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Original research paper

SUNFLOWER WAX-BASED OLEOGEL FROM OILS REFINING WASTES AS A SHORTENING ALTERNATIVE IN CUPCAKE

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Abstract: This investigation utilized sunflower wax, a by-product recovered from sunflower oil refining waste, to prepare a sunflower oil-based oleogel (SFW-BO) and evaluated its potential as a full replacement for conventional palm oil-based shortening (SH-BPO) in bakery applications. The novelty of this study lies in the use of sunflower wax obtained directly from oil refining waste, rather than commercial wax, emphasizing resource sustainability. Fourier-transform infrared (FTIR) spectroscopy confirmed the effectiveness of the purification process in producing high-purity wax. Physicochemical characterization demonstrated that 100% SFW-BO exhibited superior oil-binding capacity (OBC ≈ 99%) and a higher melting point (53.2°C) compared to SH-BPO (40.1°C). Fatty acid profiling revealed that increasing the proportion of SFW-BO significantly reduced saturated fatty acid content from 50.61% (100% SH-BPO) to 11.15% (100% SFW-BO), while increasing unsaturated fats. Cupcakes formulated with SFW-BO blends showed enhanced specific volume and reduced textural hardness, with the 100% replacement sample achieving the highest volume (1.86 cm³/g). Water activity and sensory analyses indicated no significant differences between shortening and oleogel-containing cupcakes, suggesting comparable microbial stability and consumer acceptability. These findings establish refining waste-derived sunflower wax oleogel as a functionally robust and nutritionally advantageous alternative to traditional shortening, enabling the production of baked goods with a reduced saturated fat footprint without compromising technological performance or sensory quality.

Key words: *sunflower wax, oleogel, shortening, cupcakes, saturated fatty acids, oil refining waste*

INTRODUCTION

The sunflower oil refining process yields substantial quantities of underutilized by-products, notably waxes and phospholipids, which remain underutilized at a commercial scale (Redondas, Baümler & Carelli, 2020; Lutsenko, Kharytonov & Peron, 2024). The sunflower seed contains approximately 3% wax, with nearly 80% concentrated in the hull fraction

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(Carelli, Frizzera, Forbito & Crapiste, 2002). Sunflower wax (SFW) is considered as a replacement to many types of wax, such as carnauba, rice bran and candelilla wax. The technological applications of SFW encompass diverse food sectors, including edible coatings, emulsification systems, and oleogelation, particularly as substitutes for conventional saturated fats including palm oil, hydrogenated oils, butter, margarine, and shortening. These traditional lipid sources contain elevated levels of saturated fatty acids, whose consumption has been epidemiologically linked to adverse cardiovascular health outcomes (Öğütcü & Yılmaz, 2015; Ruiz-Núñez, Dijck-Brouwer & Muskiet, 2016; Doan, Tavernier, Okuro, & Dewettinck, 2018). Consequently, reducing dietary exposure to these fats represents a significant public health objective.

Oleogelation technology provides an innovative approach to structuring liquid oils into semi-solid systems without chemical modifycation. These thermoreversible gels form when gelator molecules create three-dimensional networks that immobilize oil phases through physical interactions, yielding materials with tailored rheological properties. This technique offers distinct advantages over conventional fat modification processes such as hydrogenation, including enhanced safety profiles and processing efficiency (Hughes, Marangoni, Wright, Rogers & Rush, 2009).

Multiple compound classes demonstrate organogelation capabilities, including lecithin, sorbitan tristearate, phytosterols, oryzanol, long-chain fatty acids, fatty alcohols, monoacylglycerides, wax esters, natural waxes, ricinelaidic acid, 12-hydroxystearic acid and cellulose derivatives like ethyl and methyl cellulose (Rogers, Wright & Marangoni, (2009); Schubert et al., 2022 and Gao et al., 2024). Among these, food-grade waxes have emerged as particularly promising oleogelators due to their regulatory acceptance, cost-effectiveness, and pronounced gelling efficiency.

The efficiency of different types of waxes: plant-based, animal-derived, and petroleum-based, in converting soybean oil into gel was evaluated in a study by Hwang et al. (2012).

The tested waxes included sunflower wax, carnauba wax, beeswax, microcrystalline wax, candelilla wax, rice bran wax, Kester wax, synthetic spermaceti, paraffin wax, castor wax (hydrogenated castor oil), jojoba oil, bayberry wax, Japan wax, and shellac wax. Sunflower wax showed the highest gelation effectiveness compared to other types of wax and was able to form a gel at concentrations ranging from 0.5 to 10%.

This exceptional gelling performance originates from SFW's distinctive chemical architecture. Unlike many vegetable waxes containing heterogeneous mixtures of hydrocarbon species, alcohols, and ketones, SFW comprises predominantly long-chain esters (C40-C60), and unsaturated fatty alcohols (C18–C34), that facilitate the development of highly organized crystalline networks with superior oil-binding capacity even at low concentrations (Patel, Babaahmadi, Lesaffer & Dewettinck, 2015 and Chalapud, Baümler & Carelli, 2017). These characteristics position SFW-based oleogels as compelling alternatives to conventional solid fats in bakery applications (Öğütcü & Yılmaz, 2015).

Solid fats have a pivotal role in evaluating the functional properties of various food products, especially bakery products such as bread, cakes, cookies, biscuits, and pastries. Solid fats are often called "shortenings" due to giving a “short” or soft texture to bakery products (Ghotra, Dyal & Narine, 2002). In baking purposes, shortening performs multiple critical functions: they mediate air cell incorporation and stabilization during mixing, interrupts gluten network development, and contributes to flavor release and mouthfeel perception, facilitates heat transfer during baking, and potentially extends product shelf life (Ghotra et al., 2002; Renzyaeva, 2013 and Rios, Pessanha, Almeida, Viana & Lannes, 2014).

The present study aimed to develop and characterize an oleogel system structured by SFW purified from industrial refining waste. We systematically evaluated the physicochemical and functional properties of this novel oleogel and its blends with conventional shortening, assessing its viability as a complete replacement in cake formulations. Our investigation provides critical insights into the nutritional, technological, and sensory implications of utilizing waste-derived SFW as a sustainable alternative to traditional high-saturated fat ingredients in bakery products.

MATERIALS AND METHODS

Materials

Refined, bleached and deodorized (RBD) sunflower oil and shortening (free of added antioxidants) and crude sunflower wax from the dewaxing step were supplied by Arma Company, 10th of Ramadan, Sharkia Government, Egypt.

Sunflower wax purification

Crude sunflower wax (SFW) was purified according to the method described by Redond as et al. (2020) with a modification. Briefly, 300 g of the crude wax was refluxed with hexane at a 1:2 (w/v) ratio at 70°C for 30 min under continuous stirring. The purification temperature was set to 70°C slightly above the melting point of sunflower wax 67°C to ensure complete melting and enhance impurity separation. The supernatant was collected and stored at -18°C for 18 h to induce wax crystallization. The wax crystals were subsequently separated by centrifugation. This procedure was repeated several times, and the resultant wax crystals were washed three times with ethanol at room temperature to eliminate any remaining polar impurities. The yield of purified wax varied with the initial impurity and residual oil content in the crude wax. In this study, the recovery was 79.65%. The purified wax exhibited a lighter color and a smoother texture compared to its crude form (Fig. 1).

Fourier Transform Infrared Spectroscopy (FTIR)

The chemical profiles of both crude and purified wax were analyzed using an FTIR spectrophotometer (INVENIO S, Bruker) equipped with a diamond ATR accessory. Spectra were recorded in the range of 4000 to 500 cm^{-1}.

Preparation of oleogel and blends

Sunflower wax-based oleogel (SFW-BO) was

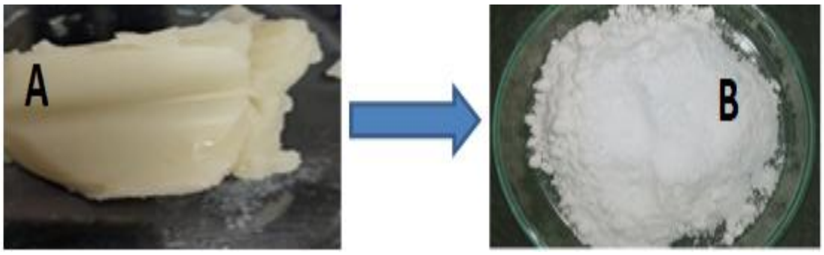

Figure1. Crude SFW (A) and purified SFW (B).

100% SH-BPO 20% SFW-BO 40% SFW-BO 60% SFW-BO 80% SFW-BO 100% SFW-BO SFO

Figure 2. Shortening-based palm oil (SH-BPO), sunflower wax-based oleogel (SFW-BO), their blends, and sunflower oil (SFO).

Table 1.
The mixing ratios of shortening-based palm oil and sunflower wax-based oleogel

Samples	Mixing ratio
100% Shortening– based palm oil (SH-BPO)	100% shortening
20% sunflower wax-based oleogel (20 % SFW-BO)	20% oleogel +80% shortening
40% sunflower wax-based oleogel (40% SFW-BO)	40% oleogel +60% shortening
60% sunflower wax-based oleogel(60% SFW-BO)	60% oleogel +40% shortening
80% sunflower wax-based oleogel(80% SFW-BO)	80% oleogel +20% shortening
100% sunflower wax-based oleogel(100% SFW-BO)	100% oleogel

prepared by adding SFW to heated sunflower oil (90°C) at a concentration of 10% (w/w), followed by stirring until complete dissolution, and subsequent cooling to room temperature (Lim, Hwang & Lee, 2017).

The formed oleogel was stored in a refrigerator. Blends with shortening (SH-BPO) were prepared following the method of Demirkesen & Mert (2019) at the ratios detailed in Table 1. The mixtures were heated to 50°C, stirred for 30 min, pre-cooled, crystallized at 20°C, kneaded, and then tempered at 25°C for 3 days before final storage at 5°C. Visual representations of the fat samples are provided in Fig. 2.

Physicochemical analysis of fats

Free fatty acids (FFAs), expressed as a percentage of oleic acid, peroxide value (PV) in meqO_2/kg oil, and the melting point of the samples were determined using standard AOAC methods (AOAC, 2019).

Fatty acid methyl esters (FAMEs) were prepared via cold saponification (ISO 12966-2:2017) and analyzed using an Agilent 6890 series gas chromatograph fitted with a DB-23 capillary column (60 m × 0.32 mm × 0.25 µm; Agilent Technologies Inc., CA, USA).

The oil-binding capacity (OBC) was assessed by solidifying approximately 3 g of the melted sample in a centrifuge tube. Centrifugation was performed at 4000 rpm (1,629×g) for 15 minutes to expel unbound oil. The tubes were then inverted and placed on tissue paper for 5 minutes to allow drainage (Onacik-Gür & Zbikowska, 2019). The sample mass was recorded before and after this process.

The percentage released oil and the OBC were calculated using the following formulas.

$$\text{Released Oil (\%)} = [(W_0 - W_a)/W_0] \times 100$$

Where W_0 = initial weight, W_a = weight after drainage

$$\text{OBC (\%)} = 100 - \text{Released Oil (\%)}$$

Cupcake preparation

Cupcakes were formulated according to AACC (2000) guidelines with slight modifications The recipe consisted of wheat flour (100g), fresh eggs (80g), sugar (60g), skim milk powder (3g), baking powder (4g), vanilla powder (1g), salt (0.5g), and fat (50g of the respective sample). Cupcakes were baked in a pre-heated oven at 180 °C for 20 min. After baking, they were cooled for 2 hr. at room temperature (30±2 °C), then packaged in polyethylene bags for subsequent analysis. Fig. 3 displays the prepared cupcake samples.

Cupcake analysis

The water activity (a_w) was determined using a digital water activity meter (Aqualab 4 TE series, Decagon, USA) (Santos, Magalhães, Okuro, Steel & Cunha, 2024).

The baking loss was measured according to Liu et al. (2020) using the following equation (1):

$$\text{Baking loss (\%)} = (W_0-W_1)/W_0 \times 100$$

where, W_0: weight of cupcake batter before baking and W_1: weight of baked cupcake after cooling for 2h.

Specific volume was measured after baking and a 2 h cooling period using the rapeseed displacement method (AACC Method 10-05.1, 2002). The specific volume was calculated as the ratio of the cupcake's volume to its weight (cm^3/g).

The color parameters of both fat and cupcake samples (crust and crumb) were determined using a Chroma meter (Minolta CR-400, Minolta, Osaka, Japan) in the CIE L*a*b* system according to Yilmaz & Öğütcü (2015). The values for L* (lightness; 100=light, 0=dark), a* (+red/-green), and b* (+yellow/-blue) were recorded. Texture profile analysis of the cupcake samples, including hardness (N), springiness (mm), cohesiveness, gumminess (N), and chewiness (mJ), was performed using a CT3 Texture Analyzer (Brookfield, Engineering Laboratories, Inc., USA) following the method of Alvarez-Ramirez (2016). A 36 mm diameter cylindrical probe was used at a test speed of 2 mm/s, targeting the center of the cupcake. The sample was compressed to 40% deformation with a trigger load of 5 g. All parameters and data were automatically recorded by the associated software (TA-CT-PRO).

The sensory attributes of the cupcakes (color, taste, odor, appearance, texture, and overall acceptability) were evaluated by a panel of 10 trained researchers from the Food Technology

Research Institute (FTRI) according to the methodology described by Hussien, Afify and Shabib (2023). Samples were coded with random three-digit numbers and presented in a randomized order under controlled lighting and ambient temperature conditions. A 9-point hedonic scale (1 = dislike extremely, 9 = like extremely) was used to rate each attribute.

The study protocol was reviewed and approved by the Ethics Committee of the Food Technology Research Institute, Agricultural Research Center (approval no. SEC-20). All participants were fully informed about the study and provided voluntary consent prior to the evaluation.

Statistical analysis

All data were statistically analyzed using CoState software (CoHort Software, Monterey, CA, USA). A one-way analysis of variance (ANOVA) under a completely randomized design was applied. Means were compared using Duncan's test at a significance level of $p < 0.05$.

Results were presented as mean values ± standard deviation (SD), as outlined by Snedecor and Cochran (1982).

Figure 3. Prepared cupcakes from shortening-based palm oil, sunflower wax-based oleogel, and their blends.

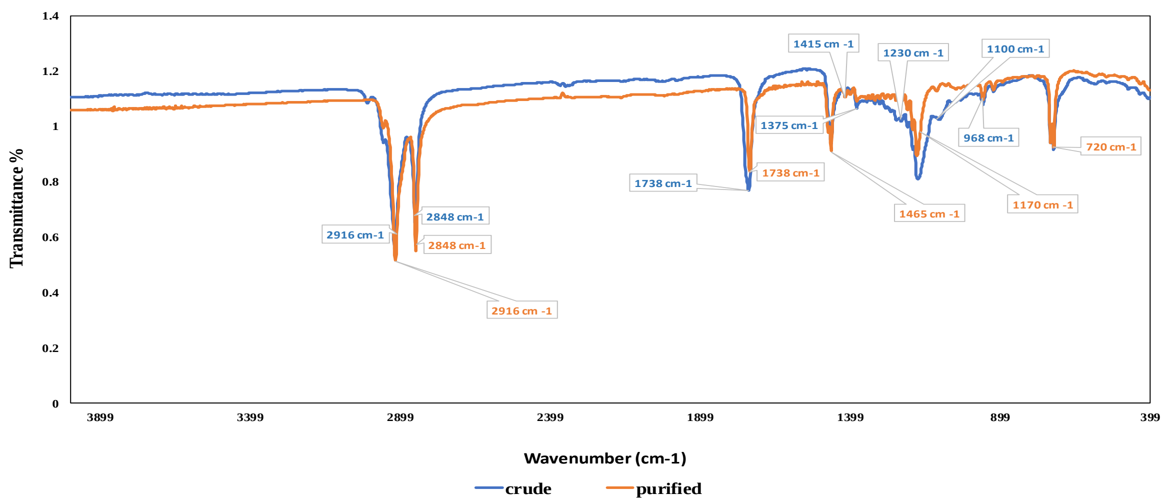

Figure 4. FTIR spectra of sunflower wax before and after purification

RESULTS AND DISCUSSION

Fourier Transform Infrared Spectroscopy (FTIR) of crude and purified sunflower wax

FTIR spectroscopy was applied for crude and purified wax to evidence the efficiency of the purification process in removing residual oil and impurities.

The FTIR spectra were recorded in the range of 4000–500 cm^{-1} (Fig. 4). In both samples, the key absorption peaks characteristic of aliphatic hydrocarbon wax components remained intact. These include the strong, sharp asymmetric and symmetric CH_2 stretches at ~2916 and ~2848 cm^{-1}, and a sharp wax ester carbonyl (C=O) stretch at ~1738 cm^{-1}. This indicates preservation of the core hydrocarbon wax structure (Knuutinen & Norrman, 2000; Du-bey, Sharma & Kumar, 2017; Dimakopoulou-Papazoglou, Zampouni, Katsanidis, Prodro-midis & Moschakis, 2024). The purified wax spectrum is defined by key vibrations of the core wax ester structure, including CH_2 ben-ding at 1465 cm^{-1}, C–O stretching at 1170 cm^{-1}, and a long-chain methylene (CH_2) rock at 720 cm^{-1}. In contrast, the unpurified crude wax exhibits a highly complex spectrum with numerous additional absorptions. These in-clude an O–H in-plane bend at 1415 cm^{-1}, a CH_3 bend at 1375 cm^{-1}, a complex profile of C–O stretches between 1230 and 1100 cm^{-1}, and a =C–H bend at 968 cm^{-1}. These additional peaks are potentially attributable to triglycerides, free fatty acids, and ester compounds commonly associated with sunflower oil residues (Yi, Yao, Xu, Wang & Wang, 2019; Stanciu, 2025). The FTIR results provide strong evidence that the purification process effectively removed unwanted materials and produced pure wax.

Physicochemical properties of fats

In Table (2), all samples exhibited low FFA (<0.1%) and PV (<1.2 meq O_2/kg) values, well below Codex Alimentarius limits (2009), which specify a maximum of 0.3% for FFAs and 10 meq O_2/kg for PV, indicating that oleo-gelation and blending did not induce significant hydrolysis or oxidation (Özer & Özer, 2023).

Oil-binding capacity (OBC) is a crucial attri-bute of oleogels, defining their ability to im-mobilize liquid oil within a semi-solid matrix. A high OBC is essential for preserving the structural integrity, texture, and functional per-formance of oleogels in food products (Yang, Yang, Chen, Chen & Liu, 2020).

The exceptional functionality of purified SFW as an oleogelator stems from its unique che-mical composition. SFW is predominantly composed of very long-chain esters (C40–C60), which, upon cooling, self-assemble into a dense, three-dimensional crystalline network that traps liquid oil via strong van der Waals and dipole-dipole interactions (Co & Ma-rangoni, 2012; Doan et al., 2018). This micro-structural superiority directly governs the macroscopic properties of the oleogel. The dense, interconnected crystal network resulted in an exceptionally high OBC for SFW-BO (98.97%), significantly surpassing that of tradi-tional shortening (80.89%).

This performance is notably superior to that of other common wax oleogels. For instance, while carnauba wax is an effective gelator, it often requires higher concentrations than SFW to achieve a similar OBC and can produce firmer, more brittle gels (Dassanayake, Kodali, Ueno & Sato, 2011; Öğütcü & Yılmaz, 2015). Similarly, beeswax oleogels, though effective, have been reported to exhibit lower OBC and a softer texture compared to SFW-based gels, which can compromise the structural integrity of baked goods (Blake & Marangoni, 2015).

The melting point (MP) of SFW-BO (53.2°C) was significantly higher ($p < 0.05$) than that of SH-BPO (40.1°C). Furthermore, a clear up-ward trend in MP was observed with in-creasing SFW-BO concentration, further underscoring the robustness of its crystalline network. This higher melting point of SFW-BO, compared to SH-BPO, highlights its thermal stability a trait where SFW often out-performs beeswax (MP ~62-64°C, but with a different crystalline structure) and is com-parable to or higher than carnauba wax -based oleogels (Hwang, Kim, Singh, Winkler-Moser & Liu, 2012). These findings are consistent with previous studies reporting that the melting points of sunflower wax-based oleogels range between 47°C and 65°C, depending on wax concentration, and that increasing oleogel con-tent in fat blends elevates melting points and enthalpy values, indicating a more structured crystal network (Co & Marangoni, 2012; Hwang et al., 2012). These results demonstrate that the melting properties of fat formulations can be tailored by adjusting the SFW-BO ratio to meet specific application needs, such as in bakery products requiring structural integrity at elevated temperatures (Qiu, 2024).

The color properties (L*, a*, b*) of the fat samples are summarized in Table 2. The lightness (L*) of 100% SH-BPO (63.11) was higher than that of 100% SFW-BO (50.09), which can be attributed to lower light reflectance caused by the opaque nature and high crystallinity of the wax (Marangoni & Garti, 2018). For the a* values, a significant shift from more negative values (green) to less negative values (more neutral/reddish) was observed, increasing from -3.42 in SH-BPO to -1.73 in 100% SFW-BO. This change may be due to the lower pigment content in sunflower wax and oil compared to palm oil (Co & Marangoni, 2012). The b* values (yellowness) were highest in the 100% SH-BPO sample (8.56) and decreased with a higher SFW-BO ratio. The color of the oleogel could be modified by adding oil-soluble colorants during preparation to enhance visual appeal for specific food applications and consumer acceptance.

Fatty acid composition of fats

A key objective was to utilize SFW-BO in bakery applications to improve the fatty acid profile by increasing the ratio of unsaturated (UFA) to saturated fatty acids (SFA). The primary nutritional benefit of using SFW-BO lies in its ability to structure inherently healthy, high-unsaturated oils.

Table 3 and Fig. 5 present the fatty acid composition of the samples. Significant differences ($p \leq 0.05$) were observed in most individual fatty acids and in the total SFA and UFA contents. The SFA content decreased substantially from 50.61% in 100% SH-BPO to 11.15% in 100% SFW-BO.

Concurrently, the UFA content increased from 49.39% to 88.85%. Thus, a higher oleogel-to-shortening ratio resulted in a more favorable fatty acid profile, rich in unsaturated fats. This shift aligns with dietary guidelines recommending that SFA intake be limited to below 10% proposed by (WHO, 2003) or even 7% by (American Heart Association Nutrition Committee, 2006) of total energy to reduce coronary heart disease risk (Mozaffarian, Micha & Wallace, 2010; De Souza et al., 2015).

Furthermore, replacing SH-BPO with SFW-BO reduced the content of palmitic acid from 46.44% to 39.12, 31.43, 23.5, and 15.2% at substitution levels of 20, 40, 60, and 80%, respectively. Palmitic acid is known to be harmful to health, according to (WHO, 2003) that reported conclusive evidence that it increases the risk of cardiovascular disease, and its continued consumption leads to greater body fat accumulation than other saturated fatty acids (Mondul et al., 2015; Senyilmaz-Tiebe et al., 2018; Vanrooijen, Plat, Zock, Blom & Mensink, 2021).

Cupcake physical properties

The transition from the fat's properties to the final cupcake quality is where the structural advantage of SFW-BO became most apparent. The baking loss, specific volume, and water activity of cupcakes are shown in Table 4. Replacing shortening with oleogel led to a decreased in baking loss from 8.21% to 6.86%, though the differences were not significant ($p \leq 0.05$). This finding aligns with Ozdemir-Orhan, Eroglu & Omac (2024), who reported that substituting shortening with oleogel did not significantly affect the baking loss of cakes.

The specific volume of cupcakes increased significantly with higher SFW-BO levels, with the 100% replacement sample achieving the highest volume (1.86 cm^3/g), compared to the control (1.27 cm^3/g). This suggests that the rigid SFW-BO network is more effective at incorporating and stabilizing air cells during mixing and baking, thereby enhancing gas retention, as supported by Alvarez-Ramirez, Vernon-Carter, Carrera-Tarela, Garcia & Roldan-Cruz (2020) and Feng et al. (2025) resulting in final the specific volume increase. Water activity (a_w) influences microbial stability, textural properties, overall quality and shelf life of bakery products (Rahman, 2009). Replacing SH-BPO with SFW-BO up to 100% did not significantly affect the a_w value of the cupcakes, which ranged between 0.72 and 0.73. These values indicate that the cakes are microbiologically stable, as most pathogenic bacteria do not grow below a_w 0.85 (Rahman, 2009). This result is consistent with Ozdemir-Orhan et al. (2024), who found no significant difference in

a_w between control cakes and those containing oleogel. The color parameters of the cupcake crust and crumb are presented in Table 5. Replacing shortening with oleogel induced a significant ($p\leq0.05$) decrease in L* (lightness) for both crust and crumb. The a* and b* values generally increased with higher oleogel levels, indicating greater redness and yellowness, except for the b* value of the 100% SFW-BO crumb, which was lower than the control. These findings align with Roufegarinejad, Ahmadi, Icyer, Toker & Khiabani, (2024) and Santos et al. (2024), who observed that oleogel replacement increased darkness, redness, and yellowness in cakes. The color changes may be due to the increased unsaturation of the oil, potentially enhancing the Maillard reaction during baking (Roufegarinejad et al., 2024).

The inherent darker color of the oleogel itself (Table 2) also contributes to this effect. The textural profile analysis of the cupcakes (hardness, cohesiveness, springiness, gumminess and chewiness) is shown in Table 6.

Hardness values gradually decreased with increasing oleogel content, with the 100% SFW-BO sample exhibiting the lowest value (10.91 N), significantly different from the control (14.24 N).

Table 2.
Physicochemical properties of shortening-based palm oil, sunflower wax-based oleogel, and their blends

Parameters		Samples					
		100% SH-BPO	20% SFW-BO	40% SFW-BO	60% SFW-BO	80% SFW-BO	100% SFW-BO
FFA %		0.06±0.01^{c}	0.09±0.00^{b}	0.08±0.02^{b}	0.10±0.01^{ab}	0.09±0.01b	0.10±0.00a
PV meq O_2/kg oil		0.85±0.04^{c}	1.01±0.02^{b}	1.05±0.05^{b}	1.08±0.10^{b}	1.00±0.05^{ab}	1.19±0.10^{a}
MP °C		40.10±0.35^{f}	44.00±1.30^{e}	46.50±0.40^{d}	48.30±0.50^{c}	50.00±0.61^{b}	53.20±0.49^{a}
OBC (%)		80.89±0.10^{f}	90.77±0.10^{e}	95.77±0.12^{d}	96.62±0.18^{c}	98.08±0.17^{b}	98.97±0.24^{a}
color	***L******	63.11±0.62^{a}	61.94±0.75^{b}	59.43±0.68^{c}	58.58±0.49^{c}	53.24±0.52^{d}	50.09±0.34^{e}
	a***	-3.42±0.30^{d}	-3.23±0.23^{cd}	-2.86±0.25^{c}	-2.36±0.15^{b}	-2.32±0.20^{b}	-1.73±0.30^{a}
	b***	8.56±0.25^{a}	6.86±0.34^{b}	6.23±0.33^{bc}	6.15±0.21^{cd}	6.75±0.46^{d}	6.17±0.27^{d}

Shortening-based palm oil (SH-BPO) and sunflower wax-based oleogel (SFW-BO).
Values are means ± SD of three replicates; different superscripts letters in the same row indicate significant differences ($p\leq0.05$).

Table 3.
Fatty acid content (%) of shortening-based palm oil, sunflower wax-based oleogel, and their blends

Fatty acid	Samples					
	100% SH-BPO	20% SFW-BO	40% SFW-BO	60% SFW-BO	80% SFW-BO	100% SFW-BO
Lauric acid (C12:0)	0.13±0.03^{a}	0.11±0.02^{d}	0.08±0.01^{cd}	0.05±0.02^{bc}	0.03±0.01^{ab}	ND
Myristic acid (C14:0)	0.87±0.07^{a}	0.72±0.06^{ab}	0.57±0.08^{b}	0.41±0.02^{c}	0.24±0.02^{d}	0.07±0.02^{e}
Palmitic acid (C16:0)	46.44±2.31^{a}	39.12±0.88^{ab}	31.43±1.43^{bc}	23.5±1.06^{cd}	15.2±0.79^{d}	6.50±0.27^{e}
Palmitoleic acid (C16:1)	ND	0.02±0.00^{e}	0.04±0.00^{d}	0.06±0.01^{c}	0.09±0.01^{b}	0.12±0.00^{a}
Margaric acid (C17:0)	ND	0.01±0.00^{d}	0.02±0.00^{d}	0.03±0.01^{cd}	0.05±0.01^{ab}	0.06±0.01^{a}
Margoleic acid (C17:1)	ND	0.01±0.00^{e}	0.02±0.00^{d}	0.03±0.00^{c}	0.05±0.00^{b}	0.06±0.00^{a}
Stearic acid (C18:0)	3.17±0.13^{cd}	3.23±0.18^{bc}	3.28±0.21^{b}	3.35±0.16^{ab}	3.39±0.38^{a}	3.49±0.39^{a}
Oleic acid (C18:1)	41.52±1.53^{a}	38.69±0.75^{ab}	35.86±1.03^{abc}	32.69±0.50^{abc}	29.50±0.90^{bc}	26.14±1.15^{c}
Linoleic acid (C18:2)	7.69±0.70^{e}	17.7±0.21d^{e}	28.11±1.93^{d}	39.06±0.96^{c}	50.39±2.29^{b}	62.26±1.73^{a}
Linolenic acid (C18:3)	ND	0.02±0.00^{e}	0.03±0.00^{d}	0.05±0.00^{c}	0.07±0.00^{b}	0.09±0.01^{a}
Arachedic acid (C20:0)	ND	0.05±0.01^{e}	0.10±0.02^{d}	0.16±0.02^{c}	0.22±0.03^{b}	0.28±0.04^{a}
Eicosenoic acid (C20:1)	0.18±0.2^{a}	0.18±0.02^{a}	0.18±0.24^{a}	0.18±0.26^{a}	0.18±0.28^{a}	0.18±0.03^{a}
Behenic acid (C22:0)	ND	0.14±0.01e	0.28±0.01d	0.43±0.02c	0.59±0.05b	0.75±0.06a
Total saturated fatty acids	50.61±2.54^{a}	43.38±1.53^{ab}	35.76±0.090^{bc}	27.93±1.04^{cd}	19.72±0.47^{de}	11.15±0.79^{e}
Total unsaturated fatty acids	49.39±0.81^{e}	56.62±0.57^{e}	64.24±1.56^{d}	72.07±0.39^{c}	80.28±2.75^{b}	88.85±2.8^{a}

Not detected (ND). Shortening-based palm oil (SH-BPO) and sunflower wax-based oleogel (SFW-BO).

Values are means ± SD of three replicates; different superscripts letters in the same row indicate significant differences (p≤0.05).

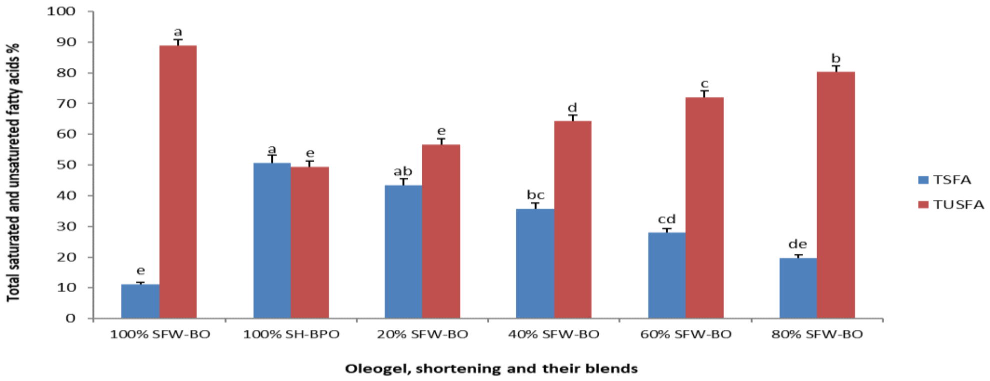

Figure 5. Total saturated fatty acids (TSFA) & total unsaturated fatty acids (TUSFA) for oleogel, shortening, and their blends. Different letters within the same trait indicate significant differences (p≤0.05).

Table 4.
Baking loss, specific volume and water activity of cupcake samples were prepared from sunflower wax-based oleogel, shortening-based palm oil, and their blends

Samples	**Baking loss (%)**	**Specific volume (cm^3/g)**	**Water activity (a_w)**
100% SH-BPO	8.21^{a}±1.02	1.27±0.19^{c}	0.73±0.005^{a}
20 % SFW-BO	7.96^{a}±0.89	1.54±0.21^{bc}	0.73±0.005^{a}
40% SFW-BO	7.55^{a}±0.92	1.76±0.12^{ab}	0.73±0.000^{a}
60% SFW-BO	7.50^{a}±1.00	1.799±0.09^{ab}	0.72±0.010^{ab}
80% SFW-BO	7.30^{a}±0.90	1.81±0.16^{ab}	0.72±0.010^{ab}
100% SFW-BO	6.86^{a}±0.97	1.86±0.22^{a}	0.72±0.010^{ab}

Shortening-based palm oil (SH-BPO) and sunflower wax-based oleogel (SFW-BO).
Values are means ± SD of three replicates, different superscripts letters in the same column indicate significant differences (p≤0.05).

Table 5.
Color of cupcake samples were prepared from sunflower wax-based oleogel, shortening-based palm oil, and their blends

Samples	**Color**					
	Crust			**Crumb**		
	L*	***a****	***b****	***L****	***a****	***b****
100% SH-BPO	62.36±0.35^{a}	8.41±0.25^{e}	39.18±0.24^{d}	75.04±0.53^{a}	-1.80±0.11^{c}	28.66±0.49^{b}
20 % SFW-BO	61.85±0.42^{b}	10.25±0.38^{d}	42.21±0.27^{a}	74.38±0.56^{a}	-1.57±0.14^{c}	30.16±0.60^{a}
40% SFW-BO	59.35±0.39^{b}	12.44±0.41^{b}	42.64±0.64^{a}	74.41±0.49^{a}	-1.14±0.09^{b}	30.55±0.67^{a}
60% SFW-BO	57.22±0.22^{d}	13.38±0.43^{a}	41.21±0.17^{b}	70.52±0.52^{b}	-0.85±0.21^{ab}	30.85±0.67^{a}
80% SFW-BO	55.11±0.23^{e}	13.25±0.35^{a}	40.44±0.51^{c}	68.60±0.47^{c}	-0.64±0.19^{a}	30.71±0.53^{a}
100% SFW-BO	58.71±0.41^{c}	11.35±0.29^{c}	40.96±0.38^{bc}	67.06±0.55^{d}	-0.62±0.23^{a}	27.26±0.72^{c}

Shortening-based palm oil (SH-BPO) and sunflower wax-based oleogel (SFW-BO).
Values are means ± SD of three replicates, different superscripts letters in the same column indicate significant differences (p≤0.05).

Table 6.
Texture profile analysis of cupcake samples were prepared from sunflower wax-based oleogel, shortening-based palm oil, and their blends

Samples	**Hardness (N)**	**Cohesiveness**	**Springiness (mm)**	**Gumminess (N)**	**Chewiness (mJ)**
100% SH-BPO	14.24^{a}±1.01	0.38^{a}±0.15	11.21^{b}±0.20	5.86^{a}±0.55	64.96^{a}±0.81
20 % SFW-BO	13.89^{a}±0.98	0.40^{a}±0.12	11.30 ^{b}±0.30	5.40 ^{ab}±0.25	61.36^{b}±1.03
40% SFW-BO	13.09^{ab}±1.23	0.41^{a}±0.19	11.14 ^{b}±0.35	5.00^{bc}±0.40	55.71^{c}±1.65
60% SFW-BO	12.52^{abc}±1.33	0.41^{a}±0.16	11.13 ^{b}±0.14	4.55^{cd}±0.39	51.02^{d}±1.02
80% SFW-BO	11.57^{bc}±1.02	0.37^{a}±0.12	11.80 ^{a}±0.17	4.32^{cd}±0.40	50.97^{d}±1.15
100% SFW-BO	10.91^{c}±0.95	0.43^{a}±0.15	12.15 ^{a}±0.14	4.15^{d}±0.37	50.22^{d}±1.20

Shortening-based palm oil (SH-BPO) and sunflower wax-based oleogel (SFW-BO).
Values are means ± SD of three replicates, different superscripts letters in the same column indicate significant differences (p≤0.05).

Table 7.
Sensory evaluation of cupcake samples prepared from sunflower wax-based oleogel, shortening-based palm oil, and their blends

Samples	Appearance	Texture	Taste	Flavor	Color	Overall acceptability
100%SH-BPO	8.33±0.58^{a}	7.33±1.15^{a}	7.50±0.50^{a}	8.00±0.50^{a}	7.83±0.29^{a}	8.16±0.29^{a}
20%SFW-BO	8.00±1.00^{a}	7.00±0.50^{a}	7.50±0.50^{a}	8.00±0.50^{a}	7.66±0.58^{a}	7.83±0.76^{a}
40%SFW-BO	8.33±1.15^{a}	7.83±0.77^{a}	7.50±0.50^{a}	8.16±0.58^{a}	7.83±0.29^{a}	8.00±0.86^{a}
60%SFW-BO	8.50±0.5^{a}	7.66±0.58^{a}	7.50±0.50^{a}	7.66±0.76^{a}	7.66±0.57^{a}	8.16±0.29^{a}
80%SFW-BO	8.50±0.5^{a}	7.50±0.50^{a}	7.66±0.58^{a}	7.16±1.26^{a}	7.83±0.28^{a}	8.00±0.86^{a}
100%SFW-BO	8.50±0.86^{a}	7.10±0.36^{a}	7.33±0.57^{a}	8.00±0.50^{a}	8.00±1.00^{a}	7.83±0.58^{a}

Shortening-based palm oil (SH-BPO) and sunflower wax-based oleogel (SFW-BO).
Values are means ± SD of ten replicates, different superscripts letters in the same column indicate significant differences (p≤0.05).

The enhanced aerated structure is the primary reason for this progressive reduction in hardness, a well-documented principle in baking science where higher specific volume correlates with softer texture (Tang & Ghosh, 2021). Springiness increased significantly at 80% and 100% substitution levels, which can be attributed to the elastic nature of the SFW crystal network, a phenomenon also noted by Wettlaufer and Flöter (2022).

Chewiness and gumminess decreased with higher oleogel levels, while cohesiveness showed no significant differences.

It is important to contextualize these textural outcomes within the broader literature. Our results are consistent with several studies on wax-based oleogels. For example, Khiabani, Tabibiazar, Roufegarinejad, Hamishehkar and Alizadeh, (2020) and Martínez-Velasco, Trujillo-Ramírez, Bustos-Vázquez and Cervantes-Arista (2024) also found that replacing palm fat with carnauba wax and candelilla wax oleogels, respectively, led to softer textures in cakes. In contrast, Ramadhan et al. (2024) reported that a marine-based oleogel increased hardness in cakes. This discrepancy underscores that functional performance is highly specific to the gelator type, with SFW demonstrating a particular aptitude for creating a desirable, soft, and aerated crumb in bakery applications.

Sensory quality is a critical factor influencing consumers' purchasing decisions. Evaluations are essential when reformulating products to ensure that modified versions are comparable to conventional ones (Schubert et al., 2022).

The performed sensory evaluation that included appearance, texture, taste, flavor, color, and overall acceptability revealed no statistically significant differences among cupcakes prepared with SH-BPO, SFW-BO, or their blends (Table 7). All attributes received consistently high scores (7.0 to 8.5), demonstrating that full replacement did not negatively influence sensory perception. These positive outcomes are critical for consumer adoption. This aligns with findings by Yılmaz and Öğütcü (2015) for cookies and Baştürk, Badem and Ceylan, (2023) for cakes, confirming that well-structured oleogels do not impart negative sensory characteristics. The high OBC of SFW-BO prevented any waxy or greasy mouthfeel, and the purification process ensured a neutral flavor profile. Furthermore, De-mirkesen and Mert (2019) found that partial substitution of shortening with beeswax-based oleogel in gluten-free cakes maintained high sensory scores.

CONCLUSIONS

This study conclusively demonstrates that sunflower wax-based oleogel (SFW-BO) is a technologically superior and nutritionally advantageous alternative to traditional palm-based shortening. The strategic upcycling of sunflower wax, a by-product refining, into a high-value oleogelator not only provides a solution for waste valorization but also aligns with circular economy principles by creating a sustainable, health-promoting food ingredient. The SFW-BO exhibited exceptional oil-binding capacity and thermal stability, which directly translated to enhanced cupcake quality, including greater specific volume, a softer, more elastic crumb, and a marked reduction in saturated fatty acid content. Significantly, these improvements were achieved without af-fectting sensory acceptability, a key criterion for consumer acceptance. For successful com-mercial translation, future work should prio-ritize scaling up the purification and oleoge-lation processes and conducting comprehen-sive oxidative stability studies to ensure pro-duct quality and shelf-life.

AUTHOR CONTRIBUTIONS

Conceptualization, A.G.A.E. and H.A.R.M.; Methodology, all authors; Investigation, A.G.A.E. and H.A.R.M.; writing-original draft preparation, Writing-review and editing, A.G.A.E., H.A.R.M. and A.A.; Supervision, A.A.

DATA AVAILABILITY STATEMENT

Data contained within the article.

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CONFLICT OF INTEREST

The authors declare no conflict of interest. No funding was received for this study. The authors had full control of the study design, data collection, analyses, interpretation of results, and writing of the manuscript.

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OLEOGEL NA BAZI SUNCOKRETOVOG VOSKA IZ OTPADA PRERADE ULJA KAO ALTERNATIVA MARGARINU U MAFINU

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Sažetak:U ovom istraživanju korišćen je vosak suncokreta, nusproizvod dobijen iz otpada nastalog tokom rafinacije suncokretovog ulja, za pripremu oleogela na bazi suncokretovog ulja (SFW-BO) kako bi se procenio njegov potencijal kao potpune zamene za konvencionalnu namensku mast (šortening) na bazi palminog ulja (SH-BPO) u finim pekarskim proizvodima. Novina ove studije ogleda se u upotrebi voska suncokreta dobijenog direktno iz otpada rafinacije ulja, umesto komercijalnog voska, čime se naglašava održivo korišćenje resursa. Fourier-transformaciona infracrvena (FTIR) spektroskopija potvrdila je efikasnost procesa prečišćavanja u dobijanju voska visokog stepena čistoće. Fizikohemijska karakterizacija pokazala je da 100% SFW-BO poseduje superiornu sposobnost vezivanja ulja (OBC ≈ 99%) i višu tačku topljenja (53,2°C) u poređenju sa SH-BPO (40,10°C). Analiza profila masnih kiselina pokazala je da povećanje udela SFW-BO značajno smanjuje sadržaj zasićenih masnih kiselina sa 50,61% (100% SH-BPO) na 11,15% (100% SFW-BO), uz istovremeno povećanje udela nezasićenih masti. Mafini formulisani sa SFW-BO mešavinama pokazali su povećan specifični volumen i smanjenu tvrdoću, pri čemu je uzorak sa 100% zamenom postigao najveći volumen (1,86 cm^3/g). Analize aktivnosti vode i senzorske evaluacije ukazale su na odsustvo značajnih razlika između mafina sa šorteningom i onih sa oleogelom, što sugeriše uporedivu mikrobiološku stabilnost i prihvatljivost od strane potrošača. Ovi rezultati potvrđuju da oleogel od voska suncokreta dobijenog iz otpada rafinacije predstavlja funkcionalno robusnu i nutritivno povoljniju alternativu konvencionalno korišćenoj namenskoj masnoći, omogućavajući proizvodnju pekarskih proizvoda sa smanjenim sadržajem zasićenih masti bez kompromisa u tehnološkim performansama ili senzorskom kvalitetu.

Ključne reči: *vosak suncokreta, oleogel, šortening, mafinsi, zasićene masne kiseline, otpad uljarske prerade*

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