Wiley
Journal of Food Biochemistry
Volume 2025, Article ID 4091024, 12 pages
https://doi.org/10.1155/jfbc/4091024

WILEY

Research Article

The Characterization of Nanoliposomes of Oleaster (*Elaeagnus angustifolia*) Extract and Their Effect on the Oxidative Stability of Low-Fat Mayonnaise

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Received 26 April 2024; Accepted 17 January 2025

Academic Editor: Mohamed El Yamani

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Due to the high fat content and the use of synthetic antioxidants in the mayonnaise formulation, in this study, nanoliposomes (NLPs) of oleaster (*Elaeagnus angustifolia* L.) extract were used, and the physical and structural properties of the mayonnaise were investigated. In the research's second phase, the quince seed mucilage (QSM) and soybean protein isolate (SPI) at concentrations of 1% and 2% were used in mayonnaise as a fat substitute. The NLPs were added to the low-fat mayonnaise formulation at concentrations of 0.5%, 0.75%, 1%, 1.5%, and 2%. Two samples without additives and TBHQ (200 ppm) were produced as a control. The samples were kept at 4°C for 6 months. The highest encapsulation efficiency, zeta potential, polydispersity index (PDI), antioxidant activity, and the smallest particle size were observed in the NLP-500 NLP ($p < 0.05$). In differential scanning calorimetry and thermogravimetry thermograms, NLP-1000 showed the lowest thermal stability and weight loss. Scanning electron microscope (SEM) and transmission electron microscope (TEM) images showed that NLPs are spherical and homogeneous. Fourier transform infrared spectroscopy (FTIR) analysis confirmed the entrapment of extract in phospholipid layers and a slight change in the peaks. All control treatments showed the highest fat content and pH ($p < 0.05$). TBHQ and treatments containing 2% QSM + SPI and 2% NLP (Sample 10) and 1% QSM + SPI and 2% NLP (Sample 5) showed the lowest acid, peroxide, thiobarbituric acid, and totox values during storage ($p < 0.05$). Therefore, NLPs containing oleaster extract can prevent the oxidation in mayonnaise.

Keywords: low-fat mayonnaise; nanoliposome; oleaster (*Elaeagnus angustifolia* L.); quince seed mucilage; soy protein isolate

1. Introduction

Mayonnaise is a type of oil in water emulsion and a colloidal system that is made from vegetable oils, vinegar, lemon juice, citric acid, egg yolk, and some permitted additives [1]. Emulsions usually contain oil, water, and a thickener/emulsifier. Mayonnaise consists of oil, water, egg yolk, salt, sugar, sweetener, and other optional ingredients. Each of these ingredients, depending on their quantity and quality, determines the qualitative characteristics of the emulsion [2]. Mayonnaise is one of the types of sauces with high fat content, which must be enriched with fat substitutes. One fat substitute is mucilage, which is obtained from various sources [3]. Quince seed mucilage (QSM) is 20%–22% of the weight of the seed. Quince seed from the Rosaceae family has nutritional and medicinal value in the Middle East, South Africa, and Central Europe [4]. Protein-based fat substitutes are usually extracted from egg, milk, whey, or vegetable

proteins such as soybean protein. Soy protein isolate (SPI) is the purest form of protein from soybean with protein content of 90% [5]. On the other hand, oxidation in mayonnaise occurs due to the high oil content and the nature of the raw materials such as the unsaturated nature of the oil. The oxidation mechanism in multiphase systems is more complex than single-phase systems. Despite the oxidation of bulk oils, the mechanism of oxidation in emulsions such as mayonnaise is not completely understood. The emulsions have three phases: aqueous phase, oil phase, and interfacial phase, and oxidation will occur in one of these three phases. In oil–water emulsions, lipid oxidation reactions usually initiate at the oil–water interface, where prooxidants in the continuous phase can come into close contact with hydroperoxides located on the droplet surface. Oxidation occurs faster in emulsions compared to bulk oil [1]. Oxidation leads to the production of toxic products, unpleasant tastes, color changes, and reduced shelf life. Therefore, preventing it has an important effect on the shelf life of mayonnaise [6]. One of the common methods of delaying lipids oxidation is antioxidants. Antioxidants slow down the rate of oxidation reactions through various reactions such as slowing down the initiation and propagation phase, inhibiting catalysts, stabilizing hydroperoxide, and destroying the radicals but it seems that most antioxidants reduce the rate of autoxidation by combining with free radicals [1]. Lipid oxidation in mayonnaise is driven by a chain of free radicals and is accelerated by the presence of metal ions. The reaction between the alkyl radical (L·) and molecular oxygen forms the peroxyl radical (LOO·), which accelerates lipid peroxidation by reacting with unsaturated lipids. While at neutral pH, the peroxidant iron ions are tightly bound to the negatively charged phosvitin, and at the acidic pH of mayonnaise, the weaker binding makes the iron ions available as a catalyst for lipid oxidation [7]. Since synthetic antioxidants have adverse effects on health, the attention of consumers and researchers has been drawn to natural antioxidants [8]. Antioxidants are compounds that prevent or delay oxidation. Spices and herbs are excellent sources of antioxidants used to preserve food. Even essential oils with low antioxidant activity can act as an intermediate in the formation of other compounds that have antioxidant activity, including linalool. Linalool is used as an intermediate in the synthesis of vitamin E, which has strong antioxidant activity [9]. The antioxidant mechanism of phenolic compounds in fats is not yet fully understood. One of the best sources of natural antioxidants is the phenolic compounds of essential oils and plant extracts. Oleaster (*Elaeagnus angustifolia* L.) is from the Elaeagnaceae family and is native to North Asia and Europe. It is rich in fiber [10] and contains polysaccharides such as glucose, mannose, galactose, fructose and rhamnose, phenols, flavonoids, coumarins, phenol-carboxylic acids, amino acids, saponins, carotenoids, vitamins, and tannins [11, 12]. Due to its high amount of tannins and flavonoids, it has cholesterol-lowering, anti-inflammatory, and cytotoxic effects [13]. One of the most important challenges in the use of essential oils and plant extracts is their stability in processing and controlling their release until consumption. Due to their simple production and the ability to release compounds with different hydrophilic properties, nanoliposomes (NLPs) can be a suitable system for the microencapsulation of fat-soluble compounds such as essential oils [14]. Liposomes are comprised of one or more phospholipid bilayers that are formed when phospholipids interact with water molecules. When the hydrophilic head groups of phospholipids are exposed to water, the hydrophobic hydrocarbon tails align in a bilayer structure. This process results in the creation of liposomes, which can encapsulate both hydrophilic molecules in the core and hydrophobic compounds between the hydrophobic tails [15]. NLPs are a class of nanoparticles whose structures form vesicles composed of membranes of one or more lipid bilayers and whose size does not exceed the scale of 100 nm. Their use in various fields from pharmaceuticals to food and cosmetics has become a subject of growing interest in the field of nanotechnology, particularly in view of their ability to encapsulate bioactive substances, which makes them interesting as vectors or carriers [16]. The preparation of NLPs depended on the physicochemical properties of the ingredients, the concentration of the encapsulated materials, the size, and the shelf life of the liposome. The main materials of liposome walls are phosphatidylcholine, phosphatidylethanolamine, phosphatidylserine, and phosphatidylglycerol. Natural phospholipids such as lecithin are the most commonly used to form liposomes from synthetic phospholipids [17]. In this research, oleaster extract in the form of NLPs was used to delay the oxidation in the low-fat mayonnaise-containing QSM and SPI.

2. Materials and Methods

2.1. Materials. Oleaster, quince seed, and mayonnaise ingredients were obtained from a local store. Chemicals were purchased from Merck Co. (Germany).

2.2. Microencapsulation of Oleaster Extract. Oleaster extract was obtained by the maceration method. To prepare NLPs, lecithin (150, 250, 500, and 1000 ppm) was hydrated with 20 mL of deionized water in a rotary evaporator (Heidolph Hei-VAP, Germany) at 30–50°C at vacuum for 24 h. The extract (1% w/w) was hydrated with lecithin at 60°C for 10 min. Then, 40 mL of phosphate buffer was mixed with the extract. Liposomal suspensions were treated using an ultrasonic probe at 24 kHz for 15 min and kept in a refrigerator for 24 h, then centrifuged for 15 min. The NLPs (NLP-150, NLP-250-NLP-500, and NLP-1000) were kept at room temperature for 30 min and then refrigerated [18].

2.3. Characteristics of NLPs

2.3.1. Encapsulation Efficiency. The encapsulation efficiency (%) was determined from the following equation [19]. First, the suspension was centrifuged at 4200 × g and 4°C for 20 min. One mL of the supernatant was separated and mixed with 5 mL of Folin–Ciocalteu reagent for 5 min. It was filtered through filter paper and left at room temperature for

24 h. The absorption was measured by a UV/Vis spectrophotometer at 750 nm. The lower layer of the system contains the encapsulated extract, and the upper layer contains the nonencapsulated extract.

$$\text{Encapsulation efficiency} = \left(\frac{\text{total extract} - \text{nonencapsulated extract}}{\text{total extract}}\right) \times 100. \quad (1)$$

2.4. Particle Size Measurements. The laser light scattering (Malvern Mastersizer 3000, United States of America) was used to determine the diameter of the particles and polydispersity index (PDI). Zetasizer (Malvern Mastersizer 3000, United States of America) checked the surface charge (ζ-potential) of NLPs. For this purpose, the suspensions were diluted 50 times with distilled water and adjusted to pH 4.7 [20].

2.5. Thermal Characteristics. Thermal properties were determined using differential scanning calorimetry (DSC, Mettler Toledo, Switzerland) and thermogravimetry (TGA, Rheometric Scientific- STA 1500, United Kingdom). The NLPs were placed in an aluminum pan, and the heating program was carried out from 30°C to 300°C with a heating rate of 10°C/min and a nitrogen flow of 15 mL/min [21].

2.6. Morphology. The structure of NLPs was investigated using scanning electron microscope (SEM, TESCAN-MIRA111, Czech Republic) and transmission electron microscope (TEM, TESCAN-MIRA111, Czech Republic) [22].

2.7. Fourier Transform Infrared Spectroscopy (FTIR). To determine the functional groups, the FTIR spectrum was obtained using a Fourier transform infrared spectrometer (PerkinElmer Spectrum 65, United States of America) in the range of 400–4000 cm^{-1} [21].

2.8. Antioxidant Properties. Antioxidant properties of NLPs were calculated by 2,2-diphenyl-1-picrylhydrazyl (DPPH) and 2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) methods and absorption measurements at 517 and 734 nm, respectively, according to the procedures previously characterized by Ahmadi et al. [18]. For the DPPH assay, the reaction was started by adding 6 mL of DPPH solution (60.8 μmol/L). The mixture was vortexed for 5 min and left in darkness for 15 min. The samples were centrifuged at 3120 × g (centrifuge MPW-54, MPW MED. INSTRUMENTS,Warsaw, Poland) for 3 min, and the absorbance of optically clear supernatant was measured at 517 nm. For the ABTS assay, 0200–0.0300 g of the mayonnaise samples was weighed to centrifuge tubes, and the reaction was started by adding 6 mL of ABTS•+reagent (diluted with ethanol to an absorbance of 0.70 ± 0.02 at 734 nm). The mixtures were vortexed for 5 min and centrifuged at 3120 × g for 3 min. The absorbance of clear supernatants was measured at 734 nm against a reagent blank (2.5 mL of ABTS•+ solution) [18].

2.9. Mucilage Extraction of Quince Seed. To extract the mucilage, 10 g of quince seeds were mixed with three times of 96% ethanol and stirred for 5 min by a magnetic stirrer. The seeds were separated from ethanol and mixed with deionized water at a ratio of 1:30 and stirred at 45°C, 1100 rpm for 15 min. The solution was filtered using Whatman paper and dried at 45°C [23].

2.10. Mayonnaise Production. The oil phase including soybean oil was mixed with the aqueous phase including egg yolk, vinegar, salt, sugar, and mustard. QSM and SPI at 1% and 2% concentrations and NLP of the oleaster extract at concentrations of 0.5%, 0.75%, 1%, 1.5%, and 2% concentrations were added to the formulation. TBHQ (200 ppm) was added to the pure oil. One sample without additives was considered as control. The samples were kept at 4°C for 6 months [1].

2.11. Chemical Properties. The fat content was measured according to AOAC, 30-10 method [24]. To determine the pH, 5 g of the sample was homogenized with 45 mL of deionized distilled water for 1 min at 100 rpm, and the pH was measured with a pH meter at room temperature (Metrohm, Switzerland).

2.12. Oxidation Characteristics. The oil was extracted using cold extraction according to the procedures previously characterized [4]. Acid (AOAC Cd3-63), peroxide (AOCS, Cd8-53), thiobarbituric acid (AOCS, Cd19-90), anisidine (AOCS, Cd18-90), and totox (peroxide value × 2 +anisidine value) values were calculated [25].

2.13. Statistical Analysis. All experiments were performed in three replicates. Analysis of variance (ANOVA) was done by SPSS software (ver. 21) to confirm the differences between means ± standard deviation (SD) at a significance level of 5% ($p < 0.05$).

3. Results and Discussion

3.1. Physicochemical Properties of NLPs. The characteristics of NLPs are shown in Table 1. The highest encapsulation efficiency, zeta potential, PDI, and the smallest particle size were observed in NLP-500 ($p < 0.05$). NLP-150 showed the lowest encapsulation efficiency and the highest particle size ($p < 0.05$).

Table 1: Physicochemical properties of nanoliposomes.

Nanoliposomes	Encapsulation efficiency (%)	Particle size (nm)	Zeta potential (mV)	PDI
NLP-150	66.37 ± 0.21^{d}	139	−17.35	0.412
NLP-250	72.81 ± 0.32^{c}	99.3	−19.64	0.392
NLP-500	88.42 ± 0.42^{a}	72.9	−31.54	0.419
NLP-1000	82.85 ± 0.27^{b}	85.1	−24.33	0.382

Note: Mean ± SD. Different letters in the column indicate a significant difference ($p < 0.05$).

3.2. Encapsulation Efficiency. Encapsulation efficiency affects physical properties, oxidative stability, physical stability, and morphology. High efficiency leads to better bioavailability, and low efficiency has been attributed to liposome membrane disruption, which may be due to long homogenization or sonication [21].

For NLP-500 and NLP-1000, the efficiency of > 82% showed the suitability of NLPs for the encapsulation of the extract. In other words, there is a small amount of the extract remained without capsules. The difference in efficiency may be due to different conditions of capsule formation [26]. Also, the particle size and specific surface area of liposomes are effective factors in encapsulation efficiency [27–29]. Ojagh and Hasani [28] and Santhanam et al. [26] produced fish oil NLPs with an efficiency of 90.12% and 77.28%, respectively. NLPs containing nettle (*Urtica dioica* L.) extract were produced with an encapsulation efficiency of 75% [30]. The white tea extract NLPs were produced by ultrasound with an encapsulation efficiency of 76.5% [18].

3.3. Particle Size. The size of particles and their distribution play an important role in the physical properties of colloidal systems such as stability, turbidity, rheological properties, bioavailability, and organoleptic properties. Reducing the size of particles to the nanometer scale increases encapsulation efficiency and oxidative stability [26]. A lower oxidation has also been reported in soybean oil-in-water emulsions with reduced particle size [31].

3.4. Zeta Potential. Zeta potential refers to surface charge or electric potential and is used to predict the stability of colloidal particles [32]. The high zeta potential indicates strong repulsive interactions between anionic groups on liposome surfaces, which prevent their aggregation [21]. Zeta potential ≤ ±30 mV indicates good electrostatic stability. Similarly, NLPs with low electrostatic stability with zeta potential < −30 mV [33] and NLPs with high electrostatic stability with zeta potential > −30 mV have been reported [32]. Therefore, the zeta potential > −30 mV in this research indicated the physical stability of NLPs. NLP-500 has the highest zeta potential (−31.54 mV) and the smallest particle size (72.9 nm). The decrease in zeta potential is consistent with the increase in particle size, which is to findings of Auwal et al. [21].

3.5. PDI. PDI usually determines the diameter distribution of particles in suspension. A smaller PDI indicates a more homogenous particle size distribution and uniformity of particles [28]. NLP-500 and NLP-1000 showed the highest and lowest PDI, respectively. White tea extract NLPs produced by ultrasound had a zeta potential of −56 mV, a particle diameter of 82.20 nm, and a PDI of 0.69 [18]. The particle size and zeta potential of NLPs containing nettle (*U. dioica* L.) extract were 269.4 nm and −20.7 mV, respectively [30]. Fish oil NLPs had a particle size of 339.2 nm and a PDI of 0.426 [28]. DLS analysis in the research of Rasti et al. [29] showed that liposomes containing omega-3 fatty acids are smaller than 200 nm with an average particle size of 73.2 ± 18.1 nm and PDI and zeta potential of 0.216 and −33.48 mV, respectively.

3.6. Antioxidant Properties. The highest and lowest antioxidant activity was reported in NLP-500 and NLP-150, respectively ($p < 0.05$) (Table 2).

The antioxidant properties of NLPs have been confirmed in many studies [18, 34–37]. The presence of the oleaster extract is probably responsible for the antioxidant effects of liposomes. Oleaster is rich in polyphenols, flavonoids, anthocyanins, vitamins, tannins, and especially fibers, and it can be used as an antioxidant source in food systems [38, 39]. Hassanzadeh et al. [40] showed total polyphenol levels in different varieties of oleaster (*E. angustifolia*) (Miandoab, Khoy, Malekan, Urmia, and Miyaneh) to be about 400–700 mg/100 g of dry matter and flavonoid levels to be about 9.73–5.226 mg/100 g of dry matter in terms of catechin, which proves that this fruit has high antioxidant properties. Increasing the concentration of phenolic compounds directly increases the ability of various extracts to scavenge free radicals. At higher concentrations of phenolic compounds, the scavenging power of the extract increases due to the increase in the number of hydroxyl groups present in the reaction medium and the possibility of donating hydrogen to the free radical [41]. Researchers examined the effect of elderberry on a specific type of fruit ice cream and observed a high level of scavenging of DPPH free radicals and a positive effect of this compound on fruit ice cream [42].

3.7. Thermal Characteristics. NLP-1000 showed the lowest melting temperature (T_m) and thus the lowest thermal stability (Figure 1). It had the lowest weight loss, while the highest weight loss was observed in NLP-500 (Figure 2).

NLPs are an effective technology to increase stability and thermal properties [18, 43, 44]. In the DSC curve, melting appears as an endothermic peak and is related to the crystalline regions. The maximum point in the first endothermic peak is considered as the melting temperature (T_m).

Table 2: Antioxidant activity of nanoliposomes.

Nanoliposomes	DPPH (%)	ABTS (%)
NLP-150	70 ± 0.32^{d}	75.48 ± 0.39^{d}
NLP-250	78 ± 0.89^{c}	88.82 ± 0.44^{c}
NLP-500	96.78 ± 0.16^{a}	97.37 ± 0.34^{a}
NLP-1000	90.67 ± 0.24^{b}	96.88 ± 0.44^{b}

Note: Mean ± SD. Different letters in the column indicate a significant difference ($p < 0.05$).

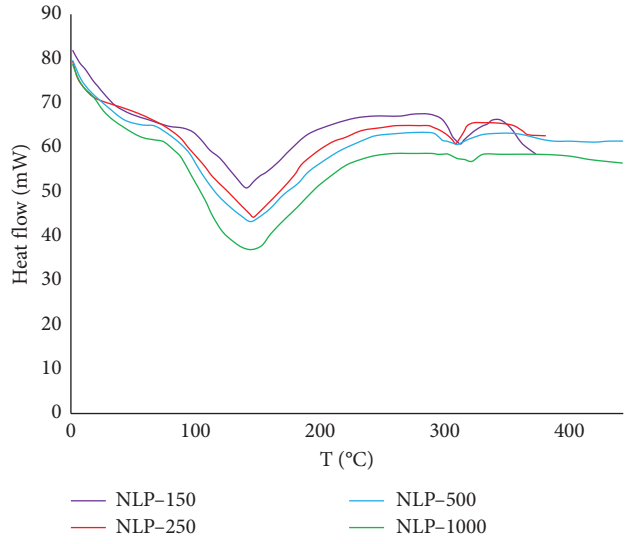

Figure 1: DSC diagram of nanoliposomes.

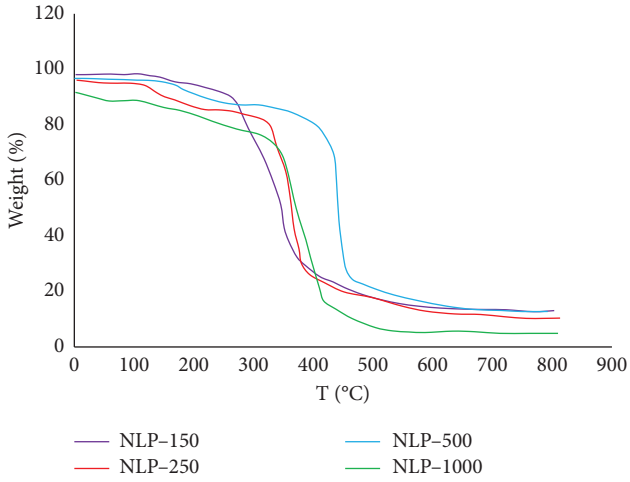

Figure 2: TGA diagram of nanoliposomes.

The endothermic peak is related to the breaking of intramolecular bonds and the melting of crystal areas. In this research, an endothermic peak was observed in all NLPs. The increase in T_m and T_g with the formation of liposomes can be attributed to the strong interactions between the hydroxyl groups of the matrix and liposome, as a result, mobility and flexibility decrease and T_g and T_m increase. The increase in T_m of the NLP-150, NLP-250, and NLP-500 can be attributed to the formation of more complete crystalline areas compared to the NLP-1000. The thermal stability may be related to the presence of the extract on the surface of the liposome, indicating that they strongly interacted through hydrogen bonds [18]. TGA thermograms show the pattern of weight loss during thermal decomposition. Up to 300°C, the samples lost about 10% of weight, but NLP-500 lost about 15% of weight, which can be a reason for the presence of the extract, which is well protected. Also, from 300°C and above, the NLP-500 decreases with a very steep slope, and up to 450°C, it had a weight loss of 96%, but the other samples had higher stability, and the weight loss was between 80% and 83% up to 400°C.

3.8. Morphology. The images of SEM (Figure 3) and TEM (Figure 4) showed that the NLPs were spherical and uniformly dispersed in the matrix with a good distribution. NLP-500 created a denser, more compact, and organized structure compared to others.

In other words, the oleaster extract was well distributed in the NLP matrix and showed a regular and homogeneous structure. In previous implementations, NLPs were shown to be spherical and homogeneous [18, 29, 45].

3.9. FTIR. FTIR spectroscopic analysis to identify the encapsulation of the oleaster extract in NLPs is shown in Figure 5.

In the FTIR spectrum, a broad peak at 3380–3427 cm^{-1} is related to hydroxyl groups (OH). A peak at 2957 cm^{-1} was related to stretching vibrations of C-H groups (CH_3 and CH_2). The peak in this region shows the formation of stronger hydrogen bonds in the NLP formation. The sharp peaks in NLP-500 and NLP-1000 in the range of 1821 cm^{-1} are related to C=O stretching vibration and 1300–1500 cm^{-1} are related to C-H bending vibration. The decrease in absorption at 1693 cm^{-1} showed the stretching vibrations of cis-C=C double bonds. The 1600–2900 cm^{-1} was observed as very smooth and narrow. The bands at 1157–1192 cm^{-1} are attributed to asymmetric P-O-C stretching vibrations. The peak at 1000 cm^{-1} indicates the asymmetric stretching vibrations of PO_2, and the polar interaction between the PO_2 group of lecithin and the polar side chains of liposomes [18]. The increase in the vibrational frequency of PO_2 indicates the dehydrated phosphate group due to the absence of a hydrogen bond between it and the hydrogen atom in the water molecule, while its decrease is proportional to the presence of the hydrogen bond and the hydrated state of the phosphate group [21].

The 1228-cm^{-1} bands were attributed to asymmetric P-O-C stretching vibrations. A relatively sharp band at 1700 cm^{-1} in the spectrum of NLP-1000 appeared as a result of the presence of carbonyl ester C=O groups. In addition, a broad peak appeared at 3427 cm^{-1} that overlapped the O-H/N-H band [18]. Mousavi Kalajahi et al. [30] showed that these spectral changes can be due to the change in the location of the carbonyl ester groups (C=O) in the phospholipid bilayer due to the trapping of the extract in the phospholipid bilayer and since the efficiency of encapsulation was high, the extract does not exist in free form, thus the change in the peaks was very small.

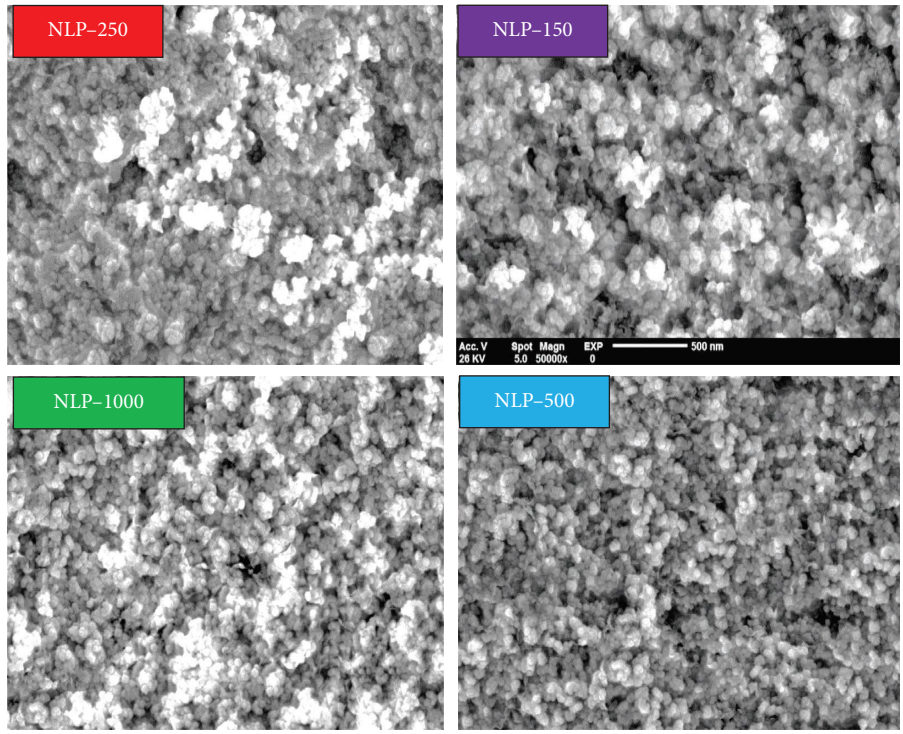

Figure 3: SEM images of liposomes at × 50,000 magnification.

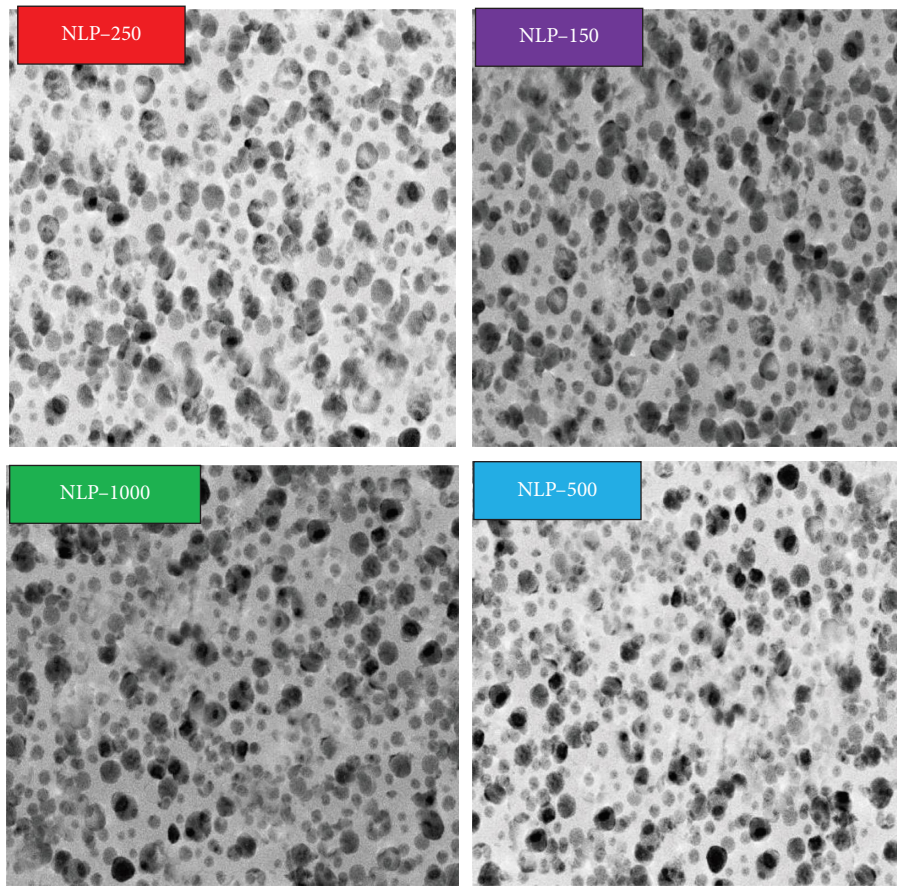

Figure 4: TEM images of nanoliposomes.

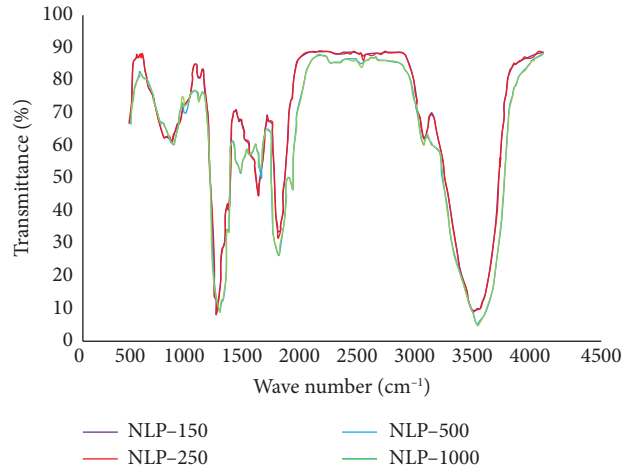

Figure 5: FTIR spectrum of nanoliposomes.

Although some peaks became wider or shifts occurred in some peaks, no new peaks were created, and NLPs had no chemical interaction with the extract. Therefore, the loading of the extract into the NLPs was physical and reversible, and no new chemical bonds were created. Naderinezhad et al. [46] showed that all the peaks in the empty liposome and drug-containing liposome were repeated in the FTIR spectrum, and the absence of an additional peak indicates that there was no chemical interaction between the drug and other components and that the loading was physical.

3.10. Chemical Properties of Mayonnaise. As can be seen in Table 3, control and TBHQ treatments showed the highest fat content and pH, and Sample 5 and Sample 10 showed the lowest fat content and pH ($p < 0.05$).

Thus, the use of QSM and SPI as fat substitutes has been effective in mayonnaise. The use of QSM and SPI in low-fat products such as yogurt [47] and cheese [48] has been reported, previously. Acidity and pH are very important chemical factors in salad dressings and mayonnaise, for which a certain limit has been defined in the Iranian National Standard Organization. According to this standard [49], the pH of mayonnaise should not be more than four and the total acidity should not be less than 0.6 g/100 g of acetic acid. According to the Iranian National Standard No. 2454 [49], the standard amount of fat in full-fat mayonnaise is 60%–65%, in reduced-fat mayonnaise 40%–50%, and in low-fat mayonnaise 15%–30%. The fat and pH values of the mayonnaise samples in this research were consistent with the national standard of Iran.

3.11. Oxidation Characteristics. As can be seen in Figure 6, at the beginning of the experiments (Month 1), the acid, peroxide, TBA, and anisidine values did not show a significant difference ($p > 0.05$), but over time, oxidation increased significantly ($p < 0.05$). During storage, TBHQ, followed by Sample 10 and Sample 5 showed the lowest oxidation, while the control sample showed the highest oxidation rate ($p < 0.05$).

Table 3: Chemical properties of mayonnaise.

Treatments	Fat (%)	pH
1	39.96 ± 0.13^{a}	4.07 ± 0.01^{bc}
2	34.41 ± 0.24^{c}	3.99 ± 0.03^{def}
3	33.88 ± 0.13^{d}	3.99 ± 0.04^{de}
4	33.31 ± 0.19^{f}	3.93 ± 0.03^{g}
5	32.79 ± 0.08^{g}	$3.93 \pm 0.02f^{g}$
6	34.99 ± 0.18^{b}	4.11 ± 0.03^{ab}
7	34.42 ± 0.19^{c}	4.01 ± 0.05^{cd}
8	33.94 ± 0.21^{d}	3.96 ± 0.02^{defg}
9	33.24 ± 0.21^{ef}	3.95 ± 0.01^{efg}
10	32.93 ± 0.17^{gf}	3.91 ± 0.02^{g}
Control	35.42 ± 0.2^{a}	4.16 ± 0.02^{a}
TBHQ	35.37 ± 0.15^{ab}	4.15 ± 0.05^{a}

Note: Mean ± SD. Different letters in the column indicate a significant difference ($p < 0.05$).

Oleaster, due to its high content of phenolic compounds, prevents fat oxidation and also delays the production of oxidation products in food. Phenolic compounds can eliminate reactive oxygen species due to the presence of hydroxyl groups in their structure and are known as antioxidants [50]. Roshandel et al. [50] reported that the rate of increase in the peroxide value in sauce samples containing 4%, 6%, and 8% oleaster extract was lower than the control sample and samples containing the synthetic antioxidant TBHQ.

3.12. Acid Value. Acidity monitoring is one of the oxidation control parameters. In general, the acidity of mayonnaise should always be in a suitable range, because if the acidity is more than 1.5%, it will cause an unpleasant taste in the final product, and if the acidity is too low, the product will spoil quickly. On the other hand, an increase in pH can cause the growth of pathogenic bacteria including *Staphylococcus aureus*. The acid value of mayonnaise samples at the beginning of the storage period was 0.04–0.05 mg KOH/g oil. During the storage period, the acid value of the mayonnaise samples (mg KOH/g oil < 2) was in the range of Iran's national standard (at least 0.6 g/100 g) [49], which shows the good quality of mayonnaise oil during storage. Regarding the gradual increase in acidity of mayonnaise, the acidity of the mayonnaise and low pH can act as a prooxidant and cause the release of iron ions from phosvitin and lipovitellin. It is made from egg yolk and acts as an activator of lipase and causes the hydrolysis of triglycerides in the oily phase, thus releasing more fatty acids during storage and increasing acidity [51].

3.13. Peroxide Value. The peroxide value is a parameter for measuring the hydroperoxides that are produced in the primary stages of oxidation [1]. The results showed that NLPs delayed the formation of hydroperoxides. Although at the time of production, the peroxide value of the treatments was similar (0.79–0.89 meq O_2/kg); it gradually increased until the end of the storage. The increase in the peroxide value over time is caused by the intensity of oxidation. The peroxide value of TBHQ (2.01 meq O_2/kg) followed by

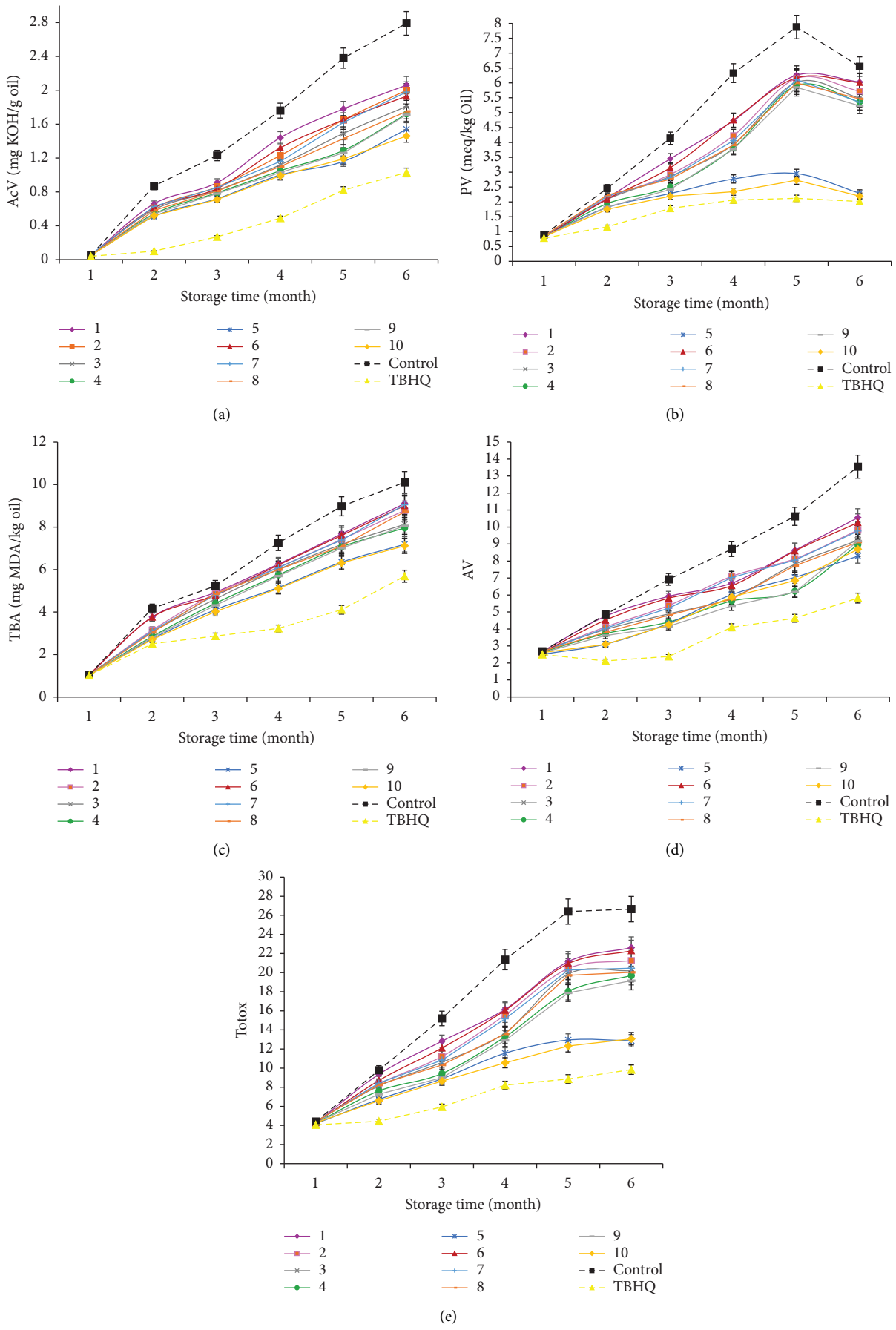

Figure 6: Oxidation changes in mayonnaise during 6 months ($p < 0.05$): (a) acid value (mg KOH/g oil), (b) peroxide value (mEq O_2/kg oil), (c) TBA (mg MDA/kg oil), (d) anisidine value, and (e) totox value.

Sample 10 and Sample 5 (2.19–2.29 meq O_2/kg) was lower compared to other samples. The control sample showed the highest peroxide value (6.55 meq O_2/kg) at the end of storage. According to the national standard of Iran [36], the permissible limit of the peroxide value of mayonnaise is maximum of 2 meq O_2/kg. Therefore, except TBHQ, Sample 10, and Sample 5, other treatments were not acceptable after 2 months. Since mayonnaise is an oil-in-water emulsion and its oily phase is in contact with a large surface of water, it is very susceptible to oxidative. On the other hand, the aqueous phase in mayonnaise carries high amounts of oxygen, which increases oxidation [1, 52]. Mayonnaise ingredients such as salt, sugar, lemon juice, and vinegar can affect lipid oxidation. Some of these ingredients contain low concentrations of iron and copper, but egg yolk, which is a traditional emulsifier in mayonnaise, is the main source of iron. Iron catalyzes the decomposition of hydroperoxides into secondary oxidation products. The contact between iron and the surface of droplets in oil-in-water emulsion causes metal-catalyzed oxidation. The surface area of the oil droplets affects the oxidation rate. Lemon juice due to the presence of ascorbic acid causes the formation of radicals in the aqueous phase of mayonnaise. Ascorbic acid acts as a prooxidant because it can create a complex between iron and ascorbate that breaks hydroperoxides at the oil–water interface. Vinegar also acts as prooxidant due to reduced pH and thus increases the release of iron from egg yolk. Salt also plays an important role in autoxidation. By pasteurizing, the oxidative stability of mayonnaise can be increased due to the inactivating oxidation agents and enzymes [51]. An increasing and then a decreasing pattern in the peroxide value during storage can be seen. An increase was observed until the fifth month, and a decrease was observed at the end of storage. This decrease was probably due to the rapid decomposition of hydroperoxides and the formation of secondary oxidation products. In other words, the accumulation of hydroperoxides is reduced and their formation is slower than their breakdown [1].

Similar results have been reported on the use of other extracts in mayonnaise, including corn extract [53] and brown rice extract [54].

3.14. TBA. Peroxides represent the primary oxidation products and malondialdehyde (MDA), which is responsible for the reaction in the TBA test, and represent the secondary oxidation products [1].

At the beginning of the experiments (Month 1), the TBA of samples (1.06–1.02 mg MDA/kg oil) did not show a significant difference but it increased over time. During storage, TBA of the control sample was higher than other treatments, and at the end of the storage, it reached 10.11 mg MDA/kg oil. The TBA in samples containing antioxidants was significantly lower than the control sample. At the end of storage, the lowest TBA was related to the TBHQ (5.69 mg MDA/kg oil), followed by Sample 10 (7.12 mg MDA/kg oil). In addition, during storage, an increase in TBA was observed for all samples. Therefore, time has an important effect on the oxidation of mayonnaise, so TBA in all samples reached its highest level in the sixth month. Similar results have been obtained in previous studies. Tananuwong and Tewaruth [54] showed that the brown rice extract due to the phenolic compounds delayed the TBA increase of mayonnaise.

3.15. Anisidine Value. The anisidine value is associated with secondary oxidation products such as aldehydes [1]. The results of the anisidine value were similar to acid, peroxide, and TBA values. The anisidine value in mayonnaise containing NLP was significantly lower than the control sample. At the end of the storage, the lowest anisidine value was related to TBHQ (5.82), followed by Sample 10 (8.69) and Sample 5 (8.29). The anisidine value of the control sample reached 13.55 in the sixth month.

In all treatments, the lowest and highest anisidine values were observed in the first and sixth month, respectively. These results are also consistent with the peroxide value because an increase in the hydroperoxides occurred in this stage, and therefore, the intensity of the decomposition of hydroperoxides also increased and caused the formation of secondary compounds [1, 52].

3.16. Totox Value. The totox value provides a better estimation of the mayonnaise oxidation. Until the sixth month, The totox value increased in all treatments, and mayonnaise containing NLP was significantly lower than the control sample. At the end of storage, the lowest totox value was related to TBHQ (9.84), followed by Sample 5 (12.87) and Sample 10 (13.07). The totox value of the control sample reached 65.26 in the sixth month. Therefore, mayonnaise containing NLPs of the oleaster extract prevented the formation of primary and secondary products and delayed oxidation. The ability of liposomes to delay oxidation is related to the phenolic compounds of the oleaster extract [38, 39]. The oil droplets in mayonnaise are surrounded by a membrane of emulsifier, which provides physical stability of the emulsion and oxidative stability as a barrier against prooxidants such as metals. Therefore, the effect of emulsifiers on the oxidative stability of mayonnaise is important. Mayonnaise is traditionally prepared from egg yolk, which acts as an emulsifier. The use of lecithin can improve the oxidative stability of low-fat mayonnaise. In addition, phospholipids may act as antioxidants and increase the oxidative stability of the emulsion [55]. Low-fat mayonnaise is expected to lower oxidation than full-fat mayonnaise, but there are conflicting results regarding the effect of fat content on lipid oxidation [56]. Therefore, other factors probably affect the oxidation in low-fat mayonnaise [51]. Similar results from other natural antioxidants such as thyme essential oil [57], black rice extract [54], yarrow essential oil [1], oregano, clove, and cinnamon essential oils [58], cumin essential oil [59], rose extract [60], garlic extract [61], rosemary extract [62], oleaster flour [63], and mustard essential oil [64] have been reported in mayonnaise.

4. Conclusion

The NLPs were spherically entrapped the oleaster extract in two phospholipid layers. The results of this research showed the positive effects of the oleaster extract NLP in reducing oxidation. SPI and QSM were successful in reducing the fat content of mayonnaise. It is expected that by their substitution in the formulation of mayonnaise while reducing calories, the product will be able to compete with the type of commercial products, and the consumption will not be limited to children, adults, and people with dietary restrictions and illnesses such as obesity, cardiovascular diseases, blood pressure, and non–insulin-dependent diabetes. Thus, the application of the oleaster extract NLP is recommended in the mayonnaise formulation. All these natural additives are safe and harmless but it seems more studies are necessary to express the toxicity effect of these compounds.

Data Availability Statement

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors have no conflicts of interest.

Funding

The researchers did not receive any specific grant from funding agencies from the public, commercial, or not-for-profit sectors.

References

[1] A. Ahmadi-Dastgerdi, H. Ezzatpanah, S. Asgary, S. Dokhani, E. Rahimi, and M. Gholami-Ahangaran, "Oxidative Stability of Mayonnaise Supplemented With Essential Oil of *Achillea millefolium ssp millefolium* During Storage," *Food science and technology* 13, no. 1 (2019): 34–41, https://doi.org/10.15673/fst.v13i1.1340.

[2] M. Taslikh, N. Mollakhalili-Meybodi, A. M. Alizadeh, M. Mousavi, K. Nayebzadeh, and A. M. Mortazavian, "Mayonnaise Main Ingredients Influence on Its Structure as an Emulsion," *Journal of Food Science and Technology* 59, no. 6 (2022): 2108–2116, https://doi.org/10.1007/s13197-021-05133-1.

[3] E. Kirtil and M. H. Oztop, "Characterization of Emulsion Stabilization Properties of Quince Seed Extract as a New Source of Hydrocolloid," *Food Research International* 85 (2016): 84–94, https://doi.org/10.1016/j.foodres.2016.04.019.

[4] A. G. Renfrew and L. H. Cretcher, "Quince Seed Mucilage," *Journal of Biological Chemistry* 97, no. 2 (1932): 503–510, https://doi.org/10.1016/s0021-9258(18)76205-4.

[5] P. Singh, R. Kumar, S. N. Sabapathy, and S. Bawa, "Functional and Edible Uses of Soy Protein Products," *Comprehensive Reviews in Food Science and Food Safety* 7, no. 1 (2008): 14–28, https://doi.org/10.1111/j.1541-4337.2007.00025.x.

[6] G. Beltran, M. P. Aguilera, and M. H. Gordon, "Solid Phase Microextraction of Volatile Oxidation Compounds in Oil-In-Water Emulsions," *Food Chemistry* 92, no. 3 (2005): 401–406, https://doi.org/10.1016/j.foodchem.2004.07.030.

[7] S. Yang, M. Takeuchi, H. Friedrich, J. P. van Duynhoven, and J. Hohlbein, "Unravelling Mechanisms of Protein and Lipid Oxidation in Mayonnaise at Multiple Length Scales," *Food Chemistry* 402, no. 134417 (2023): 134417–134419, https://doi.org/10.1016/j.foodchem.2022.134417.

[8] C. C. Berton-Carabin, M. H. Ropers, and C. Genot, "Lipid Oxidation in Oil-In-Water Emulsions: Involvement of the Interfacial Layer," *Comprehensive Reviews in Food Science and Food Safety* 13, no. 5 (2014): 945–977, https://doi.org/10.1111/1541-4337.12097.

[9] I. A. Gomes, F. Gomes, S. dos, O. Freitas-Silva, and J. P. L. da Silva, "Ingridients of Mayonnaise: Future Perspectives Focusing on Essential Oils to Reduce Oxidation and Microbial Counts," *Journal of Archivos Latino Americanos de Nutrition* 67, no. 3 (2017): 187–199.

[10] M. Khaki-Rizi, E. Ataye Salehi, L. Mosharaf, and F. Tajali, "Investigation of Physicochemical Compositions of *Elaeagnus angustifolia* L Fruit for Using in Food Industry," *Journal of Herbal Drugs* 3, no. 1 (2012): 15–20.

[11] F. A. Ayaz and E. Bertoft, "Sugar and Phenolic Acid Composition of Stored Commercial Oleaster Fruits," *Journal of Food Composition and Analysis* 14, no. 5 (2001): 505–511, https://doi.org/10.1006/jfca.2001.1004.

[12] Y. Sahan, A. Neslihan Dundar, E. Aydin, et al., "Characteristics of Cookies Supplemented With Oleaster (*Elaeagnus angustifolia* L.) Flour. I Physicochemical, Sensorial and Textural Properties," *Journal of Agricultural Science* 5, no. 2 (2013): 160–168, https://doi.org/10.5539/jas.v5n2p160.

[13] N. Erdemoglu, E. K. Akkol, E. Yesilada, and I. CalIs, "Bioassayguided Isolation of Anti-Inflammatory and Antinociceptive Principles From a Folk Remedy, *Rhododendron ponticum* L. Leaves," *Journal of Ethnopharmacology* 119, no. 1 (2008): 172–178, https://doi.org/10.1016/j.jep.2008.06.021.

[14] M. Fathi, M. R. Mozafari, and M. Mohebbi, "Nanoencapsulation of Food Ingredients Using Lipid Based Delivery Systems," *Trends in Food Science & Technology* 23, no. 1 (2012): 13–27, https://doi.org/10.1016/j.tifs.2011.08.003.

[15] Y. Ben-Fadhel, B. Maherani, S. Salmieri, and M. Lacroix, "Preparation and Characterization of Natural Extracts-Loaded Food Grade Nanoliposomes," *LWT-Food Science and Technology* 154 (2022): https://doi.org/10.1016/j.lwt.2021.112781.

[16] C. Bondu and F. T. Yen, "Nanoliposomes, From Food Industry to Nutraceuticals: Interests and Uses," *Innovative Food Science & Emerging Technologies* 81 (2022): https://doi.org/10.1016/j.ifset.2022.103140.

[17] T. Subramani and H. Ganapathyswamy, "An Overview of Liposomal Nano-Encapsulation Techniques and Its Applications in Food and Nutraceutical," *Journal of Food Science and Technology* 57, no. 10 (2020): 3545–3555, https://doi.org/10.1007/s13197-020-04360-2.

[18] E. Ahmadi, A. H. Elhamirad, N. Mollania, M. R. Saeidi Asl, and A. Pedramnia, "Incorporation of White Tea Extract in Nanoliposomes: Optimization, Characterization, and Stability," *Journal of the Science of Food and Agriculture* 102, no. 5 (2021): 2050–2060, https://doi.org/10.1002/jsfa.11544.

[19] A. F. Bafghi, B. F. Haghirosadat, F. Yazdian, et al., "A Novel Delivery of Curcumin by the Efficient Nano Liposomal Approach Against Leishmania Major," *Preparative Biochemistry & Biotechnology* 10 (2021): 1–8, https://doi.org/10.1080/10826068.2021.1885045.

[20] A. Jami, B. Fathi-Achachlouei, and R. Shaddel, "Nanoliposome of Black Fig Anthocyanins and Its Application in Kombucha Beverage," *Journal of Food Science and Technology (Iran)* 21, no. 148 (2024): 45–61.

[21] S. M. Auwal, M. Zarei, C. P. Tan, and N. Saari, "Comparative Physicochemical Stability and Efficacy Study of Lipoid S75-Biopeptides Nanoliposome Composite Produced by Conventional and Direct Heating Methods," *International Journal of Food Properties* 21, no. 1 (2018): 1646–1660, https://doi.org/10.1080/10942912.2018.1504064.

[22] K. Włodarczyk, A. Zienkiewicz, and A. Szydłowska-Czerniak, "Radical Scavenging Activity and Physicochemical Properties of Aquafaba-Based Mayonnaises and Their Functional Ingredients," *Foods* 11, no. 8 (2022): 1129–1219, https://doi.org/10.3390/foods11081129.

[23] L. M. Jafari, F. Poureini, M. Mohammadi, G. Najafpour, and S. Hamedi, "Extraction of Mucilage From Quince (*Cydonia oblonga* M.) Seed and Investigation of Its Biological Activities," *Biointerface Research in Applied Chemistry* 13, no. 6 (2023): 514.

[24] Aoac, *Official Methods of Analysis of the Association of Official Analytical Chemists* (Washington, DC, USA: Association of Official Analytical Chemists, 2019).

[25] Aocs, *Official Methods and Recommended Practices of the American Oil Chemists' Society* (1998).

[26] A. K. Santhanam, M. Lekshmi, M. K. Chouksey, G. Tripathi, and V. Gudipati, "Delivery of Omega-3 Fatty Acids Into Cake Through Emulsification of Fish Oil-In-Milk and Encapsulation by Spray Drying With Added Polymers," *Drying Technology* 33, no. 1 (2015): 83–91, https://doi.org/10.1080/07373937.2014.934832.

[27] Q. Lu, P. M. Lu, J. H. Piao, et al., "Preparation and Physicochemical Characteristics of an Allicin Nanoliposome and Its Release Behavior," *LWT-Food Science and Technology* 57, no. 2 (2014): 686–695, https://doi.org/10.1016/j.lwt.2014.01.044.

[28] S. M. Ojagh and S. Hasani, "Characteristics and Oxidative Stability of Fish Oil Nano-Liposomes and Its Application in Functional Bread," *Journal of Food Measurement and Characterization* 12, no. 2 (2018): 1084–1092, https://doi.org/10.1007/s11694-018-9724-5.

[29] B. Rasti, S. Jinap, M. R. Mozafari, and A. M. Yazid, "Comparative Study of the Oxidative and Physical Stability of Liposomal and Nanoliposomal Polyunsaturated Fatty Acids Prepared With Conventional and Mozafari Methods," *Food Chemistry* 135, no. 4 (2012): 2761–2770, https://doi.org/10.1016/j.foodchem.2012.07.016.

[30] S. E. M. Kalajahi, S. Amjadi, and S. Ghandiha, "Development of the Spray-Dried Nettle (*Urtica dioica* L.) Extract-Loaded Nanoliposome Powder for Application as a Natural Additive in Cake," *Journal of Food Processing and Preservation* 46, no. 12 (2022): https://doi.org/10.1111/jfpp.17229.

[31] S. P. O' Dwyer, D. O'Beirne, D. N. Eidhin, and B. T. O'Kennedy, "Effects of Sodium Caseinate Concentration and Storage Conditions on the Oxidative Stability of Oil-In-Water Emulsions," *Food Chemistry* 138, no. 2-3 (2013): 1145–1152, https://doi.org/10.1016/j.foodchem.2012.09.138.

[32] A. Mohan, D. J. McClements, and C. C. Udenigwe, "Encapsulation of Bioactive Whey Peptides in Soy Lecithin-Derived Nanoliposomes: Influence of Peptide Molecular Weight," *Food Chemistry* 213 (2016): 143–148, https://doi.org/10.1016/j.foodchem.2016.06.075.

[33] E. Da Rosa Zavareze, A. C. Telles, S. L. Mello El Halal, et al., "Production and Characterization of Encapsulated Antioxidative Protein Hydrolysates From Whitemouth Croaker (*Micropogonias furnieri*) Muscle and Byproduct," *LWT-Food Science and Technology* 59, no. 2 (2014): 841–848, https://doi.org/10.1016/j.lwt.2014.05.013.

[34] M. Aleman, R. Bou, F. Guardiola, et al., "Antioxidative Effect of Lipophilized Caffeic Acid in Fish Oil Enriched Mayonnaise and Milk," *Food Chemistry* 167 (2015): 236–244, https://doi.org/10.1016/j.foodchem.2014.06.083.

[35] S. Amjadi, M. Ghorbani, H. Hamishehkar, and L. Roufegarinejad, "Improvement in the Stability of Betanin by Liposomal Nanocarriers: Its Application in Gummy Candy as a Food Model," *Food Chemistry* 256 (2018): 156–162, https://doi.org/10.1016/j.foodchem.2018.02.114.

[36] M. M. El-Said, T. M. El-Messery, and H. M. El-Din, "The Encapsulation of Powdered Doum Extract in Liposomes and Its Application in Yoghurt," *Acta Scientiarum Polonorum Technologia Alimentaria* 17, no. 3 (2018): 235–245, https://doi.org/10.17306/j.afs.0571.

[37] P. Farokhzad, A. A. Dastgerdi, and J. T. Nimavard, "The Effect of Chitosan and Rosemary Essential Oil on the Quality Characteristics of Chicken Burgers During Storage," *Journal of Food Processing and Preservation* 2023, no. 1 (2023): 1–8, https://doi.org/10.1155/2023/8381828.

[38] N. Şahin, "Bioactive Components and Nutritional Properties of Fiber-Rich Cookies Produced With Different Parts of Oleaster (*Elaeagnus angustifolia* L.)," *Journal of the Science of Food and Agriculture* 103, no. 14 (2023): 6975–6983, https://doi.org/10.1002/jsfa.12778.

[39] M. Yaghoubi, K. Alirezalu, J. Hesari, et al., "Application of Oleaster Leaves (*Elaeagnus angustifolia* L.) Essential Oil and Natural Nanoparticle Preservatives in Frankfurter-Type Sausages: An Assessment of Quality Attributes and Stability During Refrigerated Storage," *Meat Science* 198, no. SP1 (2023): https://doi.org/10.1016/j.meatsci.2023.109097.

[40] Z. Hassanzadeh and H. Hassanpour, "Evaluation of Physicochemical Characteristics and Antioxidant Properties of *Elaeagnusangustifolia* L," *Scientia Horticulturae* 238 (2018): 83–90, https://doi.org/10.1016/j.scienta.2018.04.041.

[41] Z. Taskhiri, M. Mehraban Sangatash, and Z. Nazari, "The Effect of Oleaster (*Elaeagnus angustifolia*) Powder on Antioxidant, Tannin and Sensory Properties of Mint Chocolate," *Journal of Food Science and Technology (Iran)* 16, no. 90 (2019): 101–112.

[42] S. Çakmakçı, E. F. Topdaş, P. Kalın, et al., "Antioxidant Capacity and Functionality of Oleaster Flour and Crust in a New Kind of Fruity Ice Cream," *International Journal of Food Science and Technology* 50, no. 2 (2015): 472–481, https://doi.org/10.1111/ijfs.12637.

[43] A. Rashidinejad, E. J. Birch, D. Sun-Waterhouse, and D. W. Everett, "Delivery of Green Tea Catechin and Epigallocatechin Gallate in Liposomes Incorporated Into Low-Fat Hard Cheese," *Food Chemistry* 156 (2014): 176–183, https://doi.org/10.1016/j.foodchem.2014.01.115.

[44] D. Savaghebi, M. Barzegar, and M. R. Mozafari, "Manufacturing of Nanoliposomal Extract from Sargassumboveanum Algae and Investigating its Release Behavior and Antioxidant Activity," *Food Science and Nutrition* 8, no. 1 (2020): 299–310, https://doi.org/10.1002/fsn3.1306.

[45] D. Kuznetcova, M. Linder, C. Jeandel, et al., "Nanoliposomes and Nanoemulsions Based on Chia Seed Lipids: Preparation and Characterization," *International Journal of Molecular Sciences* 21, no. 23 (2020): 9079, https://doi.org/10.3390/ijms21239079.

[46] S. Naderinezhad, G. Amoabediny, and F. Haghiralsadat, "Co-Delivery of Hydrophilic and Hydrophobic Anticancer Drugs Using Biocompatible pH-Sensitive Lipid-Based Nano-Carriers for Multidrug-Resistant Cancers," *RSC advances* 7,

no. 48 (2017): 30008–30019, https://doi.org/10.1039/c7ra01736g.

[47] Z. Gürbüz, T. E. Kotan, and M. Şengül, "Evaluation of Physicochemical, Microbiological, Texture and Microstructure Characteristics of Set-Style Yoghurt Supplemented With Quince Seed Mucilage Powder as a Novel Natural S," *International Dairy Journal* 114 (2020).

[48] S. S. Kumar, S. Balasubramanian, A. K. Biswas, et al., "Efficacy of Soy Protein Isolate as a Fat Replacer on Physico-Chemical and Sensory Characteristics of Low-Fat Paneer," *Journal of Food Science and Technology* 48, no. 4 (2011): 498–501, https://doi.org/10.1007/s13197-010-0193-z.

[49] Iran National Standards Organization, *Mayonnaise and Cold Sauces Specifications and Test Methods* (2023).

[50] Z. Roshandel, R. Zibaei, and K. Abdolmaleki, "Characteristics of Reduced-Fat Mayonnaise Prepared by Oleaster as a Fat Replacer and Natural Antioxidant," *Food Science and Nutrition* 11, no. 6 (2023): 3329–3338, https://doi.org/10.1002/fsn3.3318.

[51] S. E. Ghorbani Gorji, H. Smyth, M. Sharma, and M. Fitzgerald, "Lipid Oxidation in Mayonnaise and the Role of Natural Antioxidants: A Review," *Trends in Food Science & Technology* 56 (2016): 88–102, https://doi.org/10.1016/j.tifs.2016.08.002.

[52] S. Sanei and A. Shahab Lavasani, "The Effect of Free and Encapsulated Casein Hydrolyzates on the Oxidation Rate and Structural Properties of Mayonnaise," *Journal of Food Biochemistry* 2024 (2024): 1–8, https://doi.org/10.1155/2024/3349706.

[53] C. Y. Li, H. W. Kim, H. Li, D. C. Lee, and H. I. Rhee, "Antioxidative Effect of Purple Corn Extracts During Storage of Mayonnaise," *Food Chemistry* 152 (2014): 592–596, https://doi.org/10.1016/j.foodchem.2013.11.152.

[54] K. Tananuwong and W. Tewaruth, "Extraction and Application of Antioxidants From Black Glutinous Rice," *LWT-Food Science and Technology* 43, no. 3 (2010): 476–481, https://doi.org/10.1016/j.lwt.2009.09.014.

[55] H. Magda, M. Mostafa, S. El-Deep, and Y. Kishk, "Oxidative Stability of Low Calorie-Free Cholesterol Mayonnaise," *Annals of Agricultural Science, Moshtohor* 41, no. 3 (2003).

[56] A. D. M. Sørensen, N. S. Nielsen, G. Hyldig, and C. Jacobsen, "Influence of Emulsifier Type on Lipid Oxidation in Fish Oil-Enriched Light Mayonnaise," *European Journal of Lipid Science and Technology* 112, no. 9 (2010): 1012–1023, https://doi.org/10.1002/ejlt.200900288.

[57] D. A. Ahmadi, N. Fallah, M. Zokaei, and M. Gholami-Ahangaran, "The Role of Thyme (*Zataria multiflora* Boiss) Essential Oil as Natural Antioxidant on the Lipid Oxidation in Mayonnaise," *Journal of Food Quality* 2022 (2022): 7.

[58] R. Muñoz-González, C. Pino, H. Henríquez, et al., "Elucidation of Antimicrobial and Antioxidant Activities of Selected Plant-Based Mayonnaise-Derived Essential Oils against Lactic Acid Bacteria," *Journal of Food Processing and Preservation* 46, no. 3 (2022): https://doi.org/10.1111/jfpp.16339.

[59] A. Moradi, N. Davati, and A. Emamifar, "Effects of *Cuminum cyminum L.* Essential Oil and its Nanoemulsion on Oxidative Stability and Microbial Growth in Mayonnaise during Storage," *Food Science and Nutrition* 11, no. 8 (2023): 4781–4793, https://doi.org/10.1002/fsn3.3457.

[60] O. Soltan, H. Gazwi, A. Ragab, et al., "Assessment of Bioactive Phytochemicals and Utilization of Rosa Canina Fruit Extract as a Novel Natural Antioxidant for Mayonnaise," *Molecules* 28, no. 8 (2023): 3350, https://doi.org/10.3390/molecules28083350.

[61] H. Hassanzadeh, M. Rahbari, Y. Galali, M. Hosseini, and B. Ghanbarzadeh, "The Garlic Extract-Loaded Nanoemulsion: Study of Physicochemical, Rheological, and Antimicrobial Properties and Its Application in Mayonnaise," *Food Science and Nutrition* 11, no. 7 (2023): 3799–3810, https://doi.org/10.1002/fsn3.3365.

[62] P. Savani, A. Puthiyedath, R. Chandran K, S. George, P. S. Prasad, and U. Annapure, "Evaluation of the Sensory Properties and Antioxidant Activity of Clean Rosemary Extracts for an Effective Replacement of EDTA in Mayonnaise," *Applied Food Research* 3, no. 1 (2023): https://doi.org/10.1016/j.afres.2023.100302.

[63] N. Ünver, S. Çelik, S. Sayar, B. Ergün, and Y. Yakar, "Investigation of the Possibilities of Using Oleaster Fruit Flour in the Production of Low-Fat-Low-Cholesterol Mayonnaise," *Harran Tarım ve Gıda Bilimleri Derg* 27, no. 1 (2023): 137–144.

[64] S. A. H. Goli, S. Keramat, S. Soleimanian-Zad, and R. Ghasemi Baghabrishami, "Antioxidant and Antimicrobial Efficacy of Microencapsulated Mustard Essential Oil Against *Escherichia coli* and *Salmonella Enteritidis* in Mayonnaise," *International Journal of Food Microbiology* 410 (2024): https://doi.org/10.1016/j.ijfoodmicro.2023.110484.