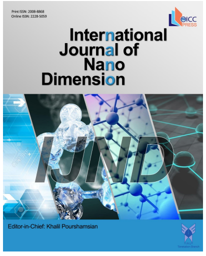

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Original Research

Recent Advances in Employing Nanoemulsions in Food Science: An Update

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Abstract:

Recent advancements in nanoemulsion technology have profoundly influenced the food industry, providing innovative approaches to enhance food product quality, stability, and functionality. Nanoemulsions (20 – 200 nm) exhibit distinct physicochemical characteristics, such as a large surface area, controlled release of bioactive compounds, high loading capacity, improved bioavailability, and biphasic behavior. This review explores the latest developments in nanoemulsion types, their components, and their applications across various food sectors, focusing on the properties they confer to food products and packaging systems. Particular attention is given to their ability to improve the bioavailability of poorly soluble nutrients, stabilize food formulations, and integrate natural preservatives to extend shelf life. The article also examines emerging trends, including the use of eco-friendly surfactants, encapsulation of plant-based bioactives, antioxidants, vitamins, and fatty acids, and their potential to enhance functional and fortified food products. Our review demonstrates that nanoemulsions significantly improve nutrient delivery, extending the shelf life of food products, and enhancing sensory characteristics. Furthermore, they offer promising avenues for sustainable packaging solutions. However, challenges related to long-term stability, regulatory approval, and consumer perception remain critical areas for future research. Furthermore, challenges like scalability, regulatory hurdles, and consumer acceptance are addressed. Based on this review, a comprehensive update on the current state of nanoemulsions in food science is essential, with a focus on establishing and refining specific standards to align with industry needs for healthier, safer, and more sustainable food systems.

Keywords: Biomaterial; Food matrix; Food packaging; Nanoemulsion; Polymer; Shelf life

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1. Introduction

Food science encompasses a wide-ranging scientific field utilized to gain a deeper comprehension and resolution of real-world issues within the intricate food system. The encompassing industry of food science involves disciplines such as biochemistry, chemistry, nutrition, microbiology, and engineering [1]. Central to food science is the examination of the fundamental composition of food, requiring scientists to grasp essential nutrition principles like carbohydrates, fats, proteins, and water to comprehend their interactions during processing or preservation. Within the field of food science, researchers delve into various processing and preservation techniques, including drying, freezing, pasteurizing, and canning, among others, to establish effective quality control measures [2]. An understanding of the microbiology and safety facets of food is also crucial for scientists in this field, who continuously strive to enhance their understanding of processing and preservation methods.

Additionally, professionals in the food science sector explore diverse areas such as food additives, flavor chemistry, product development, food engineering, and food packaging. Nanotechnology is one of the most important elements in developing food science [3].

The integration of nanotechnology with food, medical, and pharmaceutical industries has garnered considerable interest within the scientific community [4, 5]. Motivated by the escalating consumer preference for healthier and safer food options, as well as the necessity for edible systems capable of encapsulating, safeguarding, and releasing functional compounds, researchers are actively investigating nanotechnology to tackle pertinent issues related to food and nutrition [6]. Particularly suited for developing encapsulation systems for functional compounds, nanoemulsion technology plays a pivotal role in preventing compound degradation and enhancing bioavailability [7].

Nanoemulsions, characterized by small droplet sizes and kinetic stability as colloidal systems, exhibit superior functional attributes when compared to traditional emulsions. The controlled composition and structure of nanoemulsions facilitate the encapsulation and efficient delivery of bioactive lipophilic compounds [8]. Nanoemulsions hold significant potential in the food industry for dispensing nutraceuticals, coloring, and flavoring agents, as well as antimicrobials. Formulations of active ingredients in nanoemulsions can be harnessed to create biodegradable coating and packaging films, thereby augmenting the quality, functional properties, nutritional value, and shelf life of food products [9, 10].

Nanoemulsions can be generated through a variety of methods, which are commonly categorized into high-energy and low-energy approaches [11]. Each technique offers distinct benefits and practical uses depending on the specific properties sought in the nanoemulsion. The selection between high-energy and low-energy methodologies is influenced by factors such as the desired droplet dimensions, stability, and the intended application in the realms of food science or pharmaceuticals (Nicely reviewed by Çınar [12]).

Nanoemulsions serve as efficient vehicles for hydrophobic bioactive substances like vitamins, antioxidants, and essential oils. Their minute droplet size, ranging from 10 to 100 nm, enhances the solubility and bioaccessibility of these substances, thus facilitating increased absorption within the gastrointestinal environment [13]. This encapsulation shields delicate nutrients from deterioration throughout handling and storage, thereby amplifying their effectiveness in food items. Nanoemulsions can be integrated into edible coatings that encompass antimicrobial components and antioxidants [14]. These coatings aid in suppressing microbial proliferation and oxidative processes, effectively lengthening the shelf life of perishable goods like meat, dairy, and fresh produce. Moreover, they mitigate moisture loss and gas transfer, consequently upholding the quality of food products. The inclusion of nanoemulsions can heighten the sensory characteristics of food items, encompassing taste and consistency. By regulating the discharge of flavor molecules, nanoemulsions enrich the overall gustatory experience, particularly advantageous in items where flavor intensity is paramount, thus permitting a more enticing product sans excessive additives [15]. Nanoemulsions play a role in fostering sustainable food practices by facilitating the production of biodegradable packaging materials [16]. These materials can embed functional constituents that bolster the protective attributes of packaging, concurrently enhancing the nutritional value of the enclosed food products. The incorporation of nanoemulsions in food formulations can enhance digestibility and govern the release and assimilation of bioactive substances within the gastrointestinal tract [17]. This aspect holds particular significance in bolstering the health advantages of functional foods and nutraceuticals.

The utilization of nanoemulsions in the field of food science introduces a number of obstacles that must be carefully examined. Nanoemulsions are prone to a variety of destabilization processes, which encompass Flocculation (the clustering of droplets resulting in phase separation), Ostwald Ripening (the phenomenon where larger droplets grow at the expense of smaller ones, leading to an enlargement of droplet size with time), Creaming (the upward motion of larger droplets due to buoyancy, resulting in an uneven product), and Phase Separation (the complete division of oil and water phases, resulting in the loss of emulsion stability) [18].

These destabilization mechanisms can be significantly impacted by variables like ionic strength, temperature, and pH, underscoring the importance of optimizing formulation conditions for enhanced stability. Specifically, pH influences the ionization state of emulsifiers and encapsulated compounds, affecting their charge, solubility, and interaction with the surrounding medium. Changes in pH can lead to alterations in droplet surface charge, promoting aggregation or coalescence due to reduced electrostatic repulsion, especially near the isoelectric point of proteins or charged surfactants [19].

Research in food science is vital for addressing global challenges such as food security, sustainability, and public health. As the global population continues to grow, innovative solutions are required to ensure the availability of nutritious, safe, and affordable food. Scientific advancements in food processing, preservation, and packaging play a crucial role in reducing food waste and improving shelf life, thereby contributing to sustainable practices. Furthermore, research enables the development of functional foods and nutraceuticals that cater to specific dietary needs and promote overall health and well-being. This review was conducted by searching major scientific databases including PubMed, Scopus, Web of Science, Google Scholar using keywords such as 'nanoemulsions,' 'food science,' 'food applications,' 'stability,' 'bioavailability,' 'encapsulation,' and specific food matrices. The selection focused on peer-reviewed articles published predominantly within the last years, prioritizing comprehensive reviews, original research

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articles, and significant advancements. While not strictly a systematic review following PRISMA guidelines, a thorough and critical evaluation approach was employed to synthesize the most relevant and impactful literature.

While several reviews have explored nanoemulsions in food applications [20, 21, 22, 23, 24, 25, 26, 27], this current review provides a timely and unique comprehensive update, specifically focusing on the most recent advances in formulation strategies, the integration of environmentally friendly surfactants, and the encapsulation of plant bioactives, antioxidants, and vitamins. Furthermore, it critically evaluates their potential for improving functional and enriched food products, highlights emerging trends towards sustainable packaging, and addresses the critical need for developing specific industry standards, aspects not extensively covered in prior reviews.

The main purpose of this review was to study the recent progress in food science with the help of nanoemulsions. After introducing nanoemulsion, it was made to shed light on the most commonly used types of nanoemulsions in food science and their main components. Then, the main applications and functions with a focus on the main impacts of nanoemulsions on food science were discussed.

2. Nanoemulsions

2.1 Types

Nanoemulsions are colloidal emulsions consisting of two immiscible liquids, where one is dispersed in the other, with sizes ranging from 20 to 200 nm. These nanoemulsions are thermodynamically stable and can be of three types: Water-in-oil (W/O), oil-in-water (O/W), and Double emulsions (DE).

The interface in all three categories of Nanoemulsions is stabilized through a suitable combination of surfactants and cosurfactants. The primary distinction between emulsions and Nanoemulsions lies in the fact that the former, despite potentially demonstrating exceptional kinetic stability, are thermodynamically unstable and will eventually undergo phase separation. Additionally, emulsions typically appear cloudy, whereas Nanoemulsions exhibit clarity or translucence. The size of droplets is another significant difference between emulsions range in micrometers dimension and nanoemulsions range in nanometers.

The emergence of interest in nanotechnology and combinatorial chemistry has spurred the advancement of novel nano-carriers with low aqueous solubility and high lipophilicity, presenting a significant challenge to bioavailability [28]. Consequently, a range of methodologies are employed to enhance the aqueous solubility of components, with nanoemulsion emerging as an advanced and auspicious strategy. While oil-in-water and water-in-oil nanoemulsions are commonly utilized to enhance aqueous solubility, issues such as water instability, water insolubility, and the susceptibility of certain ingredients to oxidation and hydrolysis necessitate the development of nanoemulsions without an aqueous phase, known as non-aqueous nanoemulsions or anhydrous nanoemulsions [29]. These innovative kinetically stable colloidal dispersions, with a size range of 10-100 nanometers, are created by replacing the aqueous phase with a non-aqueous polar phase containing minimal oxygen content.

O/W emulsions: O/W emulsions emulsions are systems in which fine oil droplets are dispersed in an aqueous continuous phase. These emulsions are stabilized using emulsifiers or surfactants and are used to transport hydrophobic compounds and improve the sensory and functional properties of foods. The small size of the oil droplets, high stability, and the ability to customize these emulsions make them valuable tools in the food industry [30].

One important application of O/W emulsions is in functional and fortified beverages [31]. These emulsions help to evenly distribute hydrophobic compounds such as fat-soluble vitamins (A, D, E, K), omega-3 fatty acids, and vegetable oils. They also prevent phase separation and help to improve the appearance and taste of beverages. In sauces and condiments such as low-fat mayonnaise and salad dressings, O/W emulsions are used to create a smooth, creamy texture [32]. These emulsions allow for a reduction in oil content while maintaining product stability and flavor. In addition, they are very useful in producing healthier, lower-calorie products. Another prominent application of O/W emulsions is in edible coatings and food packaging [33]. These coatings are applied as a protective layer on food and prevent oxidation, moisture loss, and microbial contamination. Antioxidant-rich oils or antimicrobial agents in these emulsions can enhance the protective properties. In coatings and surface treatments, O/W emulsions are used to improve texture, reduce oil absorption during frying, and provide shine to food products such as pastries and ready-to-eat foods [34]. This application helps produce food with a more attractive appearance and better nutritional properties.

W/O emulsions: W/O emulsions are systems in which small water droplets are dispersed in a continuous oil phase. Due to their special structure, these types of emulsions provide the ability to transport and encapsulate water-soluble compounds in an oily environment. To stabilize these systems, emulsifiers are used that reduce the water-oil interface and prevent the water droplets from re-aggregating. These properties make W/O emulsions valuable in certain food applications [35].

In the food industry, W/O emulsions are widely used in the production of fatty and moisturizing products such as butter, margarine, and some confectionery and desserts. In these products, water droplets enclosed in the oil phase play an important role in creating texture and flavor. For example, in the production of butter and margarine, water droplets are used to increase moisture and improve the sensory properties of the product [36]. In addition, these emulsions help reduce water absorption from the environment and increase the shelf life of the product.

W/O emulsions are also used in bakery and confec-

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tionery products [19]. In these products, emulsions help retain moisture during baking, creating a softer texture and richer flavor. Also, in chocolate and truffle formulations, W/O emulsions are used to stabilize aqueous components and improve product uniformity (Fig. 1). Double emulsions: DE are complex colloidal systems that involve two emulsification steps. In this type, one emulsion is dispersed within another emulsion. Two common types of double emulsions are water-in-oil-in-water (W/O/W) and oil-in-water-in-oil (O/W/O). The structure of these emulsions allows for the simultaneous entrapment of hydrophilic and hydrophobic compounds, making them useful tools in advanced food formulations [37].

One of the key applications of double emulsions is in the production of low-fat food products [38]. For example, in W/O/W emulsions, an oil layer encloses the inner water droplets, while an outer aqueous phase surrounds the product. This structure helps reduce fat content without negatively affecting texture and flavor, which is very useful in the production of sauces, creams, and low-fat desserts.

Double emulsions are also used in the controlled release of active ingredients such as vitamins, probiotics, and antioxidants. These systems help to encapsulate sensitive compounds and protect them from degradation during processing or storage. In addition, they can be used for targeted release of nutrients or to improve food stability [39]. In confectionery and desserts, O/W/O emulsions can be used to encapsulate flavors or create multiple layers in multiphase products. These applications not only help improve sensory properties but also enable innovation in product design [40]. Overall, double-faced emulsions are valuable tools in the food industry with their unique capabilities in encapsulation, controlled release, and optimization of sensory properties (Table 1).

2.2 Formation approaches

The production of nanoemulsions involves the selection of appropriate raw materials, the use of advanced techniques to reduce the droplet size, and the optimization of process conditions.

In the first step, the selection of raw materials is of great importance. The oily phase can include vegetable oils or hydrophobic materials that act as carriers for the active compounds. The aqueous phase is usually composed of water or aqueous solutions. To stabilize the nanoemulsion, emulsifiers are used that prevent the re-integration of the droplets by reducing the surface tension between the phases. The type of emulsifier is selected based on the end use, biocompatibility, and product stability [81].

Nanoemulsions are produced by mechanical or chemical methods. In mechanical methods, sophisticated equipment such as high-pressure homogenizers, ultrasound devices, and colloid mills are used [82]. This equipment generates intense mechanical forces that reduce the droplet size to the nanometer scale. On the other hand, chemical methods include processes such as self-emulsification, solvent dilution, and micro emulsification, which rely on thermodynamic changes and help produce stable nanoemulsions.

Among the various production techniques, micro fluidization and high-pressure homogenization generally yield the most consistent and narrow droplet size distributions in high-energy methods. Microfluidization, in particular, often results in highly monodisperse systems due to the precisely controlled and intense shear forces generated within the micro-channels, leading to uniform droplet breakage. High-pressure homogenization also produces consistent results by forcing the emulsion through a narrow gap at high velocity, inducing intense turbulence and cavitation. In contrast, low-energy methods like spontaneous emulsification or phase inversion temperature can also yield small droplets, but their consistency in droplet size distribution can be more sensitive

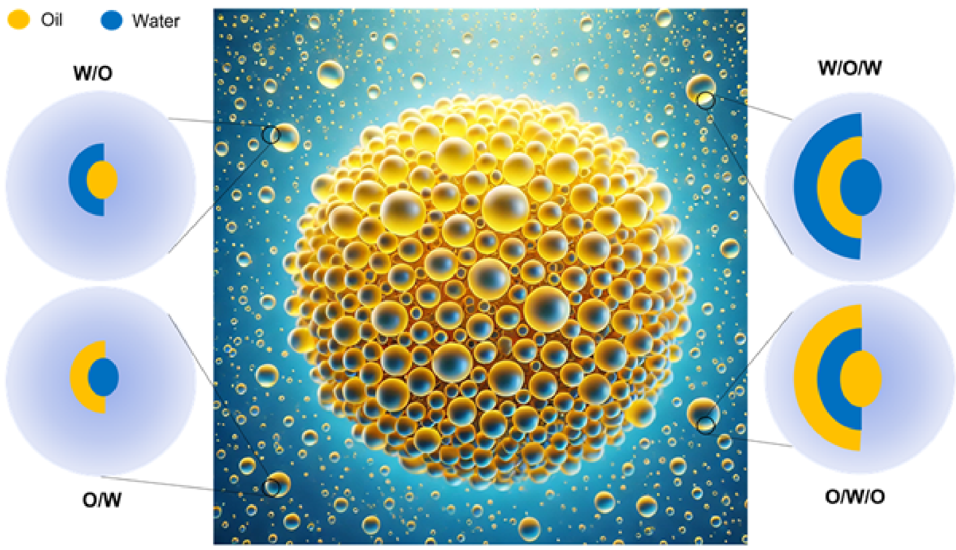

Figure 1. Schematic for the introduction of different nanoemulsion types.

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Table 1. A brief description of the main elements in nanoemulsion-based studies in food science.

Oil Phase	Surfactant	Type of NE and production technique	Size of droplets (nm)	Food under study	Ingredients/ Additives	Function/issue under the study of NE	Ref.
Sesame	Tween 80	O/W Ultrasonic	100-400	Beverage	Vitamin E	Antibacterial	[23]
Curcumin	Quillaja saponin/whey protein	O/W Microfluidization	110	Salad	-	Changes in the color and texture of the salad dressings.	[24]
Corn	Patatin and protease inhibitor	O/W Ultra-high-pressure homogenizer	500-1000	-	Nacl	Impact of pH, salt, and heat on the stability	[38]
-	-	O/W High-pressure homogenization	120-140	Stability	L-ascorbic acid	Study the stability of NE under different conditions and delivery	[41]
Edible	Tween40 – PEG6000	O/W Ultrasonic homogenizer	<500		Sio2	Oil recovery	[42]
Rapeseed	Extended surfactant (X-AES), a hydrotrope (sodium xylene sulfonate, SXS)	O/W Homogenizer	-	Stability	Nascn and Na2SO	Solubilization of long-chain triglycerides	[43]
N-dodecane	Nonionic surfactant (Brij30)	O/W Phase inversion temperature (PIT)	30-350	Stability	Nacl	Effect of sodium chloride on the formation and stability	[44]
Curcumin	Tween 20	O/W High-pressure homogenization	90-122	Milk	-	To study the long-term stability	[45]
Flax seed	Octenyl succinic anhydride modified starch/Tween-80	O/W Homogenizer & microfluidizer	-	Stability	β-carotene and α-tocopherol	The impact of β-carotene and α-tocopherol on physicochemical stability	[46]
Soybean	Oleogel	Pickering Ultra-Turrax homogenizer	250-996	Low-calorie foods	Behenic acid (BA) and ethylcellulose (EC)	Low-calorie fat replacer	[47]
Peppermint and medium-chain triacylglycerol	Purity Gum 2000	O/W Ultrasonic	<200	Aqueous food	-	Antimicrobial	[48]
Coconut, olive, sunflower	Pluronic-P107, and Cremophor EL	O/W Ultrasonic	100-300	Vegetarian diets	-	Stability assessment and pharmacokinetic evaluation	[49]
Fish Oil, γ-Oryzanol	Tween 80/Span 20	O/W Homogenizer	152	Yogurt	1% citric acid and 0.1% sodium benzoate	Improving Physicochemical Properties of Yogurt	[50]
Tarragon essential oil	Tween-80	O/W Homogenizer & Ultrasonic	150-300	Yogurt	Transglutaminase, potassium sorbate	Development, Optimization, Characterization, Bioactivity, and Storability of different formulation	[51]
Thyme oil	Tween 8	O/W Homogenizer & Ultrasonic	135-160	Yogurt	-	Improvement of yogurt safety	[52]
Soy lecithin	Polysorbate 80	O/W Inverse osmosis system	195	Yogurt and fruit puree (Strawberry and bananas)	Vitamin D3 and omega-3	Desserts for Older People	[53]

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Continued of Table 1.

Oil Phase	Surfactant	Type of NE and production technique	Size of droplets (nm)	Food under study	Ingredients/ Additives	Function/issue under the study of NE	Ref.
Corn oil	Goat milk proteins	O/W High-pressure homogenizer	880	Yogurt	Vitamine E, tocopherols	To study the influence of Bulk Pasteurization and Chilled Storage	[54]
Cuminum cyminum L. EO	Tween 80	O/W Homogenizer & Ultrasonic	100-155	Mayonnaise	-	Oxidative stability and microbial growth in mayonnaise	[55]
Oregano and clove eos	Tween 80	O/W High-pressure homogenizer	325-712	Salad	Yeast	The impact of NE Zygosaccharomyces bailii survival in salad dressings	[56]
Nigella sativa	Tween-20	O/W High-pressure homogenizer	175	Ice cream	Gum arabic, sodium caseinate	Develop ice-cream product fortified with Nigella sativa oil NE	[57]
Sunflower oil	Tween 80	O/W High-pressure homogenizer	<150	Probiotics	Soy protein isolate (SPI), gum Arabica (GA)	Enhancing the stability of probiotics (Lactobacillus delbrueckii subsp. Bulgaricus)	[58]
Fish Oil	Tween 20	O/W High-pressure homogenizer	245-422	Scomber scombrus	Maltodextrin	Exploring the effectiveness of fish oil (FO)-loaded nanoemulsions as fat substitutes in creating low-calorie cookies	[59]
Wheat germ oil	Tween 20	O/W Ultrasonic	114	Fish fillet	-	Using wheat germ oil nanoemulsion to increase oil stability in cooked fish fillets stored at 4°C	[60]
Garlic Essential Oil	Tween 80	O/W Ultrasonic	50-220	Olive oil	Citric acid	Enhancing the Antioxidant Activity, Shelf Life, and Sensory Properties of Flavored Olive Oil	[61]
Mentha piperita, Punica granatum, Thymus vulgaris and Citrus limon	Tween 80	O/W High-pressure homogenizer	10-1000	Minced meat	Chitosan, olive oil	Evaluation of the impacts of NE on the microbial diversity and chemical composition of minced meat	[62]
Lemongrass oil	Tween 80	O/W Ultrasonic	400	Beef burger	-	To study the impact of NE on effect on shelf life, microbial, chemical indices, and technological properties	[63]
Corn	Tween 80	O/W High-pressure homogenizer	257-1112	Carbonado chicken	Rosemary extract	Production of edible coatings	[64]
Litsea cubeba and Cinnamon EO	Tween 80	O/W High-pressure homogenizer	4-7	Plant-Based Meat Analogs	Chitosan	Preparation of coating for Plant-Based Meat Analogs	[65]
Curcumin	Tween 80	O/W Emulsion inversion point	9-130	Chicken fillets	Garlic EO	Preparation of coating for packaging	[66]

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Continued of Table 1.

Oil Phase	Surfactant	Type of NE and production technique	Size of droplets (nm)	Food under study	Ingredients/ Additives	Function/issue under the study of NE	Ref.
Oregano EO	Tween 80	O/W High-shear homogenizer	214-337	Cheese	Sodium alginate	Enhancing the shelf life of low-fat cut cheese	[67]
Thymol EO	Tween 20	O/W Ultrasonic	123-139	Pork	Chitosan	A coating for the preservation of refrigerated pork	[68]
Thymol EO	Tween 80	O/W High-pressure homogenizer	137-153	Chicken breast fillets	-	Extending the shelf-life of chicken breast fillets	[69]
Thyme oil	Tween 80	O/W Ultrasonic	28-38	Beef	Acetic acid, propylene glycol	Preparing polymeric film for beef packaging	[70]
Pomace Oil	Tween 40	O/W High-shear homogenizer	-	strawberries	caffeine	To develop Edible film or coatings for fruit preservation	[71]
Clove Oil	Tween 80	O/W Ultrasonic	40-50	-	Tetraethyl orthosilicate	Production of Eco-Friendly and Endurable Food Packaging	[72]
Thyme oil	Tween 80	O/W High-pressure homogenizer	90	-	lecithin	Antimicrobial activity of food packaging films	[73]
eugenol	Tween 80	O/W Ultrasonic	200	-	-	Production of active food packaging	[74]
Lippia citriodora and Laurus nobilis	Tween 80	O/W Ultrasonic	16-60	rainbow trout	lecithin	Production of active food packaging	[75]
Ginger EO	Tween 80	O/W High-shear homogenizer	229	blueberry	chitosan	Production of active food packaging	[76]
citral	Tween 80	O/W Ultrasonic	-	-	-	Production of a pH and enzyme stimuli-responsive food packaging	[77]
Pistachio peel	Tween 80	O/W microfluidizer	<200	shrimp	pectin, anthocyanin	Production of smart halochromic food packaging	[78]
Soybean	Tween 20	O/W High-pressure homogenizer	100	-	Lecithin, cocoa butter	Development of food-grade NE fortification of emulsion-based food matrices	[79]
Zhumeria majdae	Tween 80	O/W Ultrasonic	<200	Cake	Kefiran	Production of active food packaging	[80]

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to subtle variations in formulation parameters and temperature control [26, 83, 84].

For high-energy methods (e.g., high-pressure homogenization, ultrasonication), explain that they use mechanical forces to break down droplets into nano-sized particles. For low-energy methods (e.g., spontaneous emulsification, phase inversion temperature), describe how they rely on the spontaneous formation of nanoemulsions through changes in temperature, solvent, or surfactant concentration, often requiring less specialized equipment and energy. Provide a sentence or two for each, outlining their basic principle [26, 83, 84].

Optimization of process conditions is essential for producing high-quality nanoemulsions. Factors such as emulsifier concentration, pH, temperature, and the intensity of mechanical forces must be carefully adjusted [41]. After production, nanoemulsions are evaluated for droplet size, physical and chemical stability, and surface properties such as zeta potential.

Finally, the process for making nanoemulsions must be tailored to the end use. For example, in the food industry, biocompatible and stable formulations are required, while in the pharmaceutical industry, more precise control of the release of active ingredients and product safety are required. In this regard, nanoemulsions are a powerful tool for developing innovative and efficient products.

2.3 Stability of nanoemulsions

The stability of nanoemulsions refers to the ability of these systems to maintain their nanometric structure and prevent unwanted changes over time. Since the droplet size in nanoemulsions is very small, these systems are susceptible to changes such as phase separation, precipitation, aggregation, or oxidation. Therefore, maintaining the stability of nanoemulsions is of great importance to prevent a decrease in the quality and efficiency of the final product [85].

There are several factors affecting the stability of nanoemulsions, the most important of which are: the type and concentration of emulsifiers (surfactants), particle size, system viscosity, pH, and temperature [42]. Emulsifiers are substances that help reduce the surface tension between the oil and water phases and prevent the reintegration of the droplets. Choosing the right surfactant can significantly increase the stability of the nanoemulsion. The size of the nanoemulsion droplets also has a great impact on stability; Smaller droplets are generally more stable because they have a larger surface area and are less likely to aggregate. In addition, the viscosity of the system and its polymer properties can also play an important role in preventing precipitation or phase separation [85].

pH and temperature are also other factors that can have a significant impact on the stability of nanoemulsions. Changes in pH may alter the surface properties of emulsifiers, resulting in changes in the structure of the nanoemulsion. Temperature can also affect the viscosity and movement of droplets. For example, increasing temperature may reduce viscosity and cause droplet separation. Finally, to maintain the stability of nanoemulsions, it is necessary to carefully adjust the process conditions such as emulsifier concentration, pH, and temperature [43]. The stability of nanoemulsions in different systems can vary. In oil-in-water (O/W) nanoemulsions, stability depends more on the properties of the aqueous phase and the appropriate selection of emulsifiers. These systems may be vulnerable to oxidation and moisture. In contrast, water-in-oil (W/O) nanoemulsions are usually more stable because the oil phase protects the aqueous phase [86]. In addition, double emulsions, which are composed of two emulsion phases such as W/O/W or O/W/O, require more precision in the selection of emulsifiers and process conditions due to the complexity of their structure, so that both phases remain stable simultaneously. Nanoemulsion stability parameters, including droplet size, polydispersity index (PDI), and zeta potential, exhibit significant variability across diverse food matrices due to differences in composition and environmental conditions. For instance, matrices with extreme pH values (e.g., acidic beverages, alkaline dairy products) can alter the ionization state of emulsifiers and encapsulated compounds, leading to changes in surface charge and increased susceptibility to aggregation. High ionic strength can screen electrostatic repulsion, causing flocculation or coalescence. The presence of macromolecules such as proteins and polysaccharides can also induce depletion flocculation or competitive adsorption at the interface, impacting stability. Therefore, optimizing emulsifier choice and concentration, as well as considering the specific physicochemical properties of the food matrix, is crucial for maintaining long-term stability[86].

The regulatory landscape for nanoemulsions in commercial food products remains complex and evolving. Key implications concern safety and labeling. In many regions, the regulatory status often depends on the components used; if all ingredients are Generally Recognized As Safe (GRAS) by authorities like the FDA in the US, the nanoemulsion may not require specific novel food approval. However, the 'nano-effect' (i.e., whether nanoscale properties introduce new hazards) is a growing concern. Regulatory bodies are still debating precise definitions for 'nanomaterials' in food. Labeling requirements vary; some regions may mandate explicit declaration of 'nano' ingredients, while others do not. This lack of harmonization and clear guidelines presents a challenge for market entry and consumer acceptance, necessitating more comprehensive safety assessments and transparent labeling strategies [44, 87].

2.4 Emulsifiers

AS previously mentioned, emulsifiers or surfactants are substances used to create and stabilize nanoemulsions. These substances help disperse the phases by reducing the surface tension between two immiscible phases (such as water and oil) and preventing their aggregation and separation. Choosing the right emulsifier is very impor-

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tant depending on the type of nanoemulsion system and its specific properties. In this regard, different types of emulsifiers are used for different nanoemulsion systems. These substances can be divided into anionic, cationic, nonionic, and amphoteric categories [85].

One common group of emulsifiers is anionic surfactants, which, due to their negative charge, are usually used in water-in-oil (W/O) nanoemulsion systems and systems that require electrostatic stability. For example, surfactants such as sodium decyl sulfate (SDS) and sodium lauryl sulfate (SLS) are used in many nanoemulsions. These surfactants help to create a negative charge on the droplets and prevent them from agglomerating. In contrast, cationic surfactants, which have a positive charge, are more often used in systems that require interaction with specific substances. This group of surfactants, such as cetearyl ammonium chloride, is suitable for specific applications in pharmaceuticals and cosmetics [88] (Figs. 2 (a), 2 (b)).

Another group of surfactants is nonionic surfactants, which, due to their lack of electrical charge, are usually used in nanoemulsion systems that require stability at different pH conditions [89]. These surfactants, such as Tween and Span, are suitable for the production of oil-in-water (O/W) nanoemulsions. In particular, Tween 80 (Polysorbate 80) and Span 20 (Span 20) are among the most widely used surfactants in the pharmaceutical and cosmetic industries. Tweens, which are usually made from polyethylene glycol and fatty acid esters, have special capabilities in stabilizing nanoemulsions against changes in pH and temperature. Spans are also commonly used to produce water-in-oil nanoemulsions or double emulsions. Due to their special structure, these surfactants can provide good stability properties against sedimentation and aggregation of droplets [23, 90, 91].

Finally, amphoteric surfactants, which have a combination of anionic and cationic properties, are used for systems that operate under variable pH conditions or require interaction with different materials. These surfactants can be used in more complex nanoemulsions that require modification of surface properties. For example, lecithin is an amphoteric surfactant that is used in the production of double nanoemulsions and some pharmaceutical systems, especially in the food and cosmetic

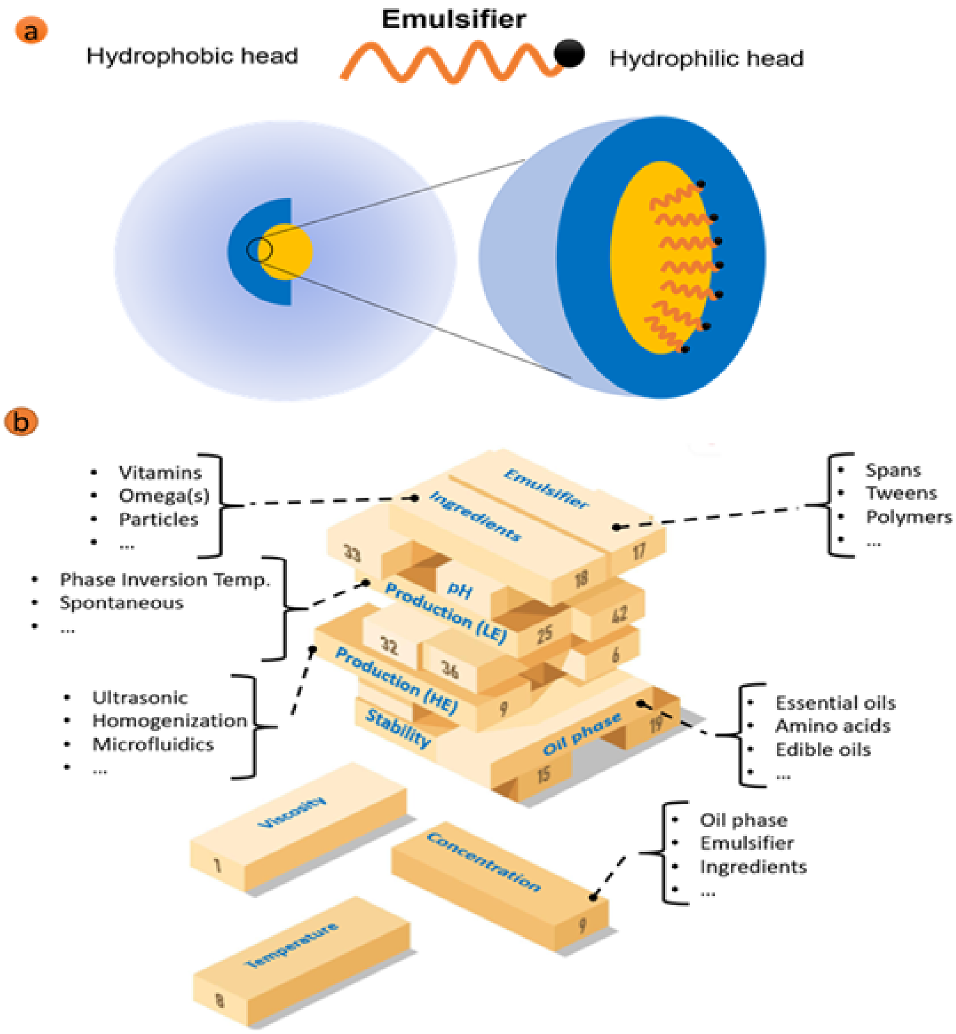

Figure 2. (a) a simple presentation about the role of emulsifiers in nanoemulsions, (b) nanoemulsions are dependent on several factors that a wrong manipulation of them destroys the whole formulation of nanoemulsions.

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industries [92].

The choice of the appropriate emulsifier for the production of nanoemulsions depends on the characteristics of the nanoemulsion system and its end use. For example, nonionic surfactants such as spans and tween are commonly used in oil-in-water (O/W) nanoemulsion systems, as these surfactants help to stabilize these types of systems. On the other hand, anionic and cationic surfactants are more commonly used in water-in-oil (W/O) nanoemulsions and double systems. Therefore, the selection of surfactants should be made according to the type of nanoemulsion system and specific process conditions to maintain the stability and efficiency of the system[23, 90, 91].

For instance, the addition of common food-grade emulsifiers such as polysorbates (e.g., Tween 20, Tween 80) and lecithins (e.g., soy lecithin, sunflower lecithin) can significantly enhance the activity of essential oils. Polysorbates, being non-ionic surfactants, are widely used for their excellent emulsifying properties and stability across a wide pH range, while lecithins are natural phospholipids favored for their biocompatibility and ability to form stable O/W emulsions, improving the dispersion and stability of hydrophobic compounds within the food matrix [23, 90, 91].

The choice of emulsifier significantly dictates the resulting droplet size and long-term stability of nanoemulsions. Tween 80, a synthetic non-ionic surfactant, is highly effective due to its low molecular weight and strong ability to reduce interfacial tension, typically leading to very small droplet sizes (e.g., < 50 nm) and good kinetic stability. Its robust adsorption at the oil-water interface effectively prevents coalescence and Ostwald ripening across a wide range of pH and ionic strengths. In contrast, lecithins, natural phospholipids, often yield slightly larger but still nanoscale droplets (e.g., 50-200 nm). While lecithins are favored for their natural origin and biocompatibility, their stability can be more sensitive to pH and ionic strength changes due to their amphoteric nature, potentially leading to aggregation or phase separation under certain food matrix conditions. However, combinations of emulsifiers are often used to leverage synergistic effects and achieve optimal stability [27, 93, 94].

2.5 Ingredients

In the production of nanoemulsions, using various types of ingredients (additives) can help improve the system's quality, stability, and performance. These additives can greatly impact the final properties of the nanoemulsion and are selected depending on the type of system and the product's final application [95]. Ingredients are divided into different categories, each of which plays a specific role in increasing the system's efficiency.

One of the most important additives in nanoemulsions is antioxidants [96]. These substances are used especially in nanoemulsions that contain oxidation-sensitive compounds such as oils and fatty acids. Antioxidants such as tocopheryl acetate (vitamin E acetate) and ascorbic acid (vitamin C) can help prevent oxidation and degradation of the oil phase and also active encapsulated ingredients over time [97]. This feature is especially important in the food industries, pharmaceutical and cosmetic industries, which need to maintain quality and long-term efficacy.

In addition to antioxidants, polymers, and thickeners are also used in nanoemulsions. These materials can increase the viscosity of the system and prevent phase separation [45]. For example, polyethylene glycol (PEG) and carboxymethyl cellulose (CMC) are known as common thickeners in nanoemulsions [98]. Increasing the viscosity of the medium restricts the movement of droplets and prevents their aggregation. This feature helps in the long-term stability of the nanoemulsion.

Other important additives are salts and ionic materials that can help adjust the pH and improve the stability of the nanoemulsion [46, 99]. These materials can change the surface properties of surfactants and prevent the aggregation of droplets. For example, sodium chloride and calcium chloride can help regulate the surface charge of the droplets and are useful in some pharmaceutical and cosmetic systems that require greater stability [100]. In addition, preservatives such as benzalkonium chloride and parabens can prevent the growth of microorganisms in the nanoemulsion and extend its shelf life [47].

In some pharmaceutical and cosmetic nanoemulsions, biologically active substances such as vitamins, peptides, and fatty acids are also added to the formulations [101]. These substances not only help with the stability of the system but also give the nanoemulsion certain therapeutic and cosmetic properties. For example, vitamins can act as antioxidants or anti-aging compounds and have positive therapeutic effects on the skin or cells.

Finally, silicates and nanoparticles are used as additives in nanoemulsions, especially to improve the uniform distribution of active ingredients in the system and also to increase stability [102]. These nanoparticles can act as carriers for the active ingredients and, in addition, improve the stability and chemical properties of the nanoemulsion. These materials are particularly useful in complex nanoemulsions that require precise control of properties. This approach resulted in a new version of nanoemulsions named "Pickering nanoemulsions" (Fig. 3).

Pickering nanoemulsions are a type of nanoemulsion stabilized by nanoparticles in which nanoparticles are used instead of surfactants or emulsifiers to stabilize and stabilize the droplets within the emulsion [48]. This method has gained great attention in various industries, especially in the pharmaceutical, food, and cosmetic industries, due to the lack of use of conventional surfactants and the ability of nanoparticles to prevent the aggregation of droplets. Silicates and nanoparticles are among the materials that are widely used in the development of Pickering nanoemulsions.

Pickering nanoemulsions, stabilized by solid particles adsorbed at the oil-water interface, offer distinct advantages over traditional surfactant-based nanoemulsions in food preservation. Their unique stabilization mecha-

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nism provides an irreversible mechanical barrier, making them highly robust against coalescence, flocculation, and Ostwald ripening, which are common destabilization pathways in traditional systems. This enhanced stability can lead to superior long-term preservation of encapsulated sensitive bioactives. Furthermore, Pickering stabilizers, often derived from food-grade particles (e.g., starch, protein aggregates, cellulose nanocrystals), can be more natural and less prone to toxicity concerns associated with synthetic surfactants. They can also contribute to sustained release of encapsulated antimicrobial or antioxidant agents over time, further enhancing food shelf life and safety [20, 103].

Silicates, especially silica nanoparticles or amorphous silica, can act as physical stabilizers in Pickering nanoemulsions. These nanoparticles create a protective layer on the emulsion droplets, especially in the water or oil phase [104]. This silicate layer, which naturally forms on the surface of emulsion droplets, reduces surface tension, and prevents droplet aggregation. Due to the surface properties of silicates that can effectively interact with oil or water droplets, these nanoparticles can act as a barrier against the combination of similar droplets and prevent phase separation and droplet aggregation.

Silicate nanoparticles, usually in nanometer dimensions, can easily adhere to the surface of droplets and form a network structure on the droplet surface. This network structure of nanoparticles, known as a solid layer, prevents the droplets from being agitated and their aggregation. In addition, silicate nanoparticles can be transformed into a kind of non-polar surface for the oil phase or a polar surface for the water phase with their surface chemical properties, which increases the stability of nanoemulsions against external factors such as changes in temperature, pH, and mechanical forces [105].

Metal, organic, and carbon nanoparticles are also used in nanoemulsion pickering alongside silicates. These nanoparticles are usually used as physical and chemical stabilizers in nanoemulsions. Nanoparticles such as iron oxide nanoparticles [105], activated carbon nanoparticles [106], or graphene nanoparticles can act similarly to silicate nanoparticles and prevent them from agglomerating by adhering to the surface of emulsion droplets. Due to their nanometric size, nanoparticles in nanoemulsion, Pickering can form a network of particles on the surface of emulsion droplets. These networks cause the droplets to be physically separated and remain dispersed. In addition, the surface properties of these nanoparticles can help improve stability against environmental changes. For example, graphene nanoparticles can effectively help stabilize nanoemulsions against external forces such as temperature and pressure changes due to their outstanding mechanical and chemical properties [107].

Environmental factors such as pH and ionic strength significantly influence the release profile of encapsulated bioactives from nanoemulsions. Changes in pH can alter the ionization state of both the emulsifier and the bioactive compound, affecting their charge and solubility. For instance, if the bioactive or emulsifier is pH-sensitive, a shift in pH can lead to a breakdown of the nanoemulsion structure or a change in the permeability of the interfacial layer, triggering premature release or, conversely, enhanced retention. Similarly, high ionic strength can screen electrostatic repulsion between droplets or within the interfacial layer, potentially leading to aggregation

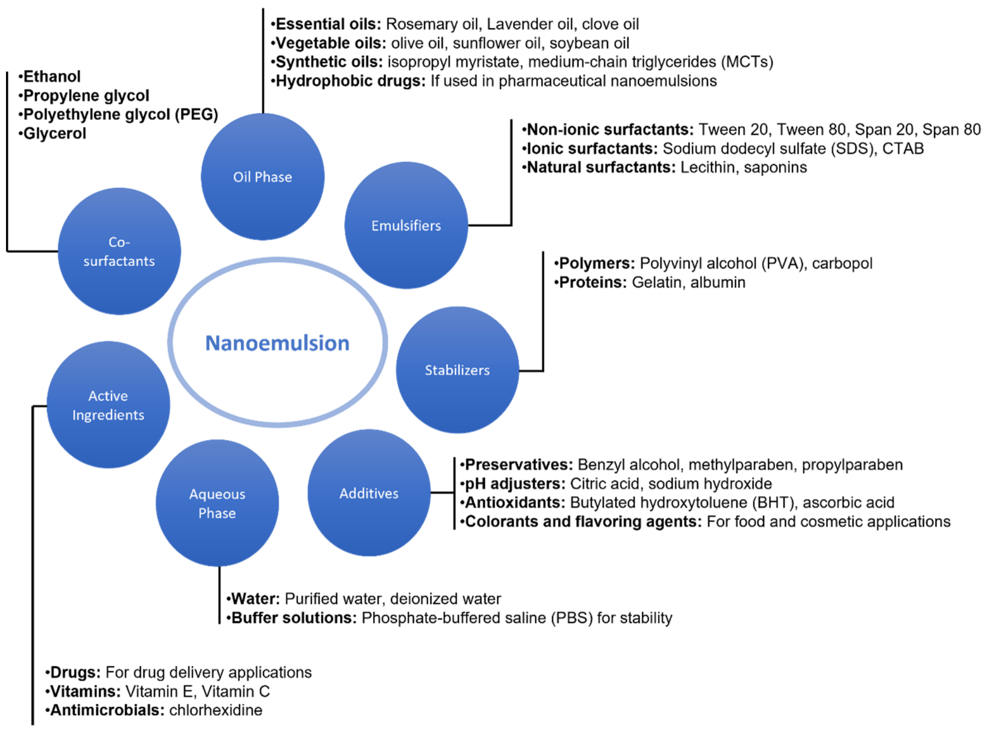

Figure 3. Main components in developing nanoemulsions. Active ingredients and additives are considered as optional components.

and a burst release of encapsulated material. Conversely, some smart delivery systems are designed to utilize these pH or ionic strength changes as triggers for controlled release in specific gastrointestinal environments, optimizing bioactive delivery [20, 21, 22, 23].

2.6 Physical and biochemical properties

Nanoemulsions, as suspension systems with very small and stable particle sizes, have specific and fundamental properties that distinguish them from other emulsion systems. In this section, the main properties of nanoemulsions are briefly discussed.

Particle size and particle size distribution: One of the prominent features of nanoemulsions is their particle size, which is usually in the nanoscale (1 to 100 nm). This small size allows for a larger contact surface and improves certain physical properties such as solubility and stability. In nanoemulsions, the particle size distribution is also of great importance; the particles must be distributed uniformly and with constant sizes.

Stability: Stability is one of the key properties of nanoemulsions, which refers to the ability of the system to maintain its properties under different conditions such as changes in temperature, pH, and pressure. Nanoemulsions are usually highly stable and can prevent droplet aggregation and phase separation due to the use of nanoparticles and appropriate emulsifiers [49].

Composition and solubility of active ingredients: One of the outstanding features of nanoemulsions is their ability to improve the solubility of active ingredients. These systems can dissolve water-insoluble substances and increase their solubility and biological availability. Due to the nano-sized particles, nanoemulsions can effectively dissolve active ingredients in aqueous or oily phases and be easily absorbed by the human or animal body [95].

Biocompatibility and safety: The biocompatibility and safety of nanoemulsions are very crucial for use in pharmaceuticals and cosmetics. Nanoemulsions are generally safer than other nanosystems due to the use of natural and non-toxic materials as surfactants and additives. This feature makes nanoemulsions attractive for pharmaceutical and cosmetic applications [50]. While nanoemulsions offer numerous advantages, potential safety concerns, particularly regarding long-term consumption, require careful consideration. Currently, comprehensive long-term toxicological studies specifically on nanoemulsion-based foods in humans are limited. Most research focuses on the safety of individual nanoemulsion components (e.g., GRAS-status emulsifiers, oils) at their intended use levels. However, theoretical concerns exist regarding potential nanoparticle accumulation, altered biodistribution, or unforeseen interactions with biological systems due to their nanoscale properties. While evidence of widespread adverse toxicological effects from current nanoemulsion food applications is not established, ongoing research, including rigorous *in vivo* studies and risk assessments, is crucial to fully understand any long-term impacts and ensure consumer safety [109].

Controllable release: Another feature of nanoemulsions is their ability to control the release of active ingredients. This feature is particularly useful in food packaging, food coating, and matrix-modified foods. Nanoemulsions can release active ingredients continuously and at a controlled rate, resulting in long-term effects such as antibacterial, antioxidant, etc. [110] (Fig. 4).

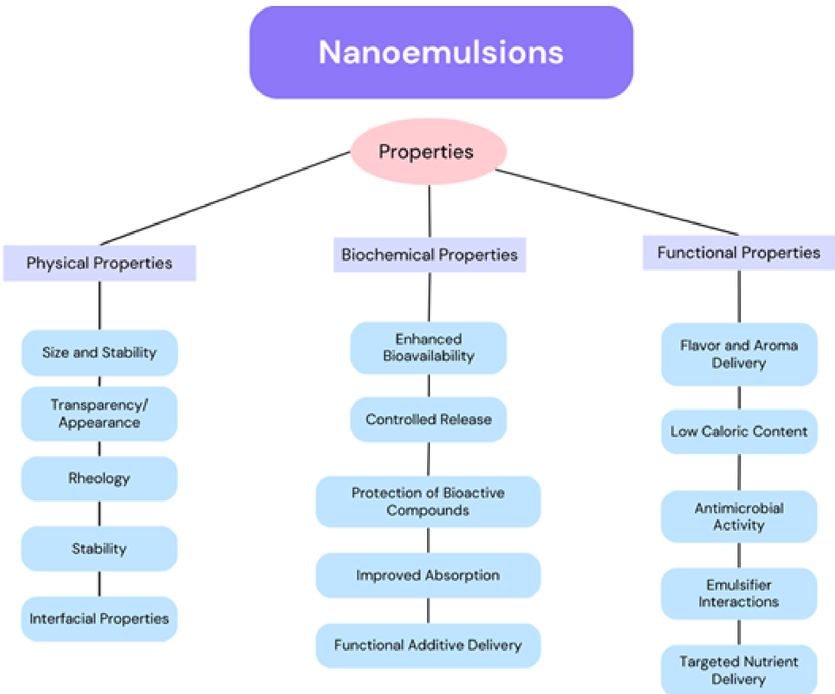

Figure 4. The main properties of nanoemulsion depending on their applications.

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3. Applications in the food industry

Nanoemulsions have been widely used in the food industry as effective systems to improve the quality, stability, and functional properties of food products. These systems are used in a variety of food products for various purposes due to their ability to solubilize active ingredients, increase stability, and improve the bioavailability of active ingredients (Fig. 5). Although the main purpose of using nanoemulsion in food might be similar, the way of synthesis, concentration, side effects, duration, interaction, etc varies from one type of food to another.

3.1 Beverages

Nanoemulsions have become a major tool in the development of new beverages due to their unique properties such as small particle size, high stability, and ability to disperse insoluble compounds. These systems have enabled the solution of challenges such as low solubility of bioactive compounds, reduced stability, and improved taste and flavor [111].

One of the most important benefits of nanoemulsions is the increased solubility of fat-soluble compounds such as vitamins (D, E, K, A), carotenoids, and omega-3 fatty acids [112, 51]. These compounds usually do not dissolve well in the aqueous environment of beverages and may precipitate or cause phase separation (Fig. 6 (a)). By converting these compounds into

Nanoemulsions, smaller and more stable droplets are dispersed in the aqueous environment, which helps to increase product uniformity and shelf life [52]. For example, in beverages enriched with vitamins D and E, the use of nanoemulsions provides greater stability and improves nutritional properties [112]. Also, in beverages containing beta-carotene, in addition to enriching the product, natural and attractive coloring is added to the product [53].

The stability of beverages containing bioactive compounds is another important challenge in this industry [113]. As previously mentioned, sensitive compounds such as antioxidants and essential oils may oxidize or lose their quality quickly under normal conditions. Nanoemulsions increase their shelf life by reducing the contact surface of these compounds with destructive environmental factors such as oxygen and light [52, 54]. For example, in beverages containing essential oils such as orange or mint, the use of nanoemulsions prevents sedimentation and phase separation and improves the taste and aroma of the product [114].

The bioavailability of bioactive compounds in the digestive tract is another important aspect of nanoemulsions [115]. The small particle size in nanoemulsions increases the contact surface of the compounds with enzymes and intestinal cells, improving their absorption. For example, beverages enriched with omega-3, which is beneficial for cardiovascular health, are more bioavailable using nanoemulsions [55]. Also, beverages containing curcumin (the active ingredient in turmeric), which is naturally poorly absorbed, have been able to better demonstrate its anti-inflammatory properties with nanoemulsion technology [111].

Nanoemulsion systems consistently demonstrate superior bioavailability for hydrophobic compounds compared to conventional emulsions or free forms due to their small droplet size, which increases surface area for enzymatic digestion and absorption. For example,

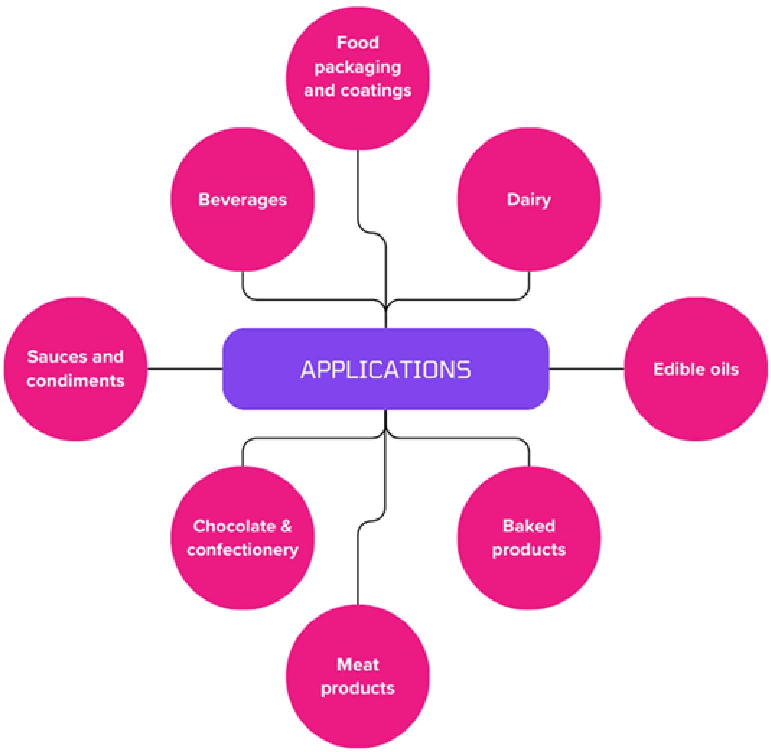

Figure 5. Main applications of nanoemulsions in food science.

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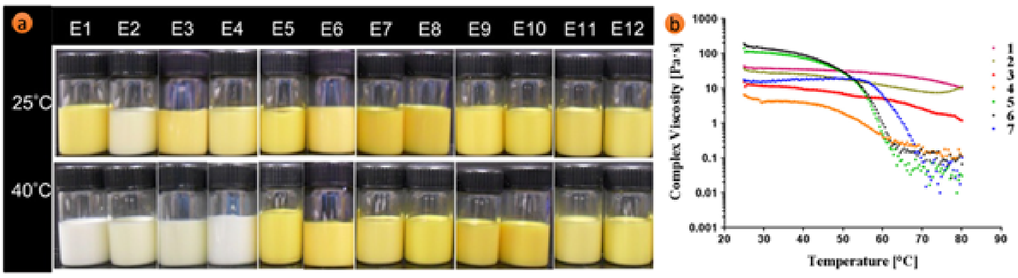

Figure 6. (a) Visual appearance of beta-carotene degradation in O/W nanoemulsions after 4 weeks of storage at 25 and 40 °C [51]. (b) Complex viscosity versus temperature curves of Oleogel (5 °C/min heating rate, 10 rad/s angular frequency for different formulations of EC:BA Oleogels with different concentrations (1–7) [108].

studies have shown a important increase in the bioavailability of curcumin when delivered via nanoemulsions compared to its coarse dispersion [116, 117, 118, 119, 56]. Similarly, nanoemulsions have been reported to enhance the absorption of fat-soluble vitamins like vitamin D and E by 1.5-3 times in animal models [26, 93, 120, 121]. These quantitative comparisons underscore the significant potential of nanoemulsions to improve the nutritional efficacy of functional foods.

Nanoemulsions can also improve the taste and flavor of beverages [57]. Many active compounds, such as polyphenols and antioxidants, produce bitter or unpleasant flavors that may not be pleasing to consumers. The use of nanoemulsions can reduce these flavors and create a better sensory experience. For example, in green tea extract beverages, nanoemulsions reduce bitterness and increase product acceptance [124].

Another application of nanoemulsions is the production of low-fat and low calories products [125]. In these cases, O/W nanoemulsions can replace fat and reduce calories by creating a similar texture. For example, in the production of low-fat dairy beverages, nanoemulsions help maintain the creamy and rich texture of the product (Fig. 6 (b)) [108]. Furthermore, in plant-based beverages such as coconut water or almond milk, the use of healthy oils along with nanoemulsions helps improve quality and stability [126].

3.2 Dairy

Nanoemulsions, as well as beverages, have gained a special place in the dairy industry due to their unique properties such as small particle size, high stability, and ability to disperse fat-soluble bioactive compounds. This technology allows for improved nutritional value, increased stability and shelf life, and enhanced texture and flavor of dairy products. The use of nanoemulsions helps produce more innovative and functional products and responds to consumer needs for healthier and tastier products [127].

One of the most important applications of nanoemulsions in dairy products is their enrichment with bioactive compounds. As mentioned previously, fat-soluble compounds such as vitamins D, E, and K, and omega-3 fatty acids, which are not naturally soluble in the aqueous environment of dairy products, are dispersed stably and uniformly using nanoemulsions. For example, kinds of milk fortified with vitamin D help improve calcium absorption and prevent osteoporosis [58]. Also, omega-3-containing yogurts produced through nanoemulsions have a positive effect on cardiovascular health, in addition to maintaining the natural taste and texture [128].

Nanoemulsions also play an important role in improving the texture and stability of dairy products [59]. In low-fat products, this technology can replace fat and create a texture similar to full-fat products [**a106**]. For example, in low-fat yogurt and dairy drinks, O/W nanoemulsions prevent phase separation and maintain product uniformity. Low-fat creams also have a rich, creamy texture that consumers prefer using nanoemulsions [59].

Another important application of nanoemulsions is the transfer of natural antimicrobial compounds and increasing the shelf life of dairy products [129]. Compounds such as plant essential oils or phenolic extracts that have antibacterial and antioxidant properties are dispersed uniformly throughout the product using nanoemulsions. For example, adding nanoemulsions containing thyme essential oil to flavored yogurt increases shelf life and reduces the growth of harmful bacteria (Figs. 7 (a), 7 (b)) [60]. The authors also confirmed that nanoemulsion can also improve the taste of dairy products. Some bioactive compounds, such as omega-3 fatty acids or polyphenols, may have a bitter or unpleasant aftertaste. Using nanoemulsions, these aftertastes can be reduced and the sensory experience of the consumer can be improved. For example, in flavored milk enriched with omega-3, nanoemulsions minimize fishy aftertaste [130].

Last but not least, another advantage of nanoemulsions in the dairy industry is increased product stability and shelf life [59]. It was reported that the small particle size in nanoemulsions reduces the oxidation of bioactive compounds and preserves their quality over time [131]. Kinds of milk enriched with vitamin E or probiotic dairy drinks are examples that have gained a longer shelf life with the help of nanoemulsions and maintain their quality even under long-term storage conditions [132]. Considering the above-mentioned information, nanoemulsions allow the production of flavored dairy products using natural essential oils. This technology helps in the uniform dispersion of flavors and prevents separation or change in flavor. For example, flavored yogurts with vanilla essential oil or buttermilks containing lemon extract have better flavor quality and shelf life

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with the help of nanoemulsions [61].

3.3 Sauces and condiments

Nanoemulsions have found wide application in the sauces and condiments industry due to their unique properties such as small particle size, high stability, and ability to transport bioactive compounds. This technology helps to improve the texture, taste, shelf life, and nutritional value of these products, leading to higher quality and healthier products (Fig. 7 (c)) [122].

One of the most important benefits of nanoemulsions in sauces and condiments is increased stability and prevention of phase separation. In products such as mayonnaise and salad dressings, which are mixtures of water and oil, phase separation can reduce product quality [133]. Nanoemulsions help create a stable system by reducing droplet size and increasing the contact surface between water and oil. For example, in oil salad dressings, nanoemulsions prevent oil separation and maintain product uniformity over time (Fig. 7 (d)) [123].

Other applications of nanoemulsions include reducing fat content and producing low-calorie products. This technology allows for the production of low-fat sauces and condiments without compromising texture and flavor [62]. It was approved that the small particle size in nanoemulsions allows for a mouthfeel similar to that of full-fat products. For example, low-fat mayonnaises produced with nanoemulsions have a rich flavor and creamy texture that consumers prefer.

As the next benefit of nanoemulsions, they can carry bioactive compounds such as vitamins, omega-3 fatty acids, and antioxidants. These fat-soluble compounds are usually difficult to use in conventional products, but with the help of nanoemulsions, they are dispersed evenly throughout the product. For example, salad dressings enriched with vitamin E or omega-3 help improve consumer health in addition to their high nutritional value [134].

Nanoemulsions can also help extend the shelf life and prevent microbial growth in sauces and condiments. This is especially useful in products that contain natural antimicrobial compounds. For example, adding thyme essential oil or rosemary extract as a nanoemulsion to sauces reduces the growth of harmful bacteria and extends the shelf life of the product [63]. A similar result was reported for oregano (Origanum vulgare L. ssp. hirtum) and clove (Eugenia spp.) [135].

3.4 Chocolate and confectionery

Nanoemulsions have found wide applications in the chocolate and confectionery industry due to their distinctive properties. This technology allows for improved texture, reduced fat content, increased shelf life, and even enhanced nutritional value of products. In this context, nanoemulsions play an important role in producing healthier and higher-quality products that are of interest to consumers [64].

Similar to sauces, one of the most important applications of nanoemulsions in chocolate and confectionery is to reduce fat content without compromising taste and

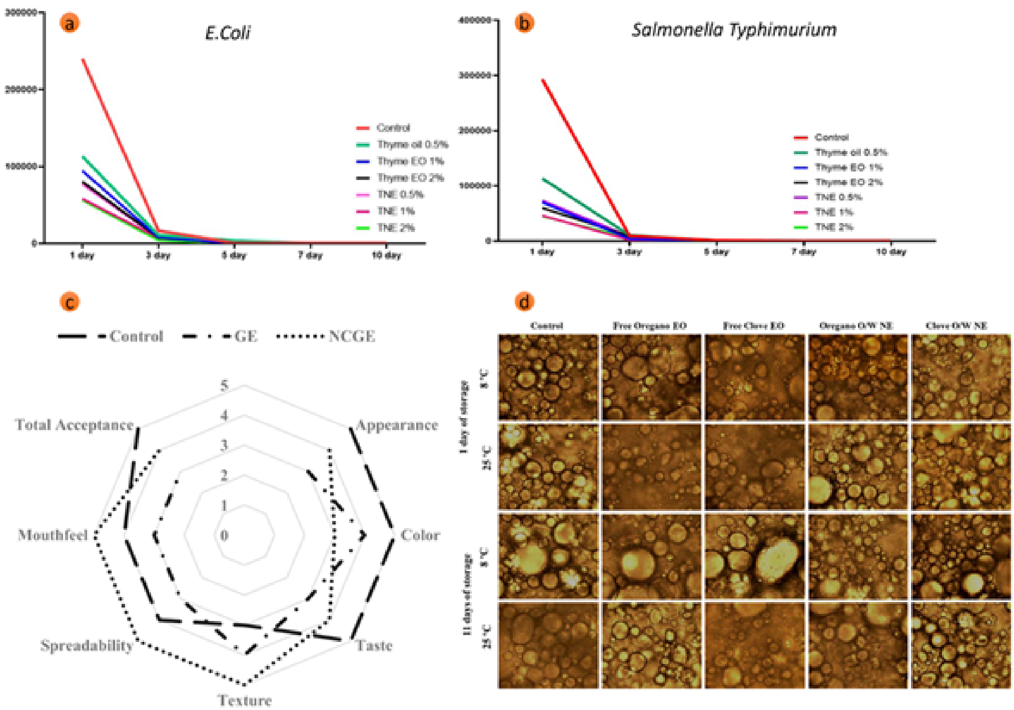

Figure 7. Effect of TEO and TNE on (a) *E.coli* O157:H7 strain (CFU/g) and (b) *Salmonella Typhimurium* strain (CFU/g) during storage of yogurt sample. (c) Spider plot for describing the sensory properties of mayonnaise formulated with garlic extract (GE), nanoemulsion (NEGE), and control [122]. (d) Microphotographs of control salad dressings and salad dressings formulated with free and encapsulated oregano and clove EO after 11 storage days at 8 ° and 25 ° [123].

texture. By using nanoemulsions, very small droplets of oil or water can be distributed throughout the product, which helps create a creamy feel similar to that of full-fat chocolates (Fig. 8 (a)) [136]. This technology helps produce products with fewer calories but with the same appealing taste and texture. For example, low-fat chocolates or cream pastries produced using nanoemulsions, while providing a pleasant taste, are a suitable choice for people looking to reduce fat intake [137].

Another advantage of nanoemulsions is the increased bioavailability of bioactive compounds. This technology allows the addition of compounds such as vitamins, antioxidants, and omega-3 fatty acids to chocolate and pastries [138]. These compounds are evenly dispersed in the product and have a higher absorbability. For example, chocolates enriched with omega-3, which contribute to cardiovascular health, are an example of products that have benefited from this feature [65].

Improved texture and taste are also one of the prominent features of nanoemulsions in this industry. The small particle size in nanoemulsions helps create a smoother and more uniform texture and creates a better mouthfeel [137]. In the production of soft and creamy chocolates or nutty sweets, this technology helps to achieve a uniform structure and prevent breakage.

On the other hand, the longer shelf life of products is also an advantage of using nanoemulsions. Natural antimicrobial compounds dispersed in the product in the form of nanoemulsions can reduce the growth of microorganisms and prevent the oxidation of fats [139]. Chocolates produced with natural extracts such as rosemary in the form of nanoemulsions have a longer shelflife and maintain their taste and texture quality for a longer time [140].

Nanoemulsions also act as carriers for natural flavors and colors. This technology allows for the uniform dispersion of these compounds and improves the stability of the taste and appearance of the products. Chocolates flavored with orange or mint essential oil, or sweets produced with natural colors, are examples of the effective use of nanoemulsions in this field [141]. In addition, nanoemulsions can act as carriers for bioactive compounds such as antioxidants, vitamins, and omega-3 fatty acids, and enhance the nutritional value of the products by increasing the bioavailability of these compounds [138].

In a study, a nanoemulsion containing crocin was added to chocolate, which improved the physicochemical properties and controlled the release of this bioactive compound in the final product [64]. The use of biopolymers such as soy protein concentrate, gum arabic, and pectin in the preparation of nanoemulsions increases the stability and viscosity of the products [142]. These compounds act as natural emulsifiers and prevent phase separation in chocolate products. For example, gum Arabic is used in the production of flavored chocolates due to its ability to stabilize oil-in-water flavoring emulsions without the need for synthetic emulsifiers.

3.5 Baked products

Nanoemulsions also in baked goods, play an important role in improving various product characteristics [143]. This technology can significantly improve the physical, chemical, and nutritional properties of products. Nanoemulsions, which consist of tiny droplets of oil or water in another phase, have a high ability to retain sensitive compounds such as vitamins, antioxidants, and omega-3, and can also help improve the texture, taste, and shelf life of baked goods [143].

One of the important applications of nanoemulsions in the baked goods industry is to improve their texture and structure. In this process, nanoemulsions can act as emulsifiers and help distribute oil or water droplets evenly in the dough. This leads to improved volume and texture of the final product, especially in products such as bread, cakes, and cookies. The use of nanoemulsions containing natural emulsifiers such as lecithin makes the dough more stable, resulting in a softer and more uniform baked product than water.

In addition to improving texture, nanoemulsions also help reduce fat and produce low-calorie products. These emulsions can distribute oil droplets evenly throughout the dough, so that the consumer experiences a similar taste and texture to full-fat products, while the fat content is reduced. For example, in the production of low-fat cakes, nanoemulsions based on vegetable oils can maintain the taste quality while reducing the calorie content of the product (Fig. 8 (b)) [66].

Nanoemulsions also help improve the shelf life of baked products. By being able to carry antibacterial and antioxidant compounds, these emulsions can reduce the growth of microorganisms and the oxidation of fats in baked products [143]. For example, nanoemulsions containing plant extracts such as rosemary or thyme can act as natural preservatives and extend the shelf life of baked goods such as bread.

In addition, nanoemulsions have a high potential to enhance the nutritional value of baked goods. By being able to carry bioactive nutrients such as vitamins, omega-3 fatty acids, and minerals, nanoemulsions can make baked goods a richer source of nutrients. For example, in the production of healthy cookies, nanoemulsions containing omega-3 can help increase the nutritional value of the product and improve the health of the consumer [66].

Nanoemulsions help improve the sensory experience of baked goods due to their ability to preserve flavor and aroma during thermal processing. These emulsions can protect sensitive flavoring agents such as natural extracts from heat so that the taste and aroma of the products are preserved after baking. The use of nanoemulsions containing vanilla extracts in cakes is an example of this application, which preserves the pleasant taste and aroma of the product [67].

Overall, nanoemulsions not only help improve the physical and nutritional properties of baked products but also lead to the production of high-quality and healthier products. This technology can help produce products

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with higher nutritional value and longer shelf life, which will ultimately lead to greater consumer satisfaction.

3.6 Edible oils

To the best of our knowledge, there is not that mush report about the usage of nanoemulsions in the edible oil industry. By the way, based on the previously mentioned information, there is a likelihood of using nanoemulsion in the edible oil industry. In this section, a review has been done about improving edible oils or encapsulating edible oils for other purposes [144, 145].

One of the main advantages of nanoemulsions is the increased stability of oils against oxidation. Edible oils are highly susceptible to oxidation due to the presence of unsaturated fatty acids, which leads to a decrease in quality, changes in taste, and unpleasant odor. Nanoemulsions have solved this problem by reducing the contact of the oil with oxygen and using stabilizing emulsifiers. For example, nanoemulsions containing natural antioxidants such as vitamin E or rosemary extract effectively prevent the oxidation of olive and sunflower oils and increase their shelf life [146].

Another important application of nanoemulsions in edible oils is to increase the bioavailability of fat-soluble nutrients. Similar to diaries and beverages, edible oils carry vitamins A, D, E, and K, as well as omega-3 and omega-6 fatty acids [68]. By encapsulating these bioactive substances, nanoemulsions increase their absorption and bioavailability in the body. For example, oils enriched with DHA and EPA via nanoemulsions are specifically used to improve heart and brain health, especially in food products for children and the elderly [147].

Another application of nanoemulsions in edible oils

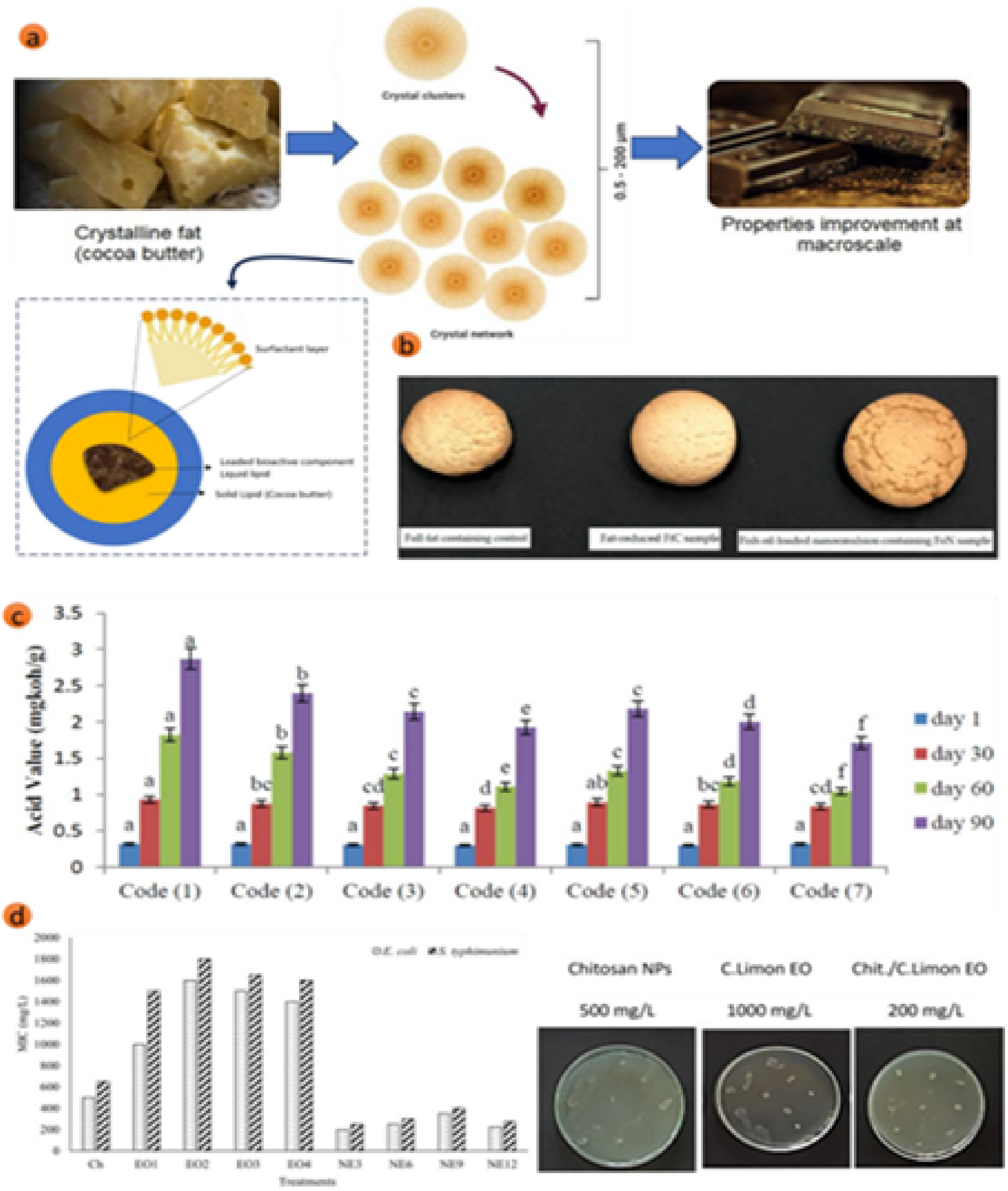

Figure 8. (a) Employing nanoemulsions to improve Cocoa butter [136]. (b) Using nanoemulsion to make Low-Calorie Cookies [66]. (c) Changes in peroxide value of olive oil samples containing GEO and GEON encapsulated with Arabic Gum over time. (d) how the presence of C. Limon EO controlled the growth.

is to reduce fat and calorie intake in food products [144]. Due to the small droplet size in nanoemulsions, a smaller amount of oil can provide the same desired taste and texture [145].

This feature is especially important in the production of frying oils and sauces, which require reduced fat consumption. For example, nanoemulsified frying oils reduce oil consumption while maintaining similar frying properties to conventional oils (Fig. 8 (c)) [148, 149].

In addition, nanoemulsions can help improve the taste and aroma of edible oils. This technology creates a better sensory experience for the consumer by preserving and controlling the release of flavor compounds. For example, it was reported by Farazi et al. that olive oils flavored with plant extracts such as basil and garlic, produced with the help of nanoemulsions, have a longer-lasting flavor and aroma [148].

Regarding water in nanoemulsions like W/O or O/W, the presence of water might be challenging in the application of the final modified edible oil. Over time, various factors such as droplet coalescence, Ostwald ripening, or creaming can cause emulsion instability. This is especially important in edible oils that require long-term stability. So, considering the final application can be used as a factor to choose the best encapsulation approach.

3.7 Meat products

Nanoemulsions, as an innovative technology, play an important role in improving the quality and characteristics of meat products. One of the basic applications of this technology in meat products is to improve their taste and texture [150]. Nanoemulsions help to enhance the taste of products by evenly distributing aromatic oils or natural flavors. Due to the nanometer size of the droplets, these emulsions create a larger contact surface with meat proteins, which causes the flavor to be distributed more evenly throughout the product [151]. Considering this point, the controlled release of flavors helps to maintain the taste of the product for a longer period (Fig. 8 (d)) [152].

Scientists showed that other advantages of nanoemulsions in the production of meat products include the reduction of fat and calories while keeping sensory qualities [150, 69]. The distribution of fat in nanometer dimensions allows the same desirable mouthfeel and sensory properties to be maintained even with a lower amount of fat. By carefully selecting the liquid phase, oil phase, and emulsifiers, nanoemulsions can improve the nutritional properties of meat products and meet the growing demand for healthier food options [69]. This feature is particularly important in the production of low-fat products such as sausages and hamburgers and helps to produce healthier and lower-calorie food products [70]. In addition, nanoemulsions help to increase the shelf life and stability of meat products. These emulsions can prevent the oxidation of fats, which is one of the main factors in quality loss and the development of unpleasant odors [155]. The use of natural antioxidants such as vitamin E or plant extracts in nanoemulsions helps to reduce this problem and reduces the need for the use of artificial preservatives [156].

Nanoemulsions also can carry bioactive and nutritional substances. It was mentioned that nutrients such as omega-3, vitamin D, or polyphenols can be incorporated into nanoemulsions. Scientists used the same approach to add to meat products. These compounds not only increase the nutritional value of the products but also contribute to the health of the consumer [157]. For example, adding omega-3s can help reduce the risk of heart disease and boost brain function [71]. In addition, scientists confirmed that nanoemulsions also help retain moisture in meat products. In products such as ham and sausage, where moisture retention and prevention of drying are important, the use of W/O nanoemulsions can help maintain quality by improving texture and preventing drying [157].

New research also shows that nanoemulsions can be effective in improving the stability of meat products against environmental changes, such as temperature and humidity [155, 158]. This is especially important in long-term supply chains or in areas where environmental conditions are not controlled. Another development in this field is the use of nanoemulsions in plant-based meat-like products [159]. These products benefit from nanoemulsions due to the need for high-quality fats and bioactive compounds to simulate the taste and texture of meat. Nanoemulsions can also be an alternative to synthetic additives in meat products, and by using plant extracts and natural compounds, they not only help with taste and shelf life but also have a positive impact on consumer health [160]. Regarding the discussed features, it can be claimed that nanoemulsions are one of the most widely used technologies in the meat and meat products industry, and they play an important role in producing healthier and higher-quality food products.

3.8 Edible coatings

Edible coatings based on nanoemulsions are recognized as an advanced technology in the food industry that has a significant impact on the quality and stability of food [161]. These coatings play an important protective role against external factors such as moisture, oxygen, and microbial agents by creating a thin and biodegradable layer on the surface of food. The use of nanoemulsions in these coatings has increased mechanical properties, improved shelf life, and reduced food spoilage [162].

One of the key features of nanoemulsions in edible coatings is their high ability to carry bioactive substances [161]. Compounds such as vitamins, omega-3 fatty acids, minerals, and antimicrobial compounds can be uniformly introduced into the coatings with the help of nanoemulsions (Fig. 9 (a)) [153]. For example, a wide range of essential oils including tea tree oil, rosemary, lavender, cinnamon, etc in nanoemulsions can enhance the antimicrobial properties of coatings and prevent the growth of harmful microorganisms [162]. This feature is particularly important for fresh foods such as fruits and

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vegetables because nanoemulsion coatings can maintain the freshness and quality of products by controlling gas exchange and preventing oxidation (Fig. 9 (b)) [163]. Figure 9 (c), shows several applications of nanoemulsions in food sectors.

Also in meat and dairy products, edible nanoemulsion coatings help to improve shelf life and reduce fat oxidation [156]. For example, using rosemary and Curcumin nanoemulsions in processed meats such as carbonado chicken and chicken fillet respectively, coatings could prevent the surface of the products from drying out and preserve their texture and flavor by reducing moisture transfer [156, 164]. The edible coating also are used in diary products. It was reported that an edible coating integrated with oregano essential oil nanoemulsion could inhibit the growth of fungi and extend the shelf life of cheese [165].

Edible coatings based on nanoemulsions not only improve functional properties but are also an environmentally preferable alternative to plastic packaging compared to metal-based nanoparticles. These coatings reduce the environmental impact by using natural and biodegradable compounds [72]. In addition, it is hypothesized that due to the edible nature of these coatings, consumers do not need to clean or remove them before consuming the food, which has led to greater product appeal.

Recent advances in the field of nanoemulsions have enabled the development of coatings with more specific properties and better performance. For example, the combination of nanoemulsions containing chitosan, vegetable oils, and natural antioxidants not only enhances antimicrobial properties but also helps to increase shelf life and reduce the use of artificial preservatives in food [73]. These approaches play an important role in improving the quality, safety, and sustainability of food and have been considered as one of the innovative solutions in the food industry.

3.9 Food packaging

Food packaging is a critical part of the supply chain that has a significant impact on food safety, quality, and shelf life. Nanoemulsions have been able to provide innovative solutions to improve food packaging systems. This technology has wide applications in creating antimicrobial and antioxidant packaging, reducing gas and moisture permeability, and developing active and smart packaging [33]. This advanced technology allows for the controlled transport and release of antimicrobial active compounds and helps reduce the growth of harmful microorganisms such as bacteria, fungi, and molds. Packaging containing antimicrobial nanoemulsions is used in a variety of food industries such as meat, fish, dairy products,

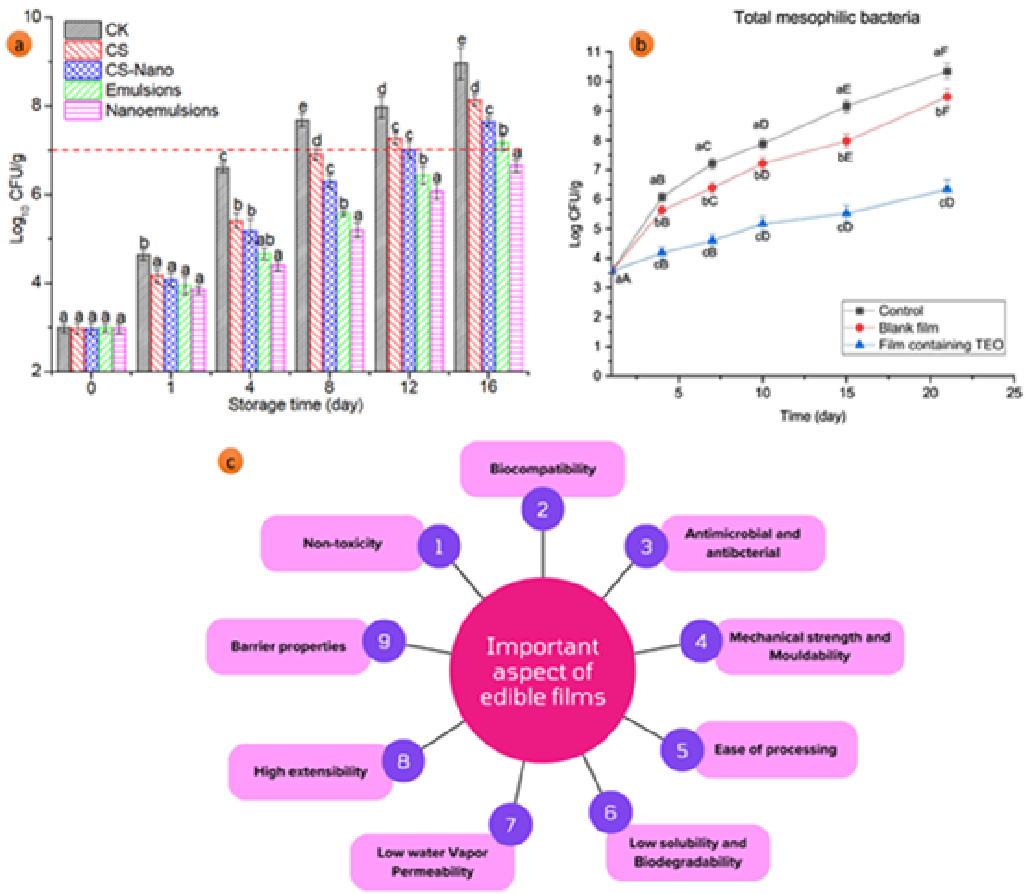

Figure 9. (a) Preservation performance indices of silvery pomfret (Pampus argenteus) during refrigerated storage [153]. (b) Effect of the edible coatings containing TEO nanoemulsion on the microbial growth (Log CFU/g) of total mesophilic bacteria psychrotrophic count [154]. (c) main properties of edible films. This can be considered for food packaging systems too.

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and fruits and vegetables [74]. For example, polymer films containing thyme oil nanoemulsions have been able to increase the shelf life of fresh meat and prevent the growth of harmful bacteria such as Escherichia coli [166]. This technology is also used in fruit packaging such as strawberries and grapes to reduce spoilage and maintain product quality [75].

3.9.1 Development of smart and active packaging

Nanoemulsions have found wide application as an innovative technology in smart and active food packaging. These types of packaging can actively influence environmental changes and offer new features such as sensors of quality changes, resistance to microorganisms, and increased shelf life of food [16].

One of the main applications of nanoemulsions in smart packaging is to increase the stability and preservation of food. These emulsions can store bioactive compounds, which in active packaging improves the shelf life and quality of products. For example, nanoemulsions containing antioxidants or antimicrobial substances can prevent lipid oxidation and the growth of microorganisms, thus increasing the quality and shelf life of food [76]. This allows active packaging to preserve the taste, texture, and appearance of food for a longer period.

Nanoemulsions can also act as smart sensors in active packaging. These sensors can detect and respond to environmental changes such as pH, temperature, or gas composition inside the package [167]. For example, nanoemulsions containing pH-sensitive compounds can change color or exhibit other properties when the pH in the package changes (which usually occurs due to food spoilage) [168]. This property allows the consumer or manufacturer to quickly learn about the quality conditions of the food and use it to make optimal decisions.

In addition, nanoemulsions can help improve the mechanical and barrier properties of polymeric materials used in smart packaging [169]. It was reported that nanoemulsions can help strengthen the packaging structure while improving its antimicrobial and antioxidant properties. This combination allows the packaging to not only protect the food but also actively control the storage conditions and improve the shelf life of the products.

3.9.2 Improving antimicrobial properties

Nanoemulsions can provide antimicrobial properties to polymer packaging. This capability is achieved by adding active ingredients such as essential oils or plant extracts such as thyme and clove to nanoemulsions [74]. These compounds reduce the growth of harmful microorganisms by controlled release from the packaging surface and delay food spoilage. The bioactive compounds present in nanoemulsions are the main factor in creating antimicrobial properties [16]. Essential oils such as thyme, clove, and cinnamon oil, as well as metal nanoparticles such as silver, copper, and zinc oxide, are among these compounds [33]. These materials can interact with the cellular structure of microorganisms and prevent their growth. For example, thyme oil has high activity in killing bacteria and fungi due to its thymol and carvacrol (Fig. 9 (b)) [154]. Nanoemulsions, by penetrating the cell walls of microorganisms, destroy their cell membranes and lead to the leakage of vital cell components. This process disrupts cell metabolism and ultimately kills microorganisms [76].

The strength of the antimicrobial properties of nanoemulsions is affected by various factors. Small droplet size increases the contact surface with microorganisms and increases effectiveness. The type and concentration of active ingredients also play an important role; for example, thyme [20, 77, 78].

Oil shows stronger antimicrobial activity at higher concentrations [60, 170]. Emulsifiers used in the manufacture of nanoemulsions can have a significant impact on the stability and antimicrobial activity. For example, polysorbates (tween) or lecithins can enhance the activity of essential oils [33]. On the other hand, the type of essential oils as well as their concentration in the nanoemulsion affect the level of antimicrobial activity. Higher concentrations usually have stronger activity, but compatibility with packaging and food should also be considered [171].

The pH of the environment has been reported to have a significant effect on the activity of antimicrobial compounds. This effect is because many essential oils have been reported to be more active in acidic environments [172]. Essential oils, like many other active ingredients, can be temperature-sensitive, meaning that temperature can affect the controlled release of active ingredients and the effectiveness of antimicrobial properties [172, 173]. It was also confirmed that packages containing nanoemulsions are usually more stable at lower temperatures. In other words, high temperatures lead to damage to the active ingredients of the nanoemulsions.

3.9.3 Reducing gas and moisture permeability

One of the challenges in food packaging is preventing the ingress of oxygen and moisture (barrier properties), which can accelerate spoilage and product quality changes. Nanoemulsions play an important role in the development of polymeric films for food packaging, especially in reducing gas and moisture permeability, which helps increase the shelf life and maintain the quality of the food [174].

The first effect of nanoemulsions in this type of film is due to the property of reducing the droplet size and creating a nanometric structure. Due to the very small size of the droplets in nanoemulsions, these emulsions can create a more uniform and dense layer on the surface of the packaging [175]. These layers can effectively prevent the penetration of gases and moisture into or out of the packaging. For example, nanoemulsions that contain biocompatible polymers can effectively prevent the oxygenation of food, which is especially important in preserving the taste and color of oxygen-sensitive foods such as fruits and vegetables [176].

The second important effect of nanoemulsions in polymer packaging is to improve the mechanical and physical properties of the films. Nanoemulsions can improve the mechanical properties of polymer materials such as flexibility, tensile strength, and tear resistance [177]. These properties make the packaging more durable and resistant to physical environmental changes, thus significantly increasing the resistance to moisture and gas permeation.

3.9.4 Increasing antioxidant properties

Foods are susceptible to spoilage due to oxidative reactions due to the presence of fats and other compounds sensitive to oxidation. These reactions reduce the quality, change the color and taste of foods, and ultimately lead to a decrease in their shelf life [155]. To prevent this process, antioxidant compounds are used in foods [178]. One of the new approaches in food packaging is the production of packaging systems with the ability to control oxidation in foods. These systems use compounds with antioxidant properties that are also releasable. Nanoemulsions have antioxidant properties that prevent the oxidation of fats in foods maintain the quality of the product and are also able to be released [79].

Nanoemulsions have emerged as promising candidates for the development of novel food packaging systems with enhanced antioxidant properties. The key to their antioxidant activity lies first in the active ingredients present in the oil phase (essential oils) and then in the incorporation of various antioxidant compounds into their structure [80]. These compounds can originate from natural sources such as phenolic compounds (flavonoids, phenolic acids, tannins), terpenoids (limonene, carvacrol, thymol), and vitamins (C and E) or synthetic sources such as BHA, BHT, and TBHQ [179]. In addition, antioxidant-rich plant extracts can also be effectively encapsulated within nanoemulsions.

By incorporating these antioxidants into nanoemulsions, several advantages are achieved. First, the nanoemulsion structure itself acts as a protective barrier, protecting the antioxidants from degradation caused by factors such as light, heat, and oxygen [149]. This increased stability ensures that the antioxidants remain active for a longer period, thereby increasing the shelf life of the food product [180]. Secondly, nanoemulsions can be designed to release antioxidants in a controlled manner, ensuring sustained antioxidant activity in food packaging. This controlled release mechanism allows for continuous protection against oxidative spoilage [149].

In addition, the small size of nanoemulsion droplets significantly increases their surface area, facilitating effective contact with the food product. This increased surface area increases the bioavailability of antioxidants, enabling them to effectively interact with and neutralize reactive oxygen species (ROS) in the food matrix. By scavenging these free radicals, antioxidants prevent the oxidation of lipids, proteins, and other sensitive food components, thereby preserving the quality and freshness of food [21]. Consequently, the antioxidant activity of nanoemulsion-based food packaging systems is primarily attributed to the presence of main ingredients in essential oils and then antioxidant compounds encapsulated in their structure.

3.9.5 Increasing environmental compatibility

The use of nanoemulsions in food packaging has increasingly attracted attention, as this technology can contribute to their biodegradable properties. Nanoemulsions can have a significant impact on the environment due to their natural and biodegradable components [181]. These properties are especially important in the food packaging industry, where the use of plastics and non-biodegradable materials is still common.

One of the main advantages of using nanoemulsions in food packaging is their use in combination with polymers (natural and synthetic), which increases the degradability of these packages [182]. Polymers such as chitosan, starch, and proteins are not only used in the production of polymer coatings but also nanoemulsions as emulsifiers and enhance the functional properties of food packaging [183, 184]. Adding biodegradable nanoemulsions to polymer packaging can reduce the environmental impact of plastics [185]. The use of natural polymers such as PLA (polylactic acid) or PLGA (Poly Lactic-co-Glycolic Acid) together with natural nanoemulsions leads to the production of environmentally friendly packaging [185, 186]. In addition to maintaining the quality of food, these types of packaging are also recyclable and biodegradable. Besides, these nanoemulsions can facilitate the degradation process of the packaging by increasing water absorption and improving interactions with microorganisms.

Nanoemulsions can also effectively improve the structure of biodegradable polymers. In this technology, the oil phase and the water phase are placed together at the nanoscale, which improves the uniform distribution of additives within the polymer matrix [187]. As a result, microorganisms will be able to degrade the packaging uniformly and effectively. These nanoemulsions can also change the hydrophilic properties of the packaging, which accelerates the degradation process by microorganisms and enzymes. In addition, nanoemulsions can help the biodegradation process by adding bioactive compounds, such as natural essential oils, antioxidants, and antimicrobials [188]. Nanoemulsions can effectively replace chemical additives in food packaging. This reduces the need for synthetic chemicals and improves the environmental compatibility of the packaging. In this way, nanoemulsions play a vital role in the development of sustainable and environmentally friendly packaging.

4. Functions of nanoemulsions

As previously discussed, nanoemulsions are made of two phases: oil and water. Bioactive substances such as plant essential oils (such as thymol, carvacrol, and eugenol), polyphenols, organic acids (such as acetic or citric acid), and compounds such as silver nanoparticles or zinc oxide are used as active components in the oil phase of nanoemulsions which cause different functionality for nanoemulsions. In this section, the main functions of

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nanoemulsions are discussed focusing on the oily phase, particularly essential oils.

4.1 Antibacterial

Nanoemulsions act through several antimicrobial mechanisms. i) Penetration into cell membranes: The nanometer size of droplets in nanoemulsions increases their permeability to the bacterial cell membrane. This penetration causes cell membrane disruption, leakage of cellular contents, and cell death. ii) Induction of oxidative reactions: Some compounds in nanoemulsions (such as essential oils or metal nanoparticles) stimulate the production of reactive oxygen species (ROS), which can damage cellular DNA, proteins, and lipids. iii) Disruption of cellular metabolism: Bioactive compounds in nanoemulsions can inactivate vital enzymes of microorganisms and disrupt their metabolism [10].

Essential oils have powerful antimicrobial properties due to their diverse bioactive compounds, such as terpenes, phenols, alcohols, and aldehydes [162]. These oils are extracted from plants and can affect microbial cells through various mechanisms. One of their main mechanisms is the destruction of the cell membrane of microorganisms. Compounds such as carvacrol, thymol, and eugenol can penetrate the cell membrane and disrupt its lipid structure. This disruption causes the leakage of internal cell materials such as ions and proteins, ultimately leading to cell death [159].

In addition, essential oils can interfere with the function of enzymes and metabolic processes in microbial cells. For example, phenolic compounds can inactivate vital enzymes involved in energy production or DNA repair. These oils also increase the production of reactive oxygen species (ROS), molecules that can damage DNA, proteins, and cellular lipids, preventing the growth and survival of microbes [189].

The antimicrobial power of essential oils depends on their specific chemical compounds. Compounds such as carvacrol and thymol are most effective due to their specific chemical structure. The type of microorganism also plays a role in this effect; gram-positive bacteria are more sensitive due to the simpler structure of their cell walls, while gram-negative bacteria are more resistant due to their lipopolysaccharide layer. Environmental conditions such as low pH and high temperature can also enhance the antimicrobial effect of these oils [190].

Essential oils have a variety of applications in different industries. As discussed previously, in the food industry, they are used to increase the shelf life of foods such as meat and vegetables directly or indirectly (packaging). In active packaging and edible coatings, these oils help reduce the growth of microorganisms. In the pharmaceutical industry, they have been considered a suitable alternative to antibiotics due to their strong antibacterial and antifungal effects. In the cosmetic industry, these compounds are also used in disinfectants and skin care products (nicely reviewed by Jilani [191]).

4.2 Antioxidant

Essential oils have strong antioxidant properties due to the presence of bioactive compounds, making them ideal for various industrial applications. These properties are due to the presence of molecules such as phenols, flavonoids, terpenes, and carotenoids. These compounds can prevent oxidative damage by neutralizing free radicals and inhibiting lipid peroxidation. Free radicals are unstable and reactive molecules that, if left unchecked, damage cells, proteins, and DNA, leading to chronic diseases and premature aging [133].

One of the most important antioxidant mechanisms of essential oils is the neutralization of free radicals. Phenolic compounds such as thymol, eugenol, and carvacrol react directly with free radicals and convert them into stable compounds [152]. This process prevents the oxidation of fats, proteins, and other biomolecules, preserving the quality of food and biological systems [152, 166]. In addition, essential oils can reduce lipid peroxidation, which is a major factor in the deterioration of food quality and the development of undesirable flavors in fats and oils [146]. Another mechanism is the inhibition of reactive oxygen species (ROS). (Figs. 10 (a), 10 (b))

Antioxidant compounds present in essential oils. Some essential oils can even regenerate natural antioxidants such as vitamins C and E and increase their effectiveness. This feature makes these oils not only help maintain the health of the biological system but also effective in food and pharmaceutical applications [180, 189]. The antioxidant activity of essential oils is affected by several factors. The type of chemical compounds plays an important role; for example, eugenol in cloves and thymol in thyme have high antioxidant activity due to their phenolic structure. Also, the method of extraction of these oils and environmental conditions such as pH and temperature affect the level and efficiency of antioxidant activity [80].

4.3 Sensitivity

Sensitivity in this section refers to the usage of nanoemulsions in food packaging systems and reacting to environmental changes like pH, specific gases, moisture, etc. Nanoemulsions play an important role in improving the performance of smart and active packaging systems.

One of the main applications of nanoemulsions in food packaging is the ability to respond to pH changes. Nanoemulsions containing pH-sensitive molecules, such as dyes or natural antioxidants, can detect pH changes and inform consumers about the freshness or spoilage of food by changing color or other characteristics [192]. For example, in the packaging of fresh meat, an increase in pH caused by protein degradation can be easily detected by these nanoemulsions. In another study, pistachio peel anthocyanin nanoemulsion was used to detect spoilage of shrimps packed by halochromic films based on gelatin/pectin [193]. Anthocyanins are a class of plant pigments responsible for the vibrant colors observed in fruits, vegetables, and flowers, ranging from

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red to purple and blue. These pigments exhibit a remarkable pH-dependent color change phenomenon. In acidic environments, anthocyanins primarily exist in the flavylium cation form, which typically appears red. As the pH increases, the flavylium cation loses a proton, forming a colorless or pale yellow Carbinol pseudobase. Further increases in pH lead to the formation of chalcone and quinoidal base forms, which typically exhibit blue or purple colors. These color changes are primarily attributed to the pH-dependent equilibrium between different molecular forms of the anthocyanin molecule. The protonation and deprotonation of the anthocyanin molecule alter its electronic structure, consequently affecting the wavelengths of light it absorbs and, thus, the color perceived by the human eye [194].

Nanoemulsions can also affect the changes in the concentration of specific gases, such as oxygen, carbon dioxide, ethylene, or ammonia [195]. For example, in the packaging of oxidation-sensitive foods, nanoemulsions embedded in the polymeric film can alter the barrier properties and prevent the diffusion of gases [196]. This feature can delay food spoilage. It is hypothesized that after the reaction of gases with nanoemulsion, color changes happen in the film color. Also, the detection of ammonia gas, which is caused by protein spoilage, is useful in meat and fish packaging.

With this approach, humidity control and management is another capability of nanoemulsions in food packaging

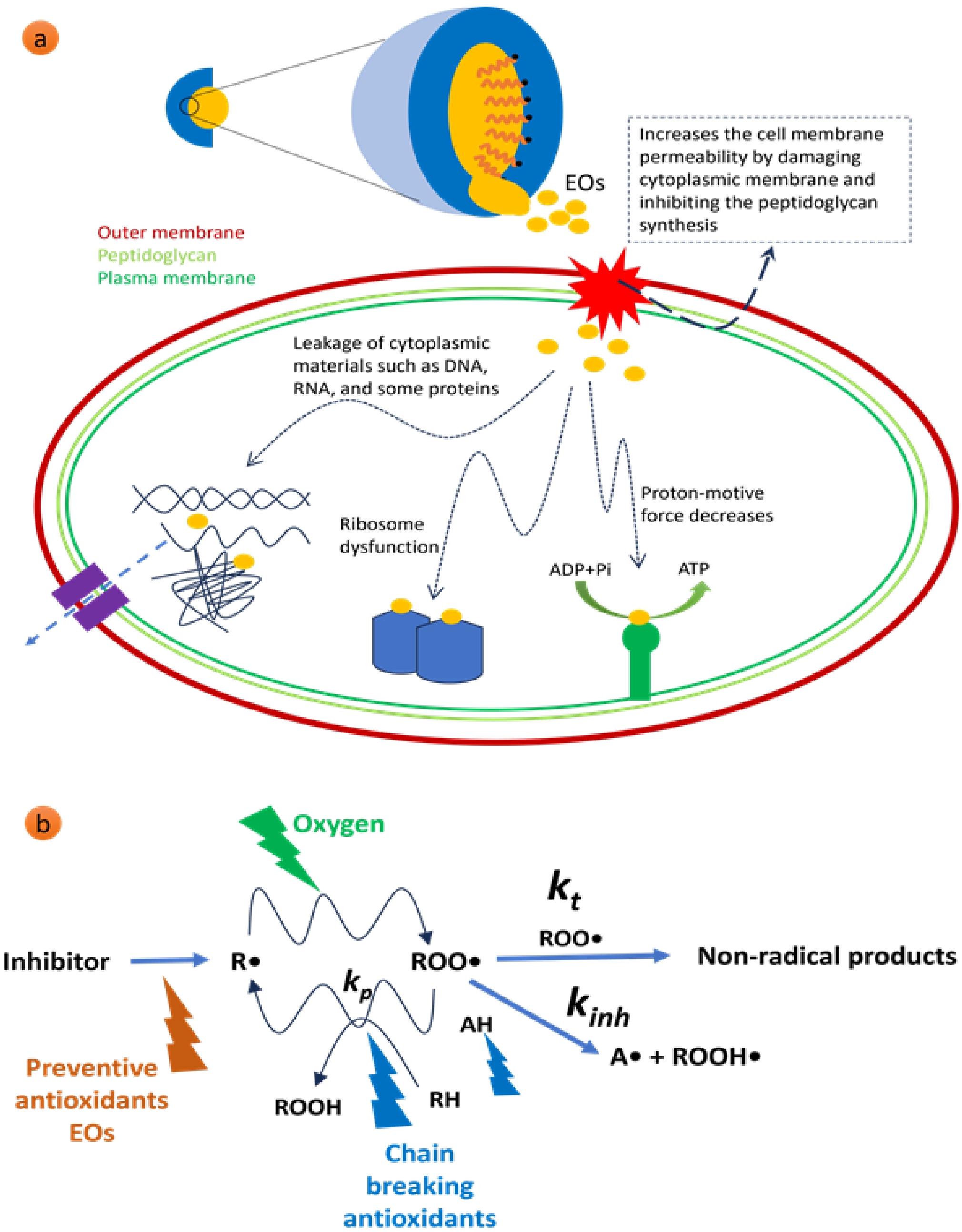

Figure 10. Schematic illustration of different nanomaterials designed for treating OP, (a) nanomaterials for regulating bone remodelling, (b) nanomaterials for therapeutic delivery, (c) combinatorial nanoengineered approach, (d) nanoengineered biomaterials designed for accelerated bone regeneration.

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[197]. Emulsions containing moisture-absorbing materials like nanocellulose can react with excess moisture inside the package and prevent mold growth or deterioration of food quality [198]. This feature is very effective for packaging products such as biscuits, chips, and other dry products.

Nanoemulsions also allow for the controlled release of active ingredients such as antioxidants or antimicrobials [199]. This capability allows food packaging to gradually release its active ingredients under specific environmental conditions, thereby maintaining the quality and safety of the food.

4.4 Strength

Nanoemulsions also showed their potential to affect the mechanical properties of packaging coatings. The positive or negative impact might be affected by the concentration of nanoemulsion. These effects, resulting from the precise combination of different phases of the nanoemulsion and nanoparticles in the coating structure, can enhance properties such as tensile strength, flexibility, and structural stability [200].

One of the main effects of nanoemulsions is to improve the tensile strength and flexibility of coatings. The presence of nanoparticles or active materials in the nanoemulsion structure creates a coordinated network in the polymer matrix that increases the tensile strength and flexibility of the coating. For example, nanoemulsions containing silicate or clay nanoparticles prevent the cracking and tearing of coatings by reinforcing the polymer chains, and this feature is especially important in sensitive packaging [201]. Increased scratch and fracture resistance is another advantage of nanoemulsions. The inorganic or polymer nanoparticles in nanoemulsions prevent the coatings from being vulnerable to abrasion, scratching, and fracture [202].

Nanoemulsions also play an important role in reducing the permeability of coatings and improving their structural integrity. The layered structure and uniform dispersion of nanoparticles in the emulsion create strong barriers to gas and moisture penetration and reduce weak spots and voids [202]. This property is very valuable in food packaging systems that require a high shelf life.

Apart from the impact of nanoemulsions on food packaging systems, the direct addition of nanoemulsions to food has significant effects on the texture of products and can improve their quality and sensory properties. These effects are mainly due to the small droplet size, high contact surface area, and uniform distribution of nanoemulsions in the food matrix, which leads to softer, more stable, and more palatable textures [203, 204].

One of the most important effects of nanoemulsions is the improvement of the smoothness and uniformity of the texture of foods [205]. Studies showed that due to the small droplet size in nanoemulsions, fat or water is distributed more evenly throughout the food structure. This feature makes products such as cakes and desserts have a softer and more attractive texture and reduces dry or hard spots in the product [206]. Nanoemulsions can reduce the stickiness of foods and create a better sensory experience. For example, in products such as sauces or chewing gum, the presence of nanoemulsions reduces the adhesion of the product to the mouth or surfaces by reducing the surface tension between different ingredients [206, 207]. This feature is especially important in products with lower fat content, which are usually stickier.

The stability of the food structure is also increased by the addition of nanoemulsions. Nanoemulsion droplets can create a regular network in the product, which prevents phase separation and gives the product a uniform appearance [208]. In beverages, this feature helps prevent sedimentation of the ingredients, and in solid products such as cheeses, it prevents crumbling or cracking.

Another effect of nanoemulsions is to increase the volume and reduce the calorie content of the food [209]. This feature is especially useful in products such as cakes and breads, where volume and lightness of texture are important [66]. This is very useful for producing healthier products, such as low-fat cakes.

Nanoemulsions can also increase the creaminess and consistency of food products such as ice cream and yogurt [127, 208, 210]. The small size of fat droplets in nanoemulsions allows for a more uniform distribution of fat, resulting in a more desirable consistency and a better sensory experience [210]. In addition, the retention of moisture in food is another positive effect of nanoemulsions. In products such as bread and processed meats, nanoemulsions prevent the product from drying out and maintain its quality during storage [211]. Overall, nanoemulsions have a significant impact on improving the texture of food by reducing surface tension, increasing structural stability, and evenly distributing active ingredients, and play an important role in improving quality and consumer acceptance.

5. Limitations and challenges

Despite the numerous advantages of nanoemulsions, the application of nanoemulsions in the food industry still faces several challenges and problems that can limit their development and widespread use. These challenges can be examined in areas such as production, stability, safety, and consumer acceptance [212].

One of the most important challenges is the high cost of producing nanoemulsions. Technologies such as high-pressure homogenization, ultrasonication, and microfluidization require advanced equipment and a lot of energy to produce nanoemulsions. Also, it is difficult to achieve uniform and stable droplet size on an industrial scale. Droplet size plays an important role in the stability and performance of nanoemulsions, and deviation from the standard range can lead to phase separation. In addition, the selection of appropriate raw materials for the production of nanoemulsions, especially emulsifiers, must be compatible with health and safety regulations, which is a challenge in itself [213].

Another challenge is the stability and storage of nanoemulsions. These structures are usually sensitive to

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environmental changes such as temperature, pH, and the presence of ions, and this sensitivity can lead to instability and phase separation [18]. In particular, oil-containing nanoemulsions are prone to lipid oxidation due to the large surface area of the droplets, which affects the quality and shelf life of the product. Also, the stability of these systems over time and under long-term storage conditions is a fundamental issue that needs to be addressed.

On the other hand, safety and consumer acceptance are another major concern. The long-term effects of nanoemulsion consumption on human health are not yet fully understood, and this could affect consumer confidence. In addition, the lack of transparency in the labeling of products containing nanoemulsions and the limited consumer awareness of their benefits reduce the acceptance of this technology. In some cultures, the use of new technologies in food may also be difficult due to psychological or cultural concerns.

Another limitation is inadequate regulations and standards [214]. Many countries still do not have detailed laws and regulations for the production, labeling, and use of nanoemulsions. Manufacturers also need to ensure that their products comply with global and regional food safety regulations, which can be time-consuming and costly.

Finally, compatibility with complex food formulations and matrices is another challenge. The addition of nanoemulsions may alter the taste, texture, or appearance of the food, which may not be pleasing to consumers. Furthermore, the performance of nanoemulsions in complex food matrices may be reduced because other components in these systems can negatively affect their efficacy [151].

To overcome these challenges, further research into the production of sustainable and cost-effective nanoemulsions, comprehensive safety assessments, and the development of clear regulations are essential. In addition, educating consumers about the benefits of this technology can help to achieve wider adoption. The performance of nanoemulsions under industrial-scale conditions often deviates significantly from lab-scale formulations due to differences in equipment, processing volumes, and precise parameter control. At the lab scale, fine-tuning of parameters (e.g., homogenization pressure, number of passes) is easier, allowing for optimal droplet size and stability. However, scaling up requires larger, more robust equipment (e.g., industrial homogenizers), which may not replicate the exact shear forces or energy dissipation profiles of lab-scale devices. Challenges include maintaining consistent droplet size distribution, preventing aggregation during large-volume processing, ensuring cost-effectiveness of raw materials, and managing energy consumption. Therefore, extensive pilot-scale trials and process optimization are critical to translate successful lab-scale formulations to industrially viable nanoemulsion products [215, 216, 217, 34].

6. Conclusions and future perspectives

In this study, it was tried to provide an update on the role of nanoemulsions in the food industry. The main was to cover distinct and not fully covered subjects related to nanoemulsions and their applications in food science. Nanoemulsions are employed to improve both food matrix and food packaging systems. Regarding the food matrix, it was observed that mostly all types of foods including meat, vegetables, fruits, diaries, beverages, and even processed foods like sausage, hamburger, mints, and marinates, etc can be affected by employing different nanoemulsions. This impact comprises changes in physical properties, taste, rheological properties, chemical stability, digestibility, Heat Stability, Color, flavor, Moisture Absorption or Loss, microorganism growth, and Shelf Life. Regarding the packaging systems, nanoemulsion demonstrated a high potential in developing active food packaging and coatings. In this case, the presence of nanoemulsion showed a good improvement in antibacterial activity, mechanical strength, antioxidant activity, and biodegradability. They also showed good potential in developing smart food packaging in combination with other ingredients like inorganic particles, pH-sensitive colors, essential oils, metal-based nanoparticles, and chemical ingredients.

Based on our survey, nanoemulsions still face some challenges in specific research areas which entails more research studies. There was no evidence of the impact of nanoemulsion on the food matrix or food packaging system during a long time similar to a real product (like from production to consumption) which might be from one day to more than six months. It would be a great idea if the quality of a food packaging system developed by nanoemulsions be studied after 1-6 months of production.

Authors contributions
Authors have contributed equally in preparing and writing the manuscript.

Availability of data and materials
The authors declare that the data supporting the findings of this study are available within the paper.

Conflict of interests
The authors assert that they do not have any identifiable conflicting financial interests or personal relationships that might be perceived to influence the work presented in this paper.

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