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ORIGINAL PAPER

Bigel-based low-fat sponge cake production for palm oil replacement

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Abstract

The development of healthier and sustainable fat replacers in bakery products has become a priority due to health concerns and environmental issues associated with palm oil. To the best of our knowledge, this is the first work to demonstrate the synergistic functionality of soy wax, beeswax, and citrus fiber in a bigel system intended for fat replacement in bakery products. In this study, food-grade bigels were formulated by combining oleogels structured with soy wax and beeswax (3%, 5%, 7%, and 10%) with 5% citrus fiber hydrogels at two phase ratios (40:60 and 60:40, oleogel:hydrogel). The rheological, textural, thermal, microstructural, and centrifugal stability properties of these bigels were systematically characterized and compared with palm oil. Rheological analyses revealed that all bigels exhibited solid-like behavior (G'>G"), with (10BW OG)60-HG40 showing the highest mechanical strength and thermal stability up to 60 °C. Thixotropy tests demonstrated excellent structural recovery in (10BW OG)60-HG40, making it suitable for high-shear processes like batter mixing. Texture profile analysis showed that (10BW OG)60-HG40 and (10BW OG)40-HG60 had the highest hardness among gels, yet (10BW OG)60-HG40 yielded the softest sponge cake, indicating improved aeration and moisture retention. Color analysis indicated brighter crumb and crust in bigel-incorporated cakes, attributed to the high water content and reduced Maillard browning. Microscopy revealed that the highest wax-containing bigels formed dense crystalline networks, correlating with superior rheological and stability characteristics. Among all formulations, (10BW OG)60-HG40 and (3SW:7BW OG)40-HG60 stood out as the most promising palm oil replacers, offering a balance between structural integrity and thermal resistance. This study provides a novel fat replacement strategy by combining soy wax, beeswax, and citrus fiber, and demonstrates its practical functionality in low-fat sponge cake applications.

Keywords Beeswax · Bigel · Citrus fiber · Oleogel · Palm oil replacer · Soy wax

Introduction

Palm oil is an almost unrivaled vegetable oil for the food industry, especially in baked goods, due to its oxidative stability, plasticity, and cost-effectiveness [1, 2]. However, due to its high saturated fat content (palmitic acid) and the environmental implications of its production (particularly deforestation and biodiversity loss), palm oil has been increasingly re-evaluated, prompting a demand for alternative lipid sources [2]. In addition, the consumption of high-fat foods, combined with urbanization and sedentary lifestyles, has sharply increased the risk of obesity, type 2 diabetes, and chronic heart disease. This is driving consumers to turn to foods that are low in fat and free of saturated and trans fats [3].

Today, there are limited methods available to provide consumers with food options that are free from saturated

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and trans fats while maintaining the structural and sensory properties typically offered by solid fats. Recent studies aimed at addressing this issue have focused on the use of bigels (also known as hybrid gels), which are formed by combining an oleogel and a hydrogel under high shear conditions [4]. In the formation of bigels, a physically stabilized hydrophilic phase (hydrogel) is combined with a stabilized lipophilic phase (oleogel). As a result, bigels possess both hydrophilic and hydrophobic characteristics. They serve as effective carriers for both hydrophilic and lipophilic bioactive compounds [5]. Moreover, due to the hydrogel component in their structure, bigels typically have a lower total fat content compared to traditional solid fats and even oleogels, making them a promising option for reduced-calorie food formulations [6, 7]. Since both phases are in stable form, they show higher thermodynamic and kinetic stability compared to oleogels, hydrogels, emulgels, or emulsions alone. This makes bigels advantageous over oleogels, hydrogels, emulgels, and emulsions alone [5].

Although various oleogelators have been identified to produce oleogels, waxes are the most promising due to their ability to form gels at low concentrations without requiring pretreatment [8, 9]. However, oleogels produced with a single wax cannot be sufficiently compatible with food to replace solid fats. On the contrary, multi-component wax-based oleogels offer improved gelation and crystallization properties by combining different oleogelators in various ratios. Interactions between these components may enhance the structural properties of the gel [10, 11].

Beeswax (BW) is a wax consisting mainly of wax esters, fatty acids and fatty alcohols with a melting temperature of 49.9 °C. BW is used as an oleogel due to its strong gelling capacity at low concentrations [12–15]. Soy wax (SW), derived from soybean oil, is a low-cost wax and a by-product of one of the world's most produced vegetable oils, ranking second after palm oil. It is more economical than other waxes, including beeswax. Soy wax is primarily composed of wax esters, monoglycerides, and diglycerides [16]. In addition, stearic acid (C18:0), a major fatty acid in soy wax, is known to reduce LDL cholesterol. However, studies that use soy wax as an oleogelator are limited [16, 17].

Citrus fiber is obtained by extracting pectin from citrus peel, a by-product of the citrus fruit juice industry. It is an economical, environmentally friendly and functional fiber source. This fiber, rich in pectin, has a high-water retention capacity. When incorporated into hydrogel networks, it enhances viscosity and delays syneresis [18].

In this study, oleogels with different hardness were developed by using the stabilizing effect of different concentrations of soy wax and beeswax (3%, 5%, 7%, and 10%). These oleogels were then combined with citrus fiber (5%) hydrogels at different ratios (40% and 60%) to form bigels. The resulting bigels were characterized and evaluated for use in sponge cake formulations. To the best of our knowledge, this is the first study to assess the triple synergistic effect of soy wax, beeswax, and citrus fiber as a fat replacer in bigel systems. The performance of these bigels in bakery products was also investigated.

Material and methods

Materials

Sunflower oil was obtained from local markets in Turkey. Citrus fiber (CF) was obtained from Plentia Superfoods (Istanbul, Turkey), Soy wax (SW) was obtained from Solman Store (Istanbul, Turkey), Beeswax (BW) was from Petekoglu (Istanbul, Turkey). Double distilled water was used for the preparation of samples and analysis.

Oleogels preparation

To prepare oleogels, sunflower oil was first heated to 70 °C. subsequently, wax blends composed of soy wax (SW) and beeswax (BW) in ratios of 7:3, 5:5, 3:7, and 0:10 (w/w) were melted separately. The heated sunflower oil (90%, w/w) and melted wax blend (10%, w/w) was mixed with a magnetic stirrer at 300 rpm, 70 °C for 30 min. Afterwards, the resulting mixture was left to cool and set at room temperature for at least 2 h to allow oleogel formation [4]. The compositions of the oleogels and their corresponding codes are presented in Table 1.

Hydrogel preparation

To form the hydrogel, 5% citrus fiber was dispersed in distilled water preheated to 70 °C and mixed until a homogeneous consistency was achieved. The mixture was then allowed to stand at room temperature for approximately 24 h to ensure complete dissolution and hydration of the citrus fiber [4].

Table 1 Formulation of oleogels

Sample Name	Soy wax (%w, w)	Beeswax (%w, w)	Sunflower oil (%w, w)
7SW:3BW OG	7	3	90
5SW:5BW OG	5	5	90
3SW:7BW OG	3	7	90
10BW OG	0	10	90

SW Soy wax; *BW* Beeswax; *OG* Oleogel

Bigels production

The compositions and their corresponding names of the bigel are presented in Table 2. Bigels were prepared by separately heating both oleogels and hydrogels to 70 °C, followed by homogenization at different ratios (40:60 and 60:40, OG:HG) using an ULTRA-TURRAX homogenizer (IKA-Works Inc.) at 10,000 rpm for 3 min. Then, the produced bigels were kept at room temperature (25 °C) for 24 h and stored at + 4 °C until further analysis [19].

Production of sponge cakes

The sponge cakes were prepared with minor modifications based on the method described by [20]. The formulations consisted of 39% (w/w) wheat flour, 20% (w/w) sucrose, 12% (w/w) oil phase (either palm oil or bigels), 1% (w/w) baking powder, and 28% (w/w) homogenized egg. All ingredients were mixed to obtain a homogeneous sponge cake batter. The batter samples were baked in a preheated oven at 170 °C for 30 min.

Rheological analysis

Rheological analyses were carried out using a controlled-stress rheometer (MCR 302; Anton Paar, Austria) equipped with a Peltier temperature control system, using a parallel plate configuration. All measurements were performed in triplicate at 25 °C. The linear viscoelastic region (LVR) was first determined by amplitude sweep at 0.1% strain. Frequency sweep tests (0.1–10 Hz) were then applied to calculate the storage modulus (G′) and loss modulus (G″) (Eq. 1 and Eq. 2) as functions of angular frequency (ω), with dynamic parameters obtained by nonlinear regression using the power-law model [21]:

$$G\prime = K\prime(\omega)^{n\prime} \tag{1}$$

Table 2 Formulation of bigels

Sample Name	Rate of Oleogel (g/100 g)	Rate of Hydrogel (g/100 g)
$(7SW:3BW\ OG)_{40}$-HG_{60}	40 g 7SW:3BW OG	60 g
$(5SW:5BW\ OG)_{40}$-HG_{60}	40 g 5SW:5BW OG	60 g
$(3SW:7BW\ OG)_{40}$-HG_{60}	40 g 3SW:7BW OG	60 g
$(10BW\ OG)_{40}$-HG_{60}	40 g 10BW OG	60 g
$(7SW:3BW\ OG)_{60}$-HG_{40}	60 g 7SW:3BW OG	40 g
$(5SW:5BW\ OG)_{60}$-HG_{40}	60 g 5SW:5BW OG	40 g
$(3SW:7BW\ OG)_{60}$-HG_{40}	60 g 3SW:7BW OG	40 g
$(10BW\ OG)_{60}$-HG_{40}	60 g 10BW OG	40 g

The first number in the sample name indicates the percentage of oleogel in the bigel (e.g., BG40 = 40% OG, 60% HG), while the second number indicates the wax blend used in the oleogel phase

$$G\prime\prime = K\prime\prime(\omega)^{n''} \tag{2}$$

where G' and G″ represent the storage and loss moduli (Pa), ω is the angular frequency (s^{-1}). K′ and K″ are consistency coefficients ($Pa\cdot s^n$), and n′ and n″ are flow behavior indices.

The three-interval thixotropy test (3-ITT) was performed on hydrogel, oleogel, and bigel samples at shear rates of 0.5 s^{-1} and 150 s^{-1}. Based on preliminary tests, the LVR was set as 50 s^{-1}. Each test involved 100 s at 0.5 s^{-1}, followed by 40 s at 150 s^{-1}, and recovery at 0.5 s^{-1}, with structural recovery monitored through G' changes.

Temperature sweep test was also performed between 20–100 °C at 10 °C/min, and variations in the G' values recorded for all samples [22].

Texture profile analysis

Textural parameters including hardness, springiness, cohesiveness, gumminess, and chewiness of oleogel, bigel, and sponge cake samples were evaluated using a texture analyzer (TA.XT2 Plus, Stable Micro Systems, UK) equipped with a 36 mm cylindrical aluminum probe and a 5 kg load cell [23]. Oleogel and bigel samples were evenly spread in Petri dishes to obtain a uniform height, whereas sponge cake samples were cut into slices of 1.5 cm thickness. All measurements were conducted at 25 °C by penetrating the samples to a depth of 10 mm at a speed of 3.0 mm/s, followed by withdrawal at 10 mm/s. A double compression test was applied at a probe speed of 1.0 mm/s with a 5 s interval between cycles, using a trigger force of 2 g and a compression ratio of 65%.

Bigel stability

The stability of the bigels was determined by centrifugation method based on the procedure described by [24]. Accordingly, 5 g of each bigel sample was placed into a 50 ml centrifuge tube and centrifuged at 5000 rpm for 10 min at 24 °C. Then, the separated liquid phase was carefully removed and the weight of the remaining gel phase was recorded. The stability of the bigels was expressed as the accelerated precipitation rate (APR), calculated using Eq. 3, where W_a is the initial mass of the bigel sample prior to centrifugation and W_b is the mass of the gel after removal of the exudate.

$$APR\% = \frac{Wb - Wa}{Wa} \times 100 \tag{3}$$

Visual appearance and microscopy

Macroscopic images of all oleogels, bigels, sponge cake batters, sponge cakes produced with the bigels, and sponge cakes produced with palm oil were taken using a smartphone camera (iPhone 13).

Microscopic images of oleogels and bigels were viewed with a polarized light microscope (Olympus BX41, Tokyo, Japan) that was equipped with a digital camera for microscopic analysis. Trace amounts of oleogel and bigel samples were placed onto a microscope slide and covered with a coverslip. Then, images of the samples were captured using 10 × magnification [22].

Color analysis of sponge cakes

Color analysis of the sponge cake samples was carried out with a chroma meter (CR-13, KONICA MINOLTA, Tokyo, Japan) [19]. Color measurements were performed separately on the outer crust and the inner crumb of baked cake samples. The results were recorded using the CIEL*a*b* color space. The overall color difference (ΔE*) between samples, hue (H*), chroma (C*), and browning index (BI) were calculated using Eq. 4–7 [25]

$$\Delta E^* = \sqrt{(L^* - L_0^*)^2 + (a^* - a_0^*)^2 + (b^* - b_0^*)^2} \quad (4)$$

$$C^* = \sqrt[2]{(a^{*2} + b^{*2})} \quad (5)$$

$$H^* = tan^{-1}\left[b^*/a^*\right] \quad (6)$$

$$BI = \frac{100}{0.17}\left(\frac{a^* + 1.75L^*}{(5.645L^* + a^* - 0.012b^*) - 0.31}\right) \quad (7)$$

Statistical analysis

All analyses were conducted in duplicate and expressed as mean ± standard deviation. Statistical evaluations were performed with SPSS (v.15.0, SPSS Inc., Chicago, IL, USA) using one-way ANOVA at a 95% confidence level ($p < 0.05$), followed by Duncan's multiple range test when significant differences were found. Nonlinear regression for determining rheological parameters based on the power-law model was carried out with STATISTICA (StatSoft Inc., Tulsa, England).

Results and discussions

Rheological properties of gels and bigels

Frequency sweep tests of hydrogel, oleogel, and bigel samples revealed key aspects of their viscoelastic performance (Figs. 1 and 2). In all cases, the storage modulus (G') exceeded the loss modulus (G"), confirming the formation of elastic, well-structured networks. Such elastic dominance is essential for fat mimetics in bakery applications, where structural integrity during mixing and heating is critical [26]. The rheological behavior observed among samples reflects a system capable of resisting deformation under dynamic conditions, mimicking the functional profile of traditional fats.

Notably, oleogels formulated with 10% beeswax exhibited the highest viscoelastic moduli (Table 3), underscoring the impact of wax-derived crystalline structure. The lipid matrix of long-chain wax esters enhances integrity, stabilizing the system against shear and thermal stress [27]. Within bigel formulations, elevating the oleogel phase from 40 to 60% markedly improved mechanical strength (Fig. 2). $(10BW\ OG)_{60}$-HG_{40} exhibited the most enhanced rheological characteristics, suggesting a synergistic interaction between the lipid and aqueous components. The improved phase composition in this formulation contributes to a stronger hybrid matrix, enhancing its suitability for high-stress processing applications [28].

Thixotropic behavior and structural recovery capacity

Three-interval thixotropy tests (3-ITT) characterized gel behavior under shear (Fig. 3). After a high shear rate, the recovery of G' reflects the sample's ability to recover its viscoelastic network. $(10BW\ OG)_{60}$-HG_{40} demonstrated the highest recovery, suggesting a reversible gel network that stays stable during mixing and aeration, an important feature for bakery applications [29]. In contrast, $(7SW{:}3BW\ OG)_{40}$-HG_{60} and $(5SW{:}5BW\ OG)_{40}$-HG_{60} had lower recovery levels, pointing to the drawbacks of using less wax. These samples showed limited ability to recover their structure, which may result in a less stable batter and poor performance during baking. These findings suggest that in addition to elasticity, having a strong structural memory is essential for bigels used in bakery products. Recent advances in 4D printing of fat-analog systems have also emphasized the importance of structural responsiveness and memory in lipid-based matrixes [30].

Temperature-dependent rheological properties

Temperature sweep tests showed that all bigel samples maintained structural integrity up to ~ 60 °C (Fig. 4b and c), with G′ remaining stable and indicating an intact gel network. This corresponds to the early stage of cake baking, when the batter begins to firm before major thermal transitions occur [31]. Above 60 °C, G′ decreased, particularly in formulations with less beeswax, highlighting their lower heat resistance. In contrast, $(10BW\ OG)_{60}$-HG_{40},

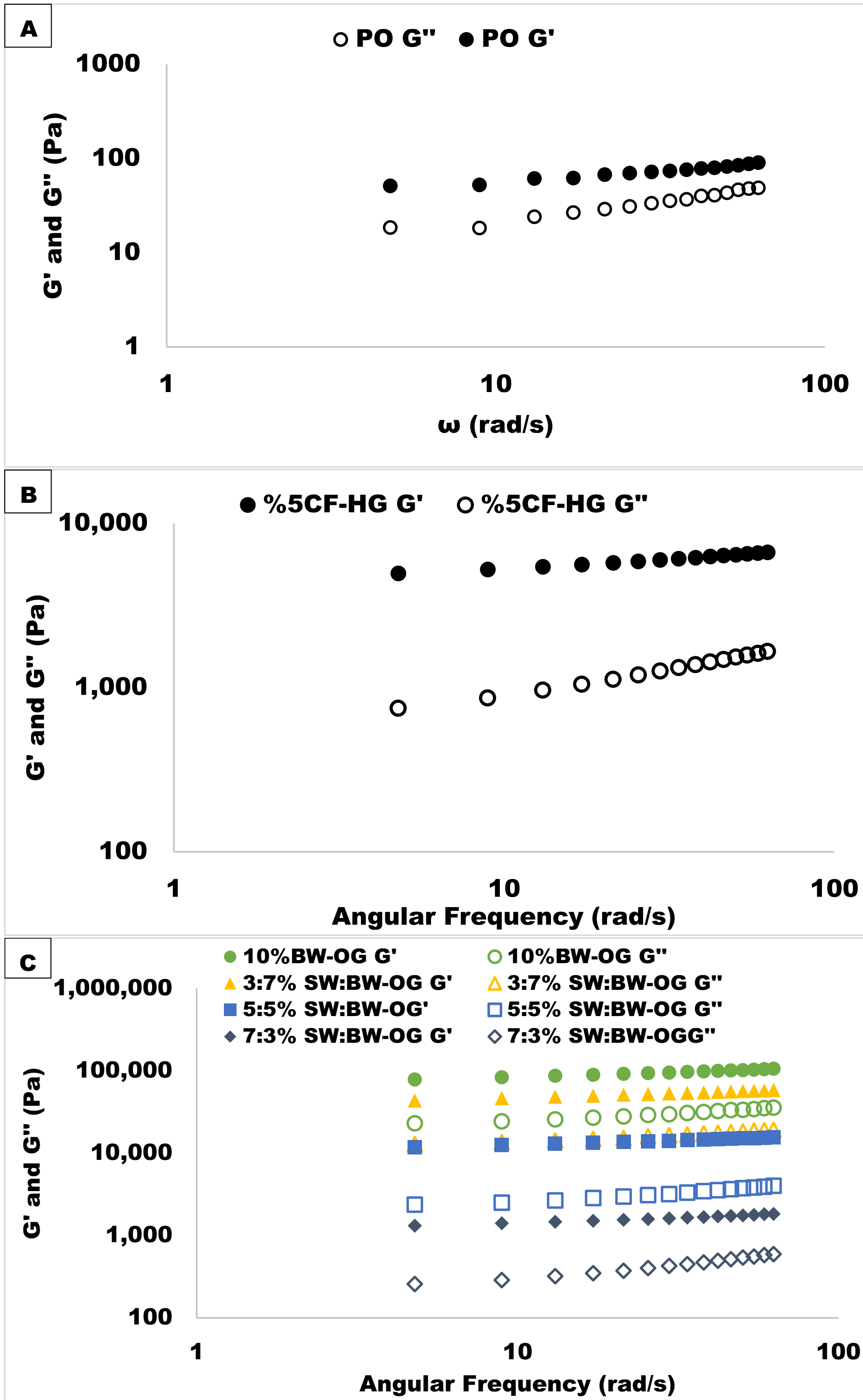

Fig. 1 Dynamic rheological properties of hydrogel (**A**), palm oil (**B**) and oleogels (**C**)

with the highest beeswax content, retained its viscoelasticity more effectively, reflecting stronger thermal stability due to a denser crystalline network. These findings confirm that wax-based crystalline domains reinforce gel structure and enhance resistance to thermal degradation [32].

Meanwhile, the citrus fiber hydrogel contributed to stability by binding water and slowing structural weakening

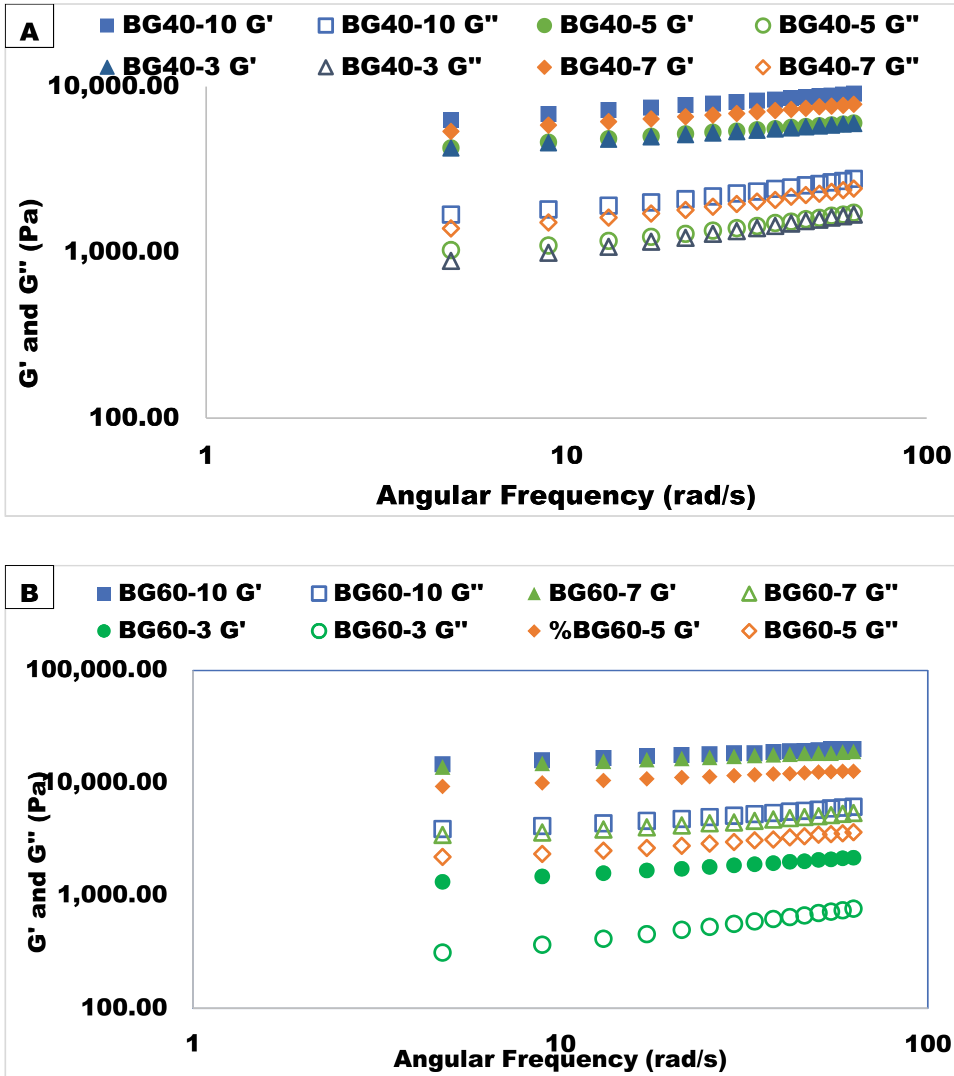

Fig. 2 Dynamic rheological properties of bigels containing 40% oleogel (**A**) and 60% oleogel (**B**)

Table 3 The power law parameters of dynamic rheological parameters of hydrogel, oleogels and bigels

	K'	n'	R^2	K"	n"	R^2
Palm Oil	37.19 ± 2.02	0.202 ± 0.001	0.97	9.39 ± 1.13	0.388 ± 0.002	0.97
7SW:3BW OG	1079.95 ± 263.15	0.124 ± 0.013	0.99	169.82 ± 43.40	0.287 ± 0.010	0.92
5SW:5BW OG	10013.36 ± 1265.45	0.105 ± 0.002	0.99	2030.71 ± 235.24	0.147 ± 0.001	0.86
3SW:7BW OG	36,101.035 ± 776.69	0.115 ± 0.002	0.99	11,059.09 ± 1266.75	0.123 ± 0.003	0.92
10BW OG	64,456.98 ± 1672.10	0.117 ± 0.020	0.99	19,884.40 ± 241.94	0.128 ± 0.008	0.91
5CF HG	4176.68 ± 59.31	0.109 ± 0.000	0.99	494.66 ± 1.04	0.284 ± 0.005	0.97
$(7SW:3BW\ OG)_{40}$-HG_{60}	3279.55 ± 282.76	0.134 ± 0.008	0.99	641.22 ± 2.55	0.218 ± 0.010	0.97
$(5SW:5BW\ OG)_{40}$-HG_{60}	3286.73 ± 162.29	0.141 ± 0.007	0.99	847.71 ± 19.33	0.155 ± 0.019	0.91
$(3SW:7BW\ OG)_{40}$-HG_{60}	4053.45 ± 312.92	0.145 ± 0.010	0.99	1025.36 ± 50.92	0.180 ± 0.004	0.94
$(10BW\ OG)_{40}$-HG_{60}	4820.47 ± 75.28	0.150 ± 0.001	0.99	1393.80 ± 5.04	0.150 ± 0.000	0.92
$(7SW:3BW\ OG)_{60}$-HG_{40}	1226.72 ± 312.46	0.163 ± 0.027	0.99	233.27 ± 67.61	0.31 ± 0.038	0.97
$(5SW:5BW\ OG)_{60}$-HG_{40}	5585.06 ± 864.80	0.125 ± 0.000	0.99	1319.14 ± 755.60	0.18 ± 0.037	0.92
$(3SW:7BW\ OG)_{60}$-HG_{40}	9288.36 ± 699.56	0.127 ± 0.000	0.99	2360.96 ± 745.48	0.15 ± 0.021	0.94
$(10BW\ OG)_{60}$-HG_{40}	9912.02 ± 756.61	0.140 ± 0.018	0.99	2725.11 ± 677.33	0.15 ± 0.006	0.95

Data are presented as mean ± standard deviation. CF: Citrus fiber; SW: Soy wax; BW: Beeswax; OG: Oleogel; HG: Hydrogel; BG: Bigel

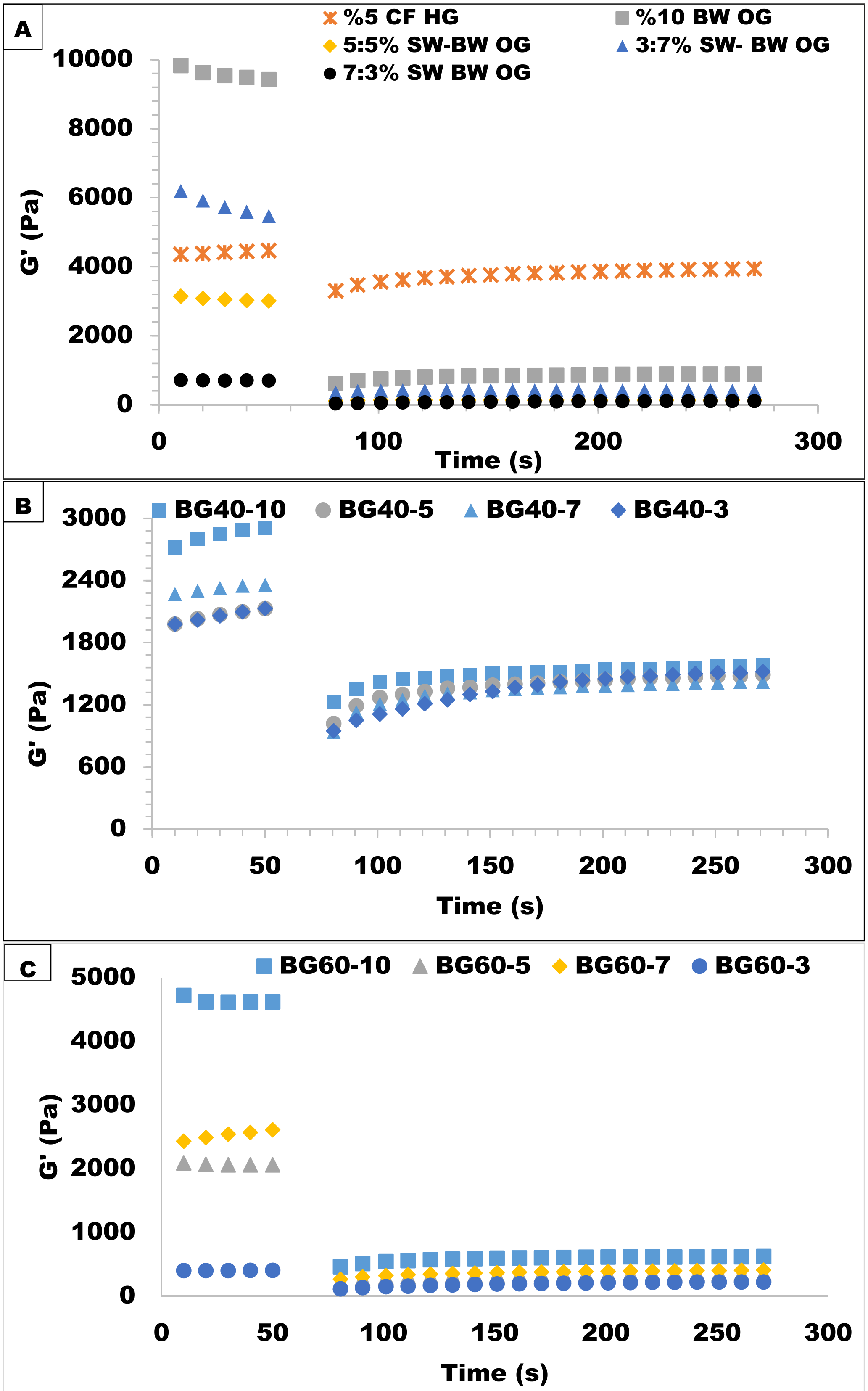

Fig. 3 3-ITT rheological properties of hydrogel, oleogels (**A**), bigels containing 40% oleogel (**B**) and 60% oleogel (**C**)

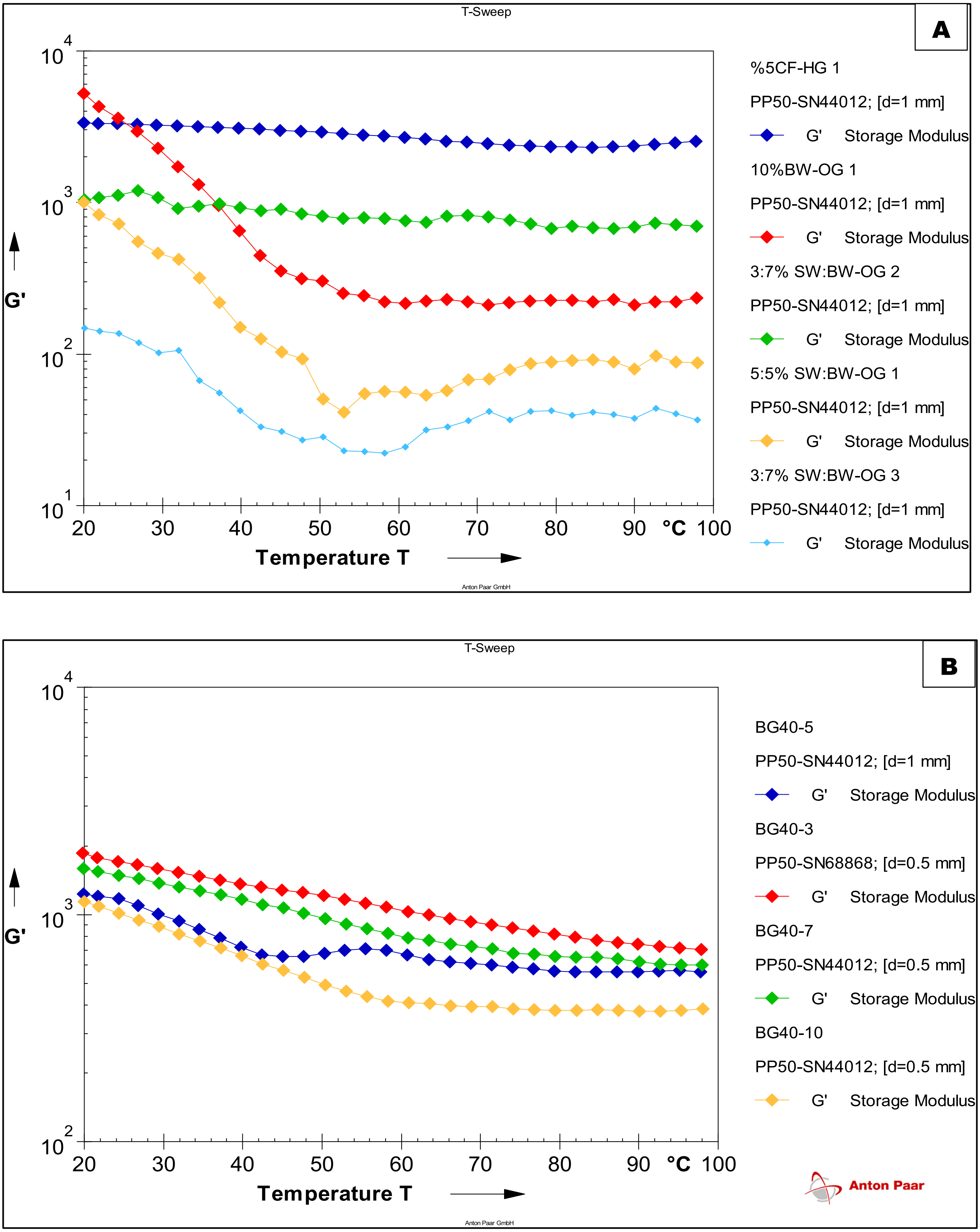

Fig. 4 Temperature sweep test of hydrogel, oleogels (**A**), bigels containing 40% oleogel (**B**) and 60% oleogel (**C**) and palm oil (D)

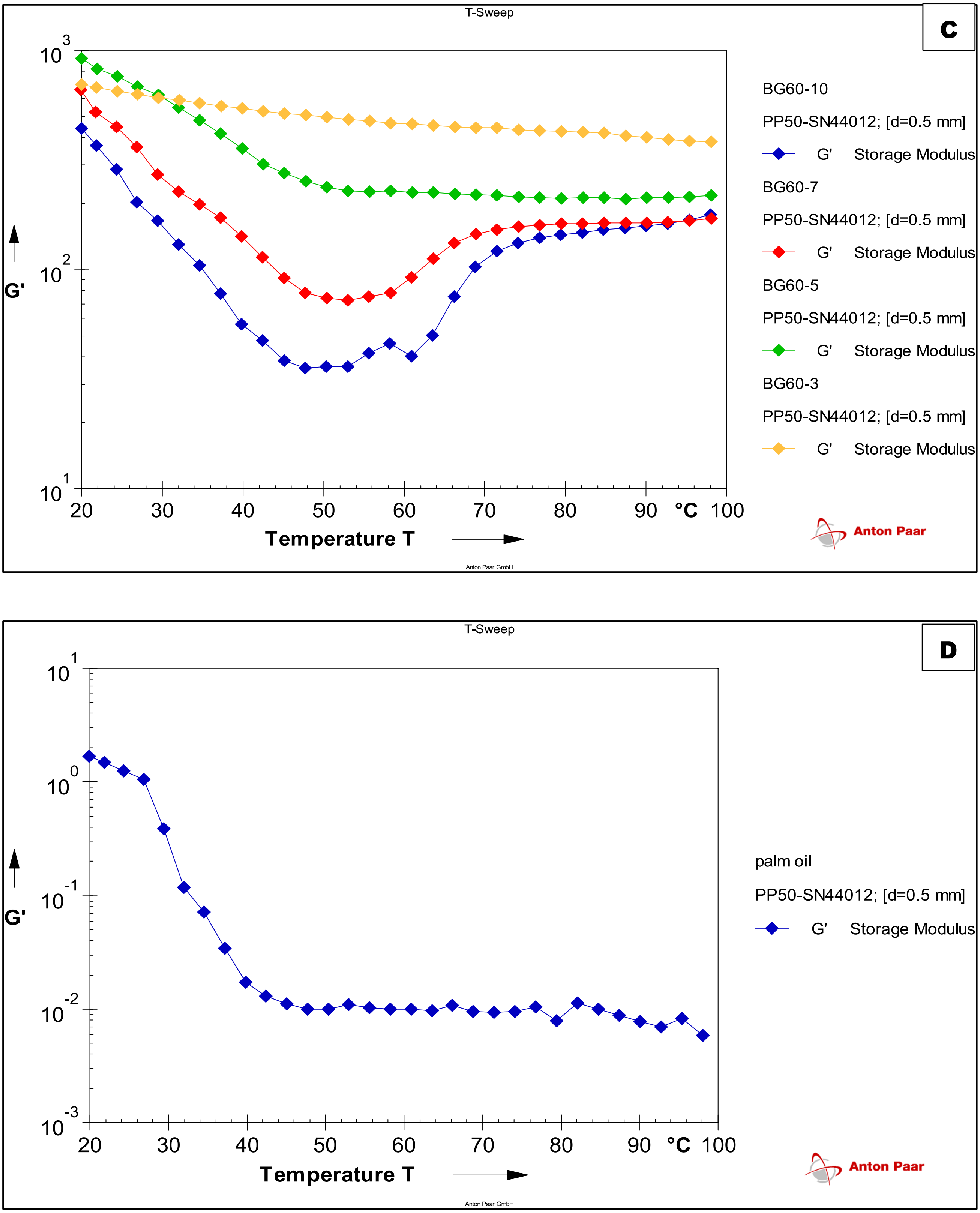

Fig. 4 (continued)

[33]. The dual network of lipid and aqueous phases supported the system during heating, protecting cake structure and minimizing texture loss. The plateau observed corresponds to the temperature range where the gel network is preserved, consistent with sponge cake baking conditions [34]. Beyond 60 °C, moduli declined more sharply in low-wax systems, confirming the role of wax concentration in thermal stability [35]. (10BW OG)$_{60}$-HG$_{40}$ again showed the greatest resistance, reflecting the protective effect of crystalline lipid structures, while citrus fiber further limited breakdown by retaining water. Together, this dual network maintained integrity under baking conditions.

Textural properties of bigels and cakes

The texture of the bigels varied significantly depending on wax concentration and oleogel ratio (Table 4). Among the gel samples, particularly (10BW OG)60-HG40 and (10BW OG)40-HG60, showed the highest hardness, reflecting compact structures consistent with elevated G′ values (Fig. 2) and dense crystalline domains under polarized light (Fig. 8), as reported in wax-based systems [36].

In contrast, the 7SW:3BW oleogel produced the lowest hardness, indicating a weaker gel network. This likely resulted from its low beeswax content and limited crystalline framework, consistent with previous observations on wax ratio effects [37]. Gumminess and chewiness followed similar trends: samples with higher wax levels and oleogel content, such as (10BW OG)$_{60}$-HG$_{40}$ and (10BW OG)$_{40}$-HG$_{60}$, showed greater resistance to deformation. These findings reflect the strength and cohesion of their internal gel networks. Springiness and cohesiveness were more uniform, although higher wax content slightly increased cohesiveness, likely due to improved phase bonding and microstructural integrity [36].

When incorporated into sponge cake formulations (Table 4), the bigels significantly affected texture. Palm oil control cakes were the firmest (3304.17), consistent with saturated fat systems [7] whereas (10BW OG)$_{60}$-HG$_{40}$ produced the softest cake (1860.99), despite it's the firmest gel texture. This unexpected result may be due to better moisture retention and improved aeration during baking [38], possibly enhanced by the dual-network structure and citrus fiber content [36]. (3SW:7BW OG)$_{40}$-HG$_{60}$ resulted in a moderately soft cake (2025.16) with high springiness (0.89) and cohesiveness (0.53), suggesting an elastic and well-integrated crumb matrix. In contrast, cakes with 5SW:5BW OG)$_{40}$-HG$_{60}$ and (7SW:3BW OG)$_{40}$-HG$_{60}$ exhibited higher

Table 4 Texture profile of hydrogel, oleogels, bigels and sponge cakes

	Hardness (N)	Springiness	Cohesiveness	Gumminess	Chewiness
GELS					
5CF HG	243.64 ± 17.36^{h}	0.91 ± 0.01^{a}	0.82 ± 0.08^{cd}	199.68 ± 15.05^{i}	181.90 ± 12.60^{g}
7SW:3BW OG	39.56 ± 2.01^{a}	0.97 ± 0.00^{defg}	0.73 ± 0.01a	28.83 ± 0.98^{a}	27.92 ± 0.82^{a}
5SW:5BW OG	85.09 ± 4.67^{c}	0.97 ± 0.00^{def}	0.77 ± 0.03^{ab}	64.64 ± 1.33^{c}	62.53 ± 1.16
3SW:7BW OG	41.81 ± 4.65^{a}	0.98 ± 0.00^{g}	0.73 ± 0.01^{a}	30.90 ± 4.04^{a}	30.17 ± 3.82^{a}
10BW OG	141.21 ± 15.19^{g}	0.97 ± 0.0^{efg}	0.87 ± 0.04^{de}	121.07 ± 10.31^{h}	117.29 ± 9.51^{f}
(7SW:3BW OG)$_{40}$-HG$_{60}$	87.21 ± 4.85^{c}	0.94 ± 0.01^{b}	0.85 ± 0.02^{de}	74.25 ± 2.24^{de}	69.47 ± 2.61^{c}
(5SW:5BW OG)$_{40}$-HG$_{60}$	88.76 ± 2.73^{cd}	0.96 ± 0.00^{d}	0.82 ± 0.01^{bcd}	71.91 ± 2.37^{cd}	68.98 ± 2.22^{c}
(3SW:7BW OG)$_{40}$-HG$_{60}$	115.80 ± 7.33^{e}	0.95 ± 0.01^{c}	0.83 ± 0.04^{cd}	94.90 ± 0.37^{g}	87.53 ± 4.58^{e}
(10BW OG)$_{40}$-HG$_{60}$	132.10 ± 3.78^{f}	0.96 ± 0.01^{de}	0.90 ± 0.01^{e}	119.16 ± 1.44^{h}	115.34 ± 0.68^{f}
(7SW:3BW OG)$_{60}$-HG$_{40}$	ND	ND	ND	ND	ND
(5SW:5BW OG)$_{60}$-HG$_{40}$	61.99 ± 0.08^{b}	0.98 ± 0.0^{fg}	0.78 ± 0.02^{bc}	48.61 ± 1.80^{b}	47.51 ± 1.15^{b}
(3SW:7BW OG)$_{60}$-HG$_{40}$	97.60 ± 1.16^{d}	0,97 ± 0.00^{defg}	0.84 ± 0.01^{d}	82.01 ± 0.19^{f}	79.45 ± 0.12^{d}
(10BW OG)$_{60}$-HG$_{40}$	142.59 ± 14.01^{g}	0.97 ± 0.00^{defg}	0.85 ± 0.03^{de}	119.88 ± 7.13^{h}	116.14 ± 6.76^{f}
SPONGE CAKES					
Palm oil	3304.17 ± 127.01^{AB}	0.77 ± 0.00^{A}	0.14 ± 0.00^{A}	459.85 ± 87.21^{B}	354.65 ± 52.17^{A}
(7SW:3BW OG)$_{40}$-HG$_{60}$	4250.18 ± 461.63^{A}	0.87 ± 0.05^{A}	0.46 ± 0.15^{A}	1946.69 ± 438.59^{A}	1706.13 ± 475.30^{A}
(5SW:5BW OG)$_{40}$-HG$_{60}$	2885.03 ± 153.80^{AB}	0.92 ± 0.04^{A}	0.61 ± 0.10^{A}	1767.62 ± 190.42^{A}	1629.71 ± 248.14^{A}
(3SW:7BW OG)$_{40}$-HG$_{60}$	2025.16 ± 45.44^{B}	0.89 ± 0.07^{A}	0.53 ± 0.30^{A}	1073.95 ± 591.10^{AB}	984.35 ± 610.63^{A}
(10BW OG)$_{40}$-HG$_{60}$	2875.64 ± 331.99^{AB}	0.85 ± 0.03^{A}	0.57 ± 0.00^{A}	1631.27 ± 186.20^{AB}	1391.29 ± 210.34^{A}
(7SW:3BW OG)$_{60}$-HG$_{40}$	3101.37 ± 62.58^{AB}	0.86 ± 0.07^{A}	0.47 ± 0.00^{A}	1449,38 ± 88.68^{AB}	1247.28 ± 170.46^{A}
(5SW:5BW OG)$_{60}$-HG$_{40}$	3314.04 ± 224.44^{AB}	0.81 ± 0.02^{A}	0.42 ± 0.00^{A}	1398.21 ± 81.08^{AB}	1476.19 ± 95.40^{A}
(3SW:7BW OG)$_{60}$-HG$_{40}$	3046.30 ± 62.58^{AB}	0.82 ± 0.14^{A}	0.58 ± 0.17^{A}	1760.87 ± 474.56^{A}	1133.07 ± 636.50^{A}
(10BW OG)$_{60}$-HG$_{40}$	1860.99 ± 341.20^{B}	0.77 ± 0.05^{A}	0.55 ± 0.03^{A}	1024.79 ± 125.43^{AB}	1476.19 ± 152.17^{A}

The different lower case letters (a-i) in the same column indicate similarity between gel samples. Capital letters (A-) in the same column indicate similarity between sponge cake samples

*ND Not detected

hardness (2885.03 and 4250.18, respectively), showing that excess wax or oleogel may produce denser, less appealing textures [7]. (10BW OG)$_{40}$-HG$_{60}$ also gave firmer cakes but with enhanced cohesiveness (0.57), partially offsetting perceived firmness.

Ultimately, (10BW OG)$_{60}$-HG$_{40}$ and (3SW:7BW OG)$_{40}$-HG$_{60}$ emerged as the most promising fat replacers, combining desirable cake texture with processing suitability, while other formulations showed greater variability, underscoring the importance of optimizing wax and hydrogel ratios [5].

Centrifugal stability and microstructural characteristics

Centrifugal separation tests (Fig. 5) highlighted clear differences in bigel stability. (10BW OG)$_{40}$-HG$_{60}$ showed the lowest separation, confirming strong phase integrity, followed by (3SW:7BW OG)$_{40}$-HG$_{60}$ and (5SW:5BW OG)$_{40}$-HG$_{60}$ with similarly low rates. In contrast, (5SW:5BW OG)$_{60}$-HG$_{40}$, (7SW:3BW OG)$_{40}$-HG$_{60}$, and particularly (7SW:3BW OG)$_{60}$-HG$_{40}$ exhibited high separation, indicating weak gel–gel interactions and insufficient crystalline structuring. These results emphasize the critical roles of wax concentration and oleogel-to-hydrogel ratio in determining physical stability, with (10BW OG)$_{40}$-HG$_{60}$ emerging as the most stable. under centrifugal force [39].

Microscopic analysis (Fig. 6) further confirmed these effects. Samples rich in beeswax, such as 10BW OG and 5SW:5BW OG, displayed dense birefringent crystalline domains, indicative of robust lipid networks typically associated with higher mechanical stability in structured fat systems [40]. In contrast, the 5CF hydrogel showed an amorphous and uniform appearance, lacking crystalline features, as expected for a purely aqueous matrix. Across bigel formulations, a gradient of organization was evident: (10BW OG)$_{40}$-HG$_{60}$ and (10BW OG)$_{60}$-HG$_{40}$ exhibited the most continuous crystalline networks, aligning with their rheological strength and phase stability [37], while (3SW:7BW OG)$_{40}$-HG$_{60}$ and (3SW:7BW OG)$_{60}$-HG$_{40}$ presented intermediate structures balancing firmness and spreadability which are desirable attributes for applications requiring both firmness and consumer-friendly mouthfeel [5, 7]. Conversely, (7SW:3BW OG)$_{40}$-HG$_{60}$ and (7SW:3BW OG)$_{60}$-HG$_{40}$ formulations displayed fragmented crystalline domains with heterogeneous phase distribution, consistent with their weaker textural performance and higher separation rates. These discontinuities suggest poor phase interactions and limited cohesive strength [39], a limitation previously linked to low oil-binding capacity and fragile networks in other bigel and emulgel systems [10]. Importantly, microstructural observations were functionally relevant: the degree of crystalline organization directly correlated with rheological strength, textural parameters, and centrifugal stability, underscoring the central role of wax-induced structuring in bigel functionality [15]. Formulations such as3SW:7BW OG)$_{40}$-HG$_{60}$ and (10BW OG)$_{60}$-HG$_{40}$ appear particularly promising, offering a balance of stability and processability. Their resilience, combined with sufficient softness, makes them suitable palm oil replacers in bakery products where both integrity and texture are critical [4]. Their structural resilience, combined with adequate softness, makes them suitable candidates as palm oil replacers in bakery matrices where both integrity and textural quality are critical.

Color analysis

Visual appearance of oleogels and bigels is presented in Fig. 7. Additionally, visual evaluations (Fig. 8a and b) and instrumental color analysis (Table 5) of the sponge cake

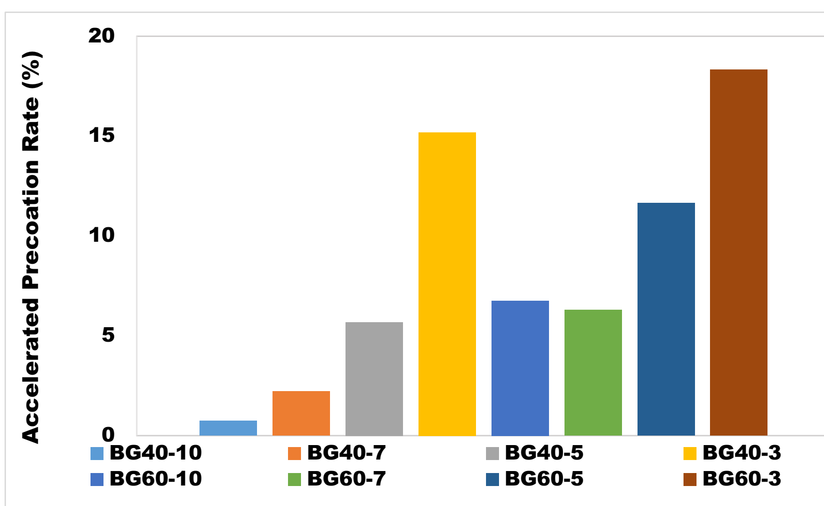

Fig. 5 Centrifugal stability of bigels

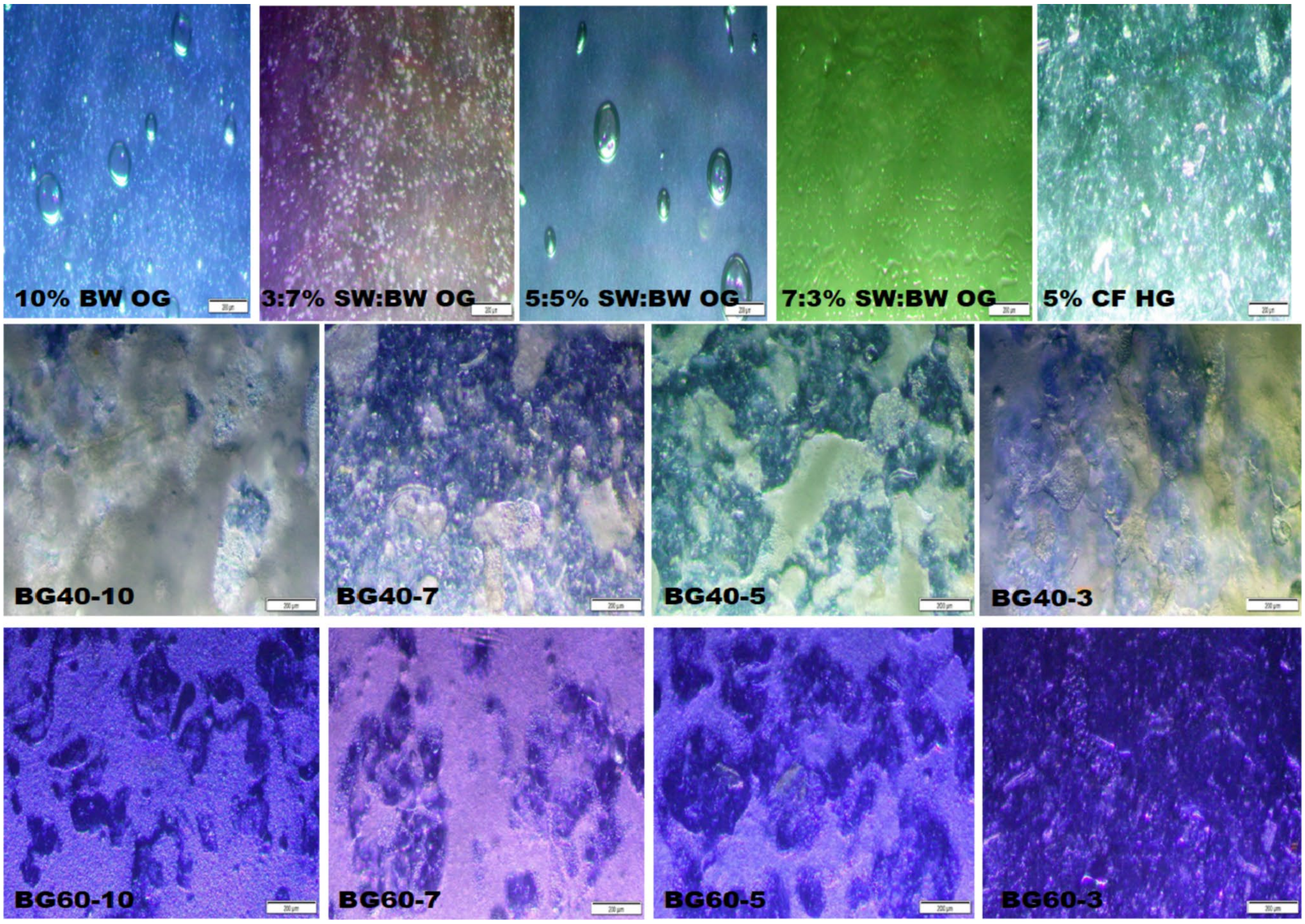

Fig. 6 Microscopic images of hydrogel, oleogels, and bigels containing 40% and 60% oleogel (Scale: 200 µm)

collectively demonstrated that the incorporation of bigels with varying oleogel content significantly influenced both crumb and crust color characteristics.

In terms of the internal structure, the L* values, indicating lightness, were significantly higher in bigel-incorporated samples compared to the palm oil control (69.94). $(10BW\ OG)_{40}$-HG_{60} (73.73) and $(7SW{:}3BW\ OG)_{60}$-HG_{40} (73.58) showing the highest L* values. The increase in lightness observed in bigel-based sponge cake (especially $(10BW\ OG)_{40}$-HG_{60} and $(7SW{:}3BW\ OG)_{60}$-HG_{40}) may be attributed to both the water-rich nature of the hydrogel phase, which dilutes pigment concentration and limits Maillard browning during baking [41] and the presence of emulsified gel matrices that enhance light scattering within the crumb structure [42]. This visual brightness was supported by the homogenous internal appearance (Fig. 8). The a* values representing redness/greenness, remained within a narrow range but showed a notable shift toward the green axis in $(5SW{:}5BW\ OG)_{40}$-HG_{60} (-0.75). This shift may be related to the dilution of red-brown Maillard pigments due to higher moisture content, which has been reported to influence color development during baking [41]. Meanwhile, b* values, representing yellowness were elevated in bigel systems, particularly in $(10BW\ OG)_{40}$-HG_{60} (26.43), indicating better pigment preservation during baking, potentially attributed to the protective effect of the oleogel phase against Maillard and caramelization reactions [17].

Crust color value also revealed meaningful trends. Cakes formulated with bigels generally exhibited higher L* values than the palm oil sponge cake, indicating lighter crust surfaces. Notably, $(5SW{:}5BW\ OG)_{40}$-HG_{60} had the lightest crust (58.62). This lightening effect may be associated with the structural characteristics of bigels, particularly their ability to modulate heat transfer and reduce surface dehydration during baking. A study similarly reported that oleogels formulated with wax-based rice bran oil produced cookies with significantly lighter crusts [43].

Crust a* values were comparable across samples, with most bigel-based cakes showing slightly higher redness than the control, except for $(5SW{:}5BW\ OG)_{60}$-HG_{40} which exhibited a minor decrease. On the other hand, b* values were generally higher bigel-containing cakes such

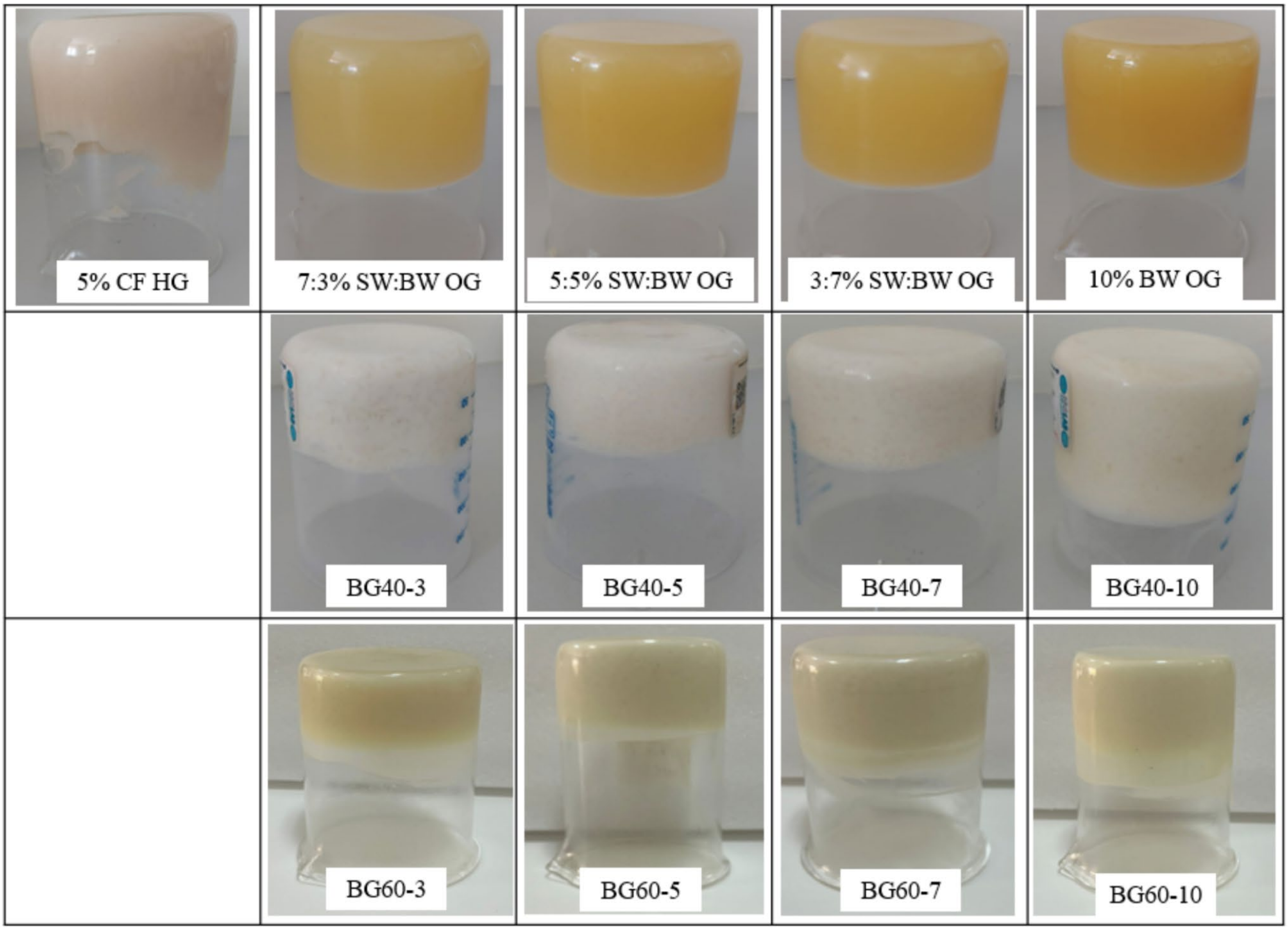

Fig. 7 Visual appearance of oleogels and bigels

as (5SW:5BW OG)40-HG60, (10BW OG)60-HG40, and (5SW:5BW OG)60-HG40, than palm oil containing cakes suggesting a shift toward yellower crust tones. This effect could be linked to altered browning kinetics and pigment composition, potentially due to water retention and heat buffering by the bigel matrix [17].

The chroma values for the crumb of the cakes ranged from 23.38 to 26.44. There were no statistically significant differences in chroma values among the samples, except for those made with palm oil, specifically (10BW OG)40-HG60 and (7SW:3BW OG)40-HG60. The hue angle values for the crumb and crust of the cakes were recorded between -0.67 and 1.80, and -0.04 to -0.93, respectively ($p > 0.05$).

The browning index values for the crumb ranged from -0.49 to 1.02, with no significant differences observed except for the samples (3SW:7BW OG)40-HG60 and (10BW OG)60-HG40. The browning index values for the crust varied between 14.23 and 16.94 ($p > 0.05$). This analysis highlights the functional role of bigel systems in modulating both crumb and crust browning in baked goods, offering potential advantages for fat replacement in bakery applications.

Conclusion

This study is the first to demonstrate the synergistic functionality of soy wax, beeswax, and citrus fiber in a bigel system as a palm oil replacer for sponge cakes. Among the formulations, (10BW OG)60-HG40 and (3SW:7BW OG)40-HG60 offered the most favorable balance of rheological stability, thermal resistance, and baking performance, producing softer and brighter cakes than palm oil controls. The dual network of wax-induced crystalline structures and citrus fiber hydrogel enhanced mechanical integrity, water retention, and reduced Maillard browning. By lowering saturated fat content while maintaining desirable texture and appearance, these bigels present a novel, scalable, and sustainable fat replacement strategy with strong potential for industrial bakery applications.

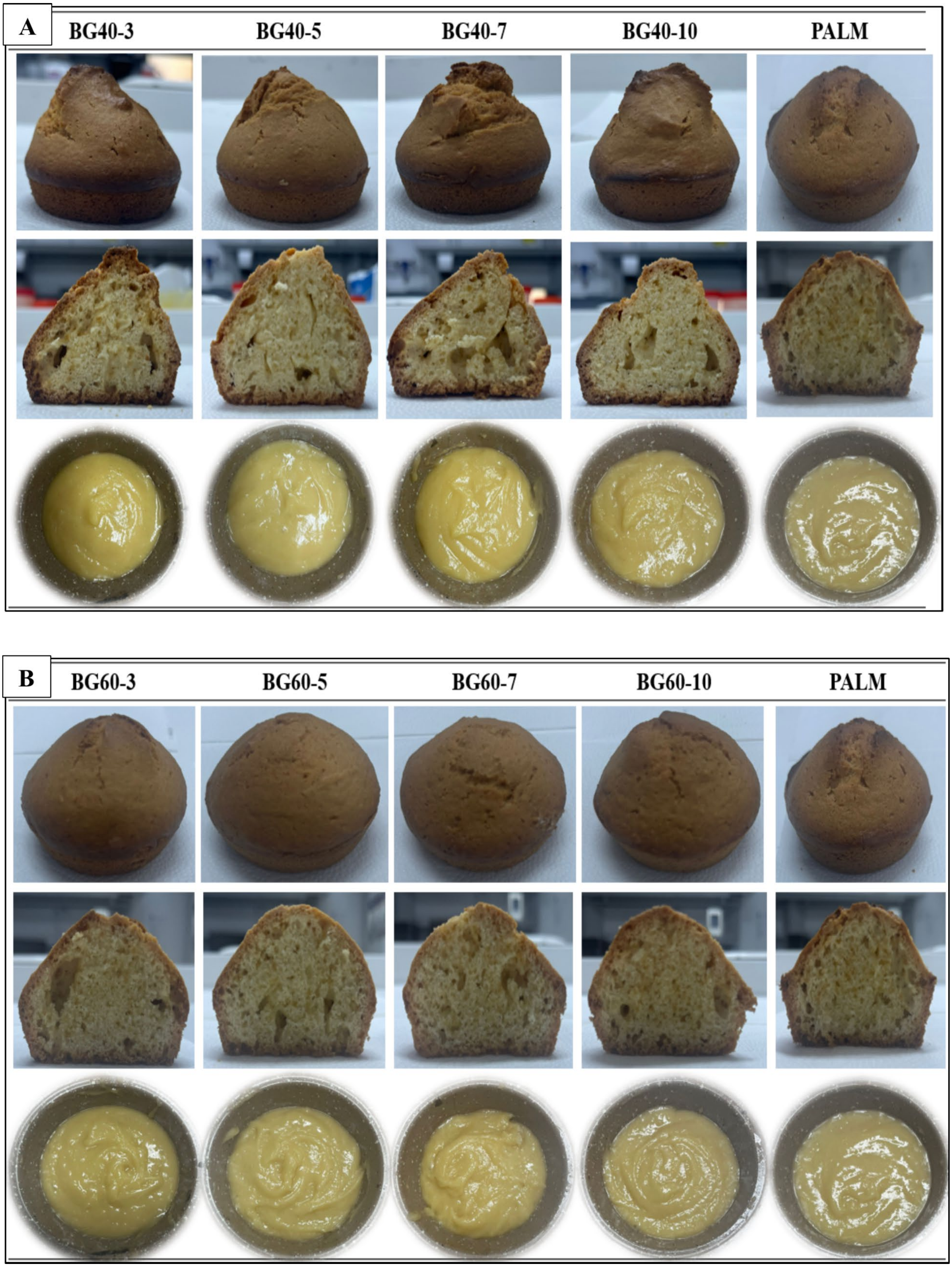

Fig. 8 Visual appearence of sponge cake doughs and sponge cakes produced from palm oil and bigels containing 40% oleogel (**A**) and 60% oleogel (**B**)

Table 5 Color profile of sponge cakes

	L*	a*	b*	ΔE*	C*	H*	BI
			Crumb				
Palm oil	69.94±0.75^{a}	-0.32±0.10^{c}	23.38±0.50^{a}		23.38±0.49^{c}	-0.03±0.49^{a}	-0.19±0.11^{bc}
(10BW OG)$_{40}$-HG$_{60}$	73.73±1.09^{c}	-0.52±0.03^{b}	26.43±0.45^{d}	4.87	26.44±0.45^{a}	-0.30±0.87^{a}	-0.37±0.03^{c}
(3SW:7BW OG)$_{40}$-HG$_{60}$	70.82±0.18^{a}	0.05±0.00^{d}	25.82±0.99^{cd}	2.62	25.81±0.71^{ab}	-0.67±0.09^{a}	1.02±0.84^{a}
(5SW:5BW OG)$_{40}$-HG$_{60}$	73.48±0.21^{c}	-0.75±0.13^{a}	24.24±0.62^{ab}	3.67	24.26±0.43^{bc}	-0.56±1.92^{a}	-0.49±0.22^{c}
(7SW:3BW OG)$_{40}$-HG$_{60}$	70.72±0.52^{ab}	0.13±0.02^{d}	26.02±0.14^{cd}	2.79	26.02±0.14^{a}	0.27±0.39^{a}	0.35±0.12^{abc}
(10BW OG)$_{60}$-HG$_{40}$	70.55±1.02^{ab}	0.50±0.11^{e}	25.68±0.07^{cd}	2.55	25.69±0.08^{bc}	-1.80±0.37^{a}	0.66±0.17^{ab}
(3SW:7BW OG)$_{60}$-HG$_{40}$	72.50±0.50^{bc}	-0.58±0.06^{b}	24.26±0.87^{ab}	2.72	24.26±0.08^{ab}	-0.12±0.46^{a}	-0.44±0.17^{c}
(5SW:5BW OG)$_{60}$-HG$_{40}$	72.85±1.23^{c}	-0.61±0.14^{ab}	25.28±0.91^{bc}	2.49	25.29±0.90^{ab}	-0.37±1.22^{a}	-0.46±0.14^{c}
(7SW:3BW OG)$_{60}$-HG$_{40}$	73.58±0.60^{c}	-0.55±0.13^{b}	25.54±0.71^{cd}	4.24	25.54±0.70^{ab}	1.07±2.06^{a}	-0.29±0.21^{c}
			Crust				
Palm oil	54.63±1.19^{ab}	11.78±0.46^{a}	24.54±2.18^{ab}		27.22±2.15^{ab}	-0.56±0.14^{a}	15.12±0.58^{a}
(10BW OG)$_{40}$-HG$_{60}$	53.94±2.89^{ab}	12.50±0.47^{a}	24.91±3.39^{ab}	1.06	27.92±2.84^{ab}	-0.50±0.40^{a}	16.25±1.42^{a}
(3SW:7BW OG)$_{40}$-HG$_{60}$	53.19±1.63^{a}	12.31±0.19^{a}	21.69±1.31^{a}	3.34	23.67±3.90^{b}	-0.04±0.36^{a}	16.94±0.91^{a}
(5SW:5BW OG)$_{40}$-HG$_{60}$	58.62±0.23^{c}	11.78±0.18^{a}	27.02±0.48^{ab}	4.70	28.61±1.55^{ab}	-0.69±0.33^{a}	15.05±1.58^{a}
(7SW:3BW OG)$_{40}$-HG$_{60}$	53.80±2.53^{ab}	12.01±1.02^{a}	23.10±2.52^{a}	1.68	26.09±1.72^{ab}	-0.42±0.40^{a}	15.67±1.99^{a}
(10BW OG)$_{60}$-HG$_{40}$	57.17±0.45^{bc}	12.03±0.07^{a}	27.14±0.11^{b}	3.64	29.69±0.10^{a}	-0.82±0.03^{a}	14.79±0.19^{a}
(3SW:7BW OG)$_{60}$-HG$_{40}$	54.98±1.69^{ab}	12.25±0.52^{a}	25.85±0.13^{ab}	1.43	28.61±0.13^{ab}	-0.61±0.14^{a}	15.63±1.08^{a}
(5SW:5BW OG)$_{60}$-HG$_{40}$	57.14±2.72^{bc}	11.52±0.82^{a}	25.88±2.36^{ab}	2.85	28.36±1.87^{ab}	-0.93±0.58^{a}	14.23±1.60^{a}
(7SW:3BW OG)$_{60}$-HG$_{40}$	53.32±1.41^{a}	11.96±0.42^{a}	22.55±0.71^{a}	2.39	25.53±0.43^{ab}	-0.33±0.14^{a}	15.71±0.91^{a}

The different lower case letters in the same column indicate similarity between sponge cake samples

Abbreviations

3-ITT	The three-interval thixotropy test
APR	Accelerated precipitation rate
BG	Bigel
BW	Beeswax
CF	Citrus fiber
g	Gram
HG	Hydrogel
Hz	Hertz
K	Consistency coefficient
kg	Kilogram
LDL	Low-density lipoprotein
LVR	The linear viscoelastic region
min	Minute
mm	Millimeter
mL	Milliliter
OG	Oleogel
Pa	Pascal
rpm	Revolutions per minute
s	Second
SW	Soy wax

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