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*Scientific article*

# Effect of incorporation of candelilla wax oleogel on the structural properties of cake-type bread

Efecto de la incorporación de oleogel de cera de candelilla sobre las propiedades estructurales de pan tipo panqué

**Gilda Avendaño-Vásquez[1], Bryan Ochoa-Martínez[2], Karen Aylin Vargas-García[2], Juan René González-Romero[2], Miguel Angel García-Muñoz[3], Elizabeth del Carmen Varela-Santos[2*]**

[1]SECIHTI -TecNM/ITS de Tierra Blanca. Maestría en Ciencias en Alimentos y Biotecnología. Av. Veracruz s/n, 95180 Tierra Blanca, Veracruz, Mexico.
[2] TecNM/ITS de Tierra Blanca. Maestría en Ciencias en Alimentos y Biotecnologia. Av. Veracruz s/n, 95180 Tierra Blanca, Veracruz, Mexico.
[3] Centro de Investigaciones Científicas, Instituto de Biotecnología, Universidad del Papaloapan, Tuxtepec, Oaxaca, México

*Correspondencia: Correo electrónico: e.varela@itstb.edu.mx (Elizabeth del Carmen Varela-Santos)
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## Abstract

The negative health effects associated with foods containing saturated and *trans* fats have prompted the search for healthier alternatives that preserve both sensory and technological quality. This study evaluated the use of candelilla wax-structured oleogels as substitutes for hydrogenated fats in cake-type bread, with emphasis on batter structure and crumb texture. The iodine value of the edible oils and the one with the most favorable unsaturation profile was selected to formulate the oleogel used and the oil and water adsorption capacity of three selected flours were determined. Among them, flour H2 exhibited consistent oil adsorption across the three types of oil tested, with no significant differences compared to the water control, suggesting a more stable interaction with lipid components. Therefore, it was used for cake-type bread. Formulations were assessed for batter density, baking yield, total porosity, mean pore size, and instrumental texture parameters (hardness, cohesiveness, elasticity, adhesiveness, stickiness, and chewiness). Oleogel-based batters showed higher density (0.90 g/cm³) and lower baking yield (13 %), indicating a more compact structure. No significant differences were observed in total porosity (≈ 0.3–0.8 %) or mean pore size (8.4–17.5 mm) compared to those made with shortening. However, the presence of smaller (≈ 8.4 mm) and more uniform pores in oleogel formulations reinforced the internal crumb structure and reduced susceptibility to deformation, thereby preserving mechanical integrity. Regarding texture, oleogel formulations exhibited a more cohesive and elastic crumb, supporting their use as a functional alternative in baked goods.

*Keywords*: **oleogel, hydrogenated fat, cake-like bread, functional properties, technological quality.**

## Resumen

Los efectos negativos de alimentos que contienen grasas saturadas y *trans* demandan la búsqueda de alternativas saludables que conserven calidad sensorial y tecnológica. El uso de oleogeles estructurados con cera de candelilla como sustituto de grasas hidrogenadas en pan tipo panqué con énfasis en las propiedades estructurales fue estudiado. Se determinó el índice de yodo en los aceites comestibles, eligiendo el de mejor perfil de insaturación para formular el oleogel y la capacidad de adsorción de aceite y agua en tres harinas seleccionadas. Para las formulaciones se evaluó la densidad de la masa, rendimiento de horneado, calidad de miga (distribución y tamaño de poro) y textura instrumental (dureza, cohesión, elasticidad, adhesividad, pegajosidad y masticabilidad). La harina H2 mostró un comportamiento de adsorción de aceite constante entre los tres tipos de aceite evaluados, sin diferencias significativas respecto al control con agua, lo que sugiere una interacción más estable con componentes lipídicos relevantes. Por lo que se seleccionó para el pan tipo panqué. Las formulaciones con oleogel exhibieron mayor densidad de masa (0,90 g/cm$^3$) y menor rendimiento de horneado (13 %). No se observó diferencia significativa en la porosidad total (≈ 0,3–0,8 %) y el tamaño medio de poro (8,4–17,5 mm) en comparación con la de manteca. Adicionalmente, los poros más pequeños (≈ 8,4 mm) y uniformes observados en las formulaciones con oleogel, en comparación con los poros más grandes (≈ 17,5 mm) en las formulaciones con manteca, reforzaron la estructura interna y redujeron la susceptibilidad a la deformación, preservando la integridad mecánica. En cuanto a la textura, se observó una miga más cohesiva y elástica en las formulaciones con oleogel, lo que respalda su uso como alternativa funcional en panificación.

*Palabras clave*: **oleogel, grasa hidrogenada, pan tipo pastel, propiedades funcionales, calidad tecnológica.**

## 1. Introduction

Flour, raising agents, fats, and oils are the key functional components in baking, as variations in these ingredients can significantly affect texture and flavor (Raghavendra et al., 2022). Wheat flour typically consists of approximately 72 % carbohydrates, 8–13 % protein, 12–13 % moisture, 2.5 % sugar, 1.5 % fat, 1.0 % soluble protein, and 0.5 % mineral salts (Sunil et al., 2019). Its functionality depends on the milling characteristics; for example, soft wheat is used in cakes, pastries, cookies, crackers, and oriental noodles, while durum wheat is used in breads (Chandra and Samsher, 2013).

Vegetable shortenings are solid fats at room temperature, manufactured through the hydrogenation of oils such as soybean, corn, palm, or cottonseed. The hydrogenation process increases fat content to nearly 100 % and eliminates cholesterol, improving product stability and handling in industrial applications (Raghavendra et al., 2022). The use of vegetable fat instead of butter in the formulation of the dough prevents the formation of a compact and rigid crumb structure, as well as the greater development of gluten strands, which affects the softness and elasticity of the bread (Buehler, 2021). This inhibition results in a lighter, spongier dough, although with reduced flavor. The presence of emulsifiers in vegetable fats helps stabilize nitrogen-filled gas bubbles, dissolve the fat particles, improve air incorporation, and enhance overall texture (Zou et al., 2022). However, vegetal fats also contain *trans* fatty acids, which have been linked to increased cardiovascular risk (Raghavendra et al., 2022). Therefore, replacing solid fats with edible oleogels composed of unsaturated vegetable oils has gained traction.

Structuring of vegetable oils into edible oleogels is a promising approach to reduce *trans* and saturated fat intake. Oleogels are semi-solid materials obtained by incorporating liquid vegetable oils into a structured network formed by gelling agents (Quiles Chuliá et al., 2022). Natural waxes, such as candelilla wax, beeswax, and carnauba wax, act by creating crystalline networks or three-dimensional structures that physically immobilize lipids, thereby conferring a consistency similar to that of solid fats on oils (Patel et al., 2014). Candelilla wax is particularly noteworthy due to its low cost, plant-based origin, high melting point, and excellent compatibility with edible oils, making it an ideal candidate for food applications. This structuring capability enables the development of healthier lipid matrices with reduced levels of trans and saturated fatty acids, without compromising desirable technological properties such as plasticity, aeration, and stability of the final product (Oh and Lee, 2018).

In baking, oleogels can replace solid fats like margarine and butter in breads, pastries, and cookies. However, their lower viscosity compared to shortenings may hinder air incorporation, reduce dough firmness, and increase density (Patel et al., 2014). Oleogels also tend to form larger, unevenly distributed air cells (Oh and Lee, 2018), a phenomenon associated with the flour's oil absorption capacity and its structural role in dough formation. While liquid oils are often preferred by health-conscious consumers, their direct use in cake-type formulations presents technological challenges. Due to their fluid nature and lack of plasticity, liquid oils are unable to retain air effectively during mixing, which compromises batter aeration, crumb structure, and overall texture. In contrast, oleogels offer a semi-solid matrix that mimics the functionality of traditional fats, enabling better air retention, improved pore distribution, and enhanced mechanical integrity. This makes oleogels a more suitable alternative than liquid oils in baked goods where structural performance is critical (Puscas et al., 2020).

Functional properties are primarily physicochemical interactions between food composition, structure, and molecular conformation. These interactions influence measurable attributes such a solubility, water retention, foaming capacity, elasticity, and absorption capacity of fats and foreign bodies. The typical functional properties include emulsification, hydration (water binding), viscosity, foaming, solubility, gelation, cohesion, and adhesion (Okaka and Potter, 1977; Sunil et al., 2019). Oil absorption capacity (OAC) is an important functional property of foods, particularly pulse flours and proteins. This property influences flavor, texture, mouthfeel, and overall product performance (Seena and Sridhar, 2005). This capacity is primarily due to the physical entrapment of oil within proteins, as well as non-covalent interactions such as hydrophobic, electrostatic, and hydrogen bonding that occur between lipids and proteins (Farooq and Boye, 2011). Additionally, oil absorption is linked to the binding of nonpolar amino acid side chains in proteins to the hydrocarbon chains of the oil (Lin et al., 1974).

OAC also contributes to improving the mouthfeel and maintaining the flavor of food products (Iwe et al., 2016). High-protein foods exhibit a considerably high oil absorption rate, which enhances their performance in various applications. The oil absorption capacity depends on intrinsic factors such as protein conformation, amino acid composition, and the polarity or hydrophobicity of the protein surface (Chandra and Samsher, 2013). Due to these characteristics, flours with good OAC are especially useful in the production of products such as pastries, sausages, and other foods where optimal oil absorption is desired, thus improving texture and flavor (Chandra and Samsher, 2013). These properties make flours with high oil absorption capacity valuable functional ingredients in products such as sausages, whipped toppings, cakes, pies, and desserts (Awuchi et al., 2019).

Porosity, defined as the distribution and size of air cells within the crumb, is a critical structural parameter in cake-type products. This characteristic directly influences the texture, softness, and sensory perception of the final product. The substitution of traditional fats with oleogels may impact this parameter, as the ability to incorporate and retain air during mixing is altered, which consequently affects bubble formation and stability during baking (Oh and Lee, 2018). Therefore, it is essential to assess how these substitutions modify the internal structure of the product and whether they compromise its consumer acceptability.

Additionally, Giacomozzi et al. (2018) reported that substituting commercial margarine with oleogels in muffins improved spreadability, increased specific volume, maintained comparable hardness, and yielded a more connected and homogeneous crumb structure. Oleogels based on stearoyl lactylate have been shown to mimic the crystalline network functionality of triacylglycerols in bread matrices Meng et al. (2018), while ethylcellulose oleogels have produced breads with stable soft textures Jung et al. (2020). These studies focused on synthetic emulsifiers or imported structuring agents that are renewable. This research explores plant-based materials native to the arid regions of Mexico and evaluates their potential to replace conventional fats commonly used in regional bakery formulation.

Despite increasing interest in oleogels as fat substitutes, limited research has focused on their effect on the structural properties of cake-type bread, particularly when formulated with candelilla wax and corn oil or popular commercial oils. Although numerous studies have explored the role of oleogels in improving the nutritional profile of baked goods, few have considered the influence of flour’s oil absorption capacity in optimizing crumb structure and porosity. This parameter, often overlooked, may significantly affect the interaction between lipid systems and the starch–protein matrix, especially under real-world baking conditions.The objective of this study was to evaluate the effect of using candelilla wax-structured corn oil oleogels as a substitute for hydrogenated fats in cake-type bread, focusing on the structural properties as well as the relevant applications in the baking industry, where controlling the quantity and type of fats can be key to the mass production of breads with specific properties.

# 2. Materials and methods

## 2.1 Raw material

Shortening INCA (ACH Foods México, S. de RL de CV), edible corn vegetable oil PATRONA (Industrial Patrona SA de CV), canola CAPULLO (ACH Foods México, S. de RL de CV), soy

NUTRIOLI (Ragasa Industrias, SA de CV), as well as candelilla wax (CC) (Alkento Ingredientes, Monterrey - NL, Mexico), were purchased from local stores, and corn oleogel, the formulation of which will be described in the following section. All-purpose wheat flour in three trademarks: Chedraui® Quality (H1), San Blas (La Italiana Industrial Group) (H2), and San Antonio (Harinera los Pirineos, SA de CV) (H3).

## 2.2 Determination of iodine value in edible oils

The Iodine Value of three edible vegetable oils and hydrogenated shortening (SH) was determined using the Wijs method, according to the Official AOAC Method 920.158. Approximately 0.3 g of each oil sample was accurately weighed and transferred to a 250 mL iodine flask. Then, 25 mL of Wijs reagent (iodine monochloride in glacial acetic acid) was added, and the flask was sealed and kept in the dark at room temperature for 30 minutes to allow the reaction to proceed.

Following the incubation period, 20 mL of potassium iodide solution (10 %) and 100 mL of distilled water were added. The liberated iodine was titrated with standardized 0.1 N sodium thiosulfate solution using starch as an indicator. A blank determination was performed under identical conditions.

The iodine value was calculated based on the volume of titrant consumed and expressed as grams of iodine absorbed per 100 g of oil sample. All reagents used were analytical grade. The sodium thiosulfate solution was calibrated daily against a potassium dichromate primary standard, and all measurements were performed in triplicate to ensure analytical reliability.

## 2.3 Determination of the water and oil adsorption index in all-purpose flour

It was determined by the method proposed by Beuchat, 1977, weighing 1 g of the sample with 10 mL of distilled water or oil in 50 mL centrifuge tubes, then the tubes were centrifuged at 5000 rpm for 30 min. The volume of the decanted supernatant was measured, and the milliliters of water or oil absorbed were calculated according to Eq. (1).

$$\mathrm{OAC} = (\text{Gel weight (g)}/\text{Sample weight (g)}) \qquad \textbf{Eq. 1}$$

## 2.4 Oleogel formulation

The oleogel (OM) was made with edible vegetable oil from PATRONA corn (Industrial Patrona SA de CV) and 5 % w/w of precipitated CC and was brought to a temperature of 68-72 °C with stirring at 350 rpm until the wax was completely dispersed in the oil according to Demirkesen and Mert, (2020)., stored for 24 h ±4 °C, covered with aluminum foil to promote complete crystallization for later use in bread making.

## 2.5 Preparing cake bread

The cakes were prepared according to the methodology of Álvarez-Ramírez et al. (2020), which includes flour, sugar, fat (shortening or corn oleogel), whole milk, egg, and chemical reagents purchased from the local market for the present study. The ingredients were weighed and added sequentially to the mixer (Oster®, model FPSTHS3611, 6 speeds, 250 watts of power, and 3.7 L capacity), beaten for 1 minute at speed 4 and 9 minutes at speed 6. Once the batter was obtained, 60 g of batter was placed in reusable aluminum molds and baked at 190 °C for 30 min. The resulting cakes were left to cool at room temperature and then placed in high-domed plastic containers for preservation during the study period.

## 2.6 Determination of cake dough density and baking yield

Cake batter density was calculated as the ratio between the weight of the batter and the weight of the equivalent volume of distilled water, following the method of (Vázquez and Hernández, 2023). To determine this, 60 g of cake batter was weighed in a previously calibrated container and compared to the weight of an equal volume of distilled water at room temperature. The density was calculated using Eq. 2:

$$\text{Density } (\text{g/cm}^3) = \text{Weight of batter / Weight of same volume of water} \quad \textbf{Eq. (2)}$$

Baking yield was assessed gravimetrically by weight loss in cakes immediately after baking and again after 24 hours of cooling at room temperature according to Anjali et al. (2023) and calculated using Eq. (3):

$$\text{Baking yield } (\%) = [(\text{Initial weight} - \text{Final weight}) / \text{Initial weight}] \times 100 \quad \textbf{Eq. (3)}$$

## 2.7 Determination of bread porosity

The cake-like bread formulated with corn oleogel was sliced vertically as shown in Fig. 1 to a dimension of 15 mm. The porosity of the bread was determined by image processing. An L5190 scanner (Epson America, Inc.) and the ImageJ 1.54g image processor (National Institute of Health, USA) were used, following the proposal by Petrusha et al. (2017).

**Figure 1**. Vertical cut of the cake-like bread piece performed to expose the internal crumb for porosity analysis. The sectioning was carried out along the central axis to ensure representative sampling of air cell distribution.
**Figura 1.** Corte vertical de una porción de pan tipo panqué para exponer la miga interna y analizar su porosidad. El corte se realizó a lo largo del eje central para garantizar una muestra representativa de la distribución de las burbujas de aire.

## 2.8 Texture analysis

Texture analysis was performed using a CT3 texture analyzer (Brookfield, Middleboro, MA 02346, USA), following the methodology reported by García-Ortega et al. (2021). A cylindrical probe with a diameter of 75 mm was used, operating at a constant test speed of 1.5 mm/s and applying a 10 % compression to the sample. Before the analysis, each experimental unit was conditioned by a uniform horizontal cut, completely removing the crust to expose the inner crumb. To standardize the measurements, all samples were prepared to a height of 2 cm. Stickiness and chewiness values were obtained using Equations 4 and 5, respectively, based on the data collected by the equipment (adhesiveness, hardness, cohesiveness, elasticity). Additionally, the specific volume was calculated as the inverse of dough density (1/ϱ),

$$\text{Stickiness} = \text{Hardness} \times \text{Cohesiveness} \quad \textbf{Eq. (4)}$$

$$\text{Chewiness} = \text{Hardness} \times \text{Cohesiveness} \times \text{Elasticity} \quad \textbf{Eq. (5)}$$

## 2.9 Statistical analysis

The data obtained from the various experiments were recorded during the study and subjected to statistical analysis using the ANOVA method. Significant differences between means were tested against the critical difference at the 5 % significance level using Statistica software (StatSoft, 2011) version 10.

# 3. Results and discussion

## 3.1 Characterization of the raw material

The iodine index values are shown in Table 1, with corn oil exhibiting the highest level of polyunsaturated fatty acids. As an indirect measure of the number of double bonds in fatty acids, it reflects the degree of unsaturation, primarily oleic and linoleic acids. Consequently, corn oil exhibits lower oxidative stability (Sanders, 2003), consistent with its elevated iodine index. This outcome may also be attributed to the extraction method, specifically pressing and refining, which helps preserve the nutritional properties of the oil.

Such characteristics make corn oil a suitable candidate for partial hydrogenation, as evidenced by the decreased iodine value following this process (Table 1). However, it is well documented that partial hydrogenation promotes the formation of *trans* fatty acids (Thirumdas, 2023), raising nutritional concerns.

Overall, the elevated iodine value in corn oil aligns with its higher unsaturation level and matches the broader trends observed among the evaluated oils. In general, oils with higher iodine values contain greater proportions of highly unsaturated fatty acids, which are more susceptible to degradation reactions such as autoxidation and polymerization. These reactions are accelerated during baking due to the high temperature and exposure to dissolved oxygen. Therefore, from a technological perspective, fats and oils with lower iodine values are often preferred in baking applications to improve oxidative stability and reduce the risk of quality deterioration.

**Table 1.** Average iodine index values of the oils evaluated in this study, determined to characterize the degree of unsaturation and support the selection of lipid sources for formulation purposes.
**Tabla 1.** Valores promedio del índice de yodo de los aceites evaluados en este estudio, determinados para caracterizar el grado de insaturación y respaldar la selección de fuentes lipídicas con fines de formulación.

| **Sample** | **Iodine Index (g $I_2$/100g oil)*** | **Tiefenbacher, 2017; Pavlovich-Abril *et al.* (2009)†** |
|---|---|---|
| Soy | 128.79 ± 9.3 | 124-139 |
| Corn | 158.84 ± 5.7 | 107-135 |
| Canola | 112.03 ± 5.7 | 105-125 |
| SH | 47.95 ± 2.45 | 43 |

SH: Shortening.
* Mean ± standard deviation, n=3.

### 3.1.1 Study of water and oil adsorption in all-purpose flours

Fig. 2 shows that the water adsorption behavior across the three commercial wheat flours did not differ significantly, indicating similar structural and compositional characteristics likely due to their shared origin. Moreover, no significant difference was observed in the adsorption capacity of soybean and canola oils regardless of the flour evaluated. In contrast, flour H3 exhibited the highest oil adsorption capacity to corn oil, followed by H1 and H2.

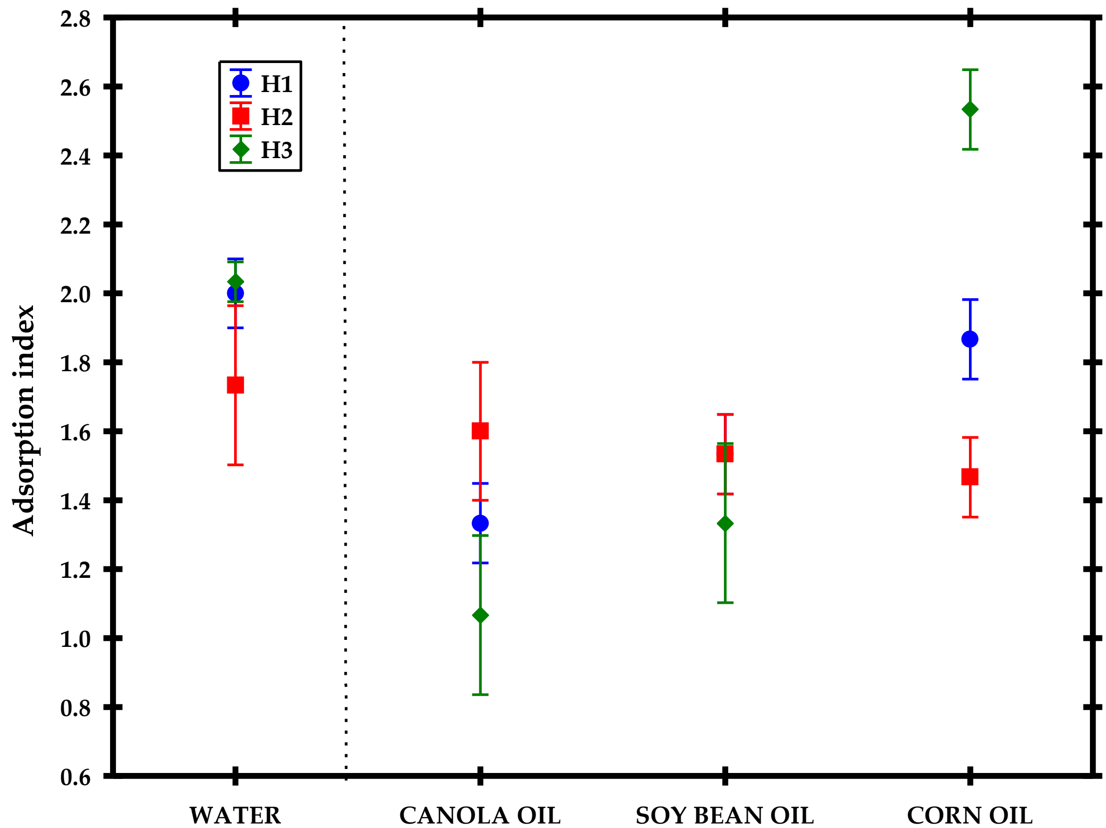



**Figure 2.** Water and oil adsorption index of three brands of all-purpose flour (H1, H2, H3) using corn, soybean, and canola oils, as well as water. Blue circles, red squares, and green diamonds represent flour brands H1, H2, and H3, respectively. Error bars indicate standard deviation. Differences in adsorption behavior reflect the interaction between flour composition and liquid type.
**Figura 2.** Índice de adsorción de agua y aceite de tres marcas de harina para todo uso (H1, H2, H3) utilizando aceites de maíz, soja y canola, así como agua. Los círculos azules, los cuadrados rojos y los rombos verdes representan las marcas de harina H1, H2 y H3, respectivamente. Las barras de error indican la desviación estándar. Las diferencias en el comportamiento de adsorción reflejan la interacción entre la composición de la harina y el tipo de líquido.

In addition, oil absorption index (OAC) has been attributed to the physical entrapment of oil within proteins and non-covalent interactions (Tabara et al., 2015). A preliminary reference obtained a single Kjeldahl determination (AOAC 992.23) to guide the selection of the most appropriate flour for cake-type bread formulation. Results showed that H3 had higher protein content (9.53 %) in comparison with than H2: (7.02 %) and H1 (6.65 %), which helps explain the corn oil adsorption mechanism taking in account that the ability of the proteins to bind oil makes these flours worthwhile in food systems where optimal oil absorption is desired (Chandra and Samsher, 2013).

However, although H3 flour showed the highest protein content and the highest oil adsorption capacity with corn oil, this does not guarantee the stability of cake-type breads, since its inclusion could generate an undesirable waxy or greasy flavor profile due to the high interaction with oleogels, compromising their sensory acceptability (Yılmaz and Öğütcü, 2015). In contrast, H2 flour showed greater stability and/or the best oil adsorption profile regardless of the oil evaluated. This stability favors better interaction with lipid matrices, including oleogels and hydrogenated fats, which could improve the crumb texture, mouthfeel, and sensory quality of the product; therefore, it was selected for subsequent cake-type bread formulation trials.

## 3.2 Effect of oil adsorption on the porosity of cake-type bread.

Considering that fats and oils influence the texture and softness of cakes by tenderizing the crumb, lubricating the dough during mixing, and providing a moist mouthfeel, the density of the batter plays a key role in evaluating baking performance and gas retention capacity (Rathnayake et al., 2018). Table 2 presents the density of cake dough (ϱ) formulated with oleogel matrix (OM) and shortening (SH), as described in section 2.6. OM-based batters exhibit higher density, indicating reduced air incorporation and thus lower aeration potential compared to SH. It was incorporated when using oleogel, and thus has a lower aeration capacity compared to SH. This also correlated with the lower oven loss observed in OM samples. Similar behavior was evidenced by (Vázquez and Hernández, 2023), who obtained similar results comparing breads made from margarines and oil/margarine mixtures.

**Table 2.** Density and oven yield of cake doughs formulated with different fats, highlighting the influence of lipid type on physical performance during baking.
**Tabla 2.** Densidad y rendimiento en horno de las masas tipo pastel formuladas con diferentes grasas, destacando la influencia del tipo de lípido en el desempeño físico durante el horneado.

| Sample | Density (ϱ, g/cm$^3$)* | % Baking yield * |
|---|---|---|
| OM | 0.90 ± 0.01a | 13 ± 5.15a |
| SH | 0.75 ± 0.01b | 38 ± 4.30b |

*Mean ± standard deviation, n=3. In the case of batter density, replicates yielded highly consistent results, with minimal variation observed.
Different letters in the same column are significantly different ($p < 0.05$).

Additionally, the percentage of weight loss was higher in SH doughs than in those formulated with OM, indicating that a greater amount of air was retained in the dough during baking in the presence of SH. This is supported by the visual comparison in Fig. 3, which reveals the formation of larger pores in OM samples compared to those observed in SH formulations. This phenomenon is attributed to the oleogels composition, as it is a material formed mostly by oil. During creaming, air bubbles are dispersed into the fat phase and are stabilized by fat crystals, meaning that the composition and properties of the fat directly affect the aeration. Consequently, OM tends to produce doughs with a higher proportion of open pores, while SH promotes the formation of closed pores that accelerate moisture transport, ultimately leading to a loss of crispy texture in the final product (Esveld et al., 2012).

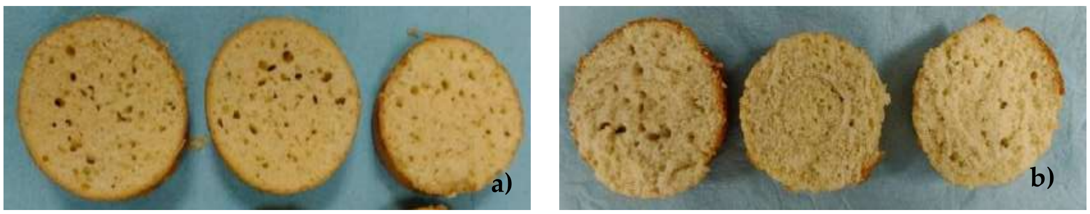
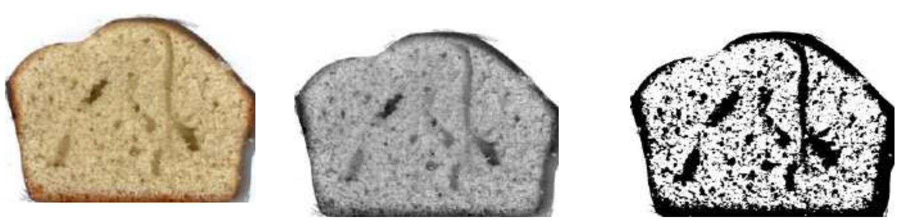



**Figure 3.** Comparative visual assessment of cake-type bread samples from treatments a) OM and b) SH, highlighting differences in crumb structure and surface characteristics to evaluate the impact of lipid source on product morphology.
**Figura 3.** Evaluación visual comparativa de muestras de pan tipo panqué de los tratamientos a) OM y b) SH, en la que se destacan las diferencias en la estructura de la miga y en las características de la superficie para evaluar el impacto de la fuente de lípidos en la morfología del producto.

Nonetheless, doughs produced with oleogels were less plastic and more difficult to handle and shape than those produced with shortenings. This defect was associated with the consistency loss suffered by oleogels during shearing during mixing (Mert and Demirkesen, 2016). Moreover, there are currently no available fat substitutes for *trans* and saturated fats that replicate the plasticity required for the formulation of margarines and spreads (Patel et al., 2020). The effect of replacing SH with OM on aeration was investigated in terms of porosity, as observed in Fig. 4 for cakes formulated with SH.



**a)** **b)** **c)**

**Figure 4.** Determination of porosity by image analysis in SH: a) original imag; b) 16-bit grayscale image; c) binarized image with percentages associated with porosity.
**Figura 4**. Determinación de la porosidad mediante análisis de imágenes en SH: a) imagen original; b) imagen en escala de grises de 16 bits; c) imagen binaria con porcentajes asociados a la porosidad.

Fig. 5A displays the results of the porosity analysis using image processing, where average values of 0.29 ± 0.25 % for corn oleogel (OM) and 0.79 ± 0.27 % were obtained for the formulation with shortening (SH). Despite this numerical difference, no statistically significant differences were observed between treatments, indicating that the higher batter density in the OM formulation did not significantly affect the overall porosity of the final baked product. The relatively high standard deviations reflect the inherent variability of the samples and the sensitivity of the image-based quantification method. This same trend was observed in the analysis of average pore size (Fig. 5B), where products with OM exhibited smaller and more irregular cells compared to those obtained with SH.

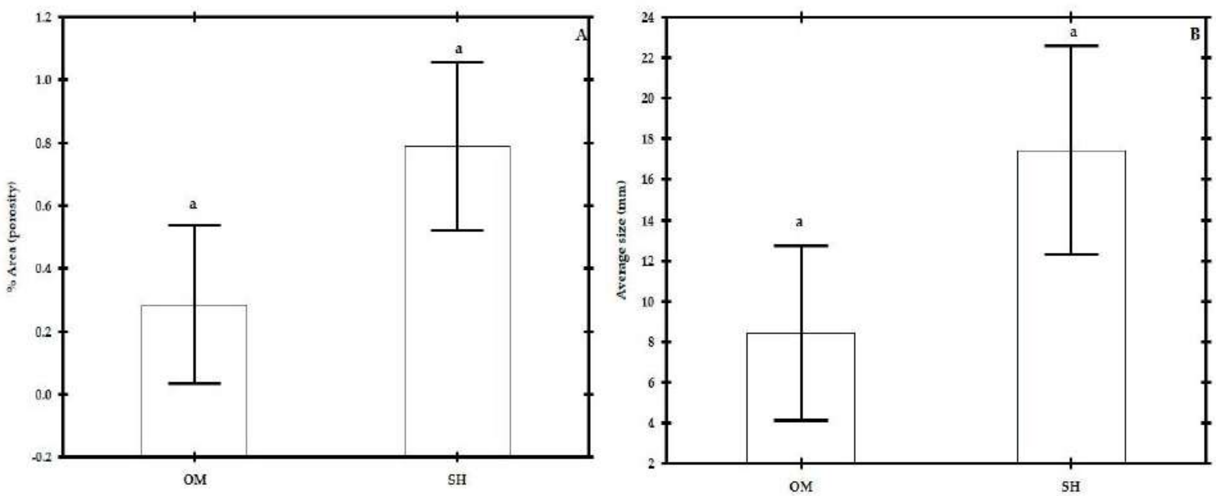



**Figure 5.** Crumb structure analysis through image processing. (A) Total porosity (%) calculated from binarized cross-sectional images. (B) Average pore size (mm) calculated from segmented pore regions. Values expressed as mean ± standard deviation (n = 3).
**Figura 5.** Análisis de la estructura de las migas mediante procesamiento de imágenes. (A) Porosidad total (%) calculada a partir de imágenes transversales binarias. (B) Tamaño medio de los poros (mm) calculado a partir de las regiones porosas segmentadas. Valores expresados como media ± desviación estándar (n = 3).

According to Rathnayake *et al*. (2018), an ideal crumb structure in bakery products is characterized by high porosity and a uniform distribution of fine gas cells. In this sense, the replacement of SH with oleogel could not fully replicate this structure, likely due to the increased batter density associated with the oil adsorption capacity of the OM system. Although the average pore size was 8.43 ± 4.30 mm for OM and 17.45 ± 5.15 mm for SH, this does not necessarily imply a structural advantage of the SH treatment. As noted by Kim et al. (2017), the presence of larger air cells may lead to a less cohesive crumb prone to crumbling, which affects the physical integrity and the characteristic shape of the product. Therefore, although OM formulations had lower overall porosity, the pores formed tended to be smaller and more open, which may contribute to a more stable crumb structure and improved resistance to collapse, offering potential benefits in terms of texture and shelf life.

The replacement of SH with oleogel does not replicate an ideal crumb structure in bakery products characterized by high porosity and a uniform distribution of fine gas cells (Rathnayake et al. 2018), likely due to the highest batter density of the OM system. As noted by Kim et al. (2017), the presence of larger air cells may lead to a less cohesive crumb prone to crumbling, which affects the physical integrity and the characteristic shape of the product. Although the average pore size and overall porosity values for OM were lower than those for SH treatment, the pores formed tended to be smaller and more open, which may contribute to a more stable crumb structure and improved resistance to collapse, offering potential benefits in terms of texture. The methodology presented offers a practical framework for scaling healthier lipid matrices in industrial bakery applications. This study offers a methodological framework for selecting flours based on oil adsorption capacity to stabilize oleogel incorporation, an approach rarely considered in cake-type formulations. The potential benefits of this methodology are promising and could lead to significant improvements in bakery product development.

## 3.3 Study of textural attributes

The complete substitution of shortening with oleogel is related to the porosity normally proven by solid fats (Kim et al., 2024). As shown in Table 3, the OM treatment exhibited significantly higher hardness, stickiness, and chewiness values compared to SH ($p < 0.05$), suggesting a firmer and more compact structure on the cakes.

**Table 3.** Instrumental texture parameters (hardness, cohesiveness, elasticity, adhesiveness, stickiness, and chewiness) of bread samples formulated under treatments SH and OM.
**Tabla 3.** Parámetros de textura instrumentales (dureza, cohesión, elasticidad, adhesividad, pegajosidad y masticabilidad) de muestras de pan formuladas con los tratamientos SH y OM.

| Treatment | Especific Volume ($cm^3/g$) | Hardness (N) | Cohesiveness | Elasticity (mm) | Adhesiveness (mJ) | Stickiness (N) | Chewiness (N) |
|---|---|---|---|---|---|---|---|
| **SH** | 1.11±0.01a | 4.3±0.67a | 0.7±0.07a | 8.4±0.81a | 0.2±0.03a | 3.2±0.62a | 26.9±7.15a |
| **OM** | 1.33±0.01b | 8.0±0.80b | 0.7±0.03a | 8.9±0.15a | 0.04±0.01b | 5.9±0.38b | 52.6±2.54b |

Results are expressed as mean ± standard deviation. Letters indicate significant differences between treatments for each parameter ($p < 0.05$).

These mechanical properties align with the reduced porosity and smaller pore size seen in Fig. 5, suggesting that a denser microstructure leads to a crumb that requires more chewing due to its stickiness and tends to stick to the palate. However, it is more resistant to fracture than formulations containing SH. Similarly, the specific volume correlates with hardness, where hardness increases as the specific volume decreases; in other words, larger pore size is linked to lower hardness and greater susceptibility to fracture (Alvarez-Ramirez et al., 2020). These studies support the hypothesis that pore size and distribution directly influence mechanical integrity, as smaller and more uniform pores may reinforce the internal structure and reduce susceptibility to deformation. The instrumental texture analysis in this study thus complements the morphological findings. It reinforces the interpretation regarding the mechanical resilience of OM, positioning pore architecture as a critical parameter in functional bread design.

While pore architecture emerges as a key determinant of mechanical resilience, it is important to consider upstream factors that influence its development. One such factor is the oil absorption capacity of the flour, which modulates the distribution and integration of oleogels within the dough matrix. This property may affect air retention and lipid–starch interactions during mixing and baking, ultimately shaping the microstructure observed in Fig. 5. Although often overlooked, this flour characteristic could explain the differences in crumb density and porosity between formulations.

The correlation between porosity and texture parameters observed in this study reinforces the interpretation of crumb density and air retention. Specifically, formulations with smaller and more uniform pores, as shown in Fig. 5, exhibited higher hardness and lower specific volume, indicating reduced air incorporation and a denser microstructure. These morphological traits are consistent with the instrumental texture results, where increased hardness and adhesiveness suggest a compact crumb with limited expansion. Thus, both analyses morphological and mechanical, converge to support the conclusion that oleogel incorporation, modulated by flour lipid interactions, affects the aeration capacity and structural integrity of cake-type bread. This integrative approach strengthens the reliability of our findings and highlights the importance of considering porosity and texture jointly when evaluating fat substitution strategies.

## 4. Conclusions

The results of this study show that corn oil oleogels structured with candelilla wax can effectively replace hydrogenated fats in cake-type bread recipes without losing key structural properties. The formulations with oleogels had higher batter density and less baking yield, while still maintaining acceptable porosity and producing a finer, more cohesive crumb. Although oleogels created smaller and less uniform pores compared to shortening, their use did not significantly impact the overall aeration or stability of the final product. These findings support the practical use of oleogels as alternatives in baked goods with high content of saturated fat, where the control of pore size can be to improve mechanical stability in functional bread formulations.

## Authors' contributions

Methodology, M.A.G.M.; Software, J.R.G.R.; Research, K.A.V.G.; Data curation, B.O.M.; Writing-original draft, G.A.V.; Writing-review and editing, E.C.V.S. All authors have read and agreed to the published version of the manuscript.

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## Conflict of interest

The authors declare that they have no conflicts of interest, nor any economic, personal, political, financial, or academic relationships that could influence their judgment. We also declare that we have not received any monetary benefits, property, or grants from any source that might have an interest in the results of this research.

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