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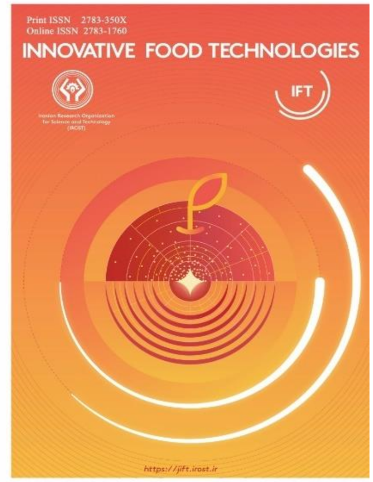

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Hot-Air Drying Characteristics and Physicochemical Properties of Olive Oil-Based Emulsion Oleogels Prepared with Basil Seed Gum

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Abstract

Excessive consumption of high-fat foods is a major contributor to cardiovascular disease, driving the demand for healthier fat alternatives that maintain desirable product quality. Oleogelation—structuring liquid oils into semi-solid matrices using biopolymers—offers a promising solution for improving foods' sensory and structural properties while reducing saturated and trans fats. This study examined the hot-air drying behavior of olive oil–based emulsions structured with Ocimum basilicum seed gum under varying process parameters: drying temperature (70–90 °C), emulsion thickness (0.25–0.50 cm), and gum concentration (1.5–2.5% w/w). Drying behavior and final oleogel quality were evaluated based on oil-binding capacity (OBC), textural firmness, and color metrics. The optimal conditions, 2% basil seed gum, 0.25 cm thickness, and 80 °C, produced oleogels with the highest OBC (up to 97%) and improved firmness (up to 5.82 N). Increased emulsion thickness negatively impacted OBC, while higher drying temperatures and gum concentrations intensified color changes (ΔE ranging from 0.17 to 0.49). These findings highlight the critical role of formulation and processing parameters in developing oleogels with optimized structural and functional performance. The results provide a practical foundation for the industrial scale-up of healthier fat systems using plant-based emulsifiers and controlled drying protocols.

Keywords: Oleogel; Basil Seed Gum; Drying; Emulsion Structuring.

1. Introduction

Rising concerns about public health have led to a growing demand for food products that not only fulfill basic nutritional requirements but also deliver additional health-promoting benefits (Valdivia-Culqui et al., 2024). Lipids play a pivotal role in food systems in enhancing flavor, texture, and overall product quality (Zulfiqar et al., 2024). Solid fats are commonly added to foods to improve texture and mouthfeel; however, they are typically rich in saturated and trans fatty acids, which have been linked to weight gain, diabetes, and cardiovascular diseases (Pang et al., 2022). Given the essential role of saturated and trans fats in food texture, adequate substitutes must replicate their structural characteristics. Various oil structuring techniques have been developed to convert liquid oils into solid or semi-solid forms (Sivakanthan et al., 2022). One such innovation is oleogelation, which allows for forming semi-solid fat systems using unsaturated oils while maintaining their chemical integrity (Qiu et al., 2024). Oleogels are semi-solid systems created by immobilizing liquid oils within a three-dimensional matrix, typically stabilized by hydrogen bonds and various molecular interactions. These structures often rely on natural substances like proteins (such as collagen and casein) and polysaccharides (including starch and gums) to maintain their integrity (Gao et al., 2024; Kim et al., 2024; Zhang et al., 2024).

Oleogels can be produced via direct or indirect methods. While direct methods are simpler, they typically require high temperatures, which can degrade unsaturated oils through oxidation. In contrast, indirect methods—such as emulsion-template techniques followed by dehydration—operate at lower temperatures, better preserving oil quality. The emulsion formation and drying stages significantly influence the final characteristics of oleogels (Lama et al., 2024). Oleogels have garnered significant interest in the food industry owing to their structural stability, smooth texture, and ability to facilitate the controlled release of ingredients (Pawar et al., 2024). These characteristics make them especially suitable for bread, margarine, and sausage products (Prakansamut et al., 2024).

The functional characteristics of oleogels are influenced by several key variables, including the specific type of oleogelator employed, the nature of the oil incorporated, and the conditions under which the formulation is processed. Key parameters like oil polarity and degree of saturation strongly influence oleogel behavior (Sun et al., 2022). While animal fats are highly saturated and oxidation-resistant, plant oils are more prone to oxidation due to their higher levels of unsaturated fatty acids, such as oleic, linoleic, and linolenic acids (Akbari et al., 2024; Espert et al., 2024; Voon et al., 2024). Among these oils, olive oil stands out due to its established nutritional benefits, including antioxidant properties, cardiovascular protection, and anticancer effects (Hashempour-Baltork Zade et al., 2024). Oleogelation provides a promising method for encapsulating such oils within a gel matrix using oleogelators (Prakansamut et al., 2024).

Oleogelators are structuring agents that create three-dimensional networks capable of entrapping oils (Zulfiqar et al., 2024). Examples include waxes, phytosterols, oryzanol, lecithin, ethyl cellulose, sorbitan derivatives, fatty acids, and fatty alcohols (Barroso et al., 2024). *Ocimum basilicum* seed gum, a hydrophilic, plant-based colloid, exhibits exceptional emulsifying, gel-forming, stabilizing, and absorption properties (Guan Ma et al., 2023). Incorporating basil seed mucilage into food systems enhances oil-binding capacity, water retention, emulsification, and texture, resulting in firmer gels and improved sensory characteristics (Nazir & Wani, 2021). Despite growing interest in oleogel-based fat replacers, limited research has systematically examined the drying charactristics of emulsion-templated oleogels using plant-derived hydrocolloids such as *O. basilicum* seed gum. Understanding how formulation and drying parameters affect oil-binding capacity, texture, and color is critical for optimizing product quality and scaling up industrial production. Accordingly, this study explores the drying behavior of olive oil–based emulsions structured with *O. basilicum* seed gum under diverse processing conditions, alongside assessing their physicochemical attributes. The primary objective is to develop practical insights that can aid in formulating structurally resilient and industrially viable oleogels for integration into functional food systems.

2. Materials and Methods

2.1 Materials

Virgin olive oil was sourced from a local retailer in Ahvaz, Iran, while *O. basilicum* seed gum was obtained from Reyhan Gum Parsian Co., located in Golestan, Iran. Tween 80 (polyoxyethylene sorbitan monooleate), used as an emulsifier, was obtained from Kian Shimi Co. (Merck, Germany).

2.2 Preparation of Basil Seed Gum Solution

To prepare the hydrocolloid solution, quantities of 1.125, 1.5, and 1.875 g of *O. basilicum* seed gum were accurately measured and slowly dispersed into 75 mL of distilled water in a 250 mL beaker. The water volume was measured using a graduated cylinder. The mixture was stirred at 400 rpm on a magnetic stirrer for 2 hours until the gum was completely dissolved. To ensure complete hydration of the gum, the beaker was sealed with aluminum foil and kept at room temperature overnight.

2.3 Emulsion Preparation

The oil-in-water emulsion was formulated following the procedure outlined by Espert et al. (2021), incorporating minor adjustments to tailor the method for this study. First, 75 g of the hydrated *basil seed gum* solution was weighed as the aqueous phase, and 0.2 g of Tween 80 was added as the emulsifier. Then, 75 g of virgin olive oil was slowly incorporated into the mixture while homogenizing at 9,000 rpm using a high-speed homogenizer. The emulsion was stirred for 5 minutes to ensure proper oil dispersion within the gum solution. Afterward, the mixture was stirred at 200 rpm for 1 hour on a magnetic stirrer to enhance its stability further. Finally, the emulsion was refrigerated at 4°C for 24 hours to improve stability (Espert et al., 2021).

2.4 Emulsion Drying Procedure

The prepared emulsion was transferred into plates according to the required sample thickness. For the 0.50 cm thickness, five plates were allocated for physicochemical analyses and one plate was used for monitoring the drying charactristics. For the 0.25 cm thickness, eight plates were used for analyses and one plate was reserved for drying behavior evaluation. All samples underwent convective hot-air drying in a laboratory oven (BINDER VD 53) until a constant weight was achieved, ensuring moisture removal and solid gel formation. Drying trials were conducted at 70, 80, and 90 °C temperatures and emulsion thicknesses of 0.25 and 0.50 cm. The airflow velocity was constant at 2 m/s, while the dryer's internal relative humidity was 10%. Drying behavior was evaluated by monitoring the weight loss of samples during hot-air drying. Sample weights were recorded at 15-min intervals during the first 3 h and subsequently at 60-min intervals until a constant weight was achieved. Moisture ratio (MR) was calculated according to Equation (1):

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad (1)$$

where M_t is the moisture content (kg water/kg dry matter) at time t, M_0 represents the initial moisture content, and M_e is the equilibrium moisture content. Since the final equilibrium moisture content was negligible compared with the initial moisture content, MR was simplified as:

$$MR = \frac{M_t}{M_0} \quad (2)$$

The drying rate constant (k) was estimated from the slope of the linear relationship between ln(MR) and drying time during the falling-rate period according to the Lewis drying model (Lewis, 1921). The obtained k values were expressed as min^{-1}.

Once a constant weight was achieved, plates intended for analyses were sealed in airtight zipper-lock bags, while those designated for moisture content evaluation were transferred to an oven set at 105°C for further drying (Saavedra et al., 2024). A complete factorial experimental design (3 drying temperatures × 2 emulsion thicknesses × 3 gum concentrations) was implemented to systematically assess the effects of formulation and processing parameters on the physicochemical properties.

3. Physicochemical Analyses

3.1 Moisture Content Determination

Initially, empty plates were weighed, and their masses were recorded. The balance was zeroed, and 1 g of emulsion was placed into each plate. The samples were then dried in a hot-air oven at 105°C. After 2.5 hours, the samples were weighed at 15-minute intervals until a constant weight was achieved. The plates were then transferred to a desiccator for 20 minutes to cool before final weighing. Moisture content was calculated using the following Equation (Mert & Demirkesen, 2016):

$$\text{Moisture (\%)} = [(\frac{\text{Initial weight} - \text{Final weight}}{\text{Initial weight}})] \times 100 \quad (3)$$

The initial and final weights refer to the total mass of the sample plus the plate before and after drying. Moisture content measurements were performed in triplicate, and the results were expressed as mean ± standard deviation (SD).

3.2 Firmness Measurement

The firmness of oleogel samples was evaluated using a texture analyzer (Stable Micro Systems, TA.XT.plus, UK). A cylindrical probe was used to compress each sample to a depth of 6 mm. The pre-test, test, and post-test speeds were set at 1, 1, and 10 mm/s, respectively. Each sample was analyzed in six replicates and the maximum compression force was recorded as firmness (N) (Espert et al., 2020). The results were expressed as mean ± standard deviation (SD).

3.3 Oil Binding Capacity (OBC)

Empty microtubes were first weighed (a), and 2 mL of molten oleogel, heated to 80°C, was transferred into each tube. After being kept at room temperature for 24 hours, the tubes were reweighed (b) and centrifuged at 1,000 rpm for 15 minutes at room temperature (Hermle Z206, Germany). The tubes were then inverted onto filter paper for 3 minutes to drain any free oil, after which the final weight (c) was recorded. Oil binding capacity was calculated using the following equations (Alizadeh et al., 2020):

$$\text{Free oil} (\%) = [(\frac{b- a) - (c - a)}{(b - a)}] \times 100 \qquad (4)$$

$$\text{OBC} (\%) = 100 - \text{Free oil} (\%) \qquad (5)$$

Oil binding capacity measurements were performed in triplicate, and the results were expressed as mean ± standard deviation (SD).

3.4 Color Measurement

Color characteristics of the oleogel samples were assessed using a colorimeter (Minolta Konica, CR-400, Japan). The parameters recorded included lightness ($L*$), redness ($a*$), and yellowness ($b*$) (Tutunchi et al., 2019). Total color difference (ΔE) was calculated using the following Equation:

$$\Delta E = \sqrt{[(L_1 - L_2)^2 + (a_1 - a_2)^2 + (b_1 - b_2)^2]} \qquad (6)$$

Where L_1, a_1, and b_1 represent the color values of the control sample, and L_2, a_2, and b_2 are the corresponding values for the treated samples. The colorimeter was calibrated using a standard white calibration plate prior to analysis. Color measurements were performed in triplicate, and the results were expressed as mean ± standard deviation (SD).

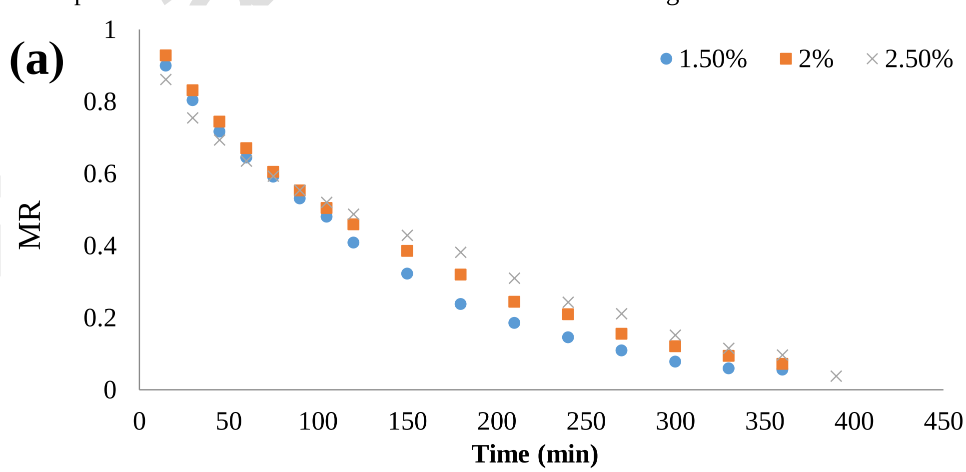
3.5 Statistical Analysis

Statistical analysis was performed using MATLAB software. A three-way analysis of variance (ANOVA) based on a factorial design was applied to evaluate the effects of drying temperature, emulsion thickness, and basil seed gum concentration, as well as their interactions, on the physicochemical properties of oleogels. The significance of individual factors and their interactions was determined at a confidence level of 95% ($p < 0.05$). Results were expressed as mean values with standard deviations.

4. Results and Discussion

4.1 Drying Charactristics

Figure 1 illustrates the drying characteristics of oleogels formulated with varying concentrations of *O. basilicum* seed gum (**Figure 1a**) and dried at different temperatures (**Figure 1b**). Regardless of the drying temperature, moisture content initially decreased nearly constantly. The drying rate declined after a specific period, depending on the drying temperature. This initial phase was characterized by rapid evaporation of free surface moisture, particularly under lower thermal conditions. As drying progressed, a gelatinous crust gradually formed on the emulsion surface—a phenomenon known as surface hardening. This crust acted as a diffusion barrier, slowing moisture removal as the remaining water within the oleogel had to migrate through the gel network. In all cases, lower air-drying temperatures resulted in longer drying times (**Figure 1b**). For example, in samples with 0.50 cm thickness and a 2.5% (w/w) basil seed gum solution, the drying duration ranged from 480 to 580 minutes at 90°C and 70°C, respectively. These findings are consistent with previous studies on similar systems, where elevated temperatures enhanced surface moisture evaporation and internal moisture diffusion within the oleogel matrix.



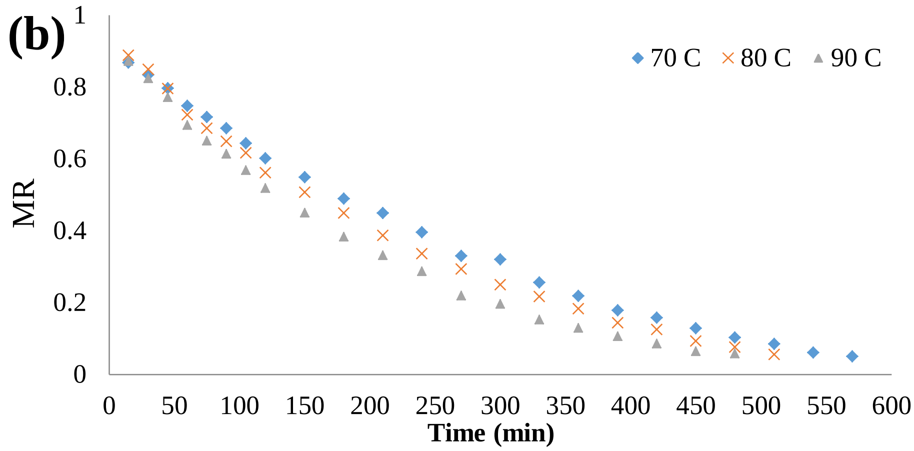


Figure 1. Drying charactristics (MR vs. Time) of oleogels: (a) effect of basil seed gum concentration (1.5%, 2%, 2.5% w/w); (b) effect of drying temperature (70°C, 80°C, and 90°C) at constant emulsion thickness.

The impact of *basil seed gum* concentration on the drying rate constant is presented in **Table 1**. An inverse relationship was observed between gum concentration and drying rate.

At 80 °C and an emulsion thickness of 0.25 cm, increasing the basil seed gum concentration from 1.5% to 2.0% and 2.5% (w/w) resulted in a decrease in the drying rate constant (k) from 0.0173 ± 0.0038 to 0.0128 ± 0.0040 and 0.0100 ± 0.0011 min^{-1}, respectively.

This significant reduction can be attributed to the increased viscosity of the emulsion at higher gum concentrations, as noted during formulation. Additionally, higher gum content enhances the stability of the water–oil phase within the gel network due to the hydrocolloid's ability to retain water at the molecular level, thereby reducing the rate of water evaporation. The drying rate was also significantly influenced by the emulsion layer thickness. As shown in **Figure 2**, samples with a 0.25 cm thickness exhibited higher drying rates than those with 0.50 cm. In thicker or denser samples, water molecules must travel more to reach the evaporation surface, thus limiting diffusion. Consequently, in 0.50 cm samples, mass transfer is hindered due to the increased path length for moisture migration. Additionally, the specific interfacial surface area (expressed as m^2/m^3 or m^2/kg) between the air and the emulsion (or gelled solid) increases as thickness decreases, enhancing heat and mass transfer efficiency.

Table 1. Effect of *O. basilicum* Seed Gum Concentration and Drying Temperature on Drying Rate Constant (min^{-1})

Drying Temp. (°C)	Basil Seed Gum (% w/w)	Drying Rate – 0.25 cm	Drying Rate – 0.50 cm
70	1.5	0.0110 ± 0.0010	0.0060 ± 0.0011
	2.0	0.0094 ± 0.0003	0.0051 ± 0.0006
	2.5	0.0071 ± 0.0009	0.0042 ± 0.0008
80	1.5	0.0173 ± 0.0038	0.0087 ± 0.0010
	2.0	0.0128 ± 0.0040	0.0065 ± 0.0008
	2.5	0.0100 ± 0.0011	0.0059 ± 0.0002
90	1.5	0.0184 ± 0.0027	0.0100 ± 0.0019
	2.0	0.0159 ± 0.0033	0.0094 ± 0.0004
	2.5	0.0148 ± 0.0029	0.0083 ± 0.0007

Values are presented as mean ± standard deviation of repeated measurements.

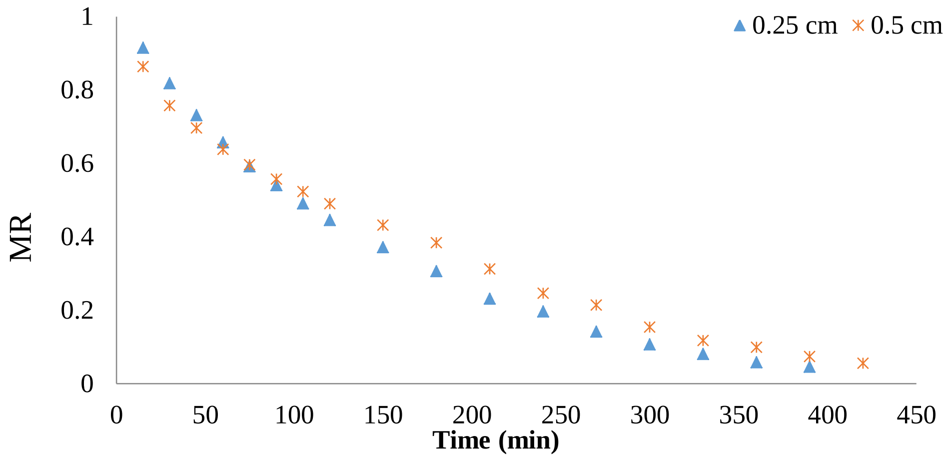


Figure 2. Constant drying rate (*k*) as a function of drying temperature for oleogels prepared with varying concentrations (1.5, 2.0, and 2.5% w/w) of *O. basilicum* seed gum at two emulsion thicknesses (0.25 and 0.50 cm).

These observations align with the drying charactristics reported by Lama et al. (2024) for emulsion-templated oleogels containing chitosan. In that study, a rapid decline in moisture content was observed during a brief induction period (less than 5 minutes), attributed to the immediate evaporation of surface water. This phenomenon formed a gelatinized surface layer—or crust—as a barrier to moisture transport from within the sample. As drying progressed, the thickening of this surface layer increased resistance to mass transfer. Higher air temperatures raise the temperature of the solid matrix, promoting surface water evaporation and enhancing internal moisture diffusion. However, increasing the temperature from 70°C to 80°C did not significantly reduce drying time. This behavior may be attributed to the accelerated formation of a protective surface layer at higher temperatures, which limits direct air contact with the emulsion matrix and impedes moisture release.

4.2 Moisture Content

The influence of *O. basilicum* seed gum concentration on the final moisture content of dried oleogels is presented in **Figure 3**. The results indicate that increasing gum concentration led to higher residual moisture levels. This can be attributed to the enhanced stabilization of the water–oil phase within the emulsion matrix, facilitated by the gum's molecular ability to retain water. The hydrocolloid structure effectively slows evaporation by entrapping water molecules, thereby increasing moisture retention. The drying rate was also significantly influenced by emulsion thickness. As shown in **Figure 3**, samples with a 0.25 cm layer exhibited faster drying than those with a 0.50 cm layer. In thicker systems, moisture must travel a longer diffusion path to reach the surface, increasing resistance to mass transfer. Moreover, the specific interfacial area (m^2/m^3 or m^2/kg) between the emulsion (or gelled material) and the surrounding air increases as thickness decreases, facilitating improved heat and moisture transfer.

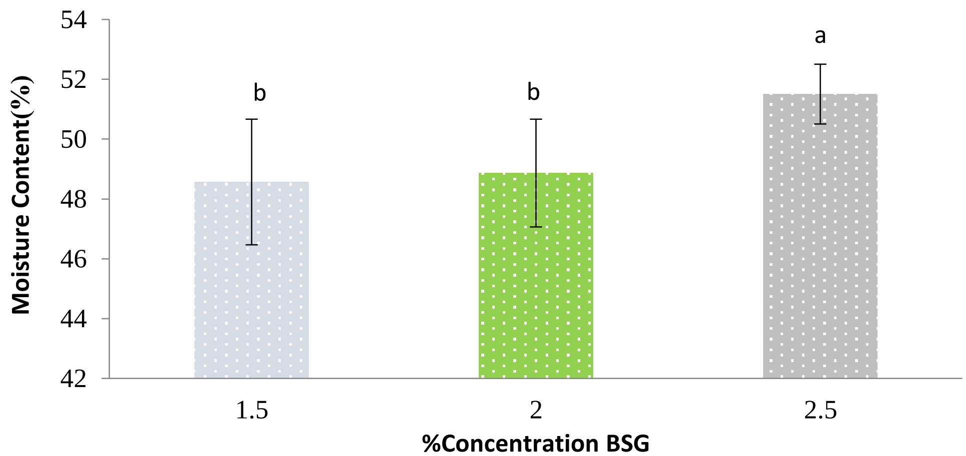


Figure 3. Effect of *O. basilicum* seed gum concentration on moisture content of samples dried at 80 °C with a 0.50 cm emulsion thickness.

As expected, the specific rate of water evaporation increased proportionally with temperature, a trend consistent for both pure water and the tested emulsions. Lama et al. (2024) corroborate these findings. In their study on chitosan-based emulsion-templated oleogels, samples with the highest chitosan concentration exhibited prolonged drying times. This was attributed to the formation of a denser, three-dimensional network that enhanced the stability of the water–oil system and provided structural resistance to moisture removal. High chitosan content and surface hardening at elevated temperatures resulted in a compact gel layer that hindered moisture transfer across the polymeric matrix. This behavior aligns with drying characteristics commonly observed in high-moisture food matrices with minimal free water.

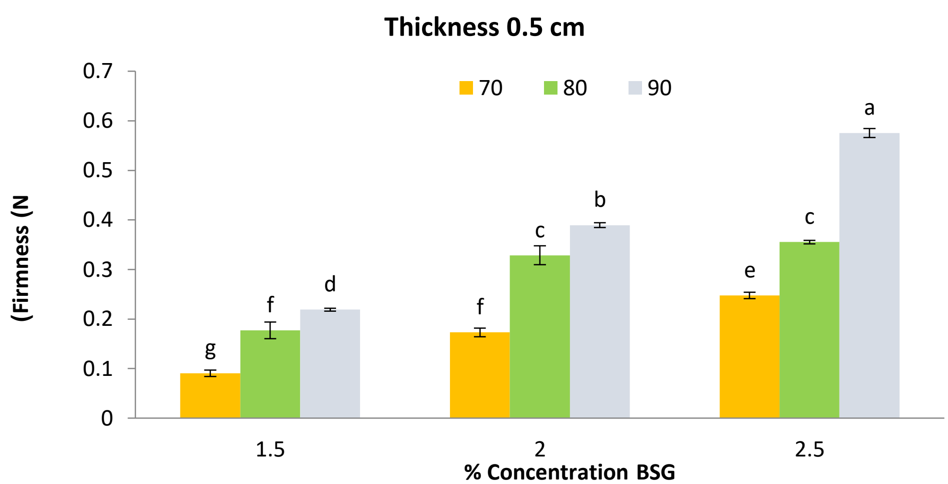
4.3 Firmness

Firmness of oleogels are critical to their functionality as fat replacers in food systems, directly influencing consumer acceptance and shelf stability. **Figure 4a** presents the firmness values of samples with a 0.50 cm emulsion thickness at different concentrations of *O. basilicum* seed gum (1.5%, 2.0%, and 2.5% w/w) and drying temperatures (70°C, 80°C, and 90°C). **Figure 4b** shows the corresponding results for samples with a 0.25 cm thickness. Across both thicknesses, increasing the gum concentration and drying temperature generally led to firmer gels, with values ranging from 0.86 ± 0.11 to 5.82 ± 0.26 N. These results are consistent with those reported by Espert et al. (2021), who observed firmness values of 1.71, 1.62, and 3.45 N in HPMC–sunflower oil oleogels at HPMC concentrations of 0.5%, 1%, and 2%, respectively.

Statistical analysis confirmed that *O. basilicum* seed gum concentration was the most influential factor affecting oleogel firmness (F = 6.74, $P < 0.024$), followed by drying temperature (F = 4.87, $P < 0.037$) and emulsion thickness (F = 3.91, $P < 0.045$). The influence of temperature, although significant, was less pronounced than that of gum concentration. Across all drying conditions, including emulsion thicknesses and temperature levels, increasing the concentration of *O. basilicum* seed gum resulted in a statistically significant ($P < 0.05$) increase in firmness. This trend supports previous findings indicating that higher concentrations of gelling agents promote the formation of more robust three-dimensional networks capable of effectively entrapping oil. In contrast, lower biopolymer concentrations failed to form cohesive structures, leading to mechanically weaker oleogels. The maximum firmness (5.82 ± 0.26 N) was observed in samples containing 2.5% *O. basilicum* seed gum, dried at 90°C with a 0.50 cm emulsion thickness.

A significant ($P < 0.05$) increase in firmness was also noted with rising temperature from 70°C to 90°C across all concentrations and thicknesses. Supporting these results, Lama et al. (2024) reported that chitosan concentration significantly affected the mechanical behavior of emulsion-templated oleogels. Lower chitosan levels increased elasticity at low (50°C) and high (80°C) temperatures. Extended drying times at lower temperatures enhanced structural resistance under compressive force.

(a)



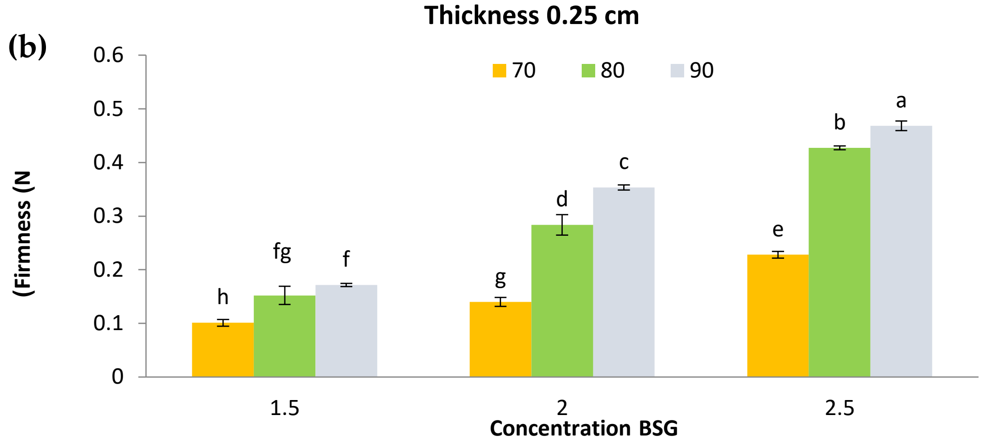


Figure 4. Effect of *O. basilicum* seed gum concentration and drying temperature (70, 80, and 90 °C) on oleogel firmness at two emulsion thicknesses:(a) 0.50 cm;(b) 0.25 cm. Different letters indicate statistically significant differences ($P < 0.05$) among gum concentration groups.

4.4 Oil Binding Capacity (OBC)

Oil binding capacity (OBC) reflects the interaction between the oleogelator and oil, particularly under mechanical stress. Statistical analysis revealed that emulsion thickness was the most influential factor affecting OBC ($F = 58.91$, $P < 0.001$), followed by drying temperature ($F = 17.6$, $P < 0.029$) and *O. basilicum* seed gum concentration ($F = 10.61$, $P < 0.041$). The effect of thickness is clearly illustrated in **Figure 5**. Oleogels dried at a thickness of 0.25 cm (**Figure 5a**) exhibited OBC values ranging from 81 ± 0.49 % to 97 ± 0.58 %, whereas increasing the thickness to 0.50 cm (**Figure 5b**) resulted in values consistently below 80%.

At 0.25 cm thickness, drying temperature significantly influenced OBC ($P < 0.05$). Increasing both temperature and gum concentration was associated with a decline in OBC. This behavior is likely attributed to the shrinkage of colloidal structures during moisture loss. As water migrates to the surface, water-soluble components accumulate and form a dehydrated crust, reducing permeability and limiting oil retention. The water solubility of *O. basilicum* seed gum suggests that its aggregation at elevated temperatures may hinder oil entrapment, particularly during the falling-rate drying phase when surface hardening intensifies. Accelerated crust formation at higher temperatures, combined with elevated gum concentrations, may amplify this barrier effect and compromise the structural integrity of the oleogel matrix. Previous studies have shown that stronger gel networks enhance oil retention and lower oil loss. Notably, prior research has reported OBC values exceeding 97 ± 0.58 % in oleogels formulated with sunflower oil (Espert et al., 2020), soybean oil (Thakur, Singh, et al., 2022), and canola or flaxseed oils (Morales, Iturra, et al., 2023). These findings underscore the critical importance of maximizing OBC for industrial applications. Based on the present results, emulsion thicknesses greater than 0.25 cm are not recommended when optimal oil retention is required.

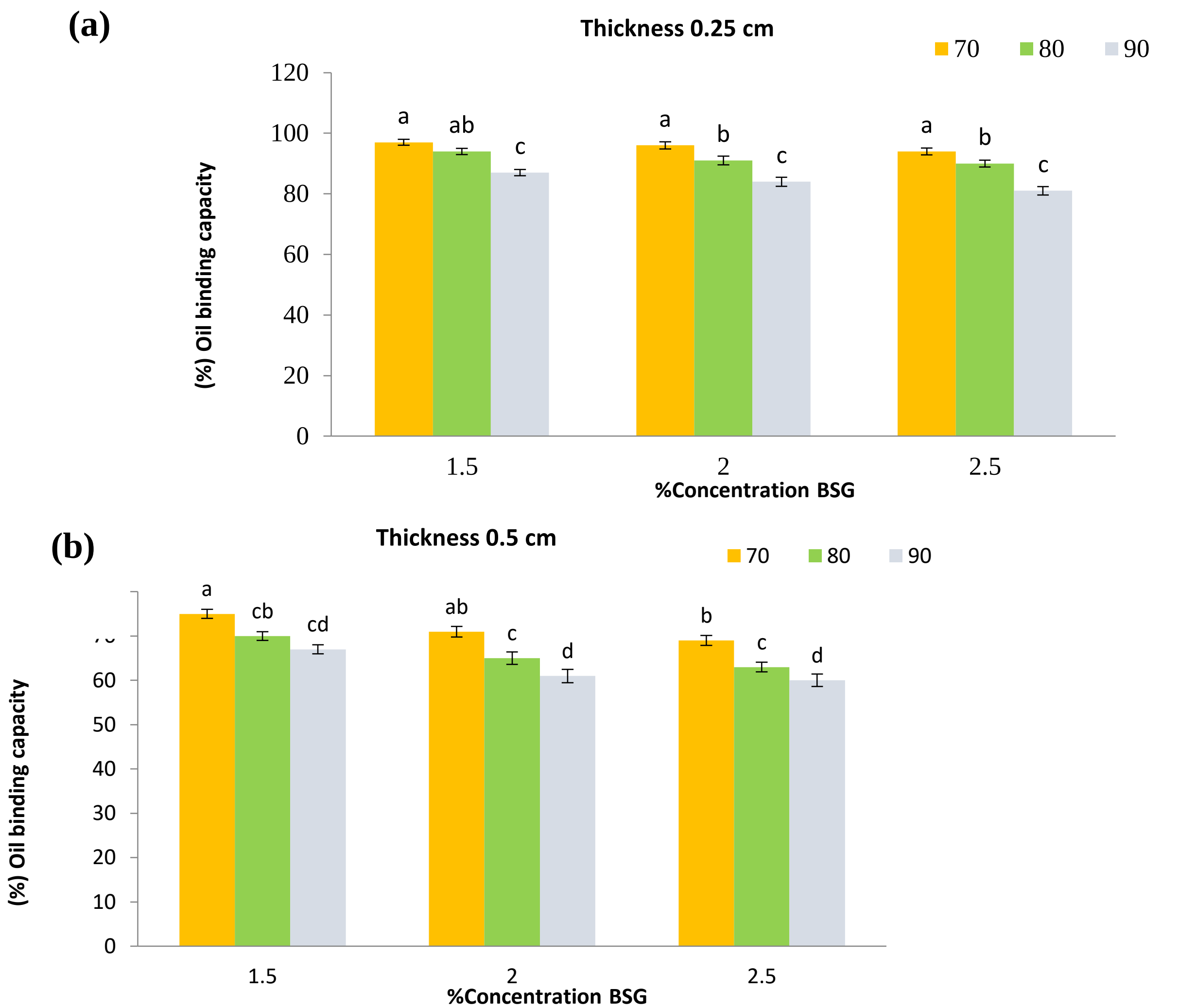


Figure 5. Effect of drying temperature (70, 80, and 90 °C) on the oil binding capacity (OBC) of oleogels prepared with different concentrations (1.5%, 2.0%, and 2.5% w/w) of O. basilicum seed gum at emulsion thicknesses of (a) 0.25 cm and (b) 0.50 cm. Different letters indicate statistically significant differences ($P < 0.05$) among gum concentration groups.

4.5 Color Analysis

Color is a critical factor in the sensory perception of novel ingredients and plays a central role in consumer organoleptic evaluation. No statistically significant differences were observed in color parameters between oleogels dried at different emulsion thicknesses in this study. However, drying temperature significantly influenced the ΔE ($P < 0.05$). For example, in oleogels containing 2% *O. basilicum* seed gum, ΔE values increased from 0.17 ± 0.09 at 70°C to 0.49 ± 0.13 at 90°C. This trend is clearly illustrated in **Figure 6**, with **Figure 6a** showing samples with 0.50 cm thickness and **Figure 6b** those with 0.25 cm. The increase in ΔE with rising temperature may be associated with thermal-induced changes and possible chemical reactions occurring during drying. However, since oxidation-related parameters were not evaluated in this study, further investigation is required to confirm the specific mechanisms responsible for color changes.

Lama et al. (2024) findings support these observations. In their study, increasing chitosan concentrations led to a slight increase in $L*$ and $b*$ values and a decrease in $a*$, indicating a shift toward a more yellow hue. The lightness coordinate ($L*$) showed a minor decline as moisture content dropped below 0.3 kg water/kg dry matter, likely due to surface darkening associated with prolonged exposure to heat during hot air drying. At identical drying temperatures, final $L*$ values were lower in systems with higher chitosan concentrations, attributed to longer drying durations and more pronounced thermal darkening. As a result, samples with higher biopolymer concentrations exhibited greater Δ*E*, which can be linked to the extended drying time required in more viscous emulsions. These findings suggest that emulsions with elevated chitosan content are more prone to color shifts due to prolonged exposure to heat and air during drying.

These findings underscore the significant influence of formulation and drying parameters—specifically basil seed gum concentration, drying temperature, and emulsion thickness—on the structural and functional characteristics of emulsion-templated oleogels. A higher gum concentration improved firmness but increased moisture retention and color variation due to a denser gel matrix. Thinner emulsions (0.25 cm) facilitated faster moisture removal and superior oil-binding capacity, while elevated temperatures accelerated drying but risked surface hardening and reduced oil retention. Notably, the interplay between these variables shaped the textural and stability outcomes of the oleogels, providing a basis for optimizing processing conditions. These insights highlight critical design considerations for tailoring oleogel systems with desirable physicochemical and functional profiles, particularly in developing scalable, health-oriented fat alternatives for functional food applications.

(a)

(b)

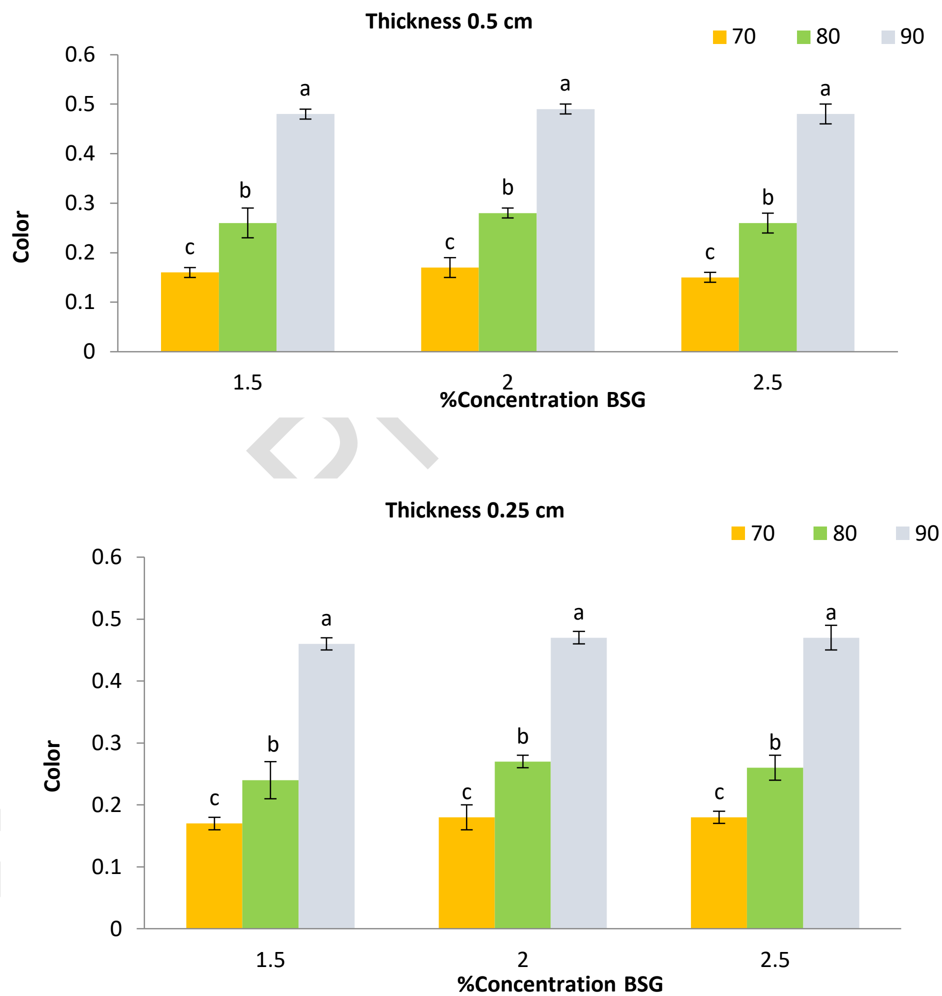


Figure 6. Total color difference (ΔE) of oleogels dried at different temperatures (70, 80, and 90 °C) and formulated with various concentrations (1.5%, 2.0%, and 2.5% w/w) of *O. basilicum* seed gum at different emulsion thicknesses: (a) 0.5 cm; (b) 0.25 cm. Different letters indicate statistically significant differences ($P < 0.05$).

5. Conclusion

Increasing the drying temperature to 80°C did not substantially reduce total drying time nor significantly enhance the structural or functional properties of the oleogels. This outcome may be attributed to the rapid formation of a surface crust, which hindered complete dehydration and limited network development. Color parameters were sensitive to drying temperature: $L*$ values increased at lower gum concentrations but declined at higher concentrations, while $a*$ and $b*$ values showed modest increases across all treatments. Firmness increased with both temperature and *O. basilicum* seed gum concentration, although the effect of concentration was more pronounced.

Emulsion thickness was identified as a critical determinant of oil binding capacity, with thinner layers (<0.50 cm) yielding significantly higher OBC values. Notably, high drying temperatures reduced oil retention, and increasing gum concentration beyond 2% w/w did not further enhance this parameter. These findings provide practical insights for refining oleogel design strategies aimed at scalable, nutritionally improved fat replacers for food applications.

6. Study Limitations and Future Perspectives

This study focused specifically on *O.basilicum*-based oleogels with olive oil, and thus, its findings should be interpreted within this formulation scope. This study provides valuable insight into the drying behavior and physicochemical properties of *O. basilicum*-based oleogels; however, several limitations must be acknowledged. First, only olive oil was used as the lipid phase, limiting generalizability. Future research should investigate alternative oils—such as canola, flaxseed, or medium-chain triglycerides—with varying polarities and fatty acid profiles to broaden applicability. Second, oxidative stability was not evaluated. Since drying temperature can influence lipid oxidation and sensory quality, future studies should include comprehensive oxidative analyses (e.g., peroxide value, TBARS) to assess product stability. Third, the investigation focused on physical parameters such as moisture content, firmness, and OBC. However, additional analyses—such as rheological characterization, microstructural imaging (e.g., SEM or CLSM), and long-term storage stability—are essential for understanding performance under real-world conditions. Finally, the absence of sensory or in vivo evaluations limits the conclusions that can be drawn about consumer acceptability. Future work should incorporate sensory profiling, bioavailability studies, and health impact assessments to support the use of these oleogels in functional food applications.

List of Abbreviations

Abbreviation	**Full Term**
$a*$	Red/green color coordinate
$b*$	Yellow/blue color coordinate
°C	Degree Celsius
ΔE	Total color difference
HPMC	Hydroxypropyl methylcellulose
L*	Lightness coordinate
OBC	Oil Binding Capacity
O. basilicum	*Ocimum basilicum* (Basil seed gum)
Rpm	Revolutions per minute
SEM	Scanning Electron Microscopy
w/w	Weight by weight

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Ethical statement

Ethical review and approval were not required for this study as it did not involve human subjects or human data, in accordance with the local legislation and institutional requirements.

CRediT authorship contribution statement

Consent for Publication

All authors have read and approved the final version of the manuscript and consent to its submission for publication.

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