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Yogurt Enriched with Mango Peel Extracts (*Mangifera indica*) in Chitosan–Xanthan Gum Dispersions: Physicochemical, Rheological, Stability, and Antioxidant Activity

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Abstract: Different strategies have been developed to incorporate bioactive compounds into food products to improve their biological activity against degradation effects. The aim of this study was to develop natural yogurt enriched with mango (*Mangifera indica*) peel extracts (MPEs) in chitosan–xanthan gum dispersions and to evaluate their physicochemical, rheological, and antioxidant activity. A hydroethanolic extract of mango peel was obtained, with a yield of 33.24 ± 1.27%, a total content of phenolic compounds of 305.04 ± 10.70 mg GAE/g, and an antioxidant activity of 1470.41 ± 59.75 µMol Trolox/g. The encapsulation of the extracts was achieved using a chitosan–xanthan gum dispersion, resulting in the rheological characteristic of a strong gel. The incorporation of dispersions into yogurt did not modify the physicochemical properties and increased their bioactive properties. The rheological properties show samples with double yield points and a decrease in viscoelastic parameters. These results show dispersions as a strategy to incorporate bioactive compounds into dairy products, preserve the physicochemical and rheological properties of yogurt, and improve their biological activities (such as antioxidant activity) and activities related to the compounds found in the MPE.

Keywords: antioxidant activity; bioactive compounds; rheological properties; yield stress; yogurt

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1. Introduction

Yogurt is widely consumed and considered one of the most popular dairy products worldwide [1]. It is produced through a fermentation process using a culture of lactic acid bacteria, primarily *Lactobacillus delbrueckii* ssp. *bulgaricus* and *Streptococcus thermophilus* [2]. These bacteria are responsible for yogurt texture and gel matrix formation through casein aggregation and post-acidification [3]. Traditionally, various studies have focused on modifying the yogurt-making process to improve its flavors, texture, nutritional content, and biological activity [4,5]. Consequently, the production of yogurts with health-promoting compounds from plant extracts has become a major concern, involving, for example, yogurt with tea and coffee extracts [3], yogurt incorporated with cranberry pomace extract [6], and others. However, the addition of extracts can affect yogurt stability because of the viability of acid lactic bacteria with the accumulation of organic acids and the subsequent decrease in pH during storage [7]. Other authors have used some vehicles to gradually release extracts into yogurt and decrease the impact on cultures, such as yogurt using carrot waste extract encapsulated in alginate as an edible material, which can ensure the stability and long shelf life of the extract in yogurt [8], and also chitosan liposomes charged with cherry extract, added to yogurt as microcapsules, which improved the biological activity and some physical characteristics of yogurt [9].

Mango (*Mangifera indica*) is a tropical fruit highly sought after for its vibrant color and sweet and exquisite flavor, and it is considered a potential source of phytochemicals with intriguing biological properties [10]. Mango peel, which represents approximately 20% of

the fruit, contains a significant number of valuable components, including polyphenols, carotenoids, enzymes, vitamin E, and vitamin C. These components show a variety of biological properties, including antitumor, antioxidant, antimicrobial, anti-inflammatory, cardiovascular, and hepatoprotective effects [11,12]. Therefore, mango peel represents an alternative to the development of new products.

Natural plant extracts contain a diverse array of phytochemical compounds with biological activities. The incorporation of these extracts into food products poses significant challenges due to their poor solubility and potential impact on the functional and technological properties of the final product. However, natural plant extracts have been used in different areas of the food industry, such as coatings, to enhance their biological activity, [13] and as additives in different food systems [14,15]. Most bioactive compounds in food are not very stable and are easily degraded during processing, storage, transport, and digestion, so different strategies have been developed, such as those involving food gels [16], liposomes [9], and microcapsules obtained by spray-drying [17].

Gels are colloidal systems that form interconnected three-dimensional molecular networks with a density similar to that of liquids, although they have a structure similar to that of a solid [18]. The strength of gels depends primarily on the structure and concentration of the gum concerned, as well as factors such as ionic strength, pH, and temperature. Most gums are safe to eat, so they are widely used for the delivery of drugs and food additives [19], i.e., guar, tragacanth, xanthan, chitosan, acacia, and alginates [20], or in the design of encapsulation and delivery systems to carry different extracts, such as gels with grape extracts [21], lemongrass essential oil encapsulated in sodium alginate dispersion [22], hydrogels to encapsulate clove essential oil [23], and chitosan with xanthan gum for drug delivery due to their synergic interaction, promoting gel formation and expanding their range of applicability [24]. Furthermore, different delivery systems have been used to carry bioactive plant extracts, such as other solutions presenting polymer–polyphenol interactions that improve the functional properties of gels [22,25]; stable emulsions formulated with different polymers to carry essential oils [26,27]; foams used to preserve and deliver turmeric (*Curcuma longa* L.) and licorice extract, which presented interesting conservation properties due to foam systems that preserve polyphenols and antioxidants [28,29]; and emulsion gels to be applied in different food products as a replacement for saturated fats for these systems, with biological activity enhanced with natural extracts isolated from mango and grape [21,30], among other things.

The present study aimed to develop natural yogurt fortified with mango peel extracts (*Mangifera indica*) in chitosan–xanthan gum dispersions and to evaluate their physicochemical, rheological and biological activity.

2. Materials and Methods

2.1. Materials

Hydrochloric acid and ethanol (99.5% purity) were purchased from Panreac (for Barcelona/Spain). Acetic acid, NaOH, Folin-Ciocalteu reagent, 2,2 azinobis (3-ethylbenzothiazoline-6-sulfonic acid) diammonium salt (ABTS radical), and phenolphthalein were purchased from Sigma-Aldrich (for St. Louis, MO/USA). Commercially pasteurized and homogenized whole milk was purchased from a local Colombian market. All other reagents were analytical grade.

2.2. Mango Peel Extracts (MPEs)

Mango (*Mangifera indica*) var. Corazón was harvested and obtained from the province of Bolivar (Colombia) at commercial maturity. The fruits were cleaned with an aqueous sodium hypochlorite solution (100 ppm), then peeled and dried using a freeze dryer (Labconco Freezone 1.5 L, Kansas City, MO, USA). Subsequently, grinding was performed using a mill (IKA MF 10.2, Burladingen, Germany) in order to obtain mango peel powder with a particle size less than 250 µm in diameter. Subsequently, ultrasound-assisted extraction (UAE) was performed following the procedures described by Quintana et al. [13], Mieles-

Gómez et al. [30], and Lastra Ripoll et al. [31] with some modifications. Briefly, a ratio of 1:10 mango peel: hydroethanolic solution (50% ethanol and 50% water) was sonicated using an ultrasonic probe (ultrasonic process FS-1200 N) with an operating frequency of 60 kHz and an input power of 240 W at a maximum temperature of 40 °C for 20 min, and an ice bath was used to avoid sudden temperature rises. After that, the mixture was filtered, and the solvent was eliminated using a rotary evaporator (IKA RV 8, Burladingen, Germany) and then freeze-dried (Labconco Freezone 1.5 L, Kansas City, MO, USA). The extraction yield (Y%) of the MPE was calculated using Equation (1):

$$Y\% = \frac{\text{mango peel extract(g)}}{\text{mango peel(g)}} \times 100 \quad (1)$$

2.3. Preparation of Chitosan–Xanthan Gum–MPE Dispersions

The xanthan gum–chitosan–MPE dispersion (XG–XH–MPE) was developed following the procedure described by Cofelice et al. [22]. A dispersion of xanthan gum (1% *w*/*v*) and chitosan (1% *w*/*v*) in water, as a continuous phase, was obtained by continuous stirring at 25 °C for 4 h. Subsequently, MPE (as dispersed phase) was added in different percentages (1, 3 and 5%) by homogenization at 10,000 rpm for 7 min using a digital Ultra-Turrax (IKA T-25, Germany). The dispersions were stirred at 4 °C until use.

2.4. Yogurt Preparation

The yogurt was prepared following the procedure proposed by Qiu et al. [32] with some modifications. The previously pasteurized cow milk was heated to 43 °C. Milk was inoculated with 0.03 g L^{-1} of a starter culture of probiotic yogurt with *Lactobacillus delbrueckii* ssp. *bulgaricus* and *Streptococcus thermophilus*; then, the milk with the culture was incubated at 42 ± 1 °C until the pH reached 4.5. The yogurt was cooled and stirred at 300 rpm for 2 min, then 3% of the chitosan–xanthan gum–MPE dispersions were added. Finally, 200 mL of each sample was stored at 4 °C.

2.5. Water Holding Capacity (WHC) and Syneresis

Water holding capacity (WHC) and syneresis susceptibility were determined following the procedures described by Ismail et al. [33] and Mohamed Ahmed et al. [1]. Briefly, 15 g of the sample was centrifugated at 4000 rpm for 15 min at 4.0 ± 1 °C, and then the separated whey weight was obtained. WHC and syneresis were calculated according to Equations (2) and (3):

$$\text{WHC}(\%) = \frac{(\text{Yogurt weight} - \text{Separated whey})}{\text{Yogurt weight}} \times 100 \quad (2)$$

$$\text{Syneresis}(\%) = \frac{\text{Separated whey}}{\text{Yogurt weight}} \times 100 \quad (3)$$

2.6. Physicochemical Analysis

The pH value of the yogurt samples was evaluated using a glass electrode pH meter (FoodCare HI-98161, Hanna, Romania). The titratable acidity (TA) of the yogurt samples was determined by titration. Briefly, 10 g of yogurt was mixed with 20 mL of distilled water and titrated with NaOH (0.1 N) in the presence of phenolphthalein, and the results were expressed as a percentage of lactic acid.

2.7. Color Analysis

Color analysis was measured using a colorimeter (Konica Minolta CR-20, Sakai, Japon). A CIELAB system was used to obtain the values of the parameters of lightness (L*), red–

green chromaticity (a*), and blue–yellow chromaticity (b*). Equations (4) and (5) were used to calculate the chroma index (C*) and color variation (ΔE*), respectively.

$$C^* = \left[\left(a^* \right)^2 + \left(b^* \right)^2 \right]^{0.5} \quad (4)$$

$$\Delta E^* = \left[\left(\Delta L^* \right)^2 + \left(\Delta a^* \right)^2 + \left(\Delta b^* \right)^2 \right]^{0.5} \quad (5)$$

2.8. Total Phenolic Content (TPC) and Antioxidant Activity

The total phenolic content (TPC) was determined using the method described by Singleton et al. [34]. The antioxidant activity was determined by scavenging ABTS free radicals according to the method described by Re et al. [35].

2.9. CG-MS

The identification and quantification of bioactive compounds from mango peel extracts were carried out following the procedures described by Mieles-Gómez et al. [30] employing a GC-MS-FID using 7890D Agilent Technologies (Santa Clara, CA, USA). A DB-5 ms capillary column (Agilent, Tokyo, Japan) (30 m × 0.25 mm × 0.25 μm) was used. Chromatographic methods started at 25 °C, then increased from 120 °C to 220 °C (40 °C/min, hold time 0.5 min), then increased to 290 °C (4 °C/min, hold time 8 min). The flame induction detector temperature was 300 °C; the hydrogen flow rate was 40 mL/min; the air flow rate was 450 mL/min; the tail gas flow rate was 1.03 mL/min; and the injection volume was 1.0 μL. Compounds were identified with the NIST 2014 mass spectral library. The relative content of each component was obtained using the peak area normalization method for quantification.

2.10. Rheological Analysis

The rheological characterization was carried out following the procedure described by Quintana et al. [13] using a Haake Mars 60 modular advanced controlled stress rheometer system (Thermo Scientific, Karlsruhe, Germany) equipped with a cone and plate geometry (1°; 35 mm diameter and 0.053 mm diameter GAP). Viscous flow tests were carried out in a steady state without shear history, analyzing the variation in viscosity in a range of deformation rates between 10^{-3} and 10^{3} s^{-1} at 25 °C. A stress amplitude sweep test was carried out within the range of 0.01–1000 Pa and with an angular frequency of 1 Hz for all samples, to determine the linear viscoelastic regime (LVR). Subsequently, the frequency sweep was carried out at 0.1 Pa to maintain stress in the LVR, within the range of 0.01–100 rad·s^{-1}.

2.11. Statistical Analysis

The assays were performed in triplicate. Data were analyzed with unidirectional ANOVA using Statgraphics software (version centurión XVI) in order to determine statistically significant differences ($p < 0.05$) between samples.

3. Results and Discussion

3.1. Mango Peel Extracts

Mango peel extracts (MPEs) were obtained using a hydroethanolic solution (50% ethanol and 50% water) as solvent. An extraction yield of 3.24 ± 1.27% was obtained in association with increased mass transfer due to the creation of waves by ultrasonic power, which promotes the penetration of solvent into vegetable tissues by violent implosions of bubble gas in the solvent. These transform potential energy into heat, resulting in a decrease in the viscosity of the solvent, which allows an easy penetration of the solvent into the plant matrix [36]. Then, by combining all these effects during sonication, there is an improvement in mass transfer and a diffusion of the bioactive compound of mango in the

solvent [37]. This means that the extraction of the yield depends on various factors such as cultivars, ripening state, and conditions during processing such as time and power, but mainly in the extraction method, such as ultrasound help [38,39].

The MPE presented 305.045 ± 10.70 mg GAE/g of extracts, recovering 101.52 ± 7.38 mg GAE/g of dry matter (DM) and a TEAC value of 489.25 ± 38.09 µMol Trolox/g DM. The obtained TPC values were similar to mango var. Keitt (103.82 mg GAE/g of DM) from Spain [40] and considerably higher than mango var. Alphonso from India (49.89 and 69.84 mg GAE/g of DM) [41] and mango var. Tommy Atkins from Brazil (6 to 13.82 mg GAE/g of DM) [42]. In addition, antioxidant activity presented similar values to Castañeda-Valbuena et al. [43] for by-products of mango var. Haden (239.1 to 1155.83 µMol Trolox/g of DM) and values higher than mango var. Tommy Atkins extracts, with values ranging from 46.7 to 73.8 µMol Trolox/g of DM [44]. TPC and antioxidant activity in mango depend mainly on genetics, cultivars, soil conditions, geographic site of production, maturity stage, postharvest practices [45]. The main compounds in mango peel that have been described are dietary fiber, polyphenols, antioxidants such as vitamin C and E, and other components with demonstrated health-promoting activities [46,47]. Therefore, MPE presents the interesting bioactive activity of mango by-products, which can be used as a raw material for innovative functional food developments as an ingredient with antioxidant activity and a great number of phytochemicals and.

Subsequently, a GC-MS analysis of MPE revealed the presence of various compounds such as 4H-pyran-4-one,2,3-dihydro-3,5-dihydroxy-6methyl; palmitic acid (Diethyl phthalate); linoleic acid (9,12-octadecanoic acid); methyl oleate (9-octadecanoic acid); stearic acid (Octadecanoic acid); and maltol. Among these, certain compounds demonstrate significant potential to exert antioxidant effects and offer various health benefits. These benefits may contribute to the prevention of chronic diseases such as cardiovascular disease, cancer, neurodegenerative disorders, and age-related conditions [48]. Bioactive substances and their metabolites, including fatty acids predominantly present in mango peel extract (MPE), have been proposed to participate as antioxidants in the mechanism of free radical elimination [49]. Furthermore, the compound 4H-pyran-4-one,2,3-dihydro-3,5-dihydroxy-6methyl has been identified as one of the compounds present in an aqueous extract that exhibits antioxidant properties due to its capacity to remove free radicals [50], which may have been facilitated by the nature of the solvent used. This compound has been attributed to a strong antioxidant capacity when isolated [51]. Maltol is a natural synergistic aromatic compound with broad-spectrum properties and a natural antioxidant and has been shown to protect nerve cells, inhibit peroxidation caused by diabetes, exhibit significant antitumor activity, and effectively inhibit liver inflammation [52,53]. Therefore, the compounds identified in MPE can contribute to its antioxidant character when used as an active ingredient in formulations.

3.2. Dispersions Enriched with Bioactive Compounds

Four dispersions of xanthan gum–chitosan with different percentages of MPE were obtained—0 (XG–CH), 1 (XG–CH–MPE-1), 3 (XG–CH–MPE-3), and 5% (XG–CH–MPE-5)—to evaluate the effect of the percentage of the extract on the rheological properties of the dispersions and their applications in yogurt. Dispersions did not show any phase separation; MPE was always dispersed in the dispersion, as bioactive compounds are entrapped by polymer systems and form complexes, which can increase the solubility and bioavailability of target bioactive molecules under gastrointestinal conditions and also reduce oxidation reactions and prolong the shelf life of some fresh products [54–56].

The color parameters a* (+, red; −, green) and b* (+, yellow; −, blue) (Table 1) are good color indicators and provide information about how this dispersion may affect or influence the final color in the matrix in which it will be applied [57]. The dispersion without extract (XG–CH) was visually more transparent than the sample with MPE. The dispersions with MPE presented lower values for a*, and this parameter decreased as a higher proportion of extract was added, portraying a subtle reddish tint that was not readily noticeable to

the naked eye and decreased as a higher proportion of extract was added. Small positive values of b* indicate that the dispersions possess a slight yellowish hue, which becomes increasingly pronounced with the addition of MPE. The brightness (L*) of the samples increased significantly with the addition of MPE, which means that the dispersions with the addition of MPE were brighter ($p < 0.05$), and the chroma (C*) showed a significant increase ($p < 0.05$). The total color difference (ΔE) was evaluated related to the color aspect that was evaluated. The ΔE value increases with the percentage of MPE. Therefore, increasing MPE concentration causes an increase in overall color difference, with this trend presented in their visual appearance.

Table 1. Color parameters obtained for chitosan/xanthan gum dispersions enriched with bioactive compounds from MPE.

Sample Code	L*	a*	b*	C*	ΔE
XG–CH	7.40 ± 1.26 ^{a}	1.30 ± 0.10 ^{a}	0.16 ± 0.06 ^{a}	1.31 ± 0.09 ^{a}	
XG–CH–MPE-1	13.70 ± 0.45 ^{b}	0.62 ± 0.31 ^{b}	3.69 ± 1.87 ^{b}	3.74 ± 0.90 ^{b}	7.43 ± 0.21 ^{a}
XG–CH–MPE-3	14.56 ± 2.73 ^{b}	0.52 ± 0.15 ^{b}	7.20 ± 1.20 ^{c}	7.21 ± 0.25 ^{c}	8.34 ± 0.36 ^{a}
XG–CH–MPE-5	19.18 ± 0.36 ^{c}	0.30 ± 0.04 ^{b}	9.16 ± 0.99 ^{c}	9.17 ± 0.99 ^{c}	10.59 ± 0.72 ^{b}

Data are the mean ± standard deviation. Different letters in the same columns express statistically significant differences ($p < 0.05$).

The flow curves for each dispersion are shown in Figure 1. In all cases, a decrease in viscosity (η) with the increase in shear rate ($\dot{\gamma}$) was observed; this behavior is characteristic of a non-Newtonian fluid, a type of shear-thinning fluid [58]. This behavior is related to structural damage and deformation in the entanglement created when the system is in equilibrium before being subjected to deformation; then, as the shear rate increases, the elongated particles begin to align in the flow direction. In addition, the system presents a loss of viscosity since the reticular structure of polysaccharides is broken and the entanglement structure cannot be recovered. This is caused by shear stress, thus showing a reduction in resistance to flow, mainly due to the hydrodynamic forces that dominate the flow properties of the material, as opposed to interparticle forces and Brownian motion [59].

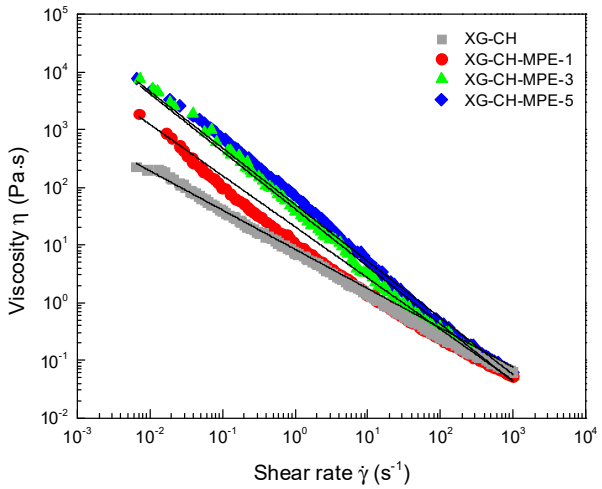

Figure 1. Viscosity η (Pa·s) vs shear rate (s^{-1}) and fitting of the flow curves with the Ostwald de Waele model of MPE-enriched dispersions at 25 °C.

Different authors have shown dispersions with shear-thinning behavior, explained by the structural deformation of the network, including systems with natural extracts such as in the case of film formation solutions prepared with chitosan/zein to incorporate α-tocopherol in the system [60], and also when using of chitosan and gelatin as carriers of

grape and jabuticaba extracts [61]. Tudrorache et al. [62] observed the same behavior for three different polysaccharides with different phytochemicals.

Since all dispersions presented a non-Newtonian fluid of the shear-thinning type, the flow curves obtained were adjusted to the Ostwald de Waele model, and this model is frequently used to describe the rheological properties of shear-thinning fluids, primarily in polymer and foam solutions [63]. The model is described by Equation (6):

$$\eta = k\dot{\gamma}^{n-1} \quad (6)$$

where η is the apparent viscosity, k is the consistency index and n is the flow behavior index.

Adjustment parameters are shown in Table 2. Although the parameter n shows significant changes with the addition of MPE, n was less than 1 in all cases, corroborating the shear-thinning behavior [64]. Further, k increases with the concentration of MPE, which means that the apparent viscosity increases; this could be explained by the creation of intermolecular interactions between polymers and polyphenols. Consequently, the greater the strength of the interactions, the higher the viscosity of the system, principally at low shear rates [65] when the system is in equilibrium. Even at a low shear rate, different types of chemical linkages could be formed between chitosan, xanthan gum, and polyphenols, such as hydrophobic interactions, van der Waals force, and hydrogen bonds. Furthermore, the large number of polyphenols can also affect the chitosan/xanthan gum interactions when dispersions are subjected at high shear rates [66]. Unlike our findings, where viscosity decreased with an increase in MPE, other studies have presented an increase in viscosity at higher extract values, and this depends mainly on the composition of the extract. Meng et al. [67] found that peanut skin extract produced an increase in viscosity of film formation solutions with an increase in extract, but for the use of peanut shell extract, the viscosity of the solutions decreased with the amount of extract used, and this was attributed to the different composition of extracts. Additionally, Tong et al. [68] observed that grape peel extract increased viscosity, but only up to a critical concentration, at which the viscosity of the solution decreased drastically.

Table 2. Ostwald de Waele model parameters for the viscous test of dispersions enriched with MPE at 25 °C.

Sample Code	K	n	R^2
XG–CH	50.32 ± 7.21^{a}	0.01 ± 0.03^{a}	0.96
XG–CH–MPE-1	49.73 ± 2.98^{a}	0.02 ± 0.01^{a}	0.99
XG–CH–MPE-3	20.69 ± 1.57^{b}	0.11 ± 0.01^{a}	0.97
XG–CH–MPE-5	8.41 ± 0.58^{c}	0.31 ± 0.01^{a}	0.97

Data are the mean ± standard deviation. Different letters in the same columns express statistically significant differences ($p < 0.05$).

The viscoelastic properties of the dispersions are shown in Figure 2. The storage modulus (G') was higher than the loss modulus (G'') throughout the mechanical spectrum studied, exhibiting a gel-like character with a strong network [69]. To analyze the effect of the addition of MPE on the viscoelastic properties of dispersions, G' and G'' as a function of the frequency were fitted to the power law by Equations (7) and (8).

$$G' = k'\omega^{n'} \quad (7)$$

$$G'' = k''\omega^{n''} \quad (8)$$

where k' and k'' represent G' and G'' modulus (Pa·$s^{n'}$ and Pa·$s^{n''}$, respectively), and dimensionless parameters n' and n'' are the frequency dependence parameter (time stability) of G' and G'', respectively [70].

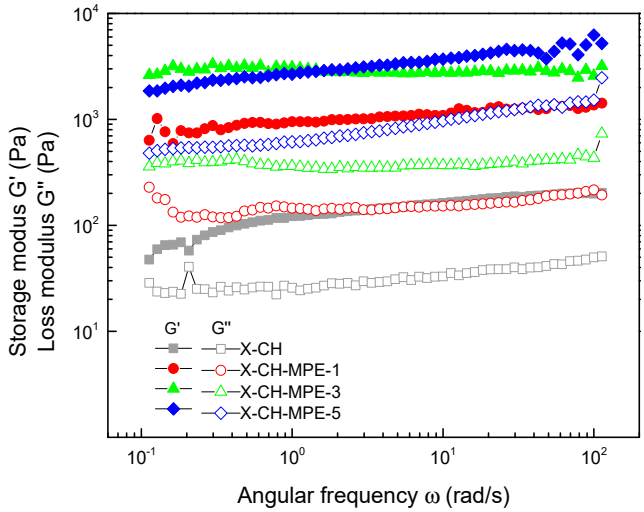

Figure 2. Viscoelastic properties of dispersions of chitosan/xanthan gum enriched with bioactive compounds from MPE at 25 °C. Frequency sweep module G′ and G″ (Pa) vs angular frequency (ω) (rad/s).

Table 3 shows the fitting values of the viscoelastic parameters using the power-law model. Systems with high consistency, such as concentrated dispersions, are structurally more similar to solids in terms of their elasticity than to liquids in terms of their viscous part, due to the ability to store more energy than they dissipate or lose during the test. This is characteristic of most food materials that have been classified as viscoelastic solids [64].

Table 3. Rheological properties of chitosan/xanthan gum dispersions enriched with bioactive compounds from MPE adjusted to the power-law model.

Sample Code	k'	n'	R^2	k''	n''	R^2
XG–CH	111.96 ± 1.88 ^{a}	1.14 ± 0.05 ^{a}	0.93	27.25 ± 0.52 ^{a}	1.11 ± 0.06 ^{a}	0.92
XG–CH–MPE-1	926.74 ± 9.51 ^{b}	1.08 ± 0.03 ^{b}	0.91	144.31 ± 3.16 ^{b}	1.05 ± 0.08 ^{a}	0.93
XG–CH–MPE-3	2921.44 ± 25.41 ^{c}	0.99 ± 0.03 ^{b}	0.95	374.85 ± 8.02 ^{c}	1.02 ± 0.08 ^{a}	0.97
XG–CH–MPE-5	2677.49 ± 41.88 ^{d}	1.14 ± 0.05 ^{a}	0.93	623.59 ± 20.19 ^{d}	1.20 ± 0.09 ^{ab}	0.95

Data are the mean ± standard deviation. Different letters in the same columns express statistically significant differences ($p < 0.05$).

The dispersions did not show a significant dependence on the frequency, since all values of n' and n'' presented values close to 1 ($n \approx 1$); these parameters indicate the frequency dependence (time-stability), suggesting that there are no strong changes in their viscoelastic properties because of bond creation between the polymeric components (chitosan and xanthan gum). Previously, these polymeric systems have demonstrated their ability to bind to bioactive components, resulting in a stronger gel matrix with any temporal instability [24,71]. Furthermore, this association presented significant changes as the storage modulus (G') and loss modulus (G'') presented an increase in their values when the percentage of MPE increased. This is a result of the polymer–polyphenolic links throughout the hydroxyl group and the -OH or -COOH groups found in phenolic compounds [67]. The addition of 5% MPE also increased the loss modulus G″ with respect to the storage modulus G′ for the XG–CH-5% dispersion, with the viscous component being more representative; therefore, the energy required to deform the system will be lower [72].

3.3. Yogurt with Dispersions Enriched with Natural Extracts

Four yogurts (Figure 3) were developed with the aim of boosting the bioactive potential of a pivotal dairy product. These formulations were designed to serve as efficient

delivery systems and have been shown to be effective in safeguarding bioactive compounds throughout the digestion process. They achieve this by maintaining optimal ionic strength and pH levels, promoting cell absorption, and preserving the biological activity of the extract and its bioactive constituents under challenging environmental conditions [73,74]. To assess the amount of extract used in the yogurt formulation without negatively affecting the final sensory, physicochemical, rheological quality, or safety attributes of the yogurt, four yogurts were prepared with three percentages of dispersions obtained. We used a control sample (Y-XG–CH) as well as XG–CH–MPE-1 (Y-XG–CH–MPE-1), XG–CH–MPE-3 (Y-XG–CH–MPE-3), and XG–CH–MPE-5 (Y-XG–CH–MPE-5).

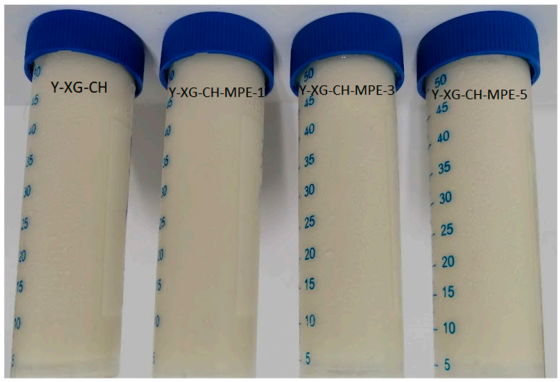

Figure 3. Yogurt with the addition of dispersions enriched with MPE.

3.3.1. Physicochemical Properties

The physicochemical properties of yogurts are shown in Table 4. The pH of yogurt did not vary (values between 4.41 and 4.49), but the acidity presented a slight increase in lactic acid (from 1.062 to 1.278% ($p > 0.05$)), related to normal acidification due to the activity of lactic acid bacteria. Mohamed Ahmed et al. [1] found different results in yogurt fortified with *Argel Hayne* leaf extract of *Solenostemma*, as did Ogusku-Quintanilha et al. [2] for yogurt with *Moringa oleifera extract*, as the pH of their samples decreased with the addition of extract. Then, the dispersion of xanthan–chitosan–MPE improves the acidity of yogurt, taking into account that the bioactive compounds are sensitive to variations in pH, leading to the production of organic acids, which decreases pH because of the release of H + ions [75].

Table 4. Physicochemical parameter of yogurts with dispersions enriched with bioactive compounds.

Sample Code	pH	TA % Lactic Acid	Syneresis %	WHC %	TPC mg GAE/g	TEAC µMol Trolox/g
Y-XG–CH	4.49 ± 0.02 ^{a}	1.062 ± 0.07 ^{a}	58.30 ± 4.01 ^{a}	41.69 ± 4.09 ^{a}	3.69 ± 0.28 ^{a}	8.05 ± 0.26 ^{a}
Y-XG–CH–MPE-1	4.47 ± 0.01 ^{a}	1.134 ± 0.07 ^{a}	58.85 ± 1.15 ^{ab}	41.14 ± 1.12 ^{ab}	9.66 ± 0.72 ^{b}	11.74 ± 0.08 ^{b}
Y-XG–CH–MPE-3	4.45 ± 0.01 ^{a}	1.152 ± 0.07 ^{a}	58.46 ± 2.17 ^{ab}	41.53 ± 2.22 ^{ab}	18.75 ± 0.71 ^{c}	21.76 ± 0.03 ^{c}
Y-XG–CH–MPE-5	4.41 ± 0.01 ^{a}	1.278 ± 0.05 ^{a}	55.78 ± 2.12 ^{b}	44.21 ± 2.07 ^{b}	23.65 ± 1.03 ^{d}	31.90 ± 0.75 ^{d}

TA: Titratable acidity. TPC: Total Phenolic Content. TEAC: Trolox Equivalent Antioxidant Capacity. Data are the mean ± standard deviation. Different letters in the same columns express statistically significant differences ($p < 0.05$).

The WHC and syneresis did not vary between the control sample (Y-XG–CH), and samples with 1 and 3% MPE (Y-XG–CH–MPE-1 and Y-XG–CH–MPE-3), with values of 58.30 ± 4.01, 58.85 ± 1.15 and 58.46 ± 2.17, respectively, for syneresis, and 41.69 ± 4.09, 41.14 ± 1.12 and 41.53 ± 2.22 for WHC, respectively. Then, yogurt with a higher addition of MPE (Y-XG–CH–MPE-5) decreased syneresis in yogurt samples ($p < 0.05$), which was associated with the interaction of polyphenols in the extract and some yogurt proteins, enhancing protein cohesion by changing the structure and affinity and thus holding more whey due to the firmness of the gel matrix of yogurt [1,76]. Other studies have shown this

behavior, where the addition of different extracts enhances WHC, thus reducing syneresis—for example, in the case of yogurt enriched with cherry extract encapsulated in chitosan, there was a significant decrease in syneresis when the extract was added [9]; the reduction in syneresis was reported due to the addition of riceberry extract in yogurt [7]; and an increase in WHC values was reported, followed by a decrease in syneresis, in yogurt with the addition of *Rosa rugosa* cv. *Plena* flower extract [32]. These parameters are important in determining the quality and stability of yogurt over time [32] since it is the ability of yogurt to retain whey or the aqueous part that contains soluble proteins and minerals and the loss of the ability to retain water that results in an increase in syneresis. Through syneresis, yogurt loses whey, and this is related to changes in microstructure [77,78].

3.3.2. Total Phenolic Content (TPC) and Antioxidant Activity

The total phenolic content (TPC) and the antioxidant activity (ABTS* scavenging activity) of the yogurt enriched with MPE are shown in Table 4. TPC and ABTS* scavenging activity for Y-XG–CH were 3.69 ± 0.28 mg GAE/g and 8.05 ± 0.26 µMol Trolox/g, respectively, and these values increased significantly with increasing MPE concentration in yogurt in all cases compared to the control ($p < 0.05$). TPC and antioxidant activity in yogurt containing the lowest percentage of extract ((Y-XG–CH–MPE-1) increased by 261.78% and 145.83%, respectively; for Y-XG–CH–MPE-3, the increase was 508.13% and 270.31%, respectively; and finally, the highest increase in yogurt bioactive activity was obtained for yogurt with the highest percentage of MPE (Y-XG–CH–MPE-5), which was 640.92% and 396.27%, respectively, presenting interesting results to improve yogurt biological activity by enriching with mango (*Mangifera indica*) by-products. This increase in the bioactivity of yogurt enriched with MPE is mainly related to the number of phenolic compounds that are added through the extract [1]. This evidence provides a basis for affirming that the incorporation of MPE through dispersions in yogurt enhances the bioactive properties and antioxidant activity and therefore its potential health benefits. Furthermore, other similar reports have been registered in different publications, such as in the case of yogurts with different plant extracts used as pigments and to improve their bioactivity, obtaining values in the range of 42.75 to 69.14 mg GAE/L of yogurt [79]; this is also evident in yogurts with *Rosa rugosa* cv. The plena flower extract presents TPC values of 25 up to 112 µg GAE/mL of yogurt, and this extract increases the antioxidant capacity of yogurts. Moreover, [1] found that yogurt fortified with the *Argel Hayne* leaf extract of *Solenostemma* presented TPC values ranging from 23.38 to 31.14 mg of GAE/100 g of yogurt, the extract also improved antioxidant activity at higher concentrations, and the results reported in this investigation were always higher. Consequently, fortifying yogurt with natural plant extracts rich in bioactive compounds, such as phenolics, may improve the health benefits of products, mainly dairy products, as they have a great daily demand [80].

3.3.3. Analysis of Color

The color properties of yogurt are some of the most important attributes that affect product marketability and directly determine consumer acceptance. In Table 5 are listed the color parameters evaluated for the different yogurts obtained. The parameter a* indicates that samples have a slight greenish tint, imperceptible to the eye, and b* shows that samples have a yellow tint. In addition, it can be observed that in all cases the addition of MPE did not affect the color of the final yogurt (ΔE values of between 1.64 ± 1.50 and 2.80 ± 1.39). Since no significant differences ($p > 0.05$) were found between yogurts with MPE and the control yogurt for any of the parameters, it can also be corroborated in the change of color ΔE, since the addition of MPE showed low values.

Table 5. Color parameters obtained for yogurt samples enriched with bioactive compounds from MPE.

Sample Code	L*	a*	b*	C*	ΔE
Y-XG–CH	76.32 ± 4.32 [a]	−2.18 ± 0.32 [a]	16.17 ± 0.34 [a]	71.18 ± 3.71 [a]	--
Y-XG–CH–MPE-1	75.60 ± 2.13 [a]	−2.16 ± 0.06 [a]	16.48 ± 0.20 [a]	70.45 ± 1.66 [a]	2.89 ± 1.66 [a]
Y-XG–CH–MPE-3	77.88 ± 2.89 [a]	−2.19 ± 0.14 [a]	16.49 ± 0.50 [a]	72.29 ± 2.51 [a]	1.64 ± 1.50 [a]
Y-XG–CH–MPE-5	77.69 ± 2.05 [a]	−2.15 ± 0.23 [a]	16.23 ± 0.71 [a]	72.30 ± 0.65 [a]	2.80 ± 1.39 [a]

Data are the mean ± standard deviation. Different letters in the same columns express statistically significant differences ($p < 0.05$).

The yogurts show a variation in color when extracts are used directly as additives, and this depends on the concentration used in yogurt. This has been corroborated with the use of plant pigment, where all the studied parameters of stirred yogurt (L*, a*, and b*) were significantly different [79]. However, contrastingly, when a delivery system is used for the extracts, the color is not strongly affected, such as in the case of yogurt containing encapsulated carrot waste extract using alginate, which did not present significant changes in color parameters [8], or the case of coating chitosan with sour cherry extract and applying it to yogurt, which exhibited the same behavior [9]. Considering that the addition of the extract did not present significant changes in the color of the final yogurt, MPE in xanthan gum–chitosan as a delivery system can be used for the formulation of dairy products to enhance bioactive potential without affecting one of the main factors consumers consider when choosing these products—the visual appearance.

3.3.4. Rheological Properties

Physical properties are vital for the popularity of yogurt products among consumers. As it depends on different factors, such as ingredients in the formulation, processing time, or different treatments, it is imperative to understand the effects of the addition of MPE on rheological characteristics, which at the same time are of great importance for sensory attributes in yogurt, principally because preferences for the body and texture of yogurt vary throughout the world for consumers [1,74] and because viscosity is one of the most important parameters for yogurt since it is highly related to formulation composition [81].

Figure 4 shows the flow properties of the prepared yogurts. A typical response of a shear-rate-dependent or non-Newtonian fluid is observed (Figure 4a), exhibiting a decrease in viscosity as the shear rate increases, which is caused by the reduction in electrostatic repulsion, the intermolecular interaction, and, principally, the breakdown of the weak bonds in the internal gel matrix of yogurt formed by flocculated casein micelles networks. This effect is a result of the increase in shear forces and the hydrodynamic forces in the fluid, which accelerate the process until the particles are aligned in the flow direction [81,82]. Most yogurts produced are within the non-Newtonian fluid classification because they usually present a weak viscoelastic gel with shear-thinning characteristics [74].

Since conventional yogurt is primarily composed of two ingredients (pasteurized milk and cultures), some other components have been used to give different properties to yogurt, and each ingredient plays a critical role in viscosity or firmness and is directly related to the composition of the formulation [74]. In this case, the component of interest is the percentage of extract in dispersions. The viscous flow shows the slight influence of dispersions containing MPE on the viscosity values of the different curves. Viscosity decreases in all cases involving extract implementation due to the ability of phenolic compounds to interact with milk protein, directly affecting the functionality of dairy products. This is also explained by the contracting effect on the micelle matrix of the casein and the dissolution of calcium and inorganic phosphate when there is a decrease in pH. As has been described for yogurt samples with the addition of MPE [9], even a small decrease in pH produces a decrease in charge, which affects the development of a stable colloidal system, making it weaker [6]. Previously, different researchers have reported

this phenomenon and the relationship existent between the reduction in viscosity and the implementation of phenolic compounds, such as in the case of Jaster et al. [78] and İçier et al. [80], where authors attribute the decreasing viscosity to the nature of the extract.

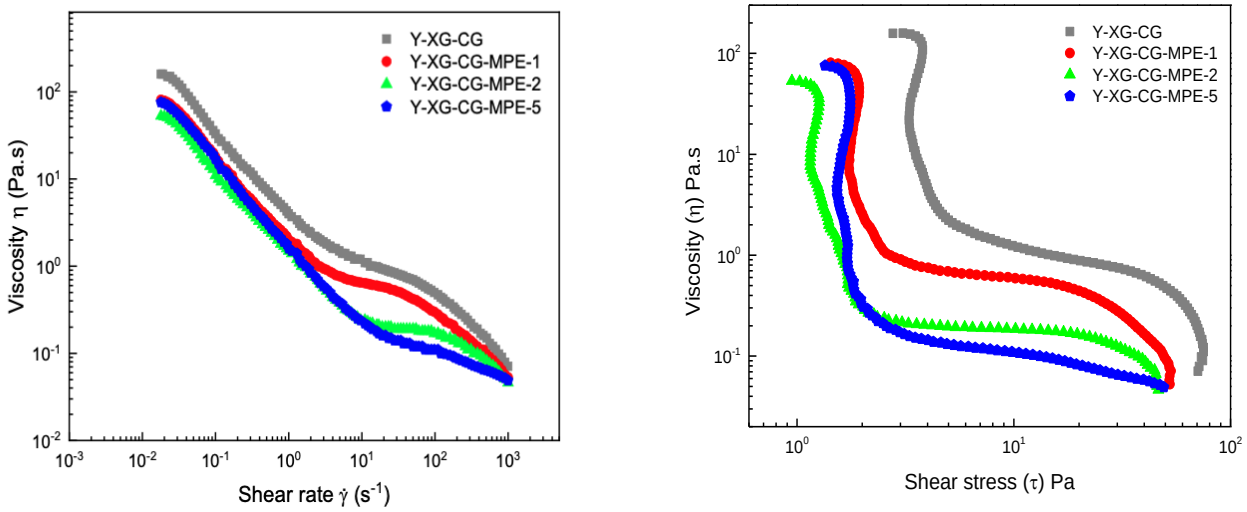

Figure 4. Flow properties of yogurt samples enriched with bioactive compounds from MPE. (**a**) viscous flow test. (**b**) Shear stress.

Although the flow behavior of yogurt was shear-thinning, Figure 4b shows the viscosity curves against the shear stress, where it can be observed that there exists a yield point in two different zones of the curve during the decrease in viscosity. The first is when there is low shear stress applied, known as the static yield point, given by the first drop in viscosity and the fluid yield point, which take place at great values of stress; and the second point could be attributed to the destruction of the structure formed by the yogurt gel and the yogurt sensitivity when they present a quasi-stable state and are subjected to the shear stress at which this state is broken [82]. Some other researchers have presented this characteristic behavior when shear stress and shear rate have values close to 50 Pa and 10 s^{-1}, respectively, such as in the case of yogurt with the addition of monk fruit extract [83] and in yogurts with the addition of hydrocolloid from a squash and xanthan gum mixture [82].

The viscoelastic properties of yogurt are dominated by different stages and aspects of the production process, such as temperature, heating pretreatment, starter culture, time and fermentation conditions, milk composition, and storage conditions of milk, which allow the formation of the internal matrix of yogurts. These properties are very useful in the food industry and consequently for yogurts, mainly to describe the strength of the internal gel structure and how it can change with the formulation of this dairy product [74,84].

Figure 5a presents the stress sweep, where the linear viscoelastic region (LVR) and the nonlinear viscoelastic region are shown. In the LVR, which takes place up to values close to 10 Pa, the storage modulus is greater than the loss modulus ($G' > G''$) and presents a long plateau zone until great values of stress are reached. Then, the modules begin to decline, losing the linear characteristic and exhibiting the static yield stress (τ_{0-1}) (previously mentioned). Additionally, the second yield stress, identified as dynamic yield stress (τ_{0-2}), listed in Table 6, occurred outside the LVR when the storage modulus tended to be in a quasi-stable state, and the increase in stress produced a sharp drop, typical for the yogurt gel network [82]. For yogurt samples prepared, the yield stress parameters τ_{0-1} and τ_{0-2} presented significant differences ($p < 0.05$) with the addition of MPE, since the yogurt system consisted of aggregated particles within a gel matrix and meant a stress value was

necessary to deform the yogurt matrix. Additionally, the change in pH as a result of the addition of MPE produced some instability in the colloidal system [3,85].

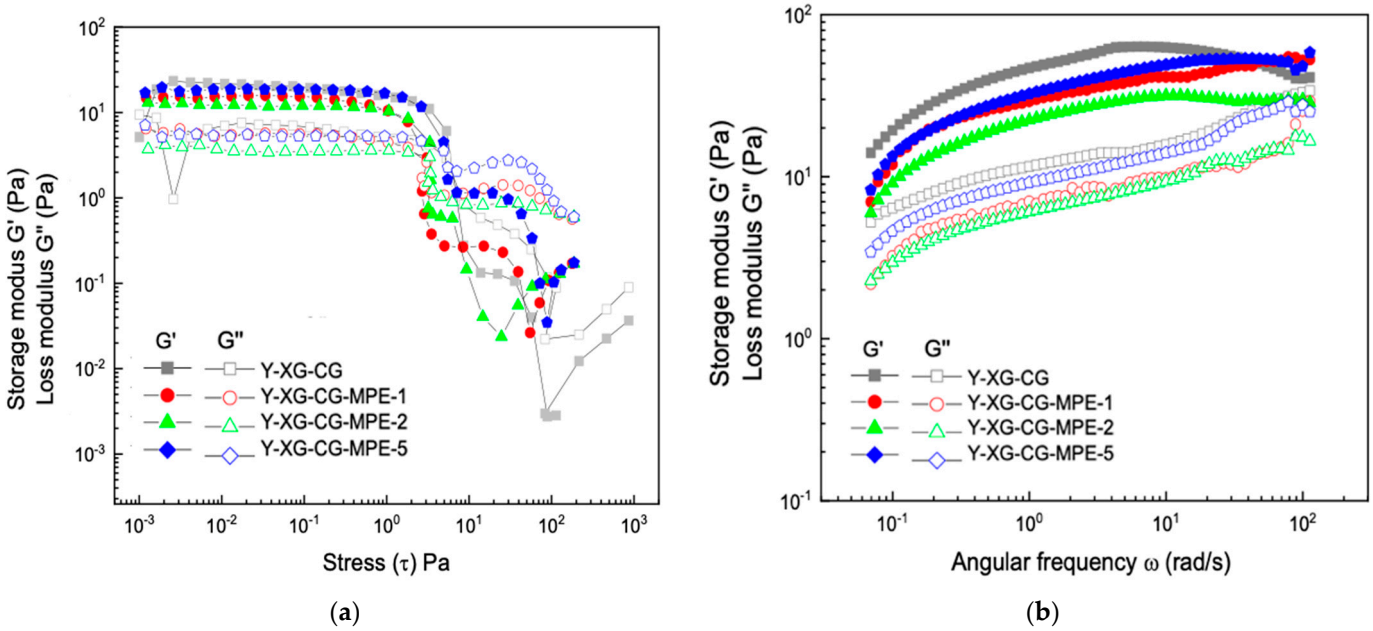

Figure 5. Viscoelastic properties of yogurt samples enriched with bioactive compounds of MPE. (**a**) Stress sweep, (**b**) Frequency sweep.

Table 6. Yield stress parameters in viscoelasticity of yogurt samples enriched with bioactive compounds of MPE.

Sample Code	τ_{0-1} Pa	τ_{0-2} Pa	$G'=G''$ Pa
Y-XG–CH	2.83 [a]	35.71 [a]	10.14 [a]
Y-XG–CH–MPE-1	0.82 [b]	15.09 [b]	2.44 [b]
Y-XG–CH–MPE-3	0.30 [c]	9.29 [c]	2.39 [b]
Y-XG–CH–MPE-5	1.05 [d]	19.27 [d]	3.18 [c]

The data present the CV coefficient of variation CV < 0.5. Different letters in the same columns express statistically significant differences ($p < 0.05$).

The frequency sweep is shown in Figure 5b, portraying the response of dynamic rheological parameters (G'andG'') that provide valuable insights into the internal structures inside the prepared yogurts. In the entire mechanical spectrum, yogurt samples showed weak gel-type behavior, since the storage modulus values were higher than the loss modulus ($G' > G''$). Furthermore, there was a slight increase in both moduli when the frequency increased, thus presenting characteristics of a cross-linked or physical gel due to the gel formation of β-lactoglobulin disulfide interaction or hydrophobic association formed by casein particles [86]. Then, the elastic component was predominant against the viscous component, as previously reported throughout the LVR, and is typical for yogurts [32,74]. This viscoelastic behavior is determined by the formation of a gel network due to the aggregation of casein as the main structural component in yogurts, which occurs during acidification caused by the metabolic process of cultures [86]. The addition of MPE presented a slight decrease in both modules, mainly for Y-XG–CH–MPE-1 and Y-XG–CH–MPE-3, as previously described, due to the reduction in colloidal stability and the increase in Y-XG–CH–MPE-5 compared to the other yogurts with extracts. This was due to the increase in polyphenol–polymer interactions, which then resulted in a reduction in the aggregation of the casein network [9,81].

The great importance of viscoelastic essays is to take control of processing variables since most of these processes can affect and lead to undesirable changes in yogurt microstructure, rheology, texture, and consequently, sensory parameters [86]. Measurements within the LVR are tested in a non-destructive mode, but in the mouth, the destruction of the structure is irreversible, so the viscoelastic properties can suggest the initial mouth sensation for consumers [81].

4. Conclusions

The hydroethanolic extract of mango peel exhibited high total phenolic content and was successfully dispersed throughout the gel matrix of the chitosan–xanthan gum dispersions. However, it caused a noticeable color change that could potentially affect the final color of the product if it was used in greater proportions than those used in this investigation.

Rheological characterization revealed that the chitosan–xanthan gum dispersion displayed non-Newtonian fluid behavior, specifically shear-thinning. The dispersion exhibited viscoelastic properties resembling those of a gel, with higher G' values than G'' values. Furthermore, mango peel extract (MPE) demonstrated a stable interaction with the chitosan/xanthan gum dispersion.

Yogurt samples enriched with MPE using chitosan–xanthan gum dispersion as a delivery system showed increased biological value. This enhancement was attributed to elevated levels of total phenolic compounds and a subsequent improvement in antioxidant activity. Furthermore, the incorporation of MPE did not significantly affect the color as a sensory parameter. However, the structure of the yogurt experienced a decrease in gel strength due to a change in pH, which affected the colloidal properties. Consequently, there was a decrease in viscosity and viscoelasticity, which are initial parameters that affect texture.

The findings of this study provide an opportunity for the technological and functional utilization of mango peel, a by-product of the fruit processing industry, to obtain functional ingredients. Furthermore, it proposes a viable delivery system for bioactive compounds, specifically in yogurt formulation. Yogurt, being one of the most important dairy products with inherent functional properties, can benefit from the incorporation of mango peel extracts, which are rich in phenolic compounds and exhibit significant antioxidant activity.

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