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Development and characterization of pomegranate seed oil bigel as a healthier shortening replacer in cake formulations

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ABSTRACT

In this study, guar gum, low methoxyl pectin (LMP), and beeswax (BW) were used to prepare hydrogels and oleogels for the production of pomegranate seed oil (PSO) bigels. The rheological and textural properties of the bigels were characterized. Bigel P7 (75% LMP hydrogel + 25% BW oleogel) showed a strong and elastic gel network with a high storage modulus (G') and rheological and textural properties closer to commercial shortenings than other bigel formulations. The fatty acid profile of P7 was rich in unsaturated fatty acids (punicic acid C18:3) and showed lower stearic acid (C18:0) and total saturated fatty acid (SFA) compared to commercial shortenings. The P7-based batter showed flow behavior (power law and Herschel-Bulkley parameters) very similar to the control batter, indicating good processability, aeration, and structural stability during the mixing process. The P7-based cake had lower specific volume, volume increase, and moisture content than the control cake on the first day and after 10 days of storage. The stale behavior of the P7-based cake was slightly higher than the control, indicating that the fat network of shortening interacts more effectively with starch and water to maintain a soft and tender crumb during storage. Overall, these results demonstrate the potential of P7 as a healthier substitute for shortening, with acceptable technological performance and improved nutritional quality.

1-Introduction

The global food industry is demanded to reformulate traditional bakery products with healthier fat that maintain acceptable quality and sensory attributes while reducing the intake of saturated and trans fatty acids. shortenings, widely used in cake formulations, are typically based on partially or fully hydrogenated vegetable oils, which provide desirable textural and rheological properties such as good aeration, volume, and crumb softness [1]. However, shortenings are rich in SFA and, in the case of partially hydrogenated oils, contain significant levels of trans fatty acids (TFA), both of which are strongly associated with increased risk of cardiovascular diseases, insulin resistance, and other metabolic disorders. As a result, global health authorities and food regulations have increasingly restricted the use of TFA and encouraged the development of alternative fat systems that combine good functionality with improved nutritional profiles [2]. The health benefits associated with polyunsaturated fatty acids (PUFAs), particularly conjugated linoleic acid (CLA) and conjugated linolenic acid (CLN), are well established. PSO is one of the richest natural sources of conjugated fatty acids. Its predominant fatty acid, punicic acid (PA; 18:3), chemically known as 9-cis, 11-trans, 13-cis-octadecatrienoic acid, has attracted considerable attention due to its unique conjugated structure [3]. PA has been described as a "super CLA" that exhibits greater biological activity than conventional CLA isomers. Several studies have linked PA consumption to cholesterol-lowering, antidiabetic, anti-inflammatory, and anticancer effects. Consequently, PSO as a partial or complete replacement for saturated fats in fat-based food products is a promising strategy for developing foods with health-promoting properties [4]. Despite their nutritional benefits, the direct use of liquid oils rich in unsaturated fatty acids in solid or semi-solid foods is technologically challenging due to their inability to provide the structural and functional roles typically performed by saturated fats. In this context, the structuring of edible oils is considered as a suitable approach to replace saturated fats while maintaining the structure, texture, and mouthfeel of the product similar to shortenings [5]. Liquid oils can be transformed into structured two-phase systems through various techniques, including direct addition of structuring agents, oil absorption, and indirect methods based on emulsion templates [6]. Gel-based fat substitutes, such as oleogels, hydrogels, and emulgels, are liquid oils in a three-dimensional gel-like structure [7]. Bigels, which are obtained by mechanically combining hydrogels and oleogels under specific temperature and conditions, are an example of a novel fat substitute in this field. They offer improved properties by utilizing the advantages of both gel phases. Unlike emulgels, which gel only one of the phases, bigels have higher stability and sensory quality due to having two gel phases. Depending on the polarity of the continuous phase, structures such as oleogel in hydrogel (O/W), hydrogel in oleogel (W/O), or bicontinuous structures may be formed. The structural and physicochemical properties of the bigel are influenced by the ratio of oleogel to hydrogel, the type of ingredients, and the shear rate [8]. In oleogels, liquid oils are structured by low-molecular-weight gelators (e.g., waxes, monoglycerides, or phytosterols) or polymeric gelators, forming a three-dimensional network that immobilizes the oil phase. Hydrogels, on the other hand, are water-rich systems structured by hydrocolloids (e.g., pectin, guar gum, or xanthan) that form a continuous aqueous network [9]. In this study, bigels were formulated by mixing an oleogel structured with BW and a hydrogel prepared using guar gum and LMP in different ratios. The most suitable bigel formulation was selected, and its performance as a shortening replacer was evaluated by examining its effects on batter characteristics and overall cake quality.

2- Materials and methods

2.1. Materials

PSO was supplied by Dashchin Aali Co. (Isfahan, Iran). Commercial shortening was obtained from Ladan Co. (Tehran, Iran). Guar gum, LMP, mono-di-glyceride, and calcium chloride were obtained from Pouya Kabak Co. (Tehran, Iran). Wheat flour and other cake ingredients were purchased from local supermarkets in Mashhad, Iran.

2.2. Hydrogel preparation

Hydrogel Guar (HG-G) was prepared by dispersing 1.0% (w/w) guar gum and 0.2% NaCl in distilled water under constant stirring (500–600 rpm) for 30 min. Then, 0.8% mono-di-glyceride was added and mixed for 10 min. The hydrogel was stored at 25 °C for 24 h to allow complete gelation [10]. Hydrogel low-methoxy pectin (HG-P) was prepared by dispersing 1.3% (w/w) LMP and 0.3% NaCl in distilled water under stirring (500–600 rpm) for 30 min. A solution of 0.4% $CaCl_2 \cdot 2H_2O$ was then added slowly to induce gelation. After that, 1.2% mono-di-glyceride was incorporated and mixed for 10 min. The hydrogel was stored at 25 °C for 24 h before use [11].

2.3. Oleogel preparation

The oleogel was prepared by dispersing 7% (w/w) BW in PSO, then the mixture was heated (80–85 °C) under continuous stirring until complete melting, followed by cooling to 70 °C [12].

2.4. Bigels preparation

Bigels were prepared by combining hydrogels and oleogel phases in different ratios to achieve a total fat phase of 16% (w/w) in the cake formulation. Different ratios of hydrogel to oleogel were prepared to form the bigel samples. For bigel formation, the hot oleogel (70 °C) was slowly added to the pre-warmed hydrogels (70 °C) under constant stirring (1000–1200 rpm) for 5–7 min. The resulting bigels were then cooled gradually and stored at 4 °C for 24 h to allow full structuring.

Table 1. Different formulated OG/HG blends.

	P1	P2	P3	P4	P5	P6	P7	P8	P9
HG-G (%)	100	-	-	75	50	25	-	-	-
HG-P (%)	-	100	-	-	-	-	75	50	25
OG (%)	-	-	100	25	50%	75	25	50	75

Bigel Formulations (HG-G: Guar Hydrogel, HG-P: Low Metoxyl Pectin Hydrogel, OG: Oleogel, P: Product code).

2.5. Cake preparation

Cake samples were prepared by considering the change in the oil phase (shortening or bigel) according to the method of Nazari et al (2022) [13].

2.6. Characterization of bigels

2.6.1. Rheological properties

The rheological behavior of hydrogel, oleogel, and bigels was evaluated using a rotational rheometer (MCR 302, Anton Paar, Austria) equipped with a Peltier temperature control system. Measurements were performed in a parallel plate geometry (PP50) with a fixed gap of 0.5 mm between the plates. To investigate the temperature dependence of the bigel, hydrogel, and oleogel samples, a temperature sweep test was performed. The storage modulus (G′) was monitored over a temperature range of 20–80 °C, with a heating rate of 5 °C per minute [14].

2.6.2. Mechanical properties

The textural properties of samples, including hardness, springiness, cohesiveness, gumminess, and chewiness, were measured using a texture analyzer (TA.XT2 Plus, Stable Micro Systems, Godalming, UK). A cylindrical needle probe (P/5, 5 mm diameter) was employed for penetration tests. The test was conducted with a trigger force of 5 g, a pre-test speed of 1 mm/s, a test speed of 5 mm/s, and a post-test speed of 5 mm/s [15].

2.7. Characterization of optimized bigel

2.7.1. Physicochemical properties

2.7.1.1. Fatty acid profile analysis

Fatty acid methyl esters were prepared following AOCS Official Method Ce 2-66 and analyzed via gas chromatography (GC) using an Agilent 7890 B GC system (Santa Clara, USA) equipped with a flame ionization detector and a BPX70 capillary column [16].

2.7.1.2. Free fatty acid content

The free fatty acid content was determined by titration with sodium hydroxide according to

the AOCS Official Method Ca 5a-40 (AOCS, 1996) and expressed as oleic acid equivalent [17].

2.7.1.3. Peroxide value

The peroxide value was measured via titration with sodium thiosulfate according to the AOCS Official Method Cd 8-53 (AOCS, 1996) [18].

2.7.1.4. Slip melting point

The slip melting point (SMP) was determined using the capillary tube method following the AOCS Official Method Cc 3-25 (AOCS, 1996) [19].

2.7.2. Rheological and mechanical properties

Evaluating the viscoelastic properties, oscillatory rheological tests, including strain and frequency sweeps, were conducted 24 h after production, following the method proposed by Meng et al. (2018). A rheometer (MCR 301, Anton-Paar GmbH, Graz, Austria) with parallel plates (40 mm diameter, 2000 µm gap) was used. Rheological parameters were analyzed using RheoPlus software (Anton-Paar, Version 3.21) [20].

2.7.2.1. Strain sweep test

A strain sweep test was conducted at a strain range of 0.01% to 1000% at a fixed frequency of 1 Hz and a temperature of 25°C [21].

2.7.2.2. Frequency sweep test

The frequency sweep test was performed in the frequency range of 0.1 to 50 Hz at a fixed strain of 0.5% (LVE region) and a temperature of 25°C. The power-law model (Equation 1) was fitted to the frequency-sweep test results.

$$G' = a\omega^b$$

G' is the storage modulus (Pa), a is a constant coefficient, ω is the angular frequency, and b is the flow behavior index [21].

2.7.2.3. Textural properties

Sample hardness was evaluated following the method of Saghafi et al. (2018) at 25°C using a TTC SR/HDP (spreadability test) with soft and hard cones (90° angle), test distance of 15 mm, test speed of 3 mm/s, test duration of 5 s, and load cell of 5 kg [22].

2.8. Characterization of bigel-based cake

2.8.1. Flow behavior of batter
To assess flow behavior, a shear test was conducted within a shear rate range of 0.1 to 100 s^{-1} using a rheometer (MCR 301, Anton-Paar GmbH, Graz, Austria) with parallel plate geometry (40 mm diameter, 1 mm gap, serrated surface to prevent slippage). The power law model and Herschel-Bulkley model were fitted to the experimental data to determine the consistency coefficients and flow behavior indices [23].

2.8.2. Specific volume and volume increase after baking
The cake volume was measured using the rapeseed displacement method following the standard AACC 10-05 (2000). To measure the volume increase, the height of the central part of the batter was recorded before baking, and the height of the same part was measured again after baking. The difference in height between the baked cake and batter was considered as the volume increase after baking, expressed in millimeters [24].

2.8.3. Moisture content

The moisture content of cake samples was evaluated on days 1 and 10 after production. A 5 g sample from both the crumb and crust cakes was mixed, and its moisture content was determined using the drying oven method at 105°C until a constant weight was reached, according to the standard method AACC 44-15 [25].

2.8.4. Texture profile analysis (TPA)
A TPA test was conducted on days 1 and 10 after production to evaluate hardness. A two-cycle compression test was performed by compressing the cake samples to 50% of their

initial height using a cylindrical probe (50 mm diameter) at sixty mm/min [26].

2.9. Statistical analysis

All experiments were performed in triplicate (n = 3), and the results were expressed as mean ± standard deviation. Data were analyzed by one-way analysis of variance (ANOVA) using SPSS software (version 26.0, IBM, USA). Differences were considered statistically significant at the $p < 0.05$ level.

3-Discussion and conclusion

3.1. Characterization of bigels

3.1.1. Rheological properties

Significant differences were observed between bigels formulated with HG-G and HG-P, indicating their fundamentally different gelation mechanisms. Guar gum forms a viscous network primarily through the intertwining of polymer chains and hydrogen bonding, without permanent bonding regions [27]. As a result, HG-G exhibits the characteristics of a weak gel, in which stress is dissipated through viscous flow rather than elastic storage. This structural limitation directly led to the lower elastic modulus and reduced structural integrity of guar gum-based bigels. In contrast, low-methoxy pectin forms a true gel network with ionic crosslinks in the presence of Ca^{2+} ions. Calcium-mediated "egg-box" connections between pectin chains create a dense, three-dimensional network with a high density of load-bearing crosslinks. This network acts as the primary elastic agent of pectin-based bigels, allowing for efficient stress storage and recovery under deformation [11]. As a result, HG-P-based bigels showed significantly higher elastic strength and more solid-like viscoelastic behavior compared to guar gum counterparts. The incorporation of oleogel into a hydrogel matrix has led to the formation of hybrid bigel systems in which the oleogel phase forms a dispersed crystalline lipid network within or simultaneously with the hydrogel phase [28]. Beeswax oleogels are structured by self-assembly and crystallization of wax molecules into needle-shaped crystals that form a network within the oil phase. This crystalline network provides stiffness, yield stress, and resistance to deformation, but due to its brittle nature, it exhibits limited elasticity. When combined with hydrogels, the oleogel phase acts as a mechanical reinforcing component, increasing the overall strength of the gel without directly contributing to elastic recovery [29]. The extent of this reinforcement depends strongly on the type of hydrogel. In guar gum-based bigels, the addition of oleogel primarily increased the apparent stiffness and consistency, but the lack of a strong elastic hydrogel network limited the development of a coherent hybrid structure. As a result, these systems showed a modest increase in mechanical strength but retained their viscous properties. In contrast, pectin-based bigels showed a significant synergistic effect between the oleogel and hydrogel phases. The pectin network with calcium crosslinks created a continuous elastic scaffold, while the oleogel crystals restricted polymer chain mobility and enhanced stress transfer within the system. This cooperative interaction resulted in significantly higher elastic moduli and improved structural integrity, confirming that oleogel reinforcement is most effective when combined with a strong, crosslinked hydrogel network [11].

All the bigel systems exhibited shear thinning behavior, as indicated by flow behavior indices (n' and n'') that were below 1. This pseudoplastic behavior is characteristic of structured gels in which the applied deformation gradually disrupts or aligns the internal network. In these systems, shear thinning primarily originates from the hydrogel phase, as hydrocolloid networks are very sensitive to deformation-induced alignment. The oleogel phase, while contributing to stiffness and yield stress, plays a secondary role in controlling shear dependence. Pectin-based bigels exhibited lower n' values compared to guar gum-based bigels, indicating a higher resistance of the calcium cross-linked network to deformation and its gradual breakdown under increasing stress or frequency.

Table 2. Rheological properties of bigels

	K′ (Pa·sⁿ′)	n′	R²	K″ (Pa·sⁿ″)	n″	R²
P1	112.4± 3.47^{i}	0.234±0.001^{a}	0.93	84.6± 1.23^{g}	0.281±0.001^{a}	0.92
P2	57599.1 ± 32.17^{a}	0.125±0.004^{h}	0.97	18342.7± 17.12^{ab}	0.168±0.003^{g}	0.96
P3	42136.8 ± 21.87^{b}	0.198±0.003^{cd}	0.95	29741.2±14.14^{a}	0.221±0.005^{d}	0.94
P4	842.6±2.14^{h}	0.219±0.004^{ab}	0.94	514.3± 1.38^{f}	0.263±0.004^{ab}	0.93
P5	2136.4±1.34^{g}	0.206±0.005^{bc}	0.95	1368.9± 3.45^{e}	0.247±0.002^{bc}	0.94
P6	4865.7±5.87^{f}	0.191±0.002^{d}	0.95	3296.4± 4.52^{d}	0.229±0.003^{cd}	0.94
P7	35654.4±16.45^{c}	0.142±0.003^{g}	0.97	13682.2± 23.76^{c}	0.176±0.006^{f}	0.96
P8	29421.6±2.76^{d}	0.156±0.001^{f}	0.96	15498.3± 43.97^{b}	0.184±0.004^{f}	0.95
P9	22136.8±17.98^{e}	0.169±0.002^{e}	0.95	16241.9± 4.45^{b}	0.201±0.001^{e}	0.95

Different superscript letters indicate significant differences ($p < 0.05$).

Textural properties measured by texture profile analysis revealed further information about the structural organization of the bigels. Bigels Stiffness were strongly influenced by the oleogel content in the system, indicating the contribution of the crystalline lipid network to the compressive strength [30]. However, stiffness alone did not define the functional quality of the bigels. Bigels with excessive oleogel (P6 and P9) content showed high stiffness but lower elasticity, indicating brittleness rather than elastic deformation. Pectin-based bigels showed a more favorable balance between stiffness, elasticity, and cohesion, indicating the presence of an elastic polymer network capable of recovering after deformation. This behavior is consistent with a gel structure in which deformation energy is stored and partially released through reversible ionic bonds. In contrast, guar gum-based bigels showed less cohesion and gumminess [31]. By adding oleogel, the gumminess and chewiness increased due to increased resistance to deformation.

Table 3. Textural Properties of bigel Samples

	Hardness	Springiness	Cohesiveness	Gumminess	Chewiness
P1	47.4±1.43^{e}	0.742±0.003^{c}	0.462±0.001^{d}	21.9±1.23^{e}	16.3±0.78^{e}
P2	62.3±1.23^{e}	0.801±0.004^{c}	0.523±0.002^{d}	32.6±1.02^{e}	26.1±1.43^{e}
P3	79.8±2.12^{d}	0.843±0.005^{b}	0.586±0.002^{c}	46.8±2.14^{d}	39.4±1.25^{d}
P4	88.6±2.65^{d}	0.914±0.005^{a}	0.781±0.006^{a}	69.2±2.12^{c}	63.3±1.23^{c}
P5	91.2±1.23^{d}	0.953±0.006^{a}	0.789±0.003^{a}	71.9±4.21^{c}	68.5±2.76^{c}
P6	118.6±6.32^{c}	0.812±0.004^{b}	0.612±0.003^{c}	72.6±3.54^{c}	59.0±2.08^{c}
P7	138.7±4.32^{c}	0.921±0.007^{a}	0.754±0.004^{b}	104.6±9.65^{b}	96.3±3.42^{b}
P8	214.3±5.76^{b}	0.884±0.004^{b}	0.721±0.003^{b}	154.5±7.68^{b}	136.6±1.95^{b}
P9	1018.4±12.54^{a}	0.711±0.003^{c}	0.653±0.004^{c}	664.7±12.45^{a}	467.9±11.34^{a}

Different superscript letters indicate significant differences ($p < 0.05$).

These findings emphasize that successful bigel design requires not only the presence of a solid lipid phase, but also a structurally appropriate hydrogel matrix capable of recovering mechanical stress. Pectin-based bigels, especially P7 formulation, exhibited the most balanced viscoelastic and textural properties, making them structurally superior hybrid gels at the gel level.

3.2. Characterization of optimized bigel (P7)

2.2.1. Physicochemical properties

The fatty acid composition of P7 reflects the intrinsic properties of pomegranate seed oil, which is structured by beeswax crystallization, resulting in a lipid profile that is different from. Unlike shortening formulated from hydrogenated or interesterified fats, P7 derives its solid-like behavior from the physical

structure rather than the chemical modification of the triglycerides. P7 is characterized by a high proportion of unsaturated fatty acids, with punicic acid (C18:3, 75.43%) as the dominant unsaturated fatty acid and a significant amount of linoleic acid (C18:2, 8.26%). These unsaturated fatty acid profiles are typical of PSO-based systems and contribute to an overall reduction in saturated fatty acid (SFA) content compared to commercial shortenings. The high level of unsaturation, by improving the ratio of unsaturated to saturated fatty acids, enhances nutritional quality, which is widely associated with more favorable lipid metabolism and cardiovascular health outcomes. The total SFA content of P7 (8.27%) was significantly lower than commercial shortenings (average more than 50%), indicating the absence of hydrogenated fat and the limited contribution of long-chain saturated fatty acids produced during industrial fat processing. In particular, the levels of lauric (C12:0) and myristic (C14:0) acids remained low in all samples. These fatty acids originate from the natural composition of the lipid and wax components, as the oleogelation process based on beeswax crystallization [32]. The fatty acid profile of P7 shows a key advantage of bigel-based fat systems: the ability to separate the lipid composition from the solid fat function. By using PSO as the lipid phase and beeswax as a physical structuring agent, P7 achieves a solid characteristic similar to shortening while maintaining a nutritionally superior fatty acid profile.

The similar free fatty acid values observed for P7 and commercial shortening indicate comparable oil quality and negligible hydrolytic degradation during oleogel and bigel preparation.

The low peroxide value (PV = 1.02 mEq O_2/kg oil) indicates the good initial oxidative quality of PSO in the bigel system. Despite the high degree of unsaturation, oxidative stability was maintained, probably due to the limited molecular mobility imposed by the wax crystal lattice and the partial encapsulation of the lipid phase in the bigel structure. Furthermore, PSO is naturally rich in phenolic compounds and tocopherols, which may contribute to oxidative resistance at early stages [33].

The sliding melting point of P7 (36.11°C) was lower than commercial shortenings, indicating a softer melting profile. This behavior is directly related to the absence of high-melting triglycerides that are typically formed during hydrogenation or interesterification. Instead, the solidity of P7 is due to beeswax crystals that form a network at low concentrations while allowing partial melting near body temperature. This melting behavior is characteristic of fats with a physical structure and indicates a less waxy mouthfeel compared to highly saturated shortenings [34].

Table 4. Fatty acid composition and physicochemical properties of bigel 7 and commercial shortenings

	P7	CS1	CS2	CS3
Lauric acid (C12:0)	0.11 ± 0.02^{c}	0.11 ± 0.02^{c}	0.12 ± 0.01^{bc}	0.14 ± 0.01^{a}
Myristic acid (C14:0)	0.73 ± 0.03^{a}	0.73 ± 0.03^{a}	0.74 ± 0.01^{a}	0.72 ± 0.01^{a}
Palmitic acid (C16:0)	33.96 ± 0.03^{a}	33.96 ± 0.03^{a}	33.55 ± 0.34^{a}	33.76 ± 0.43^{a}
Palmitoleic acid (C16:1)	0.10 ± 0.01^{a}	0.10 ± 0.01^{a}	0.10 ± 0.01^{a}	0.10 ± 0.01^{a}
Stearic acid (C18:0)	2.67 ± 0.21^{c}	13.67 ± 0.21^{b}	25.23 ± 0.04^{a}	15.78 ± 0.43^{b}
Oleic acid (C18:1)	36.83 ± 0.32^{a}	36.83 ± 0.32^{a}	31.77 ± 0.16^{c}	34.91 ± 0.56^{b}
Linoleic acid (C18:2, ω-6)	8.26 ± 0.03^{d}	13.26 ± 0.03^{c}	15.81 ± 0.26^{a}	11.48 ± 0.22^{b}
α-Linolenic acid (C18:3, ω-3)	0.50 ± 0.01^{b}	0.60 ± 0.02^{ab}	0.70 ± 0.02^{a}	0.50 ± 0.01^{b}
Punicic acid (C18:3, conjugated)	75.43 ± 0.05^{a}	0.43 ± 0.05^{c}	0.46 ± 0.05^{b}	0.43 ± 0.02^{c}
Arachidic acid (C20:0)	0.64 ± 0.01^{a}	0.64 ± 0.01^{a}	0.44 ± 0.02^{b}	0.17 ± 0.02^{c}
Eicosenoic acid (C20:1)	0.11 ± 0.02^{a}	0.11 ± 0.02^{a}	0.11 ± 0.01^{a}	0.10 ± 0.01^{a}
Behenic acid (C22:0)	0.10 ± 0.01^{a}	0.10 ± 0.01^{a}	0.13 ± 0.01^{a}	0.10 ± 0.01^{a}
Lignoceric acid (C24:0)	0.06 ± 0.00^{a}	0.06 ± 0.00^{a}	0.05 ± 0.00^{a}	0.06 ± 0.00^{a}
TFA (%)	0.05^{d}	3.05^{a}	2.03^{c}	2.95^{b}
SFA (%)	8.27^{d}	47.27^{c}	50.75^{b}	53.98^{a}
FFA (%)	0.07 ± 0.00^{a}	0.07 ± 0.00^{a}	0.07 ± 0.00^{a}	0.07 ± 0.00^{a}
PV (meq O_2/kg oil)	1.02 ± 0.02^{d}	1.02 ± 0.02^{d}	1.64 ± 0.03^{a}	1.13 ± 0.02^{c}
SMP (°C)	36.11 ± 0.22^{d}	39.11 ± 0.22^{c}	43.31 ± 0.04^{a}	41.73 ± 0.06^{b}

Different superscript letters indicate significant differences ($p < 0.05$).

3.2.2. Rheological and mechanical properties

Rheological measurements showed (Table 5) significant differences in the network strength and deformation behavior of P7 and commercial shortenings ($p < 0.05$). P7 showed significantly lower storage modulus values in the linear viscoelastic region and lower cross-link stress, indicating a softer, less stiff network. This behavior reflects the lower solid fat content and the hybrid nature of the bigel structure, in which the oleogel phase is mechanically supported by a pectin hydrogel matrix. Despite the lower modulus, P7 showed significantly higher strain at the cross-link point, indicating greater deformability and resistance to fracture. This feature is indicative of a more flexible structure, where stress can be redistributed through the polymer hydrogel network. In contrast, commercial shortenings exhibited higher modulus but lower critical strain values, consistent with dense fat crystal networks that fracture at relatively low deformations. Frequency sweep analysis further confirmed these structural differences [35]. The lower consistency coefficient and higher flow behavior index of P7 indicate a more pseudoplastic response compared to commercial shortenings. This behavior reflects the effect of the hydrogel phase in shear-dependent structural rearrangement, while the wax crystal network maintains overall integrity. The excellent fit of the power law model ($R^2 = 0.99$) in all samples confirms that both P7 and commercial shortenings exhibit gel-like behavior.

The lower hardness of P7 compared to commercial shortenings is consistent with its rheological characteristics and softer melting behavior. This reduced hardness indicates the absence of a dense triglyceride crystal network. It highlights that the combination of beeswax oleogelation and pectin hydrogel formation with calcium crosslinking creates a gel-like and deformable lipid system with shortening-like solid character, while avoiding hydrogenation and reducing the overall saturated fat content [36].

Table 5. Rheological and textural properties of P7 and commercial shortenings

		P7	CS1	CS2	CS3
Strain sweep					
	γ LVR (%)	0.32 ± 0.02^{b}	0.31 ± 0.02^{b}	0.09 ± 0.01^{d}	0.23 ± 0.02^{c}
	G′ LVR (Pa)	$12\,980 \pm 312^{d}$	$12\,880 \pm 312^{d}$	$184\,880 \pm 421^{a}$	$43\,876 \pm 214^{b}$
	G′ = G″ (Pa)	$1\,423^{d}$	$1\,453^{d}$	$5\,411^{a}$	$3\,186^{b}$
	γ at crossover (%)	50.7 ± 0.26^{d}	51.7 ± 0.26^{d}	16.7 ± 0.11^{a}	33.7 ± 0.23^{b}
Frequency sweep					
	a (Pa)	$6\,449^{d}$	$6\,438^{d}$	$273\,421^{a}$	$13\,987^{b}$
	b	0.11^{a}	0.11^{a}	0.06^{c}	0.08^{b}
	R^2	0.99	0.99	0.99	0.99
Texture					
	Hardness (N)	6.35 ± 0.06^{d}	6.36 ± 0.06^{d}	13.43 ± 0.15^{a}	9.93 ± 0.09^{b}

Different superscript letters indicate significant differences ($p < 0.05$).

3.3. Characterization of P7 cake

3.3.1. Flow behavior of P7 batter

The rheological behavior of cake batters prepared with P7 showed similarity to the control batter formulated with commercial shortening, as the parameters obtained from both the power law and Herschel-Bulkley models indicate that the addition of P7, despite the fundamentally different nature of its lipid structure, does not disrupt the flow behavior required for cake batter processing.

According to the power law model, the consistency coefficient (K) of the P7 batter (22.000 $Pa \cdot s^n$) was not significant difference with control batter (21.856 $Pa \cdot s^n$). This result indicates that P7 provides apparent viscosity and resistance to flow under shear, which are very important for batter handling operations such as mixing, pumping, and mold filling. This behavior indicates that the bigel system, although composed of both aqueous and lipid phases, behaves as a homogeneous viscoplastic system on the macroscopic scale. The dispersion of the oleogel phase (PSO structured with beeswax) in the continuous aqueous matrix, reinforced by the pectin hydrogel, allows P7 to produce a viscosity that is usually provided by crystalline lipid networks in conventional shortenings. The flow behavior index (n) values for all batters (0.33–0.34) were

significantly less than 1, confirming a significant shear-thinning (pseudoplastic) behavior. The almost identical n value of P7 batter (0.335) compared to the control batter indicates that the structural components of bigel - the beeswax crystal lattice and pectin chains with calcium crosslinks - respond to shear in a similar way to shortening [37]. This ensures low viscosity during high-shear mixing while maintaining the structure, which is essential to prevent phase separation before baking. The high coefficients of determination ($R^2 \approx 0.98$) confirm that the power law model describes the shear-dependent flow behavior of all batter systems.

The Herschel-Bulkley model provides an indication of the structural stability of batters at low shear stresses. The yield stress (η_0) of the P7 batter (4.020 Pascal) was almost similar to the control batter (4.005 Pascal), indicating comparable resistance to initial deformation. Yield stress plays a critical role in cake batters by stabilizing entrapped air bubbles and suspended solids during the early stages of baking. The ability of P7 to develop a yield stress similar to commercial shortening suggests that the P7 structure effectively contributes to the formation of a weak, three-dimensional network capable of supporting dispersed phases without excessive hardness. Similarly, the consistency coefficient (K′) showed no significant difference between batters. This means that once flow begins, the resistance to deformation remains within the optimal range for aeration and expansion of the cake batter. The flow index (n′) values were also comparable. This slight difference can be attributed to the hybrid nature of the P7 structure, where the disintegration and reorientation of the wax crystal clusters and pectin hydrogel under shear, compared to the more uniform thick crystal lattices of commercial shortenings, contributes to improved structural consistency [15]. Importantly, the excellent fit of the Herschel-Bulkley model ($R^2 \approx 0.99$) for all batters confirms that the use of P7 does not cause instability. Instead, P7 is seamlessly integrated into the batter matrix and maintains the viscoplastic properties essential for industrial cake production.

Table 6. Physicochemical and rheological properties of cake batters

	Power law			Herschel–Bulkley			
	K (Pa·s^n)	n	R^2	η_0 (Pa)	K′ (Pa·s$^{n'}$)	n′	R^2
Control batter	21.856 ± 0.971^a	0.340 ± 0.021^a	0.979	4.005 ± 0.012^a	15.456 ± 0.432^a	0.398 ± 0.011^a	0.994
P7 batter	22.000 ± 0.975^a	0.335 ± 0.020^a	0.979	4.020 ± 0.012^a	15.500 ± 0.435^a	0.395 ± 0.011^a	0.994

Different superscript letters indicate significant differences ($p < 0.05$).

3.3.2. Specific volume and volume increase after baking

The physicochemical and textural properties of cakes prepared with P7 were comparable to cakes made with commercial shortening, indicating that P7 can successfully replicate the functional role of commercial shortenings in cake formulations. The specific volume and volume increase of the P7 cake (1.81 g/ml and 27.01 mm, respectively) slightly lower than ($p < 0.05$) the control cake (1.92 g/ml and 29.01 mm). These results suggest that the bigel system effectively supports batter aeration and gas retention during baking. This functionality can be attributed to the synergistic structure of the beeswax-based oleogel and the low-methoxyl pectin hydrogel, which together form a continuous, semi-solid network capable of stabilizing air cells like crystalline fat networks in commercial shortenings [38].

The slightly lower volume values observed for the P7 cake, may be associated with the comparatively lower storage modulus (G′) and softer rheological behavior of the bigel system. During the early stages of baking, a less rigid fat network may offer reduced resistance to bubble expansion and coalescence. Nevertheless, the observed volume parameters remained within the acceptable range for high-quality cakes, confirming that the mechanical strength of P7 is sufficient to ensure proper cake structure development.

The moisture content differed significantly between the two cake formulations ($p < 0.05$). This indicates that replacing the commercial solid oil with P7 has a negative impact on water

retention during baking or short-term storage. The presence of a hydrogel phase in the bigel system probably plays an important role in this behavior.

On the first day, the hardness of P7 cake was significantly lower than the control cakes ($p < 0.05$), indicating that the P7 immediately after baking produced a soft texture. This effect is likely related to the ability of P7 to coat and lubricate the gluten and starch components, thereby weakening the internal cake matrix and reducing resistance to deformation. After 10 days of storage, all cakes showed a significant increase in hardness, reflecting the natural staling phenomenon associated with starch retrogradation and moisture redistribution. As can be seen in table 7, the increase in hardness for control cake (from 3.97 to 5.31 N) was 33% compare to the p7 cake that was 100%, indicating that P7 accelerate staling. This behavior suggests that the structured lipid phase of bigel may interact with starch differ from commercial shortenings, that the formation of amylose-lipid complexes that can't inhibit recrystallization and slow down cake crumb hardening during storage [39].

Table 7. Physicochemical and textural properties of cakes made with bigel 7 and control shortenings

	Specific volume (g/ml)	Volume increase (mm)	Moisture content (%)		Hardness (N)	
			Day1	Day10	Day1	Day10
Control Cake	1.92 ±0.02[a]	29 ±0.1[a]	18.31 ±0.11[a]	16.87 ±0.18[a]	3.97 ±0.07[a]	5.31 ±0.04[b]
P7 cake	1.81 ±0.01[b]	27 ±0.1[b]	16.13 ±0.09[b]	13.33 ±0.21[b]	3.14 ±0.01[b]	6.33 ±0.02[a]

Different superscript letters indicate significant differences ($p < 0.05$).

4- Conclusion

The present study demonstrates that a bigel system consisting of PSO beeswax oleogel and a low-methoxyl pectin hydrogel can effectively replace commercial shortenings in cake formulations while maintaining comparable physicochemical, rheological, and textural properties. P7, formulated with 12% oleogel and 4% pectin-based hydrogel, exhibits a fatty acid profile rich in unsaturated fatty acids, low trans fatty acid content, and good oxidative stability, and is a healthier alternative to conventional hydrogenated shortenings. Cake batters prepared with P7 showed flow behavior (power law and Herschel-Bulkley parameters) very similar to commercial shortening batters, indicating good processability, aeration, and structural stability during mixing and baking. P7 cakes had specific volume, volume increase, moisture, and hardness that were significantly different from the control cakes on the first day and after 10 days of storage, indicating that P7 can't supported proper volume, crumb structure, and shelf stability. The stale behavior of the P7cake was higher than the control cake, indicating that the structured fat network couldn't effectively interact with starch and water to maintain a soft and tender crumb during storage. Although P7 can't exactly mimic the performance of commercial shortening oils in cake systems, it provides a structured fat phase with good aeration, texture, and stability, offering improved nutritional properties such as lower saturated and trans fatty acid content. These results highlight the potential of PSO beeswax-based oleogel/pectin-based hydrogel as a suitable and healthier alternative to conventional shortenings in bakery applications, combining acceptable technological performance with improved nutritional quality.

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Conflict of Interest

The author has declared no conflict of interest.

Compliance with ethical standards

This article lacks research involving human or animal subjects

Authors Contributions

Zahra Nazari: Conceptualization, Methodology, Investigation, Writing, review & editing, Supervision.

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توسعه و بررسی بایژل روغن هسته انار به عنوان جایگزین سالم‌تر شورتنینگ در فرمولاسیون کیک

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چکیده

در این مطالعه، از صمغ گوار، پکتین با متوکسیل پایین (LMP) و موم زنبور عسل (BW) برای تهیه هیدروژل‌ها و اولئوژل‌ها برای تولید بایژل‌های روغن دانه انار (PSO) استفاده شد. خواص رئولوژیکی و بافتی بایژل‌ها مشخص شد. بایژل P7 (75% هیدروژل 25% + LMP اولئوژل BW)یک شبکه ژل قوی و الاستیک با مدول ذخیره بالا (G') و خواص رئولوژیکی و بافتی نزدیک‌تر به شورتنینگ‌های تجاری نسبت به سایر فرمولاسیون‌های بایژل نشان داد. پروفیل اسید چرب P7 غنی از اسیدهای چرب غیراشباع (پونیسیک اسید C18:3) بود و اسید استئاریک (C18:0)و کل اسید چرب اشباع (SFA) کمتری در مقایسه با شورتنینگ‌های تجاری نشان داد. خمیر بر پایه P7 رفتار جریانی (پارامترهای قانون توان و هرشل-بالکلی) بسیار شبیه به خمیر کنترل بود که نشان‌دهنده فرآیندپذیری خوب، هوادهی و پایداری ساختاری در طول فرآیند اختلاط است. کیک بر پایه P7 در روز اول و پس از ۱۰ روز نگهداری، حجم مخصوص، افزایش حجم و رطوبت کمتری نسبت به کیک شاهد داشت. رفتار بیاتی کیک بر پایه P7 کمی بیشتر از نمونه شاهد بود که نشان می‌دهد شبکه چربی شورتنینگ به طور مؤثرتری با نشاسته و آب تعامل می‌کند تا مغز کیک نرم و لطیفی را در طول نگهداری حفظ کند. به طور کلی، این نتایج پتانسیل P7 را به عنوان یک جایگزین سالم‌تر برای شورتنینگ، با عملکرد تکنولوژیکی قابل قبول و کیفیت تغذیه‌ای بهبود یافته، نشان می‌دهد.