low-energy methods for nanoemulsion formulation.

method has garnered significant attention compared to high-energy emulsification technologies due to its capability to produce smaller and more uniform droplets without the need for complex equipment. This simplicity makes it particularly appealing for applications involving heat-sensitive compounds (Solans and Solé, 2012).

Temperature plays a critical role in influencing the spontaneous curvature of the surfactant layer in the PIT method, especially for temperature-sensitive surfactants (Chuesiang *et al*., 2018). At lower temperatures, these surfactants dissolve in water, resulting in a positive curvature at the droplet interface. Conversely, at higher temperatures, surfactants become oil-soluble, leading to a negative curvature at the droplet interface (Van Hekken *et al*., 2019). At the PIT, surfactants exhibit equal preference for both aqueous and oleaginous phases, resulting in zero spontaneous curvature of the surfactant layer, which leads to total oil solubilisation in a bicontinuous or lamellar liquid crystalline phase (Abliz *et al*., 2021). Importantly, the oil-water interfacial tension (IFT) at the PIT is extremely low (10^{-5} to 10^{-2} mN/m), facilitating the formation of nanometre-sized droplets (Ren *et al*., 2019). Rapid cooling of samples to room temperature can yield kinetically stable O/W nanoemulsions (Ren *et al*., 2019).

While the PIT technique effectively harnesses the exceptionally low interfacial tensions at the PIT or HLB temperature to promote emulsification and the formation of tiny droplet sizes, the emulsions produced are often highly unstable, characterised by a rapid coalescence rate. The creation of kinetically stable O/W or W/O emulsions is enabled by quickly moving the system's temperature away from the PIT, either through abrupt cooling or heating (Meis *et al*., 2014). During this rapid cooling process, surfactant molecules migrate quickly from the oleaginous phase to the aqueous phase, resulting in the spontaneous generation of tiny oil droplets due to the increased interfacial area and turbulent flow generated (Ren *et al*., 2019).

Additionally, the PIT method allows for better control over droplet size and distribution, which is crucial for achieving the desired properties in nanoemulsions. The selection of surfactants and their concentration, along with the precise manipulation of temperature, are vital in optimising emulsion stability and quality. However, the effectiveness of the PIT method can be influenced by the specific formulation, surfactant system, and the conditions under which emulsification occurs (Chuesiang *et al*., 2018). The method also shows promise for large-scale production due to its simplicity and low energy requirements, making it an attractive alternative for industries seeking efficient emulsification techniques (Solans and Solé, 2012).

Phase inversion composition method

The phase inversion composition (PIC) method is a low-energy technique for preparing nanoemulsions by altering the oil-to-water ratio or surfactant concentration in each system. This approach modifies the chemical composition, leading to changes in the hydrophilic-lipophilic behaviour of the emulsifier. When salt is introduced into an O/W emulsion featuring an ionic emulsifier, the electrical charge of the surfactant shifts, resulting in the transformation of the emulsion into a W/O variant (Sousa *et al*., 2022). Conversely, a W/O emulsion with a significant salt concentration can be converted into an O/W emulsion by diluting it with water (Liew *et al*., 2010), as illustrated in Figure 2(b). This transformation occurs because the added water weakens the stability of the water droplets suspended in the oleaginous phase, prompting them to merge and create an O/W emulsion.

This process is cost-effective as it requires minimal energy and eliminates the need for organic solvents, resulting in a high level of thermodynamic stability (Perazzo *et al*., 2015). The PIC technique is frequently employed to produce food-grade nanoemulsions, particularly those with elevated vitamin E acetate content, yielding an average particle size of 0.04 µm. Although this approach can produce nanoemulsions with higher surfactant concentrations compared to methods like microfluidisation, it often does not use surfactants compatible with labelling requirements (Mayer *et al*., 2013).

Furthermore, compared to the PIT method, manufacturing nanoemulsions using the PIC method presents additional hurdles. This is primarily due to the necessity of chilling a larger sample volume in a more extensive tank, whereas the PIT method utilises a faster cooling procedure with smaller volumes in test tubes immersed in ice (Solè *et al*., 2010).

Additionally, regardless of batch size, the PIC method necessitates careful consideration of factors such as mixing and additional rates to achieve appropriate phase transitions. Maintaining stable geometric ratios and form factors is critical when working with larger scales. This method operates under the assumption of constant fluid properties, including diffusivities, density, and viscosity. Under these conditions, if the two systems (small and large batches) are geometrically equal, they may be characterised by a dimensional connection, independent of scale (Vauthier and Ponchel, 2016).

Nevertheless, the PIC method has certain advantages. It is particularly suited for producing smaller droplets, achieving sizes as small as 0.03 µm (Nantarat *et al*., 2015). The simplicity and cost-effectiveness of the PIC method make it an attractive option for industrial applications, although the need for careful optimisation of formulation parameters remains a consideration. This method also offers flexibility in terms of ingredient selection, enabling the use of various surfactants and oils, which can be tailored to meet specific product requirements.

In summary, while the PIC method offers several benefits, including cost-effectiveness and ease of use, it requires careful control of processing conditions to ensure reproducibility and stability of the resulting nanoemulsions.

Spontaneous emulsification method

Methods of self-emulsification, or spontaneous emulsification, harness the chemical energy released during a dilution process within a continuous phase, typically conducted at a constant temperature. Crucially, this method does not involve phase transitions, ensuring that the surfactant's spontaneous curvature remains unchanged throughout the emulsification process (Mushtaq *et al*., 2023). This stability in curvature is essential for achieving consistent emulsion characteristics.

As illustrated in Figure 2(c), during the dilution process, water-miscible components including solvents, surfactants, and co-surfactants from the organic phase diffuse into the aqueous phase (Gawin-Mikołajewicz *et al*., 2021). This transformation is specifically designed to create O/W nanoemulsions, leading to a significant expansion of the interfacial area, and resulting in a metastable emulsion state. The typical setup involves preparing two distinct phases, namely a hydrophilic aqueous phase containing surfactants, and an organic or oleaginous phase that includes the active ingredients, an oil-soluble surfactant, and a partially water-miscible organic solvent (*e.g.*, acetone or ethyl acetate). The organic phase is introduced drop by drop into the agitated aqueous phase, thereby forming small nanoscale emulsions. Conversely, for W/O emulsions, the reverse procedure by adding water to oil is also feasible.

New findings suggest that the characteristics of the emulsions can be significantly influenced by the selection and concentration of surfactants, the type of oil used, and the specific emulsification conditions, including temperature and mixing speed (Perazzo *et al*., 2015). These factors interact dynamically during the emulsification process, and can lead to variations in the final droplet size and stability. Additionally, the role of co-surfactants has gained attention, as they can enhance the efficiency of emulsification by modifying the interfacial properties, thereby promoting smaller droplet formation and improved stability of the nanoemulsions (Zhou *et al*., 2021). The inherent physical and chemical properties of surfactants and the oily components are critical, and these properties can be easily expanded upon in energy-efficient procedures. While high-energy methods can effectively control the size distribution and content of nanoemulsions through mechanical devices, it is important to note that such methods may lead to the degradation of sensitive components, and that the manufacturing processes may not be readily scalable (Aswathanarayan and Vittal, 2019).

Spontaneous emulsification is commonly employed to produce vitamin E acetate nanoemulsions with droplet sizes measuring around 0.05 µm, and exhibiting low polydispersity indices. To achieve finer droplets, it is essential to fine-tune the composition of the oleaginous phase and the surfactant-to-emulsion ratio. The introduction of the oil/surfactant mixture to water, combined with an increase in temperature and stirring speed, has been shown to effectively reduce particle size (Sarheed *et al*., 2020). Moreover, the process is inherently advantageous as it often requires less energy input compared to high-energy emulsification methods, making it more suitable for scaling up in industrial applications.

In summary, spontaneous emulsification offers a versatile and energy-efficient approach for producing stable nanoemulsions, provided that the formulation parameters and emulsification conditions are carefully optimised.

Physical characteristics of nanoemulsion

Table 2 shows the milk properties.

Particle size

Milk is homogenised to extend its shelf life. This technique yields fat globules that are homogeneous in size and shape. The homogenisation process reduces the size variation of fat globules in unprocessed milk, shrinking them from a range of 0.1 - 15 µm to a more uniform size of 1 - 2 µm in homogenised milk (Malvern Panalytical, 2020). These tinier droplets are unable to amalgamate into sufficiently sizable groups to facilitate cream separation, thereby prolonging the milk's storage duration. The creaming procedure is controlled by Stokes' Law and the differing densities between the fat and other liquid constituents of the milk. Additionally, the particle size of fat globules significantly influences the sensory attributes of dairy products, impacting texture, mouthfeel, flavour release, and overall consumer acceptability. Smaller fat globules contribute to a creamier and smoother texture, which is particularly important in products like milk, cream, and yogurt. Homogenised milk with fat globules reduced to sizes between 1 and 2 µm exhibits improved creaminess compared to raw milk, where fat globules can be as large as 5.5 µm (Sun *et al*., 2022). This increase in creaminess enhances the overall mouthfeel, making the product more palatable.

To determine the size of the particles, a laser diffraction analyser is commonly utilised. Changes in fat content may also be detected using laser diffraction. The particle size distribution of full milk (about 3.6% fat), 2% milk, 1% milk, and fat-free milk shrinks progressively when fat is eliminated (Rehm *et al*., 2015). Since fat-free milk lacks emulsified fat globules, the distribution is predominantly made up of protein caseins, which account for approximately 82% of milk protein. Furthermore, smaller fat globules allow for a more even distribution of flavour compounds, enhancing flavour delivery. For instance, Truong *et al*. (2016) found that a reduction in particle size resulted in a smoother mouthfeel, while Lakkis (2016) showed that smaller fat globules promoted better encapsulation and transport of flavour molecules, leading to a more intense flavour perception. Additionally, smaller droplets are associated with improved aroma release, where Ho *et al*. (2021) discovered that milk with smaller fat globules had a more pronounced aroma, further enhancing flavour profiles.

Table 2. Milk properties.

Sample	**Fat content (%)**	**Protein content (%)**	**Temperature (°C)**	**Droplet size (µm)**	**Viscosity**	**Reference**
Full cream milk powder	28.40	24.0	-	1.10, 1.20, 1.30, and 1.70	Not significant enough	Goh *et al*. (2021)
Raw milk	3.50	3.3	40	0.8,0 2.60, 3.70, 4.70, and 5.50	Increase with fat globules increase	Ho *et al*. (2021)
Raw milk	4.50	-	40	0.20, 0.28, and 0.32	No significant change	Astráin-Redín *et al*. (2023)
Anhydrous milk fat	99.92	80.0 (whey) and 92.6 (sodium caseinate)	55 - 60	0.20, 0.60, and 1.20	High (reduction of emulsion droplet size)	Truong *et al*. (2014)
Raw milk	37.00	-	85	0.74, 1.06, 1.07, 1.06, 1.09, 1.10, 2.08, and 2.97	-	Hatakeyama *et al*. (2019)
Anhydrous milk fat	36.00	2.3	-	0.16 and 0.12	Greater with decreasing particle sizes	Chen *et al*. (2016)

Milk particle size affects its microstructure, and determines its shelf life, flavour, and mouth feel. During the homogenisation process, the presence of particles spanning from 0.2 to 2 μm in size is a crucial quality characteristic for fat globules (Lakkis, 2016). Clumping caused by protein bridging or creaming due to undispersed fat globules may occur if the homogenisation process is not well regulated. These problems can also be seen in many other commercially accessible milk products. The stability of dairy emulsions is also influenced by particle size, with smaller fat droplets being less prone to coalescence and cream separation, which maintains the product sensory attributes over time. Rehm *et al*. (2015) reported that preventing cream separation not only extends shelf life but also keeps flavour and texture consistent, leading to higher consumer perception of quality. As a result, laser diffraction to assess particle size in milk is a suitable device for quality control.

Viscosity

Viscosity in a liquid indicates its resistance to flow, representing the internal friction within the fluid. Higher viscosity arises from the molecular arrangement within a liquid, impeding its motion, while lower viscosity signifies smoother movement due to reduced molecular resistance. According to Ho *et al*. (2021), milk samples exhibited increased viscosity with larger fat droplet sizes. Applying greater homogenisation pressure during milk processing resulted in smaller fat droplets, and elevated milk viscosity (Truong *et al*., 2016). The augmented viscosity in homogenised milk arises from the presence of numerous tiny fat droplets, and clusters of casein molecules adhering to these fat droplets' surfaces (Trujillo *et al*., 2016).

In milk with larger fat droplets, there are fewer fat droplets in samples with the same fat content (adjusted to 3.5% fat using skimmed milk). The fat in milk can exist as a combination of liquid fat and solid crystals with sharp edges and corners when the temperature is below 40°C (Wright and Marangoni, 2006). When viscosity is measured under conditions with significant shear force, larger fat droplets can sometimes rupture their membranes, releasing liquid fat. This leads to the aggregation of neighbouring fat droplets, likely contributing to the increased viscosity observed in milk samples containing larger fat droplets. Smaller fat droplets demonstrate greater resistance to membrane rupture (Ménard *et al*., 2010).

Based on Table 2, the size of the milk fat globules also influences the viscosity of milk and dairy emulsions. The viscosity of homogenised milk increases as the homogenising pressure increases. When milk was homogenised from 70 to 245 bar, the viscosity increased from 7.1 to 15.0% (Kielczewska *et al*., 2003). Reducing the size of fat globules in emulsions has been observed (seemingly) to lead to a minor increase in viscosity (Kielczewska *et al*., 2003; Long *et al*., 2012; Truong *et al*., 2014). In the case of 3.3% fat milk, decreasing the droplet size from 2.7 to 1.0 μm resulted in higher levels of viscosity, ranging from 1.8 to 1.96 mPa/s (Kielczewska *et al*., 2003). Smaller fat droplets lead to a more stable emulsion with higher viscosity, which contributes to a richer mouthfeel and a creamier texture that consumers often prefer.

Emulsions containing 10 to 36% milk fat, with a notably narrower size range of 0.2 - 1.3 μm, displayed similar traits. When the emulsion size was reduced from 1.2 to 0.2 μm under a shear rate of 5.6 s^{-1}, the apparent viscosities of these dairy-based emulsions increased within the range of 8 - 15 mPa/s (Truong *et al*., 2014). Long *et al*. (2012) identified that in high-fat emulsions, the smaller-sized emulsion (0.415 μm) exhibited a higher apparent viscosity (0.852 Pa/s) compared to the larger-sized one (1.291 μm; 0.398 Pa/s) containing 36% milk fat. A narrower distribution of sizes and reduced size of milk fat globules may contribute to heightened emulsion viscosity in both milk and dairy emulsions, owing to improved colloidal repulsion and closely packed uniform particles (Jain *et al*., 2019). Conversely, if the particle size of fat globules is reduced excessively, the viscosity may reach a level that disrupts the desirable sensory experience, leading to a watery texture that detracts from the expected creaminess. Maintaining an optimal viscosity through controlled processing conditions ensures that dairy products deliver a satisfying and enjoyable sensory experience.

Turbidity

It is commonly understood that homogenisation alters the look of milk. The breaking up of the fat globules allows them to scatter light, giving the milk an opaque appearance. Increased turbidity can lead to a perception of cloudiness, which may affect consumer acceptability. It has been discovered that diluting milk to the range of turbidity that can be detected in a photoelectric colorimeter can provide a rough estimate of the total solids. The turbidity per unit concentration of total solids varies with the fat content of the milk as well as the effectiveness of homogenisation, since the fat phase accounts for approximately three quarters of the overall turbidity. Larger fat globules contribute more to turbidity due to their higher scattering potential. The turbidity of the fat globules per unit concentration of fat has been demonstrated to be strongly linked to the particle size distribution after the turbidity owing to the non-fat fraction of the milk, which has been decreased to a minimal amount by the addition of ammonia.

When the particle size in dairy products is decreased, several changes occur. Smaller fat globules lead to a more stable emulsion, which can decrease turbidity levels. This decrease enhances the visual quality of products, making them appear more refined and desirable. It has been noted that homogenisation reduced fat globule size, leading to lower turbidity levels in the final product (Kielczewska *et al*., 2003). Moreover, smaller particles can improve the mouthfeel of dairy products, contributing to a smoother texture typically preferred by consumers. For instance, Ménard *et al*. (2010) reported that homogenised milk with reduced fat globule size produced a creamier mouthfeel and better overall sensory acceptance compared to non-homogenised counterparts.

However, excessive decrease in particle size can lead to unintended consequences, such as increased opacity or a milky appearance that some consumers may find unappealing. If the fat globule size is decreased too much, it can result in a watery or thin consistency that diminishes the richness expected in products like yogurt or cheese (Long *et al*., 2012). Furthermore, turbidity plays a significant role in how flavours are perceived. In dairy products, a clearer appearance often correlates with a more intense flavour experience, as turbidity can interfere with the release of volatile compounds responsible for flavour. By maintaining the right balance of particle size and turbidity, manufacturers can enhance sensory attributes, and improve consumer satisfaction.

In conclusion, it was suggested that the fat content of milk might be estimated by a turbidimetric method; however, they must assume a constant particle size distribution (Jain and Sarma, 2015). This highlights the importance of managing turbidity through appropriate processing techniques, such as homogenisation, to significantly enhance the sensory attributes of dairy products while ensuring stability and shelf life.

Foaming techniques

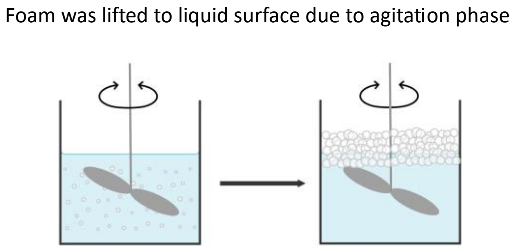
Theoretically, an action that introduces gas (air) into the bulk of milk can be used to create foam by shaking, pouring, bubbling / sparkling, mixing, agitating, supersaturating, whipping, or beating (Ho *et al*., 2022). In most coffee shops, the frothy milk topping is produced by directly injecting steam. However, this foaming technique needs practical experience due to it being hard to control, and may cause overheating of the foaming milk. There are other techniques that can be utilised to create foam such as mechanical mixing and air injection (Figure 3).

Mechanical mixing methods

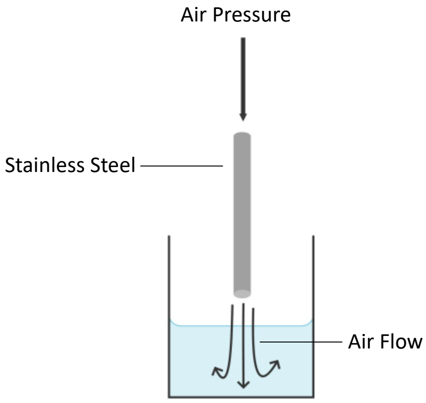
Mechanical mixing methods are widely employed in both domestic and industrial applications for producing foams through processes such as stirring, whipping, or beating. These methods involve the transfer of mechanical energy to the interface between gas and liquid, resulting in the formation of bubbles. Xiong *et al*. (2020) reported that mechanical mixing is a traditional technique utilised in the production of whipped cream, ice cream, and other dairy-based products. For instance, in commercial ice cream production, controlled mechanical agitation during the freezing process is essential for ensuring uniform air incorporation, which significantly contributes to the texture and volume of the final product (Huppertz, 2010). This consistency is critical for meeting consumer expectations and regulatory standards in the food industry.

In domestic applications, compact milk-whisking devices are commonly employed for frothing milk, while industrial contexts utilise high-shear mixers and blenders during the reconstitution of milk powders for products like infant formula and recombined milk. Such mixing techniques are integral to achieving the desired foam characteristics that enhance the sensory attributes of dairy products (Hatakeyama *et al*., 2019). Moreover, kitchen mixers are also used in scientific research to explore milk

a) Mechanical mixing



b) Air injection



c) Steam injection

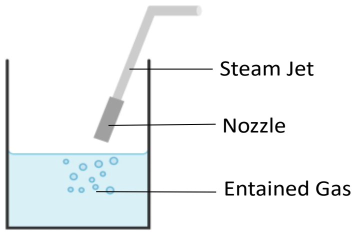


Figure 3. Foam production methods.

foam properties, with key factors influencing foam quality including the force and duration of agitation as well as the milk's temperature.

Despite their widespread use, mechanical mixing methods tend to produce inconsistent foam quality, which is a challenge in commercial applications. Variability in parameters such as mixing intensity and duration can lead to disparities in foam characteristics, which poses significant challenges for large-scale production where uniformity is critical (Ho *et al*., 2019). For example, overmixing can result in the formation of larger bubbles, thereby reducing foam stability, while undermixing may lead to inadequate foam formation. These inconsistencies highlight the difficulty in achieving optimal mixing conditions, particularly in high-volume operations where time efficiency is also a concern (Liu *et al*., 2017). Additionally, mechanical mixing methods are often slower compared to alternative foaming techniques, which may limit their scalability in high-demand environments.

In conclusion, while mechanical mixing methods are foundational in the production of dairy foams, addressing the challenges associated with foam consistency and efficiency remains crucial for enhancing the quality of dairy products in both domestic and industrial applications.

Air injection method

Cold milk aeration, or air injection, involves introducing air or another gas into milk at temperatures close to room temperature, resulting in the formation of milk foam. This process is typically achieved by infusing air through devices like stainless-steel air stones or porous surfaces such as sintered glass, which create stable, small air bubbles due to the surface-active components in milk (Long *et al*., 2012). While cold aeration is not widely applied in commercial milk processing, it is frequently used in scientific studies for its simplicity and adaptability.

In industrial applications, this technique has found successful application in automatic milk frothers used in coffee machines, which produce consistent foam for beverages like lattes and cappuccinos. The ability to create uniform foam is essential in the coffee industry, as it directly impacts the sensory attributes of the final product. For example, Deng *et al*. (2019) highlighted that the quality of micro-foam significantly influences consumer preference and overall beverage experience. Moreover, cold aeration is employed in some specialised milk processing plants where foam generation is essential for certain dairy-based products, such as whipped milk toppings and flavoured milk beverages.

Key variables that influence foaming during cold aeration include the duration of aeration, gas pressure, and milk temperature. However, in commercial use, controlling bubble size and uniformity remains a challenge. Inconsistent air injection can result in weak or uneven foam, which can negatively affect product quality and customer satisfaction. Foam stability is also highly dependent on the surface-active properties of milk, which vary with fat and protein contents. When fat content is high, foam may collapse more rapidly, leading to a decrease in the desired foaming characteristics of dairy products.

Furthermore, integrating air injection into large-scale production lines requires sophisticated equipment capable of controlling factors, such as gas pressure and temperature, which increases both operational complexity and costs. Despite these challenges, air injection remains an effective method for producing foam with smaller and more uniform bubbles, making it suitable for use in both cafés and industrial plants. The precision of equipment is critical to ensure foam consistency, as discrepancies can lead to variability in product quality, ultimately impacting consumer loyalty and market competitiveness.

Steam injection method

Steam infusion involves generating milk froth by introducing steam through a nozzle, which creates frothy bubbles while simultaneously increasing the milk's temperature. Unlike cold aeration, which only introduces air, steam infusion also heats the milk substantially. For example, as measured by Langevin (2023), steam infusion for 50 sec can raise milk temperatures above 85°C, though the froth itself does not exceed 65°C and cools to 50°C within 4 min. This method is widely used in coffee shops to create barista-style froths for beverages like lattes and cappuccinos, where steam wands are used to add both air and heat. In addition to manual use, automatic steam injection systems are common in large commercial coffee machines, allowing for consistent and automated frothing in high-volume environments.

However, steam injection presents several challenges, particularly in commercial applications. It requires skilled operators to manage the temperature and duration, as overheating can scald the milk, and compromise foam texture. While steam infusion works well for whole milk, the lower fat content in skim milk often leads to weaker foam stability. Additionally, commercial steam injection systems can be expensive to install and maintain, with variations in steam pressure or nozzle design leading to inconsistent foam quality across machines. Despite these hurdles, steam injection remains the preferred method for creating stable and creamy foam in both cafés and industrial beverage production. However, balancing temperature control and foam quality remains a key challenge, particularly when using skim milk or scaling the process for larger operations.

Foaming properties

Table 3 shows the comparison of foamability and foam stability of different types of milk.

Foamability and foam stability

Foamability pertains to the tendency of milk to create foam, and can be most conveniently gauged by the amount of foam generated from a set quantity of milk. Evaluations of foamability can be conducted using graduated cylinders, where the foam's volume is determined by subtracting the liquid volume beneath the foam from the total sample column volume. The capacity of foam to maintain its volume over time and under storage conditions is termed foam stability. Assessing foam stability is most straightforward by determining foam volume as a function of storage duration within specified

Table 3. Comparison of foamability and foam stability of different types of milk.

Sample	Foaming Technique	Foamability	Foam Stability	Foam Structure	Reference
Full cream milk powder	Mechanical Mixing	Increased due to increasing speed	Significantly improved with reduction of particle size	More uniform size on smaller particle size	Goh *et al*. (2021)
Pasteurised whole milk, skim milk	Steam Injection, Air Injection, Mechanical Mixing	Increased with fat globules increase	Slightly affected	Smaller size of air bubbles depending on the foaming techniques	Ho *et al*. (2019)
Pasteurised whole milk	Steam Injection, Mechanical Mixing	Increased with fat globules decrease	Increased with decreasing fat globules but smallest fat easily destable the foam	Smaller size of air bubbles depending on the foaming techniques. Nanofoamer showed better foam	Maklin *et al*. (2025)
Anhydrous milk	Mechanical Mixing	Increased based on emulsifier used	Foam collapsed easily with smaller particle size	-	Truong *et al*. (2014)
Raw milk	Air Injection	-	Increased with decreasing fat globules size	Smaller air bubble with decreasing fat globules size	Hatakeyama *et al*. (2019)
Raw milk	Steam Injection, Mechanical Mixing	Increased with decreasing fat globule sizes	Decreased with increasing fat globule size	Average size of air bubbles in foam increased with an increase in the particle size	Ho *et al*. (2021)
Skim milk powder	Air Injection	-	Advantageous in larger colloidal particles	Smaller air bubbles at decreasing particle size	Chen *et al*. (2016)

conditions. The term "foam half-life" which indicates the duration for the foam to diminish to half of its initial size, is frequently applied when working with water and oil combined with an emulsifying agent under specific temperature conditions. Delicate magnetic stirring facilitates the emulsifying agent's penetration into the aqueous phase, leading to an expansion of the oil-water boundary, and resulting in the formation of tiny oil droplets (Aswathanarayan and Vittal, 2019). However, one drawback of this approach lies in its extensive reliance on high quantities of artificial surfactants, which pose economic challenges, and raise regulatory and sensory concerns within the food industry.

Based on Table 2, most research shows improvements in foamability and foam stability with decreasing particle sizes depending on the foaming techniques employed. The formation of bubbles in milk is affected by two primary factors: the way air is incorporated into the milk, and the circumstances involved in creating froth. These elements have a direct effect on the inherent characteristics of milk and its constituents, such as milk fat, surface-active agents, and proteins (Ho *et al*., 2023). The techniques of mechanical mixing, air injection, and steam injection are employed to assess the ability to create foam, and the durability of the foam. In terms of mechanical mixing, a reduction in fat globule size significantly improved foamability, particularly for milk fat with smaller fat globule sizes (less than 0.8 µm) (Ho *et al*., 2021). In contrast, while the foamability differences for air and steam injections are less pronounced compared to mechanical mixing, smaller fat globule sizes still enhance foamability. Foam stability was quantified by measuring the percentage reduction in foam volume following a 10-min period of destabilisation at room temperature (25°C); a greater value indicates a lower level of foam stability.

For mechanical mixing, milk foam with smaller fat globules is more stable, and foam stability decreases as fat globule size increases. However, the foam stability of milk samples remained nearly constant across the fat globule size range of 2.6 to 5.5 µm (Ho *et al*., 2021). In the context of steam injection, fat particle dimensions did not impact foam durability, as the reduction in foam volume remained consistent at approximately 50% across all milk samples. The foam's ability to form is determined by how quickly substances like fats and proteins, acting as surfactants, move to the interface between air and liquid. Meanwhile, the characteristics of the layers that form at this interface are responsible for sustaining foam stability (Xiong *et al*., 2020). Small fat droplets disperse and adhere to the surface more swiftly than larger ones, leading to increased foam-forming ability. Conversely, larger fat droplets are incapable of engaging with each other to create a robust, stretchable absorbed layer that might hinder protein interactions between molecules. Consequently, the presence of these larger fat droplets undermines the structural integrity, unity, and rheological characteristics of the interfacial films.

Emerging methods such as shearing techniques—namely ultra-turraxing, homogenisation, and microfluidisation—improve foamability and foam stability compared to raw milk. Among these methods, microfluidised milk demonstrates the best performance, followed by homogenised milk (Ho *et al*., 2023). Smaller fat globules and modifications in the milk fat globule membrane due to shearing contribute to these improvements. Moreover, shearing increases viscosity, which slows down foam destabilisation. Surface tension plays a role, but other components like fats and proteins also influence foam quality. Specifically, homogenised milk with smaller fat globules shows enhanced foam stability compared to milk containing native fat globules of similar size. This difference in stability is due to the surface properties of the fat globules; in homogenised milk, the fat globule surface is stabilised by casein micelles and whey proteins, making it more resistant to disruption (Obeid *et al*., 2019). Earlier investigations on homogenised milk have also shown that reducing particle size through homogenisation significantly increases foamability and foam stability (Vogelsang-O'Dwyer *et al*., 2022). However, the effects may vary depending on the foaming method used, such as air injection foaming *versus* mechanical mixing and steam injection foaming.

Additionally, the incorporation of nanoemulsions into milk systems has been shown to significantly enhance foam properties. Studies indicate that nanoemulsions, due to their decreased droplet size and increased surface area, can improve the distribution of surface-active agents at the air-liquid interface, thus promoting foam stability. The presence of these nanoemulsions allows for a more uniform and stable foam structure, as they can effectively decrease the coalescence of larger bubbles, and enhance the mechanical strength of the foam films (Mushtaq *et al*., 2023). This advancement suggests that incorporating nanoemulsions can be a valuable strategy for optimising foam quality in various milk-based products.

Overall, the findings highlight the importance of shearing methods, nanoemulsion technology, and milk properties in achieving better foam quality. They contribute to our understanding of how to optimise foam formation and stability for various milk-based products, thereby enhancing their quality and consumer appeal.

Foaming structure

The bubble structure plays a crucial role in assessing milk foam in two main aspects. First, customers generally prefer small-pore, uniform milk foam as it directly impacts on their satisfaction. Second, the stability of the foam depends on the size and distribution of the bubbles. The process of Ostwald ripening, influenced by pressure differences between large and small foam bubbles, causes the number of small bubbles to decrease over time while larger bubbles grow. A lower pressure differential between the bubbles results in slower Ostwald ripening, and a more uniform foam.

According to Ho *et al*. (2021), mechanical mixing for foam production posed limitations in directly imaging the foam surface within the foaming container. To visualise the foam, it must be poured into a suitable container, leading the study to focus on the image analysis of foam produced through the steam injection method. The observed foam exhibited a polyhedral shape, consistent size, and well-defined lamellae. The analysis was conducted at two time points, *t* = 0 and after 10 min of instability. At *t* = 0, the average size of air bubbles in the foam increased with the size of fat globules. Lowering the fat globule size through increased homogenisation pressure resulted in smaller air bubbles. However, after 10 min of destabilisation, the foam with smaller fat globules showed an increase in the average size of air bubbles.

Moreover, the incorporation of nanoemulsions significantly enhances foam stability by providing a more uniform distribution of smaller droplets, which effectively stabilises the air-liquid interface. This stabilisation reduces the occurrence of coalescence and drainage, ultimately leading to improved foam structure and longevity. Studies have shown that nanoemulsions can reduce bubble size, and improve the texture and mouthfeel of dairy products, making them more appealing to consumers (Aliabbasi and Emam-Djomeh, 2024). The study also found that the milk foam with polyhedral air bubbles underwent destabilisation due to liquid film drainage and air bubble coalescence, transforming from spherical to polyhedral shapes. Comparing raw milk with shearing-treated milk samples (ultra-turraxed, homogenised, and microfluidised) during destabilisation at *t* = 0 and 10 min, shearing actions significantly reduced the size of air bubbles in the foam. Table 2 shows that the air bubble size depends on the particle size of the milk, indicating that decreasing particle size yields more homogeneous air bubble sizes. Homogenisation and microfluidisation were particularly effective in reducing air bubble size, resulting in very narrow size distribution curves.

During the disruption phase, the liquid within the foam layer drained, leading to the merging and uneven distribution of air pockets, thus resulting in larger air bubbles (Deng *et al*., 2019). Conversely, in foams with substantial fat globule sizes, including the control group, the mean size and distribution of air bubbles remained fundamentally unaltered compared to the initial measurement at *t* = 0. This resemblance can be attributed to foam instability, where significant air bubbles condensed into smaller ones while the original small bubbles expanded. Moreover, during the foaming process, sizable air bubbles spontaneously materialised and disintegrated once the milk's temperature reached the range of 30 - 35°C, potentially impacting the disruption of air bubbles within the foam.

Foam application

Introducing bubbles into food reduces the product's thickness. Although it adds a decorative touch, aeration could elevate the chances of oxidation in beverages. The presence of air trapped within the liquid over time can lead to spoilage and a decline in taste quality (Deotale *et al*., 2023). Consequently, it is crucial to exercise utmost caution during the aeration process, subsequent handling, and storage.

Frozen dessert, known as ice cream, enjoys widespread popularity across all age groups. It comprises milk proteins, complex carbohydrates, salt, ice crystals, and tiny air pockets. Reports suggest that air can make up as much as 50% of its volume, with a minimum requirement of 10 - 15% (Deng *et al*., 2019). Infusion of air within this emulsified mixture yields a consistent gas content and a delightful mouthfeel. Simultaneously, such an aerated product boasts superior texture and aesthetics, which naturally attracts consumers, and boosts the demand for aerated products (Deotale *et al*., 2020).

In the beverage industry, foaming creamers have become a swift solution for generating enduring froth in drinks like cappuccino and hot chocolate. Undoubtedly, the incorporation of proteins, emulsifiers, or surface-active substances enhances the foam stability in these beverages (Deotale *et al*., 2023). Moreover, there is growing interest among consumers in instant foaming or long-lasting foam in their drinks. Currently, there is a burgeoning trend in the beverage industry with ready-to-use reconstitutable powders that facilitate the creation of highly foamy drinks with just water. These frothy concoctions are far more appealing to consumers when compared to non-aerated alternatives.

The incorporation of nanoemulsions into foam applications has emerged as a promising approach for enhancing foam stability and texture. Studies have indicated that nanoemulsions can create smaller and more uniform air bubbles within foams, resulting in improved foam quality and longevity. By using nanoemulsions, manufacturers can reduce the reliance on conventional emulsifiers, achieving desired sensory attributes while also enhancing the nutritional profile of the products (Arboleya *et al*., 2014). Furthermore, nanoemulsions can provide better encapsulation of flavours and bioactive compounds, contributing to the overall appeal of the foam products.

Foams hold the promise of substituting several items linked to obesity, like fats, as they primarily function as enhancers of flavour and perception. In recent times, producers have taken note of this issue, and endeavoured to craft healthier, more delightful, and more nourishing beverages (Arboleya *et al*., 2014). The entrapment of huge quantities of air in the guise of water or steam could potentially diminish the caloric content of food. To lower fat content while preserving sensory attributes, numerous food matrices encase substantial quantities of water in gel form (Yiu *et al*., 2023). In line with the authors' viewpoint, aeration plays a pivotal role in crafting specialised beverages that are aligned with consumers' sensory expectations in terms of appearance, taste, and texture. As food foams or bubbles significantly influence consumer perception, the significant role of foams in the life cycle of products is now widely recognised. Consequently, the formation of foam procedures might be crucial towards developing this field.

Conclusion

Nanoemulsions hold immense promise for a variety of industries, including food, cosmetics, and pharmaceuticals, due to their specific features and superior stability over traditional emulsions. Choosing an appropriate technique and enhancing the conditions for improved nanoemulsion stability will assist in the growth of these products and their widespread use in beverage, food, and pharmaceutical industries depending on their individual requirements. Nanoemulsions are deemed as one of the most promising approaches for enhancing the solubility, functionality, and bioavailability of non-polar bioactive compounds, thus encouraging their usage in systems for the delivery of drugs. The present review examines the concept of nanodispersions and the techniques used to create them. The goal of the present review is to learn more about approaches to associate technologies with physicochemical characteristics. Different foaming techniques resulted in foam with varying qualities. While the air and mechanical mixing methods are inefficient in producing foam from milk as they produce the tiniest air bubbles, the steam injection foaming technique produces the most stable foam.

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