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Development of Bigels Using Citrus Fiber and Beeswax: Application in Cocoa Spread Formulation as Palm Oil Alternative

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ABSTRACT

In this study, bigel systems were developed as potential alternatives to palm oil in cocoa spreads. This study developed citrus fiber (CF)-based bigel systems as alternatives to palm oil in cocoa spreads. Bigels were formulated by combining hydrogels (HG) containing CF (5% and 7.5%) with olive oil oleogels (OG) structured using 10% beeswax at different HG:OG ratios (80:20, 50:50, and 20:80). All bigels exhibited higher storage (G') and loss (G'') moduli than palm oil, indicating enhanced viscoelastic behavior. Increasing the oleogel fraction improved the structural integrity of the bigel network. Bigels containing 7.5% CF were incorporated into cocoa spreads, where higher oleogel ratios increased the solid character (G'). All bigel-enriched cocoa spreads showed thixotropic behavior with lower deformation and higher structural recovery compared to palm oil-based spreads. Additionally, bigel addition improved temperature-dependent stability. These results demonstrate that CF-based bigels provide a compact, viscoelastic, and stable fat system, highlighting their potential as palm oil replacers in cocoa spread formulations.

1 | Introduction

The risk of cardiovascular disease is associated with solid fats due to the presence of high levels of saturated fatty acids (SFAs) (Wang et al. 2024). Replacing saturated fats with monounsaturated and polyunsaturated fats can lower LDL cholesterol and reduce cardiovascular disease risk (Cabezas-Zábala et al. 2016). Oils such as olive oil are recommended for their beneficial effects on heart health, while solid fats should be consumed in moderation (Saboo et al. 2019). Palm oil is a widely used vegetable oil composed of approximately 50% SFAs and 50% unsaturated fatty acids (UFAs) (Lecerf 2017). This balanced fatty acid composition confers distinctive technological properties, contributing to its high oxidative stability and versatility as an ingredient in the food industry. However, because of its high level of SFAs, particularly palmitic acid, its health implications have been controversial. Consuming palm oil has been linked to elevated oxidative stress and inflammatory markers, which can exacerbate metabolic syndrome and problems associated with obesity (Ruzicic et al. 2025; Peixoto et al. 2025). Thus, the food industry has developed various solid fat replacers that can be used in different food products, effectively lowering solid fat content while preserving flavor and texture (Baltuonytė et al. 2022). Novel gel strategies to reduce solid fats have emerged as effective alternatives, particularly through the development of polysaccharide-based oleogels and emulsion gels (Manzoor et al. 2022). Another strategy to reduce solid fat involves the formation of bigels (Quilaqueo et al. 2022; Shakouri et al. 2025). Bigels are semisolid systems that are created by combining hydrophilic and lipophilic phases—that is, hydrogels and oleogels (Eisinaite et al. 2023; Shakeel et al. 2021). Bigels have the potential to replace solid fat due to their similar rheological and textural qualities (Hashemi et al. 2024; Kaimal and Singhal 2023). Bigels are more stable than other two-phase systems, such as emulsions, due to the stabilized structure of both phases, which does not require surfactants or emulsifiers (Bruno et al. 2024).

The ratio of hydrogel to oleogel and the particular type and ratio of gelling agents are the main determinants of bigel formation (Alkabaa et al. 2024; Zampouni et al. 2023). To achieve the correct gel structure, especially when producing hydrogels, it is crucial to choose the right gelling agent (Alkabaa et al. 2024; Francavilla et al. 2023).

Citrus dietary fiber (CF) is a food substance with high-quality functional properties, produced from pulp, which is a by-product of the citrus production process, consisting of water-soluble and water-insoluble fibers and other bioactive components such as flavonoids, polyphenols, and vitamin C (Wu et al. 2023). The main polysaccharide components of CF are pectin, cellulose, and hemicellulose (Zhu et al. 2023). Cellulose and hemicellulose in the structure of CF also support the structure by increasing viscosity and water retention capacity (Zhu et al. 2023). Due to their high viscosity and propensity to retain water, pectin-rich dietary fibers are utilized in food items which reduce syneresis by binding water to the gel structure (Huang et al. 2021).

Food bigel systems have been developed and used in spreads and cream analogs. Such as sesame oleogel based with a hydrogel of sodium alginate and used in spreadable butter (Hashim et al. 2023), candelilla wax–walnut oil oleogel and chitosan hydrogel used in spread (Li et al. 2024), carnauba wax and lecithin in oleogel and agar, gelatin, collagen in hydrogel and used in vegetable oil spread (Baltuonytė et al. 2022), glycerol monolaurate and in oleogel and chitosan hydrogel used in cream analogs (Cui et al. 2022) are examples of these systems. However, research into the production, characterization, and application of food-grade bigels remains limited.

Spreads are frequently employed as fillers in cakes, biscuits, and breakfast items (Alves et al. 2026; Li et al. 2024) but the high levels of trans and SFAs in them constitute a major risk to health (Li et al. 2024; Tirgarian et al. 2023). Bigels have the potential to replace solid fats due to their similar physicochemical and sensory qualities. The purpose of this work was to develop a novel bigel system that included a healthy olive oil oleogel and CF hydrogel to reduce the solid fat content of cocoa spread (CS). In this study, CF is used in bigel systems for the first time. The rheological characteristics and microscopic images of hydrogel (HG), oleogel (OG), and bigels were analyzed. The developed bigels were used to produce CS as substitutes for palm oil. The rheological properties, oxidative stability, and temperature-dependent stability of the CS containing bigels were evaluated and discussed.

2 | Materials and Methods

2.1 | Materials

Extra virgin olive oil, palm oil, sucrose, and cocoa powder were obtained from local markets in Turkey. CF was obtained from CP Kelko Company (Limeira, Brazil), and beeswax (BW) was from Hunny Bee (Trifecta Living Co., Canada). Double-distilled water was used for the preparation of samples and analysis.

2.2 | Methods

2.2.1 | Preparation of Bigel Samples

Bigel samples were prepared according to the proposed method with a slight modification (Saffold and Acevedo 2021). Oleogels were created by heating extra virgin olive oil to 90°C with a hot plate magnetic stirrer. BW (10%) was melted and added to the heated olive oil (90%), and the mixture was mixed in a hot plate magnetic stirrer at 90°C at 400 rpm for 30 min. The oleogel was cooled by keeping it at room temperature for 24 h.

The hydrogels were created by dissolving various amounts of CF (5% and 7.5%) in distilled water for 30 min at 70°C using a hot plate magnetic stirrer. The hydrogels were cooled by keeping them at room temperature for 24 h.

Bigels were created by heating and mixing oleogel and hydrogel samples at 70°C. The mixture was homogenized in an ultraturrax homogenizer (IKA-Works Inc.) at 12,000 rpm for 3 min. These procedures were applied for six different bigels made of 20:80, 50:50, and 80:20 hydrogel:oleogel (HG:OG) ratios and two different hydrogels that contain 5% CF and 7.5% CF. The samples were stored at +4°C until analyzed.

2.2.2 | Oxidative Stability of Bigels

The OXITEST device (Velp Scientifica, Usmate, MB, Italy) was used to assess the oxidative stability of bigels and CS. Bigels and CS samples were weighed as 20 g each in the sample cells of the device. The weighed samples were distributed homogeneously into the sample cell. Samples were examined at 90°C and 6 bar of oxygen pressure. Oxidative stability values of the samples were interpreted according to the induction period (IP) data obtained from the oxitest device (Akcicek et al. 2021).

2.2.3 | Preparation of CS

CS samples were prepared according to the method reported with minor modifications (Manzocco et al. 2014). Three bigel systems, each incorporating 7.5% CF-added hydrogel, were developed as replacements for palm oil because 5%-CF addition led to formation of weak gels ($G' < 10^3$ and close G' and G''). Four distinct CS were produced, incorporating these three bigel systems and palm oil (used as the control). First, granulated sugar was ground and sieved through a 60-mesh sieve to obtain sugar with a particle size smaller than 0.25 mm. Then, the oil phase (bigels and palm oil) was heated in a temperature-controlled water bath at 80°C until completely melted. A formulation consisting of 50 g sugar, 40 g oil phase, and 10 g cocoa powder, based on a 100 g CS, was manually blended using a spatula for 2 min to achieve a uniform paste-like consistency. The CS were initially cooled to 20°C and subsequently stored at 4°C until analysis. Prior to analysis, the samples were equilibrated to 20°C.

2.2.4 | Visual Appearance and Microscopy of Bigels and CS

Images of bigel samples and CS were photographed with a smartphone (iPhone 13) camera. Samples were examined under a polarized light microscope with a digital camera (Olympus BX41, Tokyo, Japan). A small amount of oleogel, hydrogel, and bigel was placed on a slide covered with a coverslip. Images of the samples were obtained using ×4 magnification.

2.2.5 | Rheological Properties of Bigels and CS

A rheometer (MCR 302; Anton Paar, Austria) equipped with a temperature- and stress-controlled Peltier heating system was used to perform a rheological analysis on every sample in triplicate at a temperature of 25°C.

Dynamic rheological analysis of the bigels and CS samples was performed with a parallel plate configuration. First, the linear viscoelastic region (LVR) was identified by running the amplitude sweep test at a strain value of 0.1%. The frequency range of 0.1–10 Hz was used for a frequency sweep test. According to the angular velocities of the samples, the storage modulus (G') and loss modulus (G'') were calculated. Power–Law model (Equations 1 and 2) and nonlinear regression were used to calculate dynamic rheological parameters (Yoo and Rao 1996):

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

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

The G' value specified in the formula is the storage modulus (Pa), the G'' value is the loss modulus (Pa), ω is the angular velocity value (s^{-1}), K', K'' are the consistency coefficient values (Pas^n) and n', n'' are flow behavior index values.

The samples were subjected to the Three-Interval Thixotropy Test (3-ITT) to determine the extent of recovery resulting from high deformation. The measurements of the 3-ITT method were conducted at two different shear rates: a constant rate of $0.5\,s^{-1}$ and a variable rate of $150\,s^{-1}$. The samples underwent a low shear rate of $0.5\,s^{-1}$ for 100 s in the first interval, followed by a high shear rate of $150\,s^{-1}$ for 40 s in the second interval. During the third interval, the samples were subjected to the same shear rate as delivered during the first interval, and their ability to recover was evaluated. The degree of deformation induced by high shear rate and the recovery after high shear application were utilized for analysis. The parameters related to deformation (%Def) and recovery (%Rec) were determined accordingly (Equation 3 and 4):

$$\text{Dr}(\%) = \frac{G_i - G_0}{G_i} \times 100 \tag{3}$$

$$\text{Rec}(\%) = \frac{G_{30}}{G_i} \tag{4}$$

In Equations (3) and (4), G_i denotes the G' values at the initial state of the batter, G_0_represents the G' values immediately after shear rate deformation, and G_{30} corresponds to the G' values of the batter within the first 30 s following shear rate deformation.

The thermal loop test is designed to replicate the thermal stresses brought on by temperature variations and oscillations that occur during the stages of sample processing, manufacture, storage, and transportation. For this purpose, CS samples were subjected to a thermal cycle at high temperatures (23°C–45°C). The angular frequency (ω) and strain value during the cycle were determined as 10 Hz and 0.5%, respectively. The samples' heating and cooling rates were adjusted to 11°C per minute. Cycle parameters were set for only 1 cycle, but the number of cycles of the samples varied according to the sample characteristics (Tekin et al. 2020).

2.2.6 | Statistical Analysis

Every dataset was subjected to three parallel measurements, and every sample was produced in duplicate. Then, mean values were calculated, and variances were evaluated using standard deviations. The research data were statistically analyzed using the SPSS 15.0 package application. The difference between group means was determined using the analysis of variance technique (ANOVA) ($p < 0.05$), and the difference was determined by the Duncan multiple comparison test. In addition, nonlinear regression analysis was performed using STATISTICA software (Stat Soft Inc., Tulsa, England) to determine the parameters of the power law model.

3 | Results and Discussion

3.1 | Rheological Properties of Hydrogel, Oloegel, and Bigels

Figures 1 and 2 illustrate storage modulus (G') and loss modulus (G'') values of oleogel, hydrogel, and bigel samples under dynamic frequency tests. In all gel samples, the G' value was found to be higher than the G'' value throughout the whole frequency range, and no cross-over was observed during the test, which is consistent with previous studies (Kaimal and Singhal 2023; Xie et al. 2023). This is an essential characteristic of typical gels (Zheng et al. 2020). The lack of crossover points between G' and G'' proves their dominant solid elastic properties (Ghiasi et al. 2022; Kaimal and Singhal 2023; Lupi et al. 2017).

Figure 1A,B illustrates that hydrogels exhibited frequency-dependent behavior more than oleogels. Also, oleogels displayed much higher G' and G'' values, indicating their viscoelastic nature. Higher CF addition resulted in increased G' and G'' values. Previous studies have demonstrated that, in gel systems and food products, CF addition increases G' and G'' due to its high water-holding capacity, which enhances structural integrity and the elastic network (Xu et al. 2025; Wedamulla et al. 2024; Korus et al. 2020). In Figure 2, among the prepared bigel samples, only 5% CF hydrogels, including bigels showed slight frequency-dependent behavior. The increasing oleogel ratio in bigel formulation led to higher G'

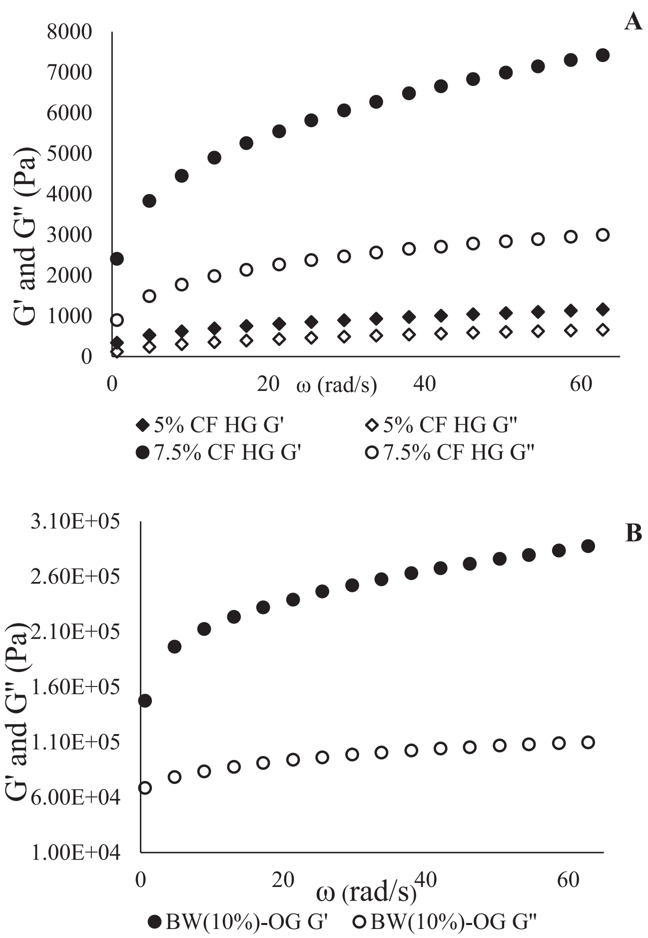

FIGURE 1 | Dynamic rheological features of citrus fiber (CF) hydrogels (A) and beeswax (BW) oleogel. G': storage modulus, G'': loss modulus, and ω: angular frequency. 5CF and 7.5CF show the ratio of CF in the produced hydrogels.

values in both hydrogel addition (5% CF and 7.5% CF hydrogels). Previous studies also found that higher hydrogel content in bigels caused a decline in elastic properties (Rehman et al. 2014). However, unlike 5% CF hydrogel containing bigels, the G' and G'' values of bigels with 7.5% CF-HG did not exhibit frequency dependency (Figure 2B). Therefore, oleogel fraction were found more dominant in the 5% CF than the 7.5% CF. In all bigel samples, an increase in the oleogel ratio increases G' value. The studies indicate that as the ratio of oleogel increases in bigels, the solid character also increases (Alkabaa et al. 2024; Eisinaite et al. 2023). Increased oleogel fractions may cause the production of bigels with a more robust crystalline network, contributing to an increase in G'. Furthermore, the interaction of the dispersion and continuous phases may have an impact on bigel's network strength (Han et al. 2024).

The Power–Law model was used to compare data from studies on the dynamic rheological properties of bigels. R^2 values are more than 0.97, indicating that this model can precisely simulate the dynamic rheological characteristics of the samples. As illustrated in Table 1, the K' value was found larger than the K'' value in all bigels, indicating viscoelastic solid behavior. The values of n' and n'' also indicate that the samples are viscoelastic solids and show shear thinning behavior. The solid quality of the samples becomes increasingly apparent as these values approach zero. In the bigel formulation, the n' value decreased as the oleogel ratio increased. The power law model parameters were consistent with the G' and G'' values. Among the bigel formulations, the 7.5% CF 20HG:80OG sample exhibited the lowest n'' value, indicating the most pronounced solid-like behavior. This sample also showed the lowest K''/K' ratio (0.23), reflecting the highest elastic character. In contrast, the highest K''/K' ratios (5% CF: 0.36; and 7.5% CF: 0.38) were observed in bigels containing 80% hydrogel within the bigel structure, indicating more viscous character. The increase in solid character in the bigel system with increasing oleogel is probably due to the high G' value of oleogel compared to hydrogel samples as shown in Figure 1.

3.2 | Oxidative Stability of Bigels

Oxitests are used to determine a product's oxidative stability based on the duration of the oxidation IP (Aksoy et al. 2021). Oxitests are used to calculate the oxidative stability of a product by measuring the length of the oxidation IP (Zhang et al. 2023). The palm oil exhibited an IP of 25:15 (h:min), indicating high oxidative stability. The IP values of the 20HG:80OG, 50HG:50OG, and 80HG:20OG bigel samples were found to be 18:58, 12:48, and 0:48 (h:min), respectively. The results show that bigels are less stable against oxidation than palm oil. The oleogel fraction of the bigels was composed of olive oil; consequently, the higher degree of unsaturation may account for the observed oxidative instability. The oxidative stability of bigel samples decreased with increased ratio of hydrogels. This difference can be attributed to the presence of water and the extensive water/oil interfacial area in bigels, which facilitates oxygen diffusion and subsequently enhances lipid oxidation (Samui et al. 2021). This is supported by previous findings indicating that the diffusion rate of oxygen is significantly higher in the aqueous phase compared to olive oil (Pénicaud et al. 2010). Consistently, converting the water phase to hydrogel form did not affect the oxidative stability of bigels favorably (Quilaqueo et al. 2022). Moreover, the oxidative stability has been found to increase with the quantity of oleogel in the bigel structure, and the bigel with a 20HG:80OG ratio exhibits strong oxidative stability since oil is trapped in the gel structure of oleogels, which slows down oxidation and provides great oxidative stability (Zhang et al. 2023).

3.3 | Microscopy and Visual Appearance

Optical microscopy images of pure oleogel, pure hydrogel, and bigel samples containing 7.5% CF at different oleogel-to-hydrogel ratios are displayed in Figure 3. The morphological structure of bigels is significantly altered by the HG:OG ratio. The BW oleogel exhibits a structure with oil crystals arranged in tiny, needle-like clusters. Molecules can be trapped within the compact structure created by incorporating oleogels into the hydrogel. In other words, the crystals become smaller than the hydrogel. Then, bigel showed that more compact structures were formed with larger droplet size for the higher hydrogel content (7.5% CF 80–20). The literature suggests that

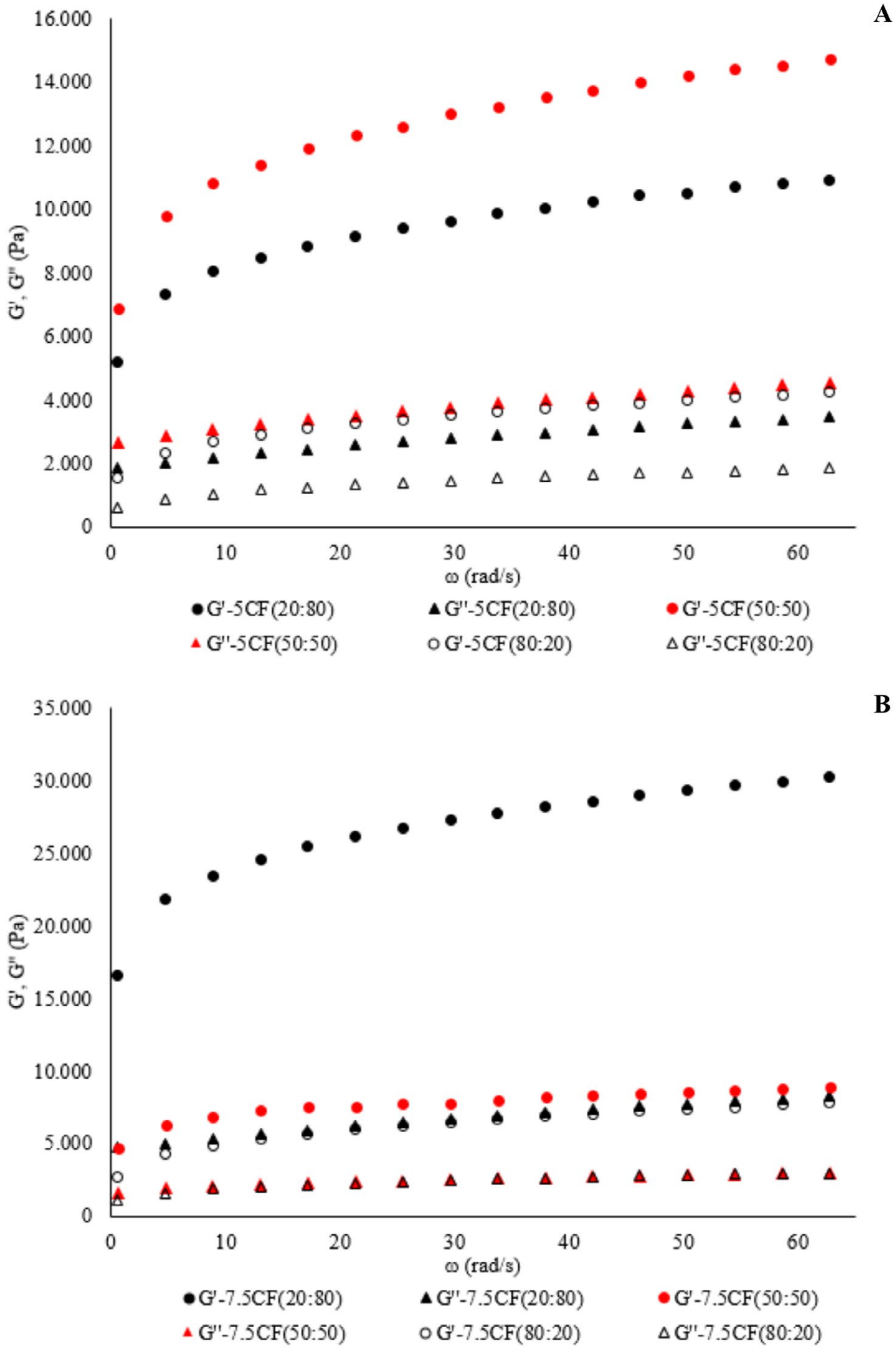

FIGURE 2 | Dynamic rheological properties of bigels at different hydrogel: Oleogel ratios (HG:OG). (A) Hydrogel formed with 5% CF and oleogel containing 10% BW and (B) hydrogel formed with 7.5% CF and oleogel containing 10% BW. G': Storage modulus, G'': Loss modulus, and ω: angular frequency.

the structural integrity of the bigel formulation rises with an increase in the oleogel ratio (da Silva et al. 2019; Habibi et al. 2022; Han et al. 2024).

The visual appearance of hydrogel, oleogel, bigel, and CS samples formulated with different hydrogel-to-oleogel (HG:OG) ratios is presented in Figure 4. Pure oleogels with beeswax were opaque and slightly yellowish in color. Furthermore, bigel samples showed a soft, solid-like texture and a pale yellow color that suggested they could be utilized as solid fats. In a previous study, bigels were also recommended as a butter alternative due to their similar visual features (Han et al. 2024). The color of the bigel samples changed from bright yellow to dark yellow when the oleogel ratio increased because of the color of BW (Moghtadaei et al. 2018). Furthermore, every bigel and cacao spread sample had a uniform texture and smooth structure. The color of the bigel samples changed from bright yellow to dark yellow when the oleogel ratio increased because of the color of BW

TABLE 1 | The power law parameters of dynamic rheological parameters of bigels.

Samples	K'	n'	R^2	K''	n''	R^2
5 CF (20:80)	4866.12 ± 1039.75^{d}	0.162 ± 0.002	0.99	1333.64 ± 329.02^{d}	0.187 ± 0.013	0.99
5 CF (50:50)	4787.87 ± 194.21^{d}	0.160 ± 0.001	0.99	1233.74 ± 71.28^{cd}	0.149 ± 0.001	0.97
5 CF (80:20)	1374.66 ± 365.17^{b}	0.241 ± 0.020	0.99	501.53 ± 12.009^{b}	0.280 ± 0.008	0.99
7.5 CF (20:80)	$16{,}321.62 \pm 1859.30^{e}$	0.133 ± 0.005	0.97	3705 ± 298.20^{e}	0.165 ± 0.002	0.97
7.5 CF (50:50)	4138.24 ± 298.10^{d}	0.176 ± 0.05	0.99	1421.10 ± 183.37^{d}	0.182 ± 0.002	0.97
7.5 CF (80:20)	2795.94 ± 175.92^{c}	0.238 ± 0.004	0.99	1057.04 ± 73.62^{c}	0.240 ± 0.005	0.99

Note: The ratios in the parenthesis show different hydrogel: oleogel ratios (HG:OG) in bigels. 5 CF and 7.5 CF show the ratio of CF in produced hydrogel. Lowercase letters (a–e) in the same column indicate the statistical significance of the difference between palm oil and bigel samples ($p < 0.05$).

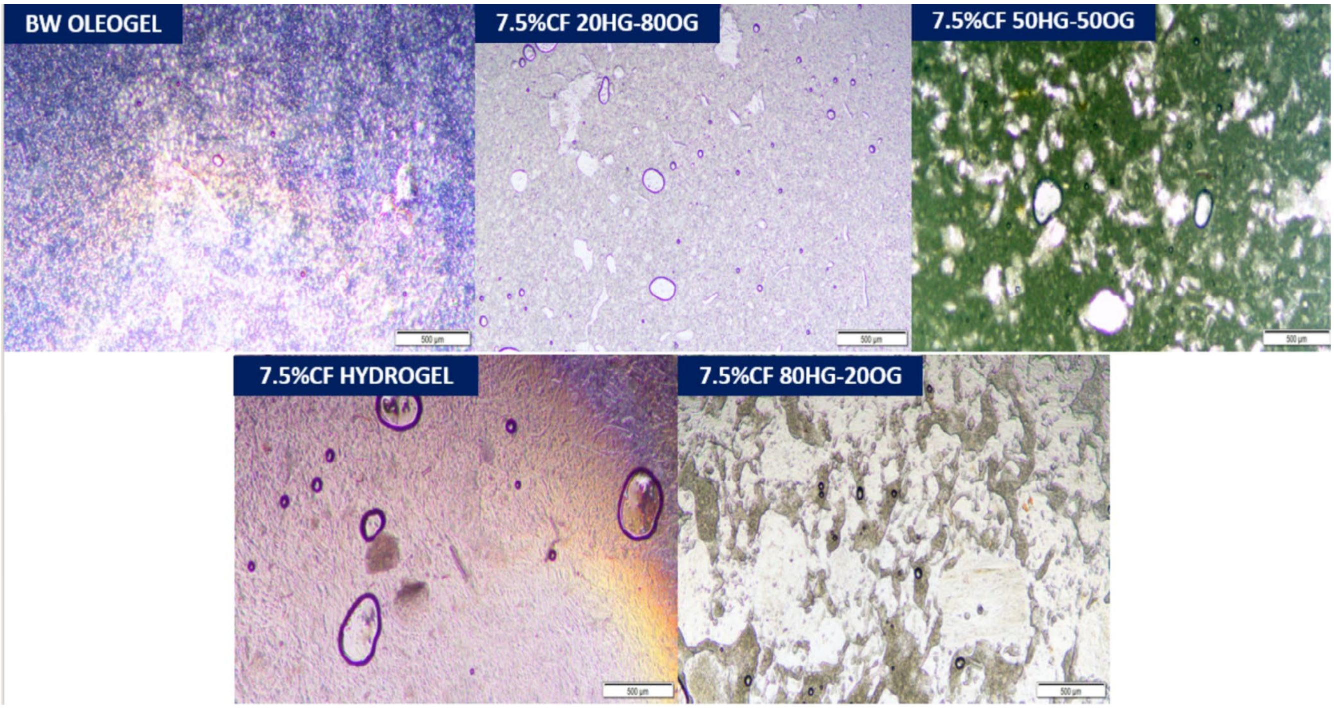

FIGURE 3 | Microscopy of beeswax (BW) oleogel and 7.5% citrus fiber (CF) bigels. HG: hydrogel, OG: oleogel. (Scale bar = 500 µm.)

(Moghtadaei et al. 2018). Furthermore, every bigel and cacao spread sample had a uniform texture and smooth structure.

3.4 | The Rheological Properties of the CS

3.4.1 | The Dynamic Rheological Properties and 3-Interval Time Test

The dynamic and 3-ITT rheological characteristics of the CS are shown in Figure 5. Figure 5A demonstrates that all of the cocoa spreadable samples have G' values that are larger than G'' values, indicating that the samples behave elastically (Acan et al. 2021; Mezger 2012). This gel-like behavior were also reported for hydrocolloid-based oleogel in chocolate spreads (Bascuas et al. 2021; Fayaz et al. 2017) and monoglycerides, beeswax, and propolis wax oleogel in chocolate spreads. Food spreads with a chocolate or hazelnut base are examples of semisolid or solid-like substances (Acan et al. 2021; Daubert et al. 1998). The increase in oleogel concentrations led to increased G' values of the CS. A more homogeneous structure was observed in spreads created with partial oleogel replacement, which is most likely due to the components' chemical compatibility and the structural network's strengthening (Bascuas et al. 2021; Shahamati et al. 2024). This increase may be attributed to the chemical compatibility and the formation of robust structural networks within the oleogels. The dynamic rheological properties of the CS were modeled by Power Law model and parameters were given in Table 2 (R^2 0.96–0.99). The K' of the CS higher than the K'' values indicating that viscoelastic behavior. Also, the K' and K'' values were found compatible with the G' and G'' values. The 20HG:80OG CS was found to have the highest K value, and the 80HG:20OG CS was found to have the lowest K value among the bigel CS. For CS, spreadability is an important criterion.

The three-interval thixotropy test (3-ITT) is a valuable rheological method used to evaluate the impact of sudden deformation or external force on the structural recovery of food systems. It

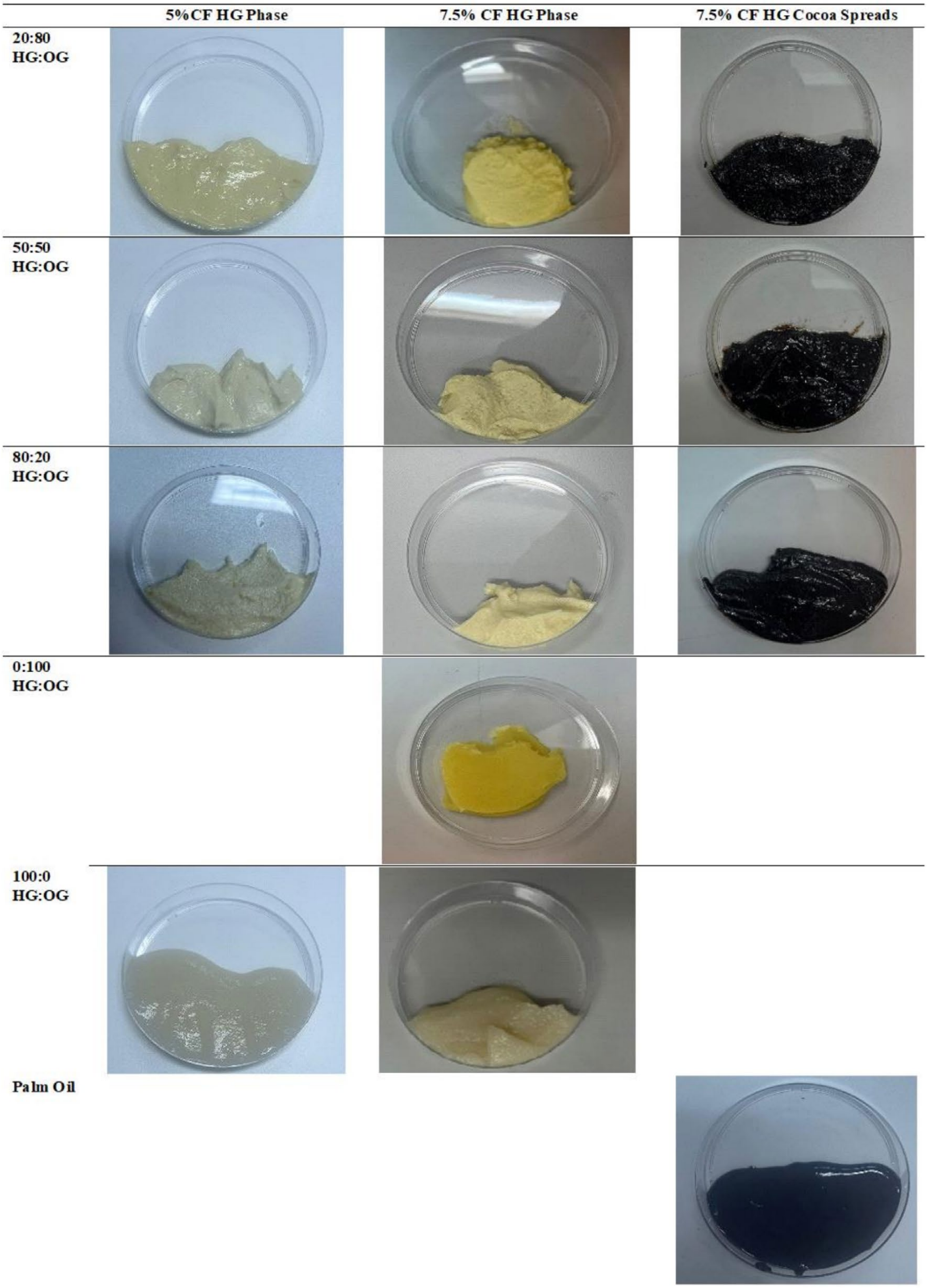

FIGURE 4 | Visual appearance of bigels and cocoa spreads. CF: citrus fiber, HG: hydrogel, OG: oleogel. HG: OG is hydrogel/oleogel ratio in bigels.

effectively simulates common food handling practices such as squeezing, shaking, and twisting (Toker et al. 2015). Following the application of shear, the recovery behavior of the gel network provides insight into the structural resilience of solid fat-containing systems (Yilmaz et al. 2021). This is particularly important for spreadable products, where the ability to recover from deformation directly affects their performance during spreading. Figure 5B illustrates the influence of applied shear rate on the recovery behavior of the samples. During the first interval, the storage modulus (G') of the CS increased with rising oleogel content in the bigel matrix. G' values of all samples remained stable in this phase. Upon increasing the shear rate from 0.5 to 150 s^{-1}, a pronounced decrease in G' was observed across all formulations, indicative of shear-thinning behavior. This phenomenon is attributed to the alignment of gel structure particles with the direction of shear, disrupting intermolecular interactions and reducing consistency (Ghiasi et al. 2022). Once the shear rate was reduced back to 0.5 s^{-1}, the G' values began to recover, with an upward trend evident in the third interval. CS formulated with bigel exhibited a recovery percentage (%Rec) ranging from 68.8% to 73.1% (Table 2), closely aligning with the threshold of 70% often cited as indicative of good thixotropic recovery. In contrast, the palm oil-based CS demonstrated significantly lower structural recovery, with a %Rec of 45.8 and a higher structural deformation (%Def) value of 72.4, compared to 32.5%–37.9% for bigel-containing samples (Table 2). These results suggest that the incorporation of bigel enhances the consistency and structural resilience of CS under mechanical stress. This observation is consistent with findings from previous studies, where bigel addition improved the recovery behavior of other semisolid food matrices such as mayonnaise (Alkabaa et al. 2024). Overall, bigel-based CS exhibit superior viscoelastic recovery following abrupt mechanical processing (e.g., homogenization, pumping) and consumer-related handling (e.g., squeezing, spreading), indicating their potential for maintaining structural integrity during both production and consumption (Alkabaa et al. 2024; Ghiasi et al. 2022; Toker et al. 2015). Cocoa and hazelnut spreads rheological characteristics are crucial and have an impact on spreadability (Acan et al. 2021). Spreads are expected to flow under applied deformation while resisting flow under their own weight. After deformation, the preservation of viscoelastic properties contributes to the stabilization of spreads on the product surface. Therefore, the incorporation of bigels may provide a more stable texture after spreading in CS due to their high %Rec values and elevated G'. The K''/K' ratio reflects the flowability of CS; a high oleogel proportion in bigels containing 80% oleogel resulted in the lowest K''/K' value (0.33). Higher fat content may reduce spreadability due to increased hardness, as indicated by higher G' values (Glibowski et al. 2008). Higher texture-based spreadability values, indicating greater resistance to spreading, whereas samples with lower G' values showed lower resistance to spreading (Aden et al. 2025). CS samples with higher hydrogel content showed decrease in G' value and lower resistance to spreading and easier to spread. Accordingly, improved ease of spreading may be achieved by using bigels with lower oleogel content. Nevertheless, spreadability remains a subjective attribute associated with the ease of uniform distribution over the surface.

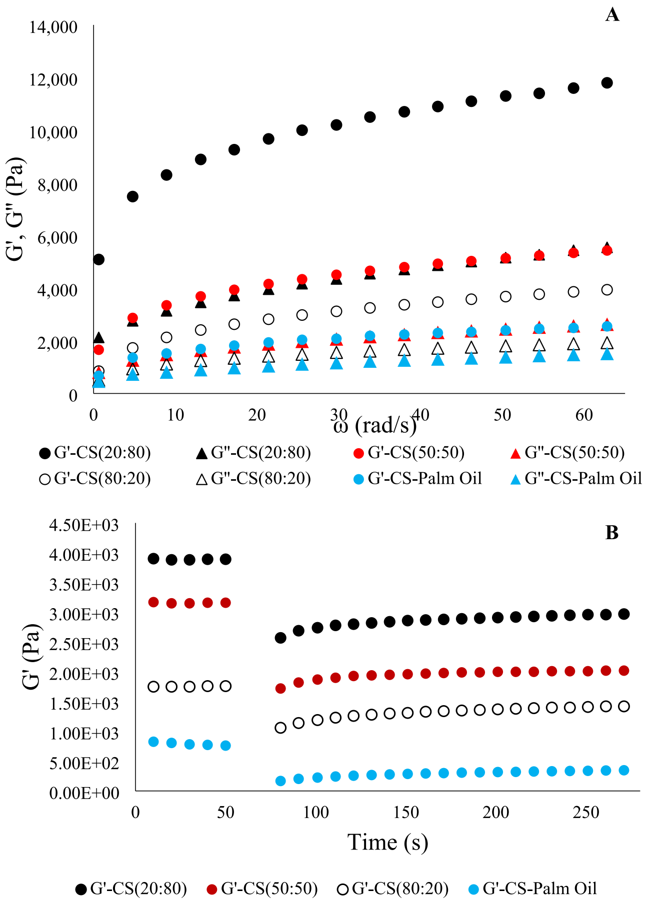

FIGURE 5 | Frequency sweep (A) and 3-ITT (B) rheological properties of cocoa spreads. HG:OG ratio in used bigels is given in parenthesis. G': storage modulus, G'': loss modulus.

3.4.2 | Temperature-Dependent Stability of CS

The thermal loop test applies heat treatment over a number of thermal cycles to determine thermal stability. Samples are subjected to several thermal cycles during thermal loop testing, ranging in temperature from 23°C to 45°C. This test simulates the effects of thermal stress on food throughout production, processing, storage, and transportation (Karasu et al. 2015). Figure 6 shows the temperature-dependent stability of CS containing 7.5% CF. The physical stability of the samples during thermal cycling is expressed by the change in their G' value. As shown in Figure 6, the storage modulus (G') decreased with increasing temperature up to 45°C, which was consistent with expected thermal behavior, while it increased upon cooling to 23°C, likely due to the enhancement in consistency at lower

TABLE 2 | Dynamic and 3-ITT rheological properties of cocoa spreads.

Samples	K'	n'	R^2	K''	n''	R^2	%Def	%Rec
CS—palm oil	498.63 ± 55.32[a]	0.326 ± 0.088	0.97	267.18 ± 48.56[a]	0.362 ± 0.059	0.99	72.6	45.8
CS (20:80)	5652.02 ± 87.81[d]	0.164 ± 0.021	0.96	1869.14 ± 18.40[d]	0.226 ± 0.045	0.97	37.9	72.4
CS (50:50)	1905.67 ± 29.14[c]	0.255 ± 0.055	0.99	811.06 ± 6.08[c]	0.283 ± 0.002	0.99	37.3	68.9
CS (80:20)	1136.53 ± 119.45[b]	0.313 ± 0.009	0.99	632.12 ± 48.211[b]	0.277 ± 0.008	0.99	32.6	73.1

Note: The ratios in the parentheses show different hydrogel (7.5 CF): oleogel ratios (HG:OG) in bigels used in cocoa spread formulation. Lowercase letters (a–d) in the same column indicate the statistical significance of the difference between the cocoa spreads ($p < 0.05$).

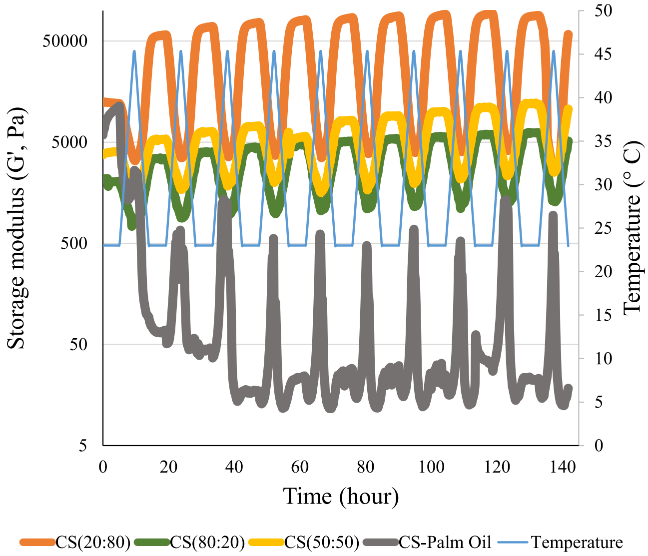

FIGURE 6 | Temperature cycle-dependent elastic behavior of bigel-added cocoa spreads (CS). The hydrogel/oleogel ratio of the bigels is given in parentheses.

temperatures. However, the fluctuation in G' values remained constant, indicating its stability. Significant G' change was observed in the palm oil, showing weak temperature stability. This suggests that their structure degraded easily during the cycles, which is detectable by using various loops. The results demonstrated a distinct difference in thermal behavior between CS formulated with bigels and those containing palm oil. In particular, the storage modulus (G') appeared largely unaffected by temperature changes, indicating notable thermal stability attributed to the presence of CF in bigels. CF formed a solid structure and increased the physical stability of the samples. The results showed that the samples exhibited excellent physical stability when subjected to thermal stress at higher temperatures in consistent with a previous study (Botega et al. 2021).

3.5 | Oxidative Stability of CS

The IP of palm-based cocoa spread was found to be 35.55 (h:min), whereas 80HG:20OG, 50HG:50OG, and 2HG:80HG bigels added CS exhibited IPs of 10.27, 15.13, and 18.33, respectively. The incorporation of bigels into formulation instead of palm oil decreased oxidative stability. This may be attributed to the increased rate of UFAs in bigels. A previous study showed oleogelation caused an increase in oxidative stability (Pan et al. 2021). This was due to the entrapment of oils in gel structure, which prevents air exposure. Oil structuring in an oleogel or bigel form can increase oil resistance to oxidation and thus reduce product deterioration. Higher oxidative stability may result from high antioxidant compounds found in the oil phase. The differences between the oleogel samples and the bigel samples may be attributed to the water content and large water/oil interface, which enables oxygen diffusion that can promote oil oxidation (Samui et al. 2021). The high diffusion rate of oxygen in the water phase compared with its diffusion in olive oil was previously reported (Pénicaud et al. 2010). Moreover, a previous study, which explored the effect of moisture content on the peroxide value of unrefined sesame oil, found that high moisture content increases the peroxide value, which in turn reduces the quality of the oil and shortens its shelf life (Akinoso et al. 2010). Consistent with previous findings, CS formulated with bigels containing higher proportions of hydrogel exhibited reduced oxidative stability. Although oleogelation is a well-established strategy for enhancing oxidative stability, additional formulation or processing approaches may be required to achieve oxidative stability levels comparable to those observed in palm oil-based CS.

4 | Conclusion

In this study, bigels were developed as palm oil alternatives in spreadable cocoa products. CF was used at varying concentrations in hydrogel preparation, while 10% beeswax and olive oil formed the oleogel phase. The study examined CF's role as a stabilizer and the impact of bigels as fat replacers. Changes in OG/HG ratios and CF concentrations affected the rheological, textural, and microstructural properties. Increasing the oleogel ratio, especially at 7.5% CF, enhanced solid-like characteristics (G', K'). Microscopy showed that oleogel reduced aggregation, and all samples exhibited a smooth, semisolid gel structure. These findings suggest that CF has potential as a structuring agent for producing bigels with desirable viscoelastic properties. The resulting bigels were incorporated into spreadable cocoa formulations, where samples containing 7.5% CF exhibited superior viscoelasticity and structural recoverability compared to those prepared with palm oil. The study's findings showed that CF has potential as a plant-derived resource for bigels manufacturing, and that CF synthesized with 25%, 50%, and 75% OG might be used as a fat replacer in CS formulations. Although the oxidative stability of CS improved with increasing oleogel content in the incorporated bigels, it did not reach the level observed in CS formulated with palm oil. To enhance oxidative stability, future studies may focus on incorporating antioxidant-active compounds into the gel systems.

Author Contributions

Ezgi Genc Yılmaz: investigation, writing – original draft, data curation, writing – review and editing, visualization. **Alican Akcicek:** writing – original draft, writing – review and editing, methodology, data curation. **Taylan Kablan:** data curation, methodology, investigation. **Muhammed Özgölet:** investigation, writing – review and editing, conceptualization. **Salih Karasu:** conceptualization, writing – review and editing, supervision, investigation, formal analysis.

Data Availability Statement

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

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