scientific reports

OPEN

Fabrication of curcumin-loaded emulgel and its application in low-calorie and functional cake

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In response to the growing need for healthier bakery products, this study aimed to partially replace fat with curcumin-loaded emulgels in cake formulations. Emulgels were prepared using Persian gum, sodium alginate, and inulin, with curcumin incorporated into sesame oil. Three concentrations of emulgel (30%, 50%, and 70% of fat) were incorporated into the cake mixture. The inclusion of 70% emulgel resulted in an increase in both storage (G′) and loss (G″) moduli, while simultaneously reducing the batter viscosity. The highest concentration of emulgel increased the moisture content of the cake by approximately 5.5%. The sample containing 70% emulgel exhibited similar specific volume (2.38%), porosity (22.92%), and texture properties (hardness, chewability, cohesiveness, gumminess, and springiness) when compared to the control. Additionally, the fortification of the cake led to a reduction in brightness (from 53.25 to 45.69) and a significant increase in the b index (from 47.21 to 55.03). Emulgel incorporation enhanced the antioxidant activity of the cake from 45.64% to 89.49%, while substituting fat with 70% emulgel resulted in a substantial reduction in peroxide value after 30-day storage (61.28% decrease). Sensory evaluation indicated that the cake containing 70% emulgel was more acceptable to panelists.

Keywords Fortified cake, Emulgel, Hydrocolloids, Antioxidant activity, Rheological properties

Consumer demand for healthier dietary options has led to the development of alternatives to solid fats, which are linked to chronic health issues such as diabetes[1], obesity[2] and cardiovascular disease[3]. The World Health Organization (WHO) recommends reducing saturated fat intake and replacing solid fats with unsaturated oils[4]. Traditional bakery products, particularly cakes, often rely on shortenings or butter—rich in saturated and trans fats—for structure, texture, and palatability[5]. This has motivated researchers to explore healthier fat substitutes that do not compromise the quality and sensory properties of baked goods.

Although several fat replacement strategies have been studied in bakery products, each has limitations when applied at higher substitution levels. For example, inulin and resistant starch may impair texture and flavor release[6,7], protein-based mimetics such as microparticulated whey protein can raise allergenicity and cost issues[8], and hydrocolloids alone often fail to reproduce the full lubricating and mouth-coating properties of fat. Moreover, oleogels, while promising, have been reported to reduce cake volume and texture quality when used in large amounts[9]. In light of these challenges, it was necessary to explore a novel system that provides both technological and nutritional benefits.

An emerging approach involves the use of hydrogel-based emulsified systems—also known as emulgels—which are composed of a continuous hydrocolloid network entrapping emulsified oil droplets. Emulgel systems offer a dual role: (i) mimicking the functionality of solid fats by improving moisture retention, viscosity, and texture, and (ii) acting as carriers for bioactive compounds[10–12]. Unlike oleogels that rely solely on oil structuring agents, emulgels utilize both hydrophilic gelators (e.g., inulin, sodium alginate, Persian gum) and emulsification techniques, leading to improved mechanical and sensory properties[13]. The inclusion of natural polysaccharides like inulin and Persian gum has been shown to increase batter viscosity, enhance moisture retention, and contribute to the structural integrity of baked products[14,15].

Curcumin, a bioactive compound with well-documented antioxidant, anti-inflammatory, and antimicrobial effects, has attracted growing interest in the food industry[16]. It is approved as a food additive under the code E100 and is increasingly applied in functional food development due to consumer demand for clean-label, natural ingredients[17]. In addition to its health-promoting properties, curcumin provides a natural yellow

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pigment that can enhance the visual appeal of bakery products. However, its poor water solubility and instability during processing limit its direct use in food matrices[18]. Emulgel systems have demonstrated effectiveness in encapsulating curcumin and protecting it from degradation, thereby improving its bioavailability and allowing its integration into functional foods such as cakes, yogurts, and beverages[12].

This study explores the use of curcumin-loaded emulgels as both a fat replacer and a delivery system for curcumin in low-calorie cake formulations. By partially replacing fat with water and hydrocolloids, the emulgel system lowers the caloric density of the cake while simultaneously providing a protective matrix that enhances the stability and bioavailability of bioactive compounds such as curcumin, thereby delivering both nutritional and functional benefits beyond those of unsaturated oils alone[19,20]. The emulgel was created by combining sesame oil, sodium alginate, Persian gum, and inulin—ingredients selected for their synergistic gelation properties, clean-label functionality, and moisture retention capacity. Sesame oil was chosen as the lipid phase due to its oxidative stability, nutritional profile, and compatibility with curcumin[21,22]. The effects of different emulgel concentrations (30%, 50%, and 70%) on the batter's properties and the resulting cake's texture, moisture content, antioxidant activity, and sensory attributes were evaluated. To the best of our knowledge, this is the first study to investigate the application of a sesame oil-based hydrocolloid emulgel enriched with curcumin in cake formulation. This research aims to provide valuable insights into the potential of such dual-purpose emulgels for improving the nutritional and functional properties of bakery products.

Materials and methods

Material

The wheat flour (11% moisture, 11.3% protein, 0.82% ash, and 27% wet gluten, according to the AACC 2000) was obtained from Pishgam Co., Mashhad, Iran. Other ingredients of emulgel include Curcumin (assay > 95%) and Sodium alginate powder (MW = 250 kDa, M/G ratio = 5.92) (Sigma-Aldrich, St Louis, MO, USA), inulin (Roosendaal, Netherlands), Persian gum (Freer Co., Isfahan, Iran) and Sesame oil (Sanaye Mahdasht Co., Iran) were prepared. 2,2-Diphenyl-1-picrylhydrazyl (DPPH, 90%) was obtained from Sigma (St. Louis, MO, USA). Ingredients of cake formulation such as eggs (Telavang Co., Iran), milk (Pegah Co., Iran), vanilla (Bartar Co., Iran) baking powder and sugar were also purchased from a local market, Mashhad, Iran. Other chemical reagents used in this study were obtained from Sigma-Aldrich Co. (USA). All reagents and chemicals were of analytical grade.

Methods

Preparation of curcumin-loaded emulgels

The hydrocolloid-based emulgels were prepared using inulin, Persian gum, and sodium alginate powders. Inulin was dissolved in deionized water (1% w/w) and placed in a water bath, where it was heated to 45 ± 1 °C to obtain a clear solution. Subsequently, the inulin solution was homogenized on a hotplate stirrer, during which 1.31% Persian gum and 0.96% sodium alginate were added. To ensure complete hydration, the solution was stirred for 2 h at 26 °C and then stored in the refrigerator for 24 h. To complete the gelation process, calcium and sodium pyrophosphate salts (0.1%) were added to the gel mixture, which was then homogenized at 1500 rpm for 20 s. These salts act as ionic crosslinking agents, promoting the interaction between guluronic acid blocks of alginate chains, thereby enhancing gel network formation and structural stability. Sodium pyrophosphate serves to control the release of calcium ions and prevent premature gelation, allowing for better manipulation and homogenization of the system. Curcumin (0.04% w/w) was dissolved in sesame oil, which constituted 30, 50 and 70% of the total emulgel formulation. This concentration was selected based on a previous optimization study that evaluated the stability and antioxidant activity of curcumin in hydrocolloid-based oil structuring systems. The oil phase was gradually added to the gel mixture while stirring at 200 rpm for 10 min until fully emulsified. The prepared gels were then poured into molds and stored at 4 ± 1 °C for 24 h before analysis[23].

Cake formulation

The cake formulation presented in Table 1. In the cake formulations, emulgel replaced 30%, 50%, and 70% of the sunflower oil by weight, following a 1:1 substitution ratio (w/w). The total amount of fat-related ingredients (sunflower oil + emulgel) was maintained at the same level (w/w) across all treatments, although the true fat content decreased due to the aqueous and hydrocolloid matrix of the emulgel. Sugar, egg, and vanilla were mixed for 3 min using a mixer (Kenwood, UK), after which milk and sunflower oil were incorporated. Finally, flour and baking powder were mixed for 1 min. From the resulting batter, a 60 g portion was transferred to each baking pan (6 cm diameter) for baking in a conventional oven (Zuccihelli, Italy) at 180 °C for 30 min[24,25]. This amount was used to ensure consistent sample size and baking conditions across all treatments. The cake samples

Sample	Sunflower oil (g)	Emulgel (g)	Other ingredients*
Control	20	0	Same amount
30% emulgel	14	6	Same amount
50% emulgel	10	10	Same amount
70% emulgel	6	14	Same amount

Table 1. Composition of control and reformulated cake samples with different levels of emulgel fat replacement. * comprised 100 g of wheat flour, 20 g of sunflower oil, 30 mL of milk, 60 g of sugar, 3 g of baking powder, and 0.55 g of vanilla.

were allowed to cool at 25 °C for 2 h. The emulgels were incorporated at three levels (30%, 50% and 70%) of fat content.

The batter characteristics

Specific gravity and pH The specific gravity of batter was determined by dividing the weight of the batter by the weight of the equal volume of distilled water. The pH of the batter was measured according to AACC (2000) using a pH digital meter (Metrohm, Herisau, Switzerland)[26,27].

Rheological properties The rheological properties of the cake batters were assessed using a universal stress rheometer (Model MCR 301, Austria) equipped with a 10 mm parallel plate geometry. The dynamic viscoelastic properties of the samples, based on the storage modulus (G′) and loss modulus (G″) were investigated as a function of angular frequency (0.01–10 rad/s) at 25 °C[26].

Characteristics of cake samples

Physicochemical properties The moisture content of the cake was determined following the guidelines set by the AACC (No: 44-15-01, 2000) using the following equation:

$$\text{MoistureContent}(\%) = \left[\frac{W_1 - W_2}{W_1}\right] \times 100$$

where W_1 is the initial weight of the sample and W_2 is the weight after oven-drying.

Water activity (a_w) was analyzed at room temperature using the Novasina ms1-$a_w$water activity meter from Axair Ltd, Switzerland (AOAC, 1995). The volume of the cake samples was assessed using the seed displacement method outlined by the AACC (2000). The volume was calculated as the difference between the volume of seeds with and without the cake sample. Porosity was evaluated through image processing techniques. Images of 5 × 5 mm slices were captured using a scanner (300 dpi) and saved in JPG format. Subsequently, ImageJ software (version 1.47v, National Institutes of Health, USA) was used to convert the RGB images to grayscale and apply the appropriate plugin. Porosity was calculated using ImageJ software by converting scanned grayscale images into binary (black and white) format. The following equation was applied[28]:

$$Porosity\ (\%) = (Area\ of\ black\ pixels\ /\ Total\ image\ area) \times 100$$

Here, black pixels represented the air voids within the cake matrix.

Peroxide value (PV) The peroxide value (PV) of cake samples was determined according to the National Standard method of AOCS (Cd 8–53) and expressed as milliequivalents (meq O_2/kg) of active oxygen per kilogram of extracted fat. Fat was extracted from each sample prior to the analysis. Measurements were performed on days 0, 15, and 30 of storage.

Antioxidant capacity (DPPH) The antioxidant activity of the cake samples was assessed by evaluating their ability to scavenge free radicals using the DPPH (2,2-diphenyl-1-picrylhydrazyl) assay. Each cake sample was mixed with 50% ethanol (v/v) at a ratio of 1:10 and shaken for 24 h at 25 °C. Afterward, the mixture was filtered through Whatman filter paper, and the solvent was evaporated at 40 °C. The resulting extract was stored at 4 °C for subsequent DPPH analysis. A volume of 0.1 mL of the extract was then added to 3.9 mL of a DPPH solution (0.1 g/L in methanol) and thoroughly mixed. The mixture was allowed to react in the dark for 30 min at 25 °C. Finally, the absorbance was measured at 517 nm via a UV-Vis spectrophotometer (DR 5000, HACH). The antioxidant activity was calculated according to Eq. (1)[29]:

$$DPPH\ (\%) = ((A_{DPPH} - A_{Extract})\ /\ A_{DPPH}) \times 100 \quad (1)$$

Where A_{DPPH} is the absorbance of the DPPH blank sample, and $A_{Extract}$ is the absorbance value of the sample solution.

Texture analysis The effect of curcumin-loaded emulgels on the texture characteristics of fortified cake samples (2 h after baking) was assessed using a double-compression test with a texture analyzer (Farnell, Hertfordshire, UK). The cake was cut into a cylindrical shape (5 cm× 5 cm with 1.5 cm thickness). A cylindrical probe with 2.5 cm diameter at a 0.5 mm/s pretest speed, 1 mm/s test speed, and 0.5 mm/s post-test speed to compress the cake up to 50% of the original height. The textural characteristics analyzed in terms of hardness, springiness, cohesiveness, chewiness, and adhesiveness[30].

Color parameters The color of the cake samples was analyzed using a Hunter lab colorimeter (Reston, USA), which provided values for L^* (lightness, ranging from 0 to 100), a^* (redness to greenness), and b^* (yellowness to blueness). The total color difference (ΔE) between the control sample and the fortified cake was calculated as follows (Eq. 2)[31]:

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (2)$$

Sensory evaluation The sensory attributes of the cake samples were assessed by a panel of 30 participants (15 males and 15 females, aged 20 to 40 years, with a mean age of 29.8 ± 4.2 years). The samples were coded with random three-digit numbers and presented in a randomized order to each panelist to avoid positional bias. A five-point hedonic scale was used to evaluate sensory properties, including color, texture, porosity, and overall acceptance, with scores ranging from 1 (strongly dislike) to 5 (strongly like). All evaluations were conducted under standardized lighting and environmental conditions[32].

Statistical analysis
The results were analyzed using analysis of variance (ANOVA) with Minitab statistical software version 16. Duncan's Multiple Range Test was used to identify significant differences ($p < 0.05$). Duncan's Multiple Range Test was selected as a post-hoc method due to its effectiveness in comparing all treatment means and identifying statistically significant differences among them with better sensitivity compared to more conservative methods. All experiments were performed in triplicate, and the data are reported as mean ± standard deviation.

Results and discussion
Batter characteristics
Table 1 presents the pH values of the fortified batters. The pH measurements for both the control and the batters enhanced with emulgels did not show significant differences, indicating that substituting fat with emulgel in the batter did not alter its pH, suggesting that the substitution did not interfere with acid–base balance during formulation. This is consistent with findings by Santos et al. (2020), who reported similar stability when emulgels were used in pound cake systems[33].

The specific gravity of the batter serves as an indicator of its capacity to retain air bubbles, thereby influencing volume and mechanical aeration during the mixing process[34]. The specific gravity of the control sample was recorded at the lowest value (0.91 g/cm³), although no significant differences were observed with emulgel incorporation up to 50% (see Table 1). Conversely, the batter containing 70% emulgel exhibited the highest specific gravity (1.04 g/cm³). Increased levels of emulgels resulted in higher specific gravity values. This trend indicates a denser batter with reduced aeration capability at higher emulgel levels. The increased viscosity and gel-like structure of the emulgels may limit the ability of the batter to trap and retain air, potentially influencing the final cake volume[35]. Other studies have corroborated that substituting fat with emulgels increases specific gravity as emulgel levels rise[35–37]. However, Lim, Hwang[38] found that specific gravity was unaffected by replacing fat with oleogels at levels up to 50%.

The effects of substituting curcumin-loaded emulgels for fat in the batter on flow behavior, viscoelastic properties, and moduli are summarized in Table 2. The flow behavior of batters containing emulgel indicated a decrease in apparent viscosity compared to the control, with the lowest viscosity observed at 30% emulgel. The final volume of the cake is influenced not only by the initial amount of air mixed into the batter but also by how much air is retained during baking. Batters with lower viscosity tend to release carbon dioxide and do not trap air cells effectively during baking, resulting in reduced cake volume. Similar behaviors have been noted in other studies regarding the replacement of saturated fats in cakes, where adding oleogels caused a reduction in the apparent viscosity of the batter[33,39].

These observations are consistent with the findings of Bruno et al. (2022), who demonstrated that the rheological behavior of emulgels is strongly dependent on the concentration of structuring agents, with higher fiber content leading to reduced apparent viscosity and improved viscoelastic stability[40]. Similarly, Jeong et al. (2023) reported that muffin batters formulated with peanut sprout oil emulsion gels exhibited decreased viscosity and enhanced structural integrity, indicating that emulgel systems generally improve batter stability while modifying flow behavior[41].

The batter containing a high level of 70% emulgel demonstrated the highest storage modulus (G′), while the control batter, which contained 100% fat, exhibited the lowest G′ value (Table 2). A similar trend was observed for the loss modulus (G″), where increasing emulgel levels corresponded with higher G″ values. The batter with 70% emulgel showed greater G′ than G″, indicating its elastic characteristics. Lee[37] confirmed that replacing shortening with hydroxypropyl methylcellulose-based oleogels in muffin batter increased tan δ, suggesting a more viscous nature. Jyotsna, Prabhasankar[42] and Jang, Bae[43] concluded that increasing frequency improved both G′ and G″ moduli in batters containing emulgels and oleogels while reducing apparent viscosity. The entrapment of oil within the emulgel matrix yielded higher G′ and G″ values compared to cake batters made with shortening[33]. Furthermore, Mohanan, Tang[44] noted that increased air incorporation in cake batter can enhance its viscoelastic properties, leading to elevated moduli values, which aligns with the specific gravity observations inserted in Table 1. Our results are also in line with Jeong et al. (2023), who found that muffin batters containing

Batter samples	pH	Specific gravity (g/cm³)	Apparent viscosity (mPa.s)	G′ (Pa)	G″(Pa)
Control	7.32 ± 0.01^{a}	0.92 ± 0.07^{b}	5.65 ± 0.92^{a}	280.24 ± 2.45^{d}	285.35 ± 1.17^{c}
30% emulgel	7.33 ± 0.01^{a}	0.95 ± 0.02^{b}	4.57 ± 0.23^{c}	350.01 ± 1.12^{c}	337.49 ± 1.44^{b}
50% emulgel	7.30 ± 0.02^{a}	0.98 ± 0.01^{b}	5.09 ± 1.03^{b}	410.34 ± 1.03^{b}	398.01 ± 0.95^{a}
70% emulgel	7.28 ± 0.01^{a}	1.04 ± 0.02^{a}	4.85 ± 0.17^{b}	560.78 ± 2.14^{a}	400.63 ± 1.65^{a}

Table 2. Rheological and physicochemical properties of fortified batter containing curcumin-loaded emulgels. Different small letters in each column indicate the significant differences ($p < 0.05$).

emulsion gels had higher storage and loss moduli compared to controls prepared with shortening, confirming that emulgel incorporation enhances the elastic character of bakery batters[41].

Overall, these results show that curcumin-loaded emulgels can modify batter rheology by improving its viscoelastic profile without significantly disrupting pH or batter aeration at moderate levels. This structural reinforcement contributes to stable batter behavior and supports the application of emulgels as effective fat replacers in bakery formulations, aligned with the study's goal of enhancing nutritional and functional properties in cake systems.

Characteristics of fortified cake with curcumin-loaded emulgel

Physicochemical properties

This study examined the effects of replacing fat with curcumin-loaded emulgels at three different levels (30%, 50%, and 70%) on cake properties, as summarized in Table 3. The results indicated a clear increasing trend in specific volume with higher levels of emulgel substitution. Cakes with 70% emulgel exhibited the highest specific volume (2.42 ± 0.13 cm^3/g), followed by 50% and 30% replacements. In contrast, the control sample, which lacked emulgel, showed the significant lowest volume (1.81 ± 0.11 cm^3/g). This improvement can be attributed to the high viscosity and structural properties of the emulgel matrix, composed of Persian gum, sodium alginate, and inulin, which likely enhanced air incorporation and retention during mixing and baking. Similar observations were reported by Chen et al. (2016), who showed that cakes prepared with zein-based oil-in-glycerol emulgels enriched with β-carotene exhibited comparable specific volume and structural characteristics to standard cakes[45]. Likewise, Jeong et al. (2023) demonstrated that muffins formulated with peanut sprout oil emulsion gels maintained high volume and stable pore structure, further confirming the ability of emulgel systems to sustain cake expansion[41]. Similar results were reported by Pehlivanoğlu et al. (2021) when oleogels improved volume and porosity of bakery products, as well as by Meng and Kim (2020), who emphasized the role of hydrocolloids in stabilizing gas bubbles. Consequently, increasing emulgel content can mitigate the adverse effects of oil reduction, thereby decreasing the need for fat in cake formulations. Meng and Kim[26] found that incorporating locust bean gum, Arabic gum, and xanthan gum enhanced the stability of gas cells, allowing them to better retain the expanding gas generated during steaming. This improvement occurs due to the breakdown of hydrated polymer chains at elevated temperatures, which releases water molecules and strengthens the interactions between the polymer chains, forming a temporary network that minimizes gas loss. Pehlivanoğlu, Demirci[46] reported similar findings when shortening was replaced with oleogel made from cotton oil. Thus, the data demonstrate that curcumin-loaded emulgels can improve specific volume even at high substitution levels, aligning with the study's goal of creating low-fat baked products without compromising volume or structure.

While specific volume is a standard measure of baking quality, it is not the sole indicator. Cake quality is also characterized by a porous structure and uniform cell size. Porosity values ranged from 18.92% to 23.22%. The control sample (23.22 ± 1.24%) and the cake with 70% emulgel (22.92 ± 0.87%) exhibited the highest porosity, with no significant difference between them ($p > 0.05$). However, cakes with 30% and 50% emulgel showed reduced porosity, particularly at 30% emulgel (18.92 ± 1.07%), which was significantly lower than the control. These findings indicate that although low levels of emulgel may decrease porosity due to reduced air entrapment, higher emulgel concentrations can restore the cake's porous structure to levels comparable with traditional fat-based formulations. In traditional formulations, fat crystals encase air bubbles during baking, but this protective layer diminishes when oil is replaced with emulgels, reducing porosity. However, higher emulgel concentrations can offset this reduction[43,47]. Similar results were noted by Lim, Jeong[48], who found that muffins with 25% oleogels matched the volume and porosity of control samples. In agreement with our results, Turabi et al. (2008) found that incorporating gums and emulsifier blends in rice cake formulations increased porosity and specific volume, producing softer and more aerated products[49]. Similarly, Jeong et al. (2023) confirmed that emulsion gels in muffins supported the development of porous structures comparable to control formulations[41]. These results suggest that at suitable concentrations, emulgels not only preserve but can even restore the desired porous structure in cakes, supporting their use as solid fat alternatives.

Water activity (aw) is crucial for the shelf-life determination of baked goods. Using emulgels led to decreased water activity in cake samples compared to the control, with the lowest a_w (0.77 ± 0.01) recorded for the 70% emulgel sample. The maximum a_w was observed in the cake containing 30% emulgel and the control sample with no significant difference ($p < 0.05$) (Table 3). The hydrophilic hydroxyl groups present in the hydrocolloids of the emulgel interact with water molecules, thus reducing moisture loss from the cake crumb[50], and lowering free water content. Giacomozzi, Carrín[51] noted that muffins containing oleogels exhibited high water-holding capacity (WHC) during storage, extending their shelf life by minimizing free water content. Lower water activity in emulgel cakes enhances microbial stability and shelf-life—an added functional benefit that supports their

Cake sample	Specific volume (cm^3/g)	Porosity (%)	Moisture (%)	a_w
Control	1.81 ± 0.11^{bc}	23.22 ± 1.24^{a}	$26.66^{b} \pm 0.92^{b}$	0.81 ± 0.03^{a}
30% emulgel	2.20 ± 0.08^{b}	18.92 ± 1.07^{b}	28.35 ± 1.22^{ab}	0.81 ± 0.02^{a}
50% emulgel	2.38 ± 0.19^{a}	21.52 ± 1.86^{ab}	31.5 ± 1.09^{a}	0.78 ± 0.02^{b}
70% emulgel	2.42 ± 0.13^{a}	22.92 ± 0.87^{a}	32.16 ± 1.16^{a}	0.77 ± 0.01^{b}

Table 3. Physicochemical properties of the fortified cakes with curcumin-loaded emulgel at three different concentrations (30, 50, and 70%). Different small letters in each column indicate the significant differences ($p < 0.05$).

industrial applicability. Consistent with this, Puşcaş et al. (2025) observed that emulgel-based biscuits exhibited similar color and stability to controls with margarine, suggesting that emulgel matrices not only improve structural integrity but can also contribute to extended shelf-life through reduced water mobility[52].

Moisture is one of the desirable factors in the cake, as decreasing the moisture content resulting in a firmer crumb. The moisture contents results of the fortified cakes were presented in Table 3. Specifically, samples containing 50% and 70% emulgel exhibited the highest moisture content, with statistical significance ($p < 0.05$). Combining emulgel with ingredients like Persian gum, sodium alginate, and inulin contributed to this effect, as these components are effective at trapping moisture within the emulgel network during baking. Furthermore, raising the emulgel content could inhibit moisture migration to the cake's starch[38]. This is also supported by Jeong et al. (2023), who noted that muffins containing peanut sprout oil emulsion gels retained higher moisture levels during baking[41], while Leahu et al. (2023) demonstrated that the incorporation of oilseed by-product–based emulsion gels improved water retention and sensory quality in low-fat formulations[53]. Overall, these findings confirm that curcumin-loaded emulgels not only serve as viable fat replacers but also contribute functionally by maintaining or improving key physicochemical parameters such as volume, porosity, moisture, and water activity.

Oxidative stability

Oxidation of oils serves as an important indicator of the quality and shelf life of bakery products during storage[54]. the maximum permissible peroxide value (PV) for cake is 2 meq/kg; values exceeding this threshold indicate rancidity and render the product unusable. Incorporating curcumin, an antioxidant compound, may mitigate oxidation in cakes. As illustrated in Fig. 1, samples with varying concentrations of curcumin-loaded emulgel exhibited different levels of oxidative stability over a 30-day storage period ($p < 0.05$). Notably, the cake containing 70% emulgel recorded the lowest PV at 0.82 ± 0.01 meq/kg oil. It demonstrated the smallest percentage change in PV during the storage period (45.3% increase), remaining within the acceptable range for bakery products. In contrast, the control sample displayed a higher PV on the production day (1.26 ± 0.34 meq/kg oil), which escalated to a maximum of 3.9 ± 0.18 meq/kg oil by the end of the storage period. Furthermore, increasing the concentration of emulgel from 30% to 70% significantly decreased PV values, indicating a delay in oil oxidation (Fig. 1). These findings suggest that curcumin-loaded emulgel functions as a potent antioxidant[55]. The stability of the semi-solid network formed in the emulgel, due to the presence of Persian gum, inulin, and sodium alginate, effectively trapped sesame oil within this gel matrix, thereby protecting it from oxidation. Similar stabilization effects were observed by Akcicek et al. (2023), who reported that cakes formulated with psyllium husk–beeswax bigels exhibited improved structural stability and resistance to deterioration compared to palm oil cakes. The enhanced stability of the bigel matrix, which limited liquid migration and protected entrapped oil, is consistent with our findings that curcumin-loaded emulgels delayed lipid oxidation during storage[56]. These results suggest that the improved oxidative stability is due to the synergistic effect of the emulgel matrix, which limits oxygen permeability, and curcumin's antioxidant activity. Both components work together to delay lipid oxidation during storage. Kozłowska, Żbikowska[57] investigated the impact of green tea extract at concentrations of 0.02%, 0.2%, and 1% on the oxidative stability of oily cakes over 28 days. They found that increasing concentrations of green tea extract reduced PV and enhanced the oxidative resistance of the cakes. Chen, Fu[58] declared samples containing β-carotene-loaded emulgels exhibited significantly lower oxidation levels compared to those containing oil alone, attributing this effect to β-carotene's capacity to inhibit oxidation and limit the diffusion of reactive singlet oxygen or radical species. Lim, Hwang[38] investigated PV in

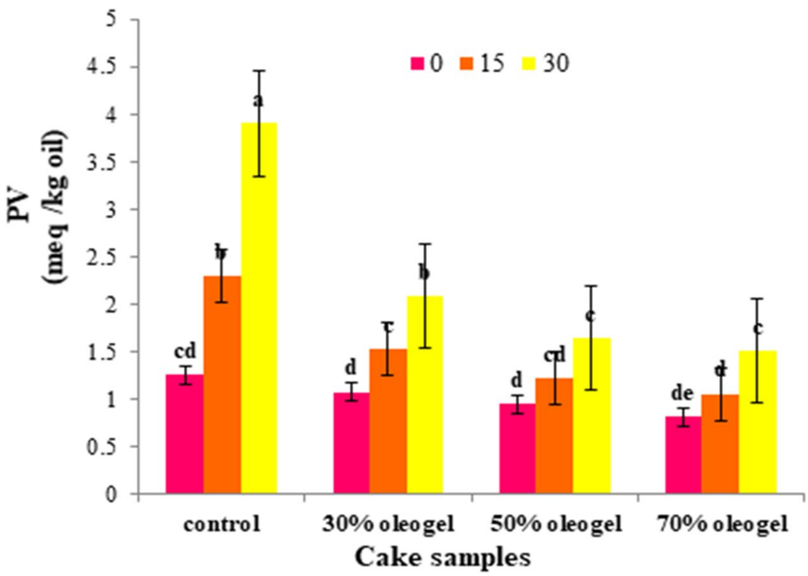

Fig. 1. Peroxide values of the fortified cakes with curcumin-loaded oleogel at three different concentrations (30, 50, and 70%) during 30 days.

instant noodles fried in soybean oil, palm oil, and oleogels over a 12-day storage period, noting that while PV increased in all samples, those containing oleogel exhibited the lowest oxidative reactions. Similarly, Tabibazar, Hamishekar[59] assessed PV in oleogels and unheated soybean oil over 90 days, confirming that samples with oleogel demonstrated significantly higher oxidative stability.

Antioxidant activity

The antioxidant activity of cakes containing curcumin-loaded emulgel was evaluated using DPPH free radical scavenging assays. As depicted in Fig. 2, the highest DPPH scavenging activity was observed in cakes fortified with 70% curcumin-loaded emulgel, while the control sample exhibited the lowest and statically different activity level. This substantial enhancement is primarily attributed to the presence of curcumin, a well-known natural polyphenolic compound with strong antioxidant properties. The emulgel matrix—comprising Persian gum, sodium alginate, and inulin—likely protected the curcumin from thermal degradation during baking, maintaining its radical-scavenging efficiency. Chen et al. (2016) similarly demonstrated that zein-based oil-in-glycerol emulgels enriched with β-carotene enhanced antioxidant protection by limiting lipid oxidation and improving the stability of bioactive compounds[45]. Moreover, the encapsulation of curcumin within the gel network may have improved its dispersion and availability in the cake matrix. Although no reference antioxidant standard was used, the relative comparison between treatments confirms the functional contribution of curcumin. Curcumin's ability to inhibit oxidation depends on its concentration and reactivity toward reactive oxygen species. Additionally, antioxidant ability is often linked to the phenolic compound content, as their extensive conjugated π-electron systems facilitate electron donation from hydroxyl groups to oxidizing radicals[60,61]. Song, Hyeonbin[62] confirmed that adding black carrot, a polyphenol compound, to sponge cakes enhanced DPPH scavenging activity. Park, Lim[63] indicated that increasing turmeric powder content up to 8% significantly boosted antioxidant activity, with DPPH scavenging reaching 88%. They reported that curcumin, a naturally occurring phenolic compound in turmeric, exhibited strong antioxidant properties. Comparable improvements in antioxidant potential were also observed by Leahu et al. (2023), who noted that emulsion gels enriched with oilseed by-products enhanced the nutritional and functional properties of low-fat systems[53]. In this study, the enhancement in antioxidant activity (from 45.64% to 89.49%) may be attributed to the inclusion of curcumin in cakes containing 70% emulgel, which could be suggested as a functional food. In summary, the results confirm that cakes fortified with curcumin-loaded emulgels, particularly at the 70% level, can serve as functional food products with enhanced antioxidant capacity, aligning with current consumer demand for healthier and clean-label bakery products.

Color parameters

The color characteristics of cakes are influenced by various factors, including the interactions and transformations of ingredients, as well as color changes that occur during processing. Specifically, the moisture content of the crust and the presence of pigments in the formulation are critical determinants of cake crust color[64]. Similarly, Turabi et al. (2008) reported that the type of hydrocolloids and emulsifier blends significantly influenced the brightness and color parameters of rice cakes, confirming that formulation components play a major role in determining crust color[49]. As presented in Table 4, the brightness (L) of the cake samples varied from 53.35 in the control sample to 45.69 in the sample containing 70% curcumin-loaded emulgel, indicating that the addition of emulgel reduced the brightness compared to the control. The brightness (L*) values significantly decreased ($p < 0.05$) in cakes containing 50% and 70% emulgel compared to the control. Similarly, the b* value significantly increased in the 70% emulgel sample, while the control exhibited the lowest and statistically different b* value (Table 4). These results suggest that incorporating curcumin-loaded emulgel significantly increased the b* index, likely attributable to the yellow hue of curcumin. Consistently, Akcicek et al. (2025) demonstrated that bigel-

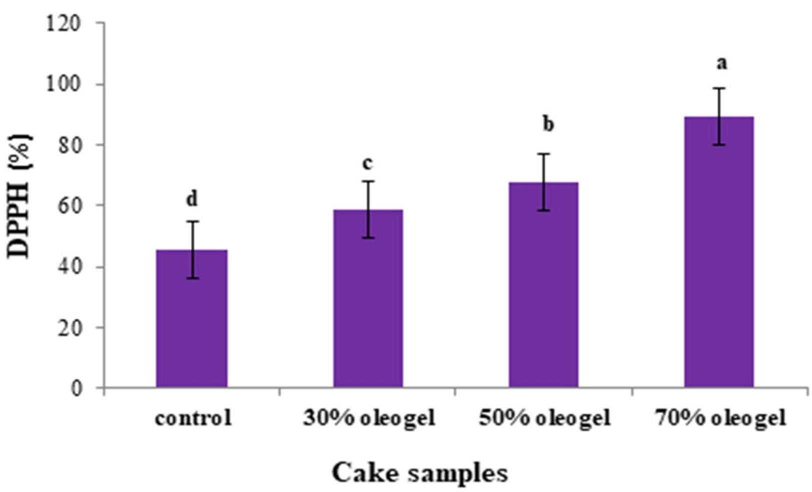

Fig. 2. DPPH radical scavenging activities of the fortified cakes with curcumin-loaded oleogel at three different concentrations (30, 50, and 70%).

Cake sample	L^*	a^*	b^*	ΔE
Control	53.25 ± 1.48[a]	19.17 ± 0.16[a]	47.21 ± 1.21[c]	73.50 ± 1.57[a]
30% emulgel	49.15 ± 1.24[b]	20.81 ± 0.69[a]	49.27 ± 1.16[b]	72.19 ± 1.62[ab]
50% emulgel	47.19 ± 1.25[bc]	18.88 ± 0.88[a]	50.37 ± 1.12[b]	71.56 ± 1.69[b]
70% emulgel	45.69 ± 1.32[c]	18.43 ± 1.13[a]	55.03 ± 1.16[a]	74.37 ± 1.18[a]

Table 4. Color parameters of the fortified cakes with curcumin-loaded o emulgel Leogel at three different concentrations. Different small letters in each column indicate the significant differences (*p < 0.05*).

Cake sample	Adhesion (mJ)	Cohesiveness (*N*.s)	Chewiness (mJ)	Hardness (*N*)	Springiness (mm)
Control	0.73 ± 0.00[a]	1.11 ± 0.01[a]	271.77 ± 1.68[a]	19.66 ± 1.08[a]	11.14 ± 1.09[a]
30% emulgel	0.69 ± 0.01[ab]	0.66 ± 0.02[c]	186.24 ± 1.42[b]	39.26 ± 1.25[c]	7.31 ± 0.97[c]
50% emulgel	0.71 ± 0.01[a]	0.81 ± 0.04[b]	222.27 ± 1.47[ab]	23.02 ± 1.16[ab]	9.34 ± 1.16[b]
70% emulgel	0.72 ± 0.01[a]	0.98 ± 0.02[ab]	268.25 ± 1.68[a]	20.17 ± 1.23[a]	11.05 ± 0.65[b]

Table 5. Texture properties of the fortified cakes with curcumin-loaded emulgel at three different concentrations (30, 50, and 70%). Different small letters in each column indicate the significant differences ($p < 0.05$).

based fat replacers in cakes also led to noticeable changes in L, a*, and b* values, where higher hydrogel ratios produced cakes with reduced brightness and altered yellowness compared to the control[56]. This finding aligns with Mahmud, Islam[60], who reported a similar impact of curcumin-loaded emulgel on the yellowness of fried nuggets.

Adding curcumin-loaded emulgel did not significantly affect the a^* value of the cakes (*p < 0.05*). The increase in b^* and decrease in brightness observed in samples containing 70% emulgel led to a reduction in ΔE. Lee[37] confirmed that the lightness of muffin crusts decreased when using hydroxypropyl methylcellulose-based oleogels, particularly at concentrations up to 50%. They also noted that adding oleogel at 25% and 50% concentrations did not influence the a^* and b^* values of muffins. Similarly, Tabibazar, Hamishekar[59] demonstrated a reduction in L^* values by applying 50% oleogel but suggested that oleogels containing adipic acid improved L^* values. Notably, there was no statistically significant difference in a^* and b^* values between carnauba wax at 6% and a combination of carnauba wax at 2% with adipic acid at 4%. Overall, the color data confirm that curcumin-loaded emulgels influence the visual attributes of cakes by reducing brightness and enhancing yellowness, which may contribute to consumers' perception of a more natural or functional product. The incorporation of curcumin in this format provides a dual benefit—both functional and aesthetic—without negatively impacting key color characteristics.

Texture

The texture analysis results for the fortified cakes are presented in Table 5. The highest hardness (the maximum force required to compress the sample) was significantly observed ($p < 0.05$) in the cake containing 30% curcumin-loaded emulgel, while the control and the sample with 70% emulgel showed significantly lower hardness values with no statistical difference between them. The analysis indicated that the hardness of cakes with 30% and 50% emulgel was greater than that of the control, likely due to the fat replacement and the reduction in batter volume necessary to maintain gas cell structure. Additionally, factors such as low porosity and high density significantly contributed to the increased hardness. Similarly, Akcicek et al. (2025) found that cakes formulated with psyllium husk hydrogel–beeswax oleogel bigels showed increased hardness and chewiness compared to the control, depending on the hydrogel/oleogel ratio[56]. It appears that incorporating an appropriate concentration of emulgel can enhance cake hardness. The hydrophilic properties of the hydrocolloids used in the emulgel help retain water within the system, thereby improving hardness. Research findings regarding the impact of oleogel on the texture of bakery products have varied. Ramadhan, Firdaos[65] discovered the hardness of sponge cake with 25% and 50% marine oleogel substitutions was not statistically different from the control, while 75% substitution enhanced the hardness considerably. Lim, Jeong[48] suggested that oleogels soften cake texture by retaining moisture and preventing its migration, which could lead to the crystallization of starch strands. According to Patel, Rajarethinem[66], hardness increased when oleogel was used, attributing this to structural densification resulting from oil removal. Margarines and shortenings in the cake formulation have a large amount of fat crystals, which prevent the formation of a gluten network by creating a barrier. In contrast to these findings, Naji-Tabasi and Mohebbi[64] demonstrated that oleogel application enhanced cake softness by creating a three-dimensional network of fatty acids, facilitating better incorporation of air bubbles into the batter.

No significant differences in adhesion were noted among the samples (Table 5). The cohesiveness (the internal resistance of the cake structure during the second compression relative to the first) of the cake made with 70% emulgel was comparable to that of the control and higher than that of other fortified cakes. Furthermore, chewiness (the energy required to chew the sample until ready for swallowing, calculated as hardness × cohesiveness × springiness) values increased with the substitution of fat for 70% curcumin-loaded emulgel, while the lowest chewiness value was associated with the 30% emulgel sample. Higher emulgel concentrations

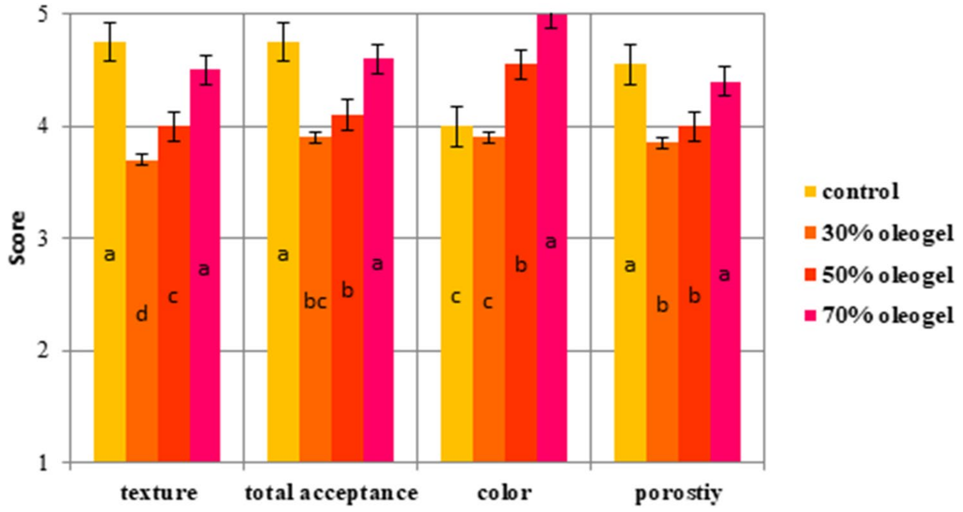

Fig. 3. Sensory properties of the fortified cakes with curcumin-loaded oleogel at three different concentrations (30, 50, and 70%), different letters indicate significant differences among each properties ($p < 0.05$).

contributed to increased solids, enhancing both elasticity and chewability. However, at lower levels (30%), the cake exhibited reduced plasticity and chewability. Springiness (the ability of the cake to recover its original height after the first compression) values demonstrated elasticity or the ability of a bakery product to recover to its initial structure after pressure exposure[65]. The springiness parameter ranged from 7.31 to 11.14 mm, with the sample containing 70% emulgel demonstrating the highest springiness, which was not significantly different from that of the control at a 95% significance level (Table 5).

Tabibazar, Hamishekar[59] confirmed that the springiness, cohesiveness, and hardness values of cakes prepared with optimized oleogel (derived from soybean oil) were similar to those of the control. They proposed that oleogels possess emulsifying properties that reduce surface tension in the liquid phase, leading to an increase in air bubbles within the batter, which subsequently improved softness, porosity, elasticity, and springiness. The softer texture observed in cakes formulated with optimized oleogel was attributed to a three-dimensional network facilitating greater air retention in the batter[67]. According to Chen, Fu, cakes produced with zein-based emulgels at low fat content (approximately 60% oil fraction) exhibited comparable textural characteristics to those of the control regarding firmness, cohesiveness, adhesiveness, and springiness. This is consistent with our results, where curcumin-loaded emulgels at appropriate concentrations maintained similar cohesiveness and springiness to the control while also preserving acceptable hardness and chewiness[45]. Lee[37] found that hydroxypropyl methylcellulose-based oleogels (up to 50%) produced soft and chewy muffins, which became springier and more cohesive at higher oleogel concentrations. Kim, Lim[36] also noted that there was no significant difference in hardness between control cakes and those fortified with 25% oleogel; similarly, no significant differences in cohesiveness and springiness were observed when shortening was replaced with 50% or 75% oleogels. These results collectively suggest that emulgels, when used at appropriate concentrations, can preserve or even enhance the textural quality of cakes, supporting their potential as a functional fat replacer in baked goods.

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Sensory attributes

The sensory evaluation results are illustrated in Fig. 3. Sensory evaluations indicated that cakes made with curcumin-loaded emulgel received lower scores; however, there were no significant differences in overall acceptance among the control (Score: 4.2) and 70% curcumin-loaded emulgel (score: 4.4) samples ($p > 0.05$). The cake containing 70% curcumin-loaded emulgel achieved the highest score for overall acceptance (score: 4.4), suggesting that this optimized concentration could enhance sensory attributes. A comparison between the cake containing 70% emulgel and the control sample revealed no significant differences in texture (4.3 vs. 4.2) and porosity (4.2 vs. 4.1) scores. Moreover, the cake with 70% emulgel received the highest score for color (score: 4.5) which was significantly different from control sample (score: 4.3). Similarly, Akcicek et al. (2025) observed that cakes prepared with psyllium husk–beeswax bigels as fat replacers exhibited acceptable crumb structure and texture, with sensory scores comparable to the control[56].

Tabibazar, Hamishekar[59] reported that cakes formulated with optimized oleogel (carnauba wax at 2% and adipic acid at 4%) had sensory scores closely aligned with those of the control sample (soybean oil) concerning taste, odor, color, texture, and overall acceptance. Pehlivanoğlu, Demirci[46] confirmed that sensory parameters such as color, cell structure, taste, aroma, chewiness, and overall acceptability were not adversely affected in cakes containing oleogel prepared from high oleic acid and cottonseed oil. They further suggested that emulgel could be used as a shortening substitute to reduce saturated fatty acid content. Research by Mahmud, Islam[60] indicated that incorporating curcumin into hydroxypropyl methylcellulose-oleogel did not result in any considerable variations in the sensory properties of fried chicken nuggets. According to Badem and Baştürk[68], fortified cakes with oleogel were acceptable in terms of organoleptic characteristics and texture compared to cake fabricated via shortening. Their sensory analysis demonstrated that some emulgel -loaded cakes were found to be more acceptable than the control group. Consistent with our findings, Turabi et al. (2008) reported that the incorporation of oleogels as fat replacers did not negatively affect consumer acceptance, confirming their potential to maintain desirable sensory quality in bakery products[49]. Overall, the sensory findings suggest that curcumin-loaded emulgels, particularly at 70% substitution, can be used effectively to produce health-enhanced baked products with desirable sensory properties, supporting their potential as a market-ready functional fat replacer.

Conclusions

This study demonstrated that curcumin-loaded emulgels can effectively replace up to 70% of sunflower oil in cake formulations without compromising key quality attributes. The 70% emulgel sample maintained comparable specific volume, porosity, and texture to the control, while significantly increasing antioxidant activity (from 45.64% to 89.49%) and reducing peroxide values by 61.28% after 30 days. Sensory results also indicated higher consumer acceptability at this replacement level. These findings confirm the dual functionality of emulgels as fat replacers and carriers of bioactive compounds, contributing to improved nutritional quality and oxidative stability of cakes. Overall, curcumin-loaded emulgels offer a promising clean-label strategy for developing healthier bakery products. Future research should focus on scaling up production, evaluating shelf life in commercial settings, and exploring applications in other food categories such as cookies, muffins, and dairy-based systems.

Data availability

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

Received: 2 May 2025; Accepted: 10 October 2025
Published online: 26 November 2025

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Author contributions

B.M.: Data curation; Investigation; Methodology; Writing—original draft.A.A.: Conceptualization; Supervision. Validation; Visualization; Writing—review and editingA.M.S.K.: Supervision; Validation;.S.N.T.: Validation; Writing—review and editing.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declarations

Conflict of 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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