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Applicability of the Cox–Merz Relationship for Mayonnaise Enriched with Natural Extracts

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Abstract: The Cox and Merz rules are empirical correlations between the apparent viscosity of polymers with the effect of shear rate and the complex dynamic viscosity with the effect of frequency. In this study, the rheological properties of mayonnaise-type emulsions enriched with *Averrhoa carambola* extracts were investigated using small-amplitude oscillatory shear (SAOS) and steady shear flow. The results showed that the shear-thinning behavior of the samples was non-Newtonian with yield stress and had time-dependent characteristics, as evidenced by curves from non-oscillatory measurements. It was observed that the experimental data on the complex and apparent viscosity of the samples obeyed the Cox–Merz rule.

Keywords: mayonnaise; natural extracts; viscoelastic properties; rheology; Cox–Merz rule

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1. Introduction

The viscoelastic properties of complex fluids can be determined by oscillatory deformation; therefore, the fluid deforms by applying shear strain $\gamma(t)$ or shear stress $\tau(t)$ induced by the harmonic periodic oscillation of frequency (ω) to obtain the transfer function $\gamma(\omega j) \overset{G(\omega)}{\rightarrow} \tau(\omega j)$, where $G^*(\omega) = G'(\omega) + G''(\omega)j$ and $G'(\omega)$ are the storage modulus (i.e., elastic) and $G''(\omega)$ are the loss modulus (i.e., viscous modulus). For these, Cox and Merz [1] suggested an empirical correlation between the apparent viscosity of the polymers to the effect of the shear rate and the complex dynamic viscosity $\eta^*(\omega)$ to the effect of frequency; additionally, they reported that the steady-state viscosity $\eta_{ss}(\dot{\gamma})$ and the complex viscosity $\eta^*(\omega) = \left[\sqrt{G'(\omega)^2 + G''(\omega)^2}\right]/\omega$ are similar in the sense that $\eta_{ss}(\dot{\gamma}) = \eta^*(\omega)|_{\omega=\dot{\gamma}}$.

The onset of the Cox–Merz rule of uniform apparent viscosity and complex viscosity and its applicability range is still lacking a detailed explanation, i.e., Bistany and Kokini [2] were pioneers in the application of the Cox–Merz rule to food and found that dynamic viscosity $\eta^*(\omega)$ was much higher than steady viscosity $\eta_{ss}(\dot{\gamma})$ in many cases, indicating the nonlinear nature of biological reactions; then, the Cox–Merz superposition rule was applied to some starch pastes [3,4], salep glucomannan milk drinks [5], tomato juice [6], and sage seed gum [7]. However, there are many examples of materials that do not comply with the Cox–Merz rule, such as worm-like, inulin–waxy maize starch mixtures [8], micellar systems [9], salad dressing-type emulsions [10], polymer-like liquid [11], ice cream mixes [12], and *Eruca sativa* starch mixtures [13], among many other systems.

Mayonnaise is an oil-in-water emulsion in which oil is the dispersed phase and water is the dispersion medium obtained by emulsifying edible vegetable oil in vinegar (aqueous phase) [14]. The rheological characteristics of mayonnaise have been extensively studied; it presents a non-Newtonian-type shear thinning behavior with yield stress and time-dependent characteristics [15].

Several articles have been published on the flow properties and oscillatory shear measurement of mayonnaise [16–18]. For steady shear measurement, the models of the power law [19], Carreau [20], Herschel–Bulkley [21], and Casson [19] have been widely used to describe the flow properties of mayonnaise-type emulsions.

Oscillatory shear measurement has exhibited a pronounced plateau with a storage modulus (G′) higher than the loss modulus (G'') as a solid-like gel [22,23]. Various studies investigated the rheological properties of mayonnaise-type emulsion, including the flow and viscoelastic properties of the products. Ma and Barbosa-Canovas [24] stated that the viscoelastic properties (elastic modulus and complex viscosity) of mayonnaise increased with increasing oil and xanthan gum concentration. Manciani et al. [25] demonstrated that alginate concentration and molecular weight influence functional mayonnaise properties. Dolz et al. [26] reported that modified starch with xanthan gum increased emulsion thixotropy. Flamminii et al. report that the addition of olive leaf phenolic extract, free form and encapsulated in Alginate/Pectin microcapsule, decreased friction factors obtained by tribological measurements. Roshandel et al. [27] determined the effect of oleaster as a fat replacer led to obtaining samples with homogeneous structures and good stability, high antioxidants, and suitable viscoelastic properties; but there is little literature on the rheological properties of phenol-rich mayonnaise-type emulsions. However, if the emulsion is not properly formulated and processed, it is highly susceptible to physical instability due to its chemical, physical, and structural properties [28] and phase inversion, creaming, and flocculation, and Ostwald maturation can cause emulsion instability [29–31]. The addition of phenol compounds affects the degree of instability [32], which is significantly different from the surface activity of mayonnaise. The stability of the system determines the appreciation of the consumer for emulsified food products by contributing to quality and sensory properties, such as creaminess, aroma taste perception, and rheological parameters that define stability [33,34].

Because the physical and structural properties of the emulsion are related to food components, which can affect the physical properties of the water phase, different physical, structural, and sensory properties may result. In the mayonnaise industry, the empirical textural index depends on the viscosity of the final product and is used to measure the viscoelasticity. The empirical textural index related to the viscoelasticity of the final products, which depends on the colloid mill gap, is used in the mayonnaise industry. As the colloid mill gap increases, the size of the oil droplets increases, and the thickness of the product decreases. The viscosity characteristics of mayonnaises are closely related to the close packaging of droplets, which interact with each other in the matrix; then, the addition of polyphenol compounds induces some surface activity and affects the emulsification process [35,36] in the case of complex real formulations [32]. This is one of the main characteristics of the rheological properties of oil–water emulsions, such as the viscosity value [37]; that is, the use of phenol-rich olive oil or artificially enriched olive oil in the production of mayonnaise significantly affected the dispersion of the corresponding mayonnaises, such as emulsions [38] and mayonnaise based on extra-virgin olive oil. The gel network of mayonnaise samples prepared with extra-virgin olive oil presents a smaller number of links with weaker interactions [35].

In particular, no attempt has been made to study the rheological properties of microstructural food products enriched with phenolic compounds in the aging process, especially in dynamic modules using small dynamic oscillatory deformation.

To design unit operations, process standardization, and develop a quality product from conventional ingredients, it is necessary to characterize raw materials and products in terms of rheological properties [6]. Flow behavior curves or rheograms are the most useful representations to describe the rheology of samples. However, several phenomena in a viscoelastic sample may not be described in terms of viscosity functions, and thus the elastic behavior needs to be considered and measured. Understanding the viscoelastic properties is, therefore, valuable in the design of processing conditions, the selection of appropriate machinery for material handling, and the quality control of product stability.

Dynamic oscillating rheometers help monitor the development of the structure over time without breaking the structural elements that form in the sample over time. In mayonnaise enriched with the *Averrhoa* extraction system, it is also important to understand the interaction of components to improve the rheological properties and storage stability of mayonnaise products [39]. Samples that obey the Cox–Merz rule can be correlated with the structure, and then a simple ambient pressure technique will become available to provide the essential shear-thinning properties of lubricants [40]. Furthermore, this may provide additional information on the differences between the dynamics of a food system, particularly when modeling these systems is sought [9]. The comparison between the steady-state flow curve and complex viscosity provides a quantification of shear-induced structural breakdown in food systems [2,41]. Samples that obey the Cox–Merz rule are typical of solid-like gels, which are not associated with any structure alteration [18]. Moreover, the evolution of other rheological parameters related to shear-induced structural breakdown, such as the critical strain for the onset of nonlinear viscoelastic behavior and the relative deviation of the Cox–Merz rule, indicates a more developed and resistant structural network [10]. Then, the applicability of the Cox–Merz rule is used for mayonnaises [22] and salad dressing-type emulsions [10,26]. Therefore, the present work investigated the applicability of the modified Cox–Merz rule to mayonnaise enriched with *A. carambola* extract. This rheological study involves small-amplitude oscillatory shear (SAOS) and steady shear flow.

2. Materials and Methods

2.1. Materials

Xanthan gum, citric acid, and lecithin were purchased from Tecnas SA (Medellín, Colombia). Ethanol (99.5%). Hexane and glacial acetic acid (99.5%) were obtained from Panreac (Barcelona, Spain). Sodium hydroxide (NaOH) was obtained from EMSURE. Acetic acid, Tween 80, phenolphthalein, gallic acid standard (>98%), anhydrous sodium carbonate (99.5%), phenylmethyl siloxane (5%), diammonium salt of 2,2′-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid) (ABTS, ≥95%), and Folin–Ciocalteu reagent were purchased from Sigma–Aldrich (St. Louis, MO, USA). Extracts of *A. carambola* were used with 4661.14 ± 15.51 mg Acid Gallic Equivalent (GAE)/g of extract and 81.67 ± 0.95 µMol Trolox/g of extract.

2.2. Formulation of Mayonnaise

Mayonnaise with different percentages of *A. carambola* extract (0, 0.1, 0.2, 0.3, and 0.4 wt%) was made following the procedures described by Quintana et al. [42] and Guo et al. [43] with some modifications. Initially, a continuous phase was carried out by dispersion of xanthan gum (0.5 wt%) in distilled water (18 wt%) with Tween 80 (1.5 wt%) until being constantly stirred for 10 min at 25 ° C to achieve a homogeneous solution. Then, whole eggs (10 wt%), salt (3% wt), vinegar (3 wt%), sodium citrate (1 wt%), and extract (0, 0.1, 0.2, 0.3, or 0.4 wt%) were mixed and stirred for 15 min. Subsequently, olive oil (64 wt%) was added in a continuous phase by homogenization at 10000 rpm for 5 min using an Ultra Turrax homogenizer. The samples were packaged and refrigerated (5 °C) until analysis.

2.3. Emulsion Stability

The mayonnaises obtained containing extracts of *A. carambola* were placed in glass containers and then kept at 20–25 °C for 28 days. Emulsion stability (ES) was calculated by Equation (1):

$$ES = \left(\frac{e_v}{t_v}\right) \times 100 \quad (1)$$

where e_v and t_v are the emulsified volume and the total volume of the emulsion, respectively.

2.4. Rheological Analysis

The stationary and dynamic assays were performed following the methodology described by Mieles-Gómez et al. [44] using a controlled stress rheometer (Haake Mars 60, Thermo-Scientific, Bremen, Germany) with a rough plate geometry of 35 mm in diameter and 1 mm in the gap. The samples were equilibrated 10 min before the rheological assay to ensure the same mechanical and thermal history.

2.4.1. Steady Shear Flow Rheology

The viscous flow test was carried out at a temperature of 25 °C with a shear rate range of 10^{-3} to 10^{3} s^{-1} for 20 min.

2.4.2. Dynamic Oscillatory Rheology

Stress sweep: Stress sweeps were performed at 0.01, 0.1, and 1 Hz, applying an ascending stress value from 0.001 to 1000 Pa, to determine the linear viscoelasticity range (LVR).

Frequency sweep: The frequency sweeps were then performed to obtain the mechanical spectrum applying a stress value, within the LVR in a frequency range of 10^{-2} to 10^{2} rad/s, obtaining different viscoelastic properties, such as G′, G″, and η*.

G′ and G″ were modeled as a power function of ω (Equations (2) and (3)) and are commonly used for describing the viscoelastic behavior of food and dispersions [45]:

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

$$G'' = K'' \cdot \omega^{n''} \quad (3)$$

Complex viscosity ($|\eta^*|$) was described by the following equation:

$$\eta^* = K \cdot \omega^{n-1} \quad (4)$$

where K′, K″, and K are constants, n, n′, and n″ are referred to as the frequency exponents, and ω is the frequency. The correlations between the values of the dynamic and steady-state shear parameters were evaluated using the Cox–Merz rule, which states that the steady-state viscosity (η_{ss}) at a specific shear rate ($\dot{\gamma}$) is equal to the complex viscosity (η^*) at a specific angular velocity (ω), when $\dot{\gamma} = \omega$ (Equation (5)) [45]:

$$\eta^*(\omega) = \eta_{ss}(\dot{\gamma})\big|_{\dot{\gamma}=\omega} \quad (5)$$

when this rule is valid, the rheological properties of the mayonnaise-type emulsion enriched with *A. carambola* phenolic extract can be determined by oscillatory or steady-state shear experiments, which are useful due to the limitations in each type of experiment [46]. The parameters of each model were obtained using the nonlinear Excel Solver-GRG algorithm [47].

2.5. Statistical Analysis

All analyses were performed in triplicate. The results obtained were statistically analyzed using ANOVA with Statgraphics Centurion version 16.1 to determine statistically significant differences ($p < 0.05$) between samples.

3. Results

3.1. Steady-State Behavior

The flow behavior of mayonnaise enriched with *A. carambola* extract is shown in Figure 1. The samples present an increase in shear stress with the shear rate, a typical behavior of non-Newtonian flow behavior type shear thinning. Similar results for mayonnaise-type emulsions were obtained in previous studies [15,16,18,48–53] where rheological properties can be used to understand the structure and interaction of components in emulsions. The changes observed in shear stress are a consequence of the addition of

A. carambola extracts, which are associated with the interaction of phytochemicals and complexation. Then, different rheological models were employed for the characterization of flow curves of mayonnaises [24,54,55]; in this case, all mayonnaise was adjusted to the Herschel–Bulkley model (Equation (6)):

$$\tau = \tau_c + k\,\dot{\gamma}^{n} \quad (6)$$

where τ (Pa) is the shear stress, τ_c (Pa) is the yield stress, k the consistency index (Pa $s^{n'}$), $\dot{\gamma}$ (s^{-1}) is the shear rate, and n is the flux index.

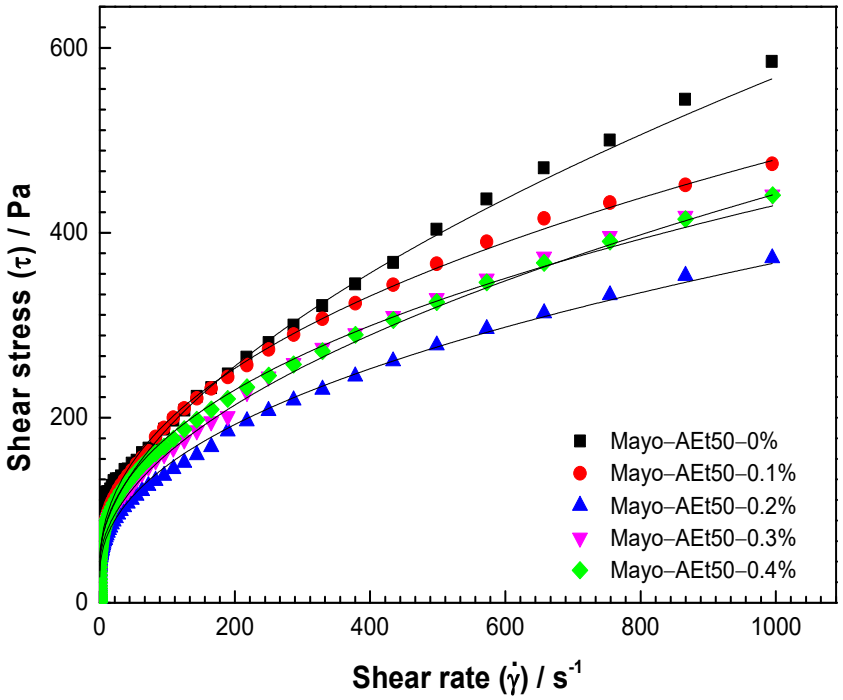


Figure 1. Flow behavior of mayonnaise enriched with *A. carambola* extracts adjusted to the Herschel–Bulkley model.

The model parameters with a high fitting degree ($R^2 > 0.96$) are given in Table 1. The τ_c (yield stress) ranged from 27.22 to 39.72 Pa of samples with extracts of *A. carambola*, presenting lower values than samples without extracts (Mayo−AEt50−0% τ_c = 48.87) that could be attributed to polysaccharide–phenolic complexation. k (consistency index) presents values of 10.00 ± 1.79, 21.38 ± 1.37, 15.39 ± 1.19, 11.05 ± 1.11 and 19.20 ± 1.48 for Mayo−AEt50−0%, Mayo−AEt50−0.1%, Mayo−AEt50−0.2%, Mayo−AEt50−0.3%, and Mayo−AEt50−0.4%, respectively, showing an increase with the addition of extracts. In all cases, n values were lower than 1, with values between 0.44 and 0.57 indicating shear thinning fluids [56]. Then, mayonnaises present a shear thinning behavior as a result of the alignment of molecules in the direction of flow and a decrease in viscosity with an increase in the shear rate. Similar results demonstrate the use of the Herschel Bulkley model for the characterization of mayonnaises, i.e., Ma and Barbosa-Cánovas [24] for mayonnaises with different concentrations of oil and xanthan gum; Izidoro et al. [57] for commercial mayonnaise (traditional and light); Yüccer et al. [58] for low cholesterol mayonnaises; and Park et al. [59] for low-fat mayonnaises.

Table 1. Adjustment parameters of the flow behavior of mayonnaise enriched with *A. carambola* extracts adjusted with the Herschel–Bulkley model.

Sample Code	τ_c Pa	K Pa·s^n	n	R^2
Mayo−AEt50−0%	48.87 ± 5.08 ^{c}	10.00 ± 1.79 ^{a}	0.57 ± 0.02 ^{b}	0.96
Mayo−AEt50−0.1%	33.91 ± 1.82 ^{b}	21.38 ± 1.37 ^{c}	0.43 ± 0.01 ^{a}	0.98
Mayo−AEt50−0.2%	27.22 ± 1.62 ^{a}	15.39 ± 1.19 ^{b}	0.44 ± 0.01 ^{a}	0.98
Mayo−AEt50−0.3%	39.72 ± 1.94 ^{b}	11.05 ± 1.11 ^{a}	0.52 ± 0.01 ^{b}	0.98
Mayo−AEt50−0.4%	34.70 ± 1.96 ^{b}	19.20 ± 1.48 ^{c}	0.43 ± 0.01 ^{a}	0.98

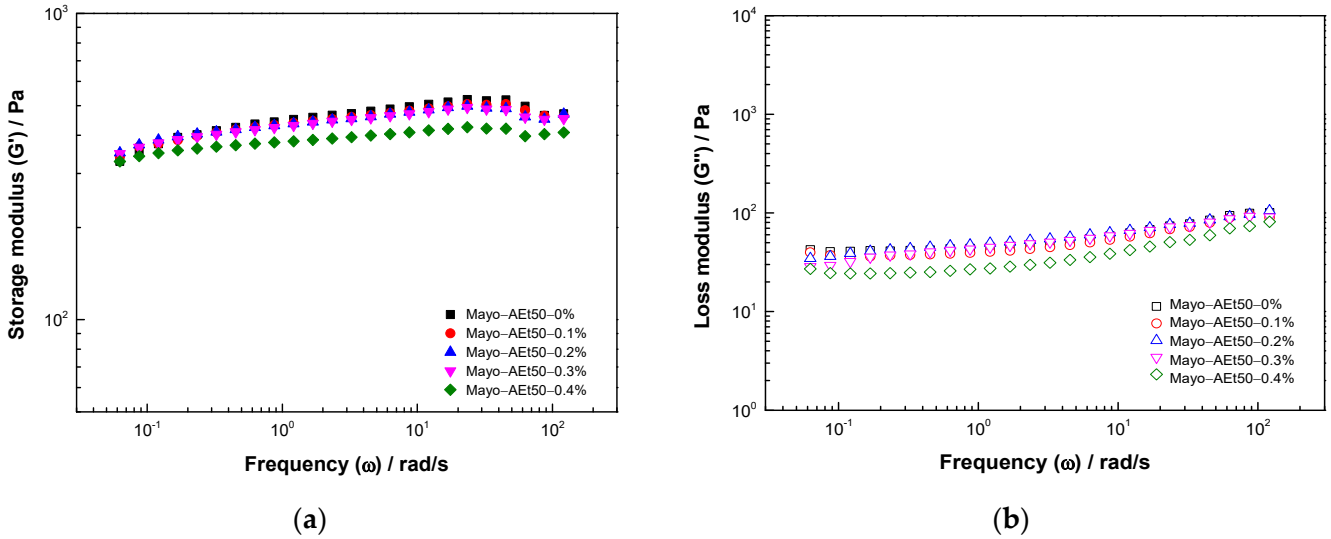
Data are the mean ± standard deviation. Different letters in the same column express statistically significant differences ($p < 0.05$).

Furthermore, the addition of phenolic compounds in food matrices modified the rheological properties; that is, Tudorache and Bordenave [60] report that the addition of phenolic compounds can lead to the aggregation of polysaccharides in a solution and the modification of the rheological properties of the solution toward lower viscosity and less pseudoplastic behavior (more Newtonian). Quintana et al. [61] report that the pure chitosan solution presented shear thinning behavior, where the addition of licorice extracts decreased the shear stress value and presented a shear thickening behavior, probably due to the hydroclustering of particles and an order-to-disorder transition.

3.2. Viscoelastic Properties

A dynamic rheological test was carried out in order to determine the viscoelastic properties of the samples. In the dynamic test, sinusoidal oscillation stress is applied as a function of frequency (ω) to measure the phase difference between the stresses and the amplitude ratio. The strain produces two stress components from the strain: the storage (G′) and loss (G″) components [62]. Initially, a stress sweep was performed to determine the linear viscoelastic range (LVR); then, mayonnaise samples present LVR between 1 and 150 Pa, choosing 10 Pa to develop a frequency sweep to evaluate the viscoelastic properties.

The viscoelasticity properties of the mayonnaise samples enriched with *A. carambola* extract are shown in Figure 2.



(**a**) (**b**)

Figure 2. (**a**) Storage modulus (G') and (**b**) loss modulus (G'') in function of frequency (ω) of mayonnaise enriched with *A. carambola* extract.

An elastic material is termed to behave more like a solid if the elastic or storage modulus is much greater than the loss modulus ($G' > G''$); however, if $G' < G''$, the material exhibits liquid-like behavior [63]. Overall, all samples exhibited frequency-dependent

behavior, where G′ and G″ increase with frequency [64], and this shows the dominant contribution of the elastic component to mayonnaise, which is attributed to a format among lipoproteins adsorbed all over oil droplets [65]. The G′ values were higher than G″ in all samples within the frequency range, implying that mayonnaise has a gel-like structure of a flocculated and entangled network and tends to behave more like an elastic solid [66]. Similar behavior has been reported for food systems such as traditional full-fat mayonnaises [24], inulin–water gels [67], jam and yogurt [68], mayonnaise incorporated with Himalayan walnut oil [69], mayonnaises [25], and olive oil-based mayonnaise [32].

The well-known power-law model was selected to uncover the frequency dependence of the G′ and G″ values (Equations (1) and (2)). The viscoelastic adjustment parameters are shown in Table 2. The adjustment correlation coefficient (R^2) shows good fitness ($R^2 > 0.812$) for G′ (Equation (1)), except for G′ at a lower concentration of extracts (<0.3%), and a good correlation G″ ($R^2 > 0.909$), indicating the sensitivity of elastic properties to the incorporation of phenolic extracts. In all cases, k' was higher than k″, indicating a typical weak gel behavior [70]. n′ values close to 0 and 1 reflected elastic and viscous behavior, respectively [71]. The obtained values were similar to those reported by Sun et al. [72] for low-fat mayonnaises (n′ = 0.059–0.124, n″ = 0.022–0.086, k′ = 334–888.9 Pa·$s^{n'}$, k″ = 100.9–129.3 Pa·$s^{n'}$) and are lower than those obtained by Peressini et al. [73] for light mayonnaises (n′ = 0.08–0.15, k′ =2.37–2.90 KPa·$s^{n'}$). Then, the parameters confirmed the viscoelastic properties of mayonnaises. k′, k″, and n′ decrease with *A. carambola* extract concentration, while the n″ increase confirmed the stronger network formed by the higher concentration.

Table 2. Viscoelastic parameters of mayonnaise enriched with extracts of *A. carambola* adjusted to Equations (1) and (2).

Sample Code	k′ Pa·$s^{n'}$	n′	R^2	k″ Pa·$s^{n''}$	n″	R^2
Mayo−AEt50−0%	468.11 ± 5.92 ^{b}	0.042 ± 0.00 ^{c}	0.731	61.80 ± 1.20 ^{c}	0.150 ± 0.00 ^{a}	0.921
Mayo−AEt50−0.1%	457.53 ± 4.64 ^{b}	0.039 ± 0.00 ^{b}	0.781	56.42 ± 1.26 ^{b}	0.158 ± 0.01 ^{a}	0.909
Mayo−AEt50−0.2%	453.52 ± 4.24 ^{b}	0.033 ± 0.00 ^{b}	0.757	63.72 ± 0.66 ^{c}	0.148 ± 0.00 ^{a}	0.976
Mayo−AEt50−0.3%	447.60 ± 4.27 ^{b}	0.034 ± 0.00 ^{b}	0.761	58.17 ± 0.45 ^{b}	0.157 ± 0.00 ^{a}	0.988
Mayo−AEt50−0.4%	395.64 ± 2.47 ^{a}	0.026 ± 0.00 ^{a}	0.812	40.69 ± 1.09 ^{a}	0.201 ± 0.01 ^{b}	0.920

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

Loss tangent (tan δ) (the ratio between loss and storage modulus) is a direct measure of viscous and elastic effects in the sample, indicating gel-like behavior (tan δ < 1) [74]. The loss of the tangent of mayonnaise enriched with *A. carambola* extract is shown in Figure 3. Tan δ present values of 0.099, 0.090, 0.109, 0.099, and 0.069 at 1 rad/s for Mayo−AEt50−0%, Mayo−AEt50−0.1%, Mayo−AEt50−0.2%, Mayo−AEt50−0.3%, and Mayo−AEt50−0.4%, respectively, denoting the development of a solid elastic character with gelation. Therefore, it can be inferred that tan δ established a gel-like character development with gelation but could not discriminate the relative elastic/viscous nature of mayonnaises using 0.1 to 0.4% of *A. carambola* extracts.

The complex viscosity (η^*) of mayonnaise enriched with *A. carambola* extract with the change in frequency (ω) is shown in Figure 4. The oscillatory dynamic test shows that mayonnaises exhibit a shear-thinning behavior, decreasing η^* and increasing (ω) due to the network breakup, as shown by the η curves of non-oscillatory measurements. The reduction in complex viscosity is the outcome of network breakup between mayonnaise enriched with *A. carambola* extract and among polymer chains, where the molecules of the polymer matrix are aligned with the flow.

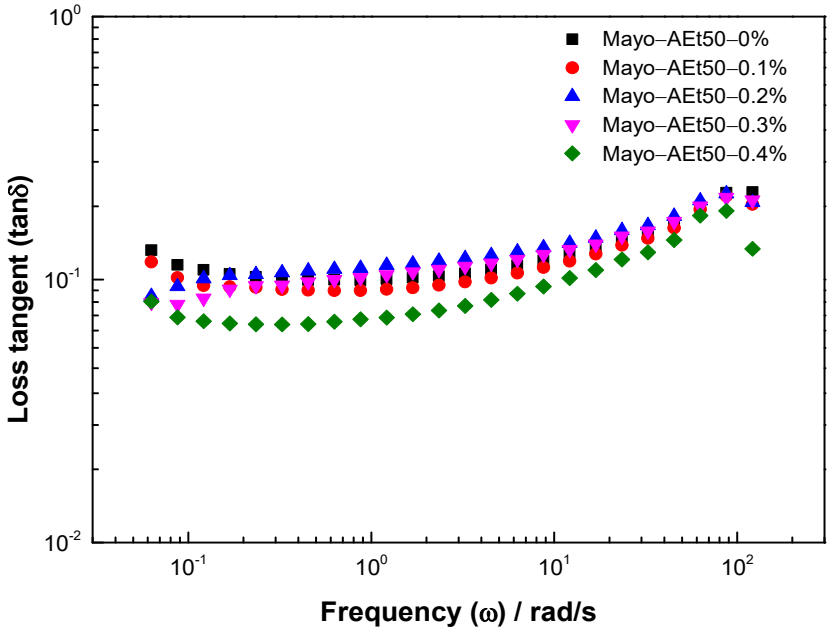


Figure 3. Loss tangent of mayonnaise enriched with *A. carambola* extract.

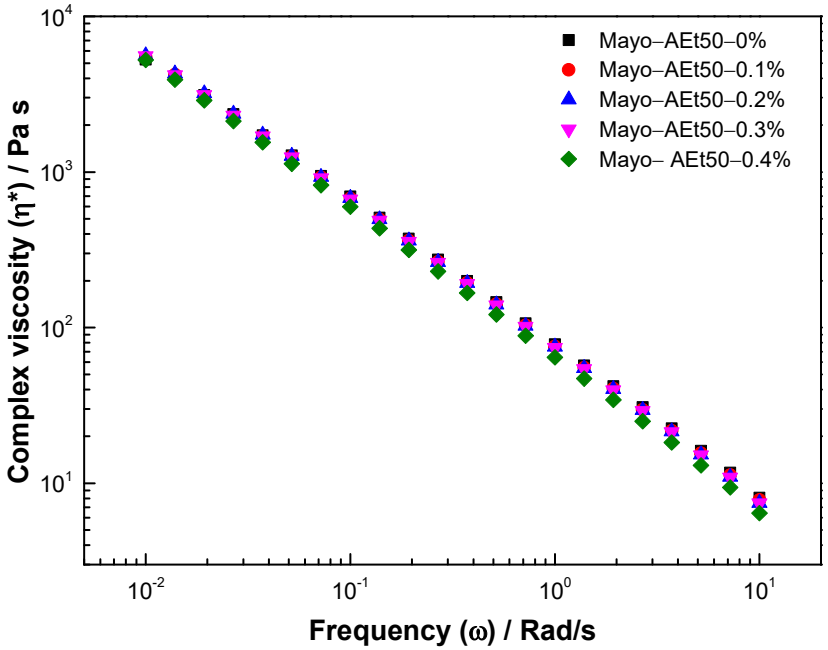


Figure 4. Complex viscosity of mayonnaise-type emulsion enriched with phenolic extract from *A. carambola*.

3.3. Applicability of the Cox–Merz Rule

The steady shear properties were correlated with the dynamic properties, verifying the applicability of the Cox–Merz rule [1,75]. In order to evaluate the applicability of the Cox–Merz rule, the steady state viscosity $\eta_{ss}(\dot{\gamma})$ and complex viscosity $\eta^*(\omega)$ of mayonnaise enriched with *A. carambola* as a function of frequency and shear rate are shown in Figure 5.

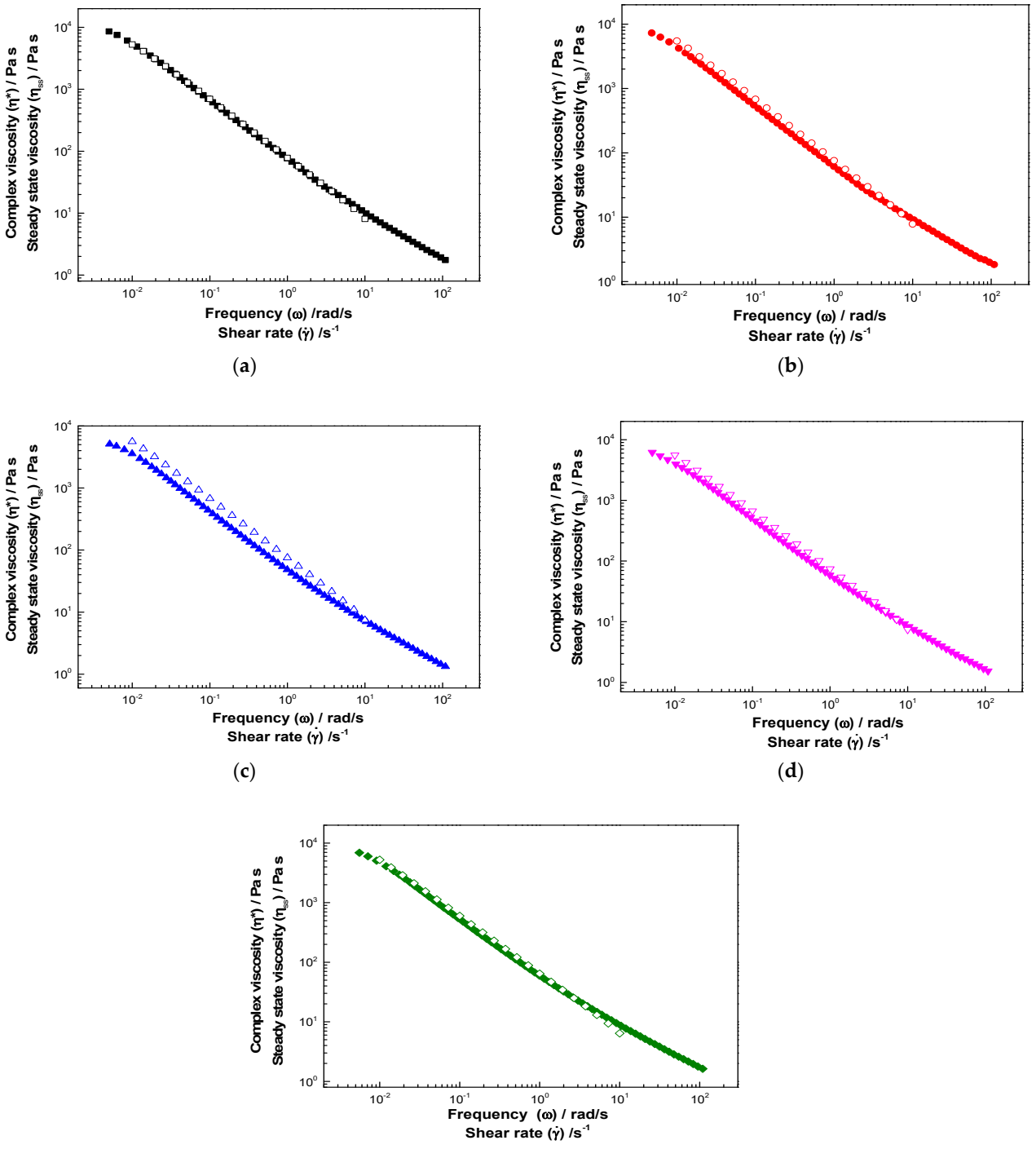


Figure 5. Complex (empty symbols) and apparent (filled symbol) of mayonnaise enriched with *A. carambola* extracts. (**a**) Mayo−AEt50−0%, (**b**) Mayo−AEt50−0.1%, (**c**) Mayo−AEt50−0.2%, (**d**) Mayo−AEt50−0.3%, and (**e**) Mayo−AEt50−0.4%.

It was observed that the experimental data of steady-state viscosity $\eta_{ss}(\dot{\gamma})$ and complex viscosity $\eta^*(\omega)$ for the samples obeyed the modified Cox–Merz rule. This indicates that similar molecular rearrangements may occur in the two flow patterns over the applied shear rate or frequency range [47,76]. In addition, a linear (Equation (7)) and power-modified (Equation (8)) Cox–Merz rule was used:

$$\eta^*(\omega) = \lambda\eta_{ss}(\dot{\gamma})\big|_{\dot{\gamma}=\omega} \quad (7)$$

$$\eta^*(\omega) = \alpha \left[\eta_{ss}(\dot{\gamma})\right]^{\beta}\Big|_{\dot{\gamma}=\omega} \quad (8)$$

where α is related to the magnitude difference between steady-state viscosity $\eta_{ss}(\dot{\gamma})$ and complex viscosity $\eta^*(\omega)$; similarly, β is related to the differences in behavior between steady-state viscosity $\eta_{ss}(\dot{\gamma})$ and complex viscosity $\eta^*(\omega)$ in relation to the shear rate ($\dot{\gamma}$) and frequency (ω), and the λ parameter, which is related to both magnitude and behavior differences, showed values close to 1, indicating that the data obeyed the Cox–Merz rule [6].

The values of the parameters λ, α, and β are shown in Table 3. In both cases (linear and power-modified Cox–Merz rule), the adjustment coefficient (R^2) was 0.99. Then, λ were higher than 1 in all cases, with values of 1.013, 1.257, 1.606, 1.371, and 1.083 for Mayo−AEt50−0%, Mayo−AEt50−0.1%, Mayo−AEt50−0.2%, Mayo−AEt50−0.3%, and Mayo−AEt50−0.4%, respectively, which can be attributed to the fact that shear forces have a destructive effect on intermolecular interactions of the constituents compared with the oscillatory deformations. However, no correlation with the percentage of the extract was identified, where the samples with the highest value present 0.3% of the extract. For α, the values were between 0.824 and 1.927, and the lowest value was from Mayo−AEt50−0% (0.824), followed by Mayo−AEt50−0.4% (0.850), Mayo−AEt50−0.3% (0.928), Mayo−AEt50−0.1% (1.263), and Mayo−AEt50−0.2% (1.263), and for β, the samples present values closer to 1.

Table 3. Modified Cox–Merz rule parameters of mayonnaise enriched with *A. carambola* extracts.

Sample Code	$\eta^*(\omega)=\lambda\eta(\dot{\gamma})\big\|_{\dot{\gamma}=\omega}$		$\eta^*(\omega)=\alpha\left[\eta(\dot{\gamma})\right]^{\beta}\big\|_{\dot{\gamma}=\omega}$		
	λ	R^2	α	β	R^2
Mayo−AEt50−0%	1.013 [a]	0.99	0.824 [a]	1.025 [a]	0.99
Mayo−AEt50−0.1%	1.257 [b]	0.99	1.263 [c]	0.999 [a]	0.99
Mayo−AEt50−0.2%	1.606 [c]	0.99	1.927 [d]	0.997 [a]	0.99
Mayo−AEt50−0.3%	1.371 [b]	0.99	0.928 [b]	1.049 [a]	0.99
Mayo−AEt50−0.4%	1.083 [a]	0.99	0.850 [a]	1.029 [a]	0.99

Data present CV < 0.05. Different letters in the same column express statistically significant differences ($p < 0.05$).

The parameters λ (Equation (7)) and α and β (Equation (8)) showed a similar behavior in relation to the addition of *A. carambola* extract. The parameters λ and α first increase until the addition of 0.3% of extract and then decrease (Mayo−AEt50−0.3%, Mayo−AEt50−0.4%), while parameter β followed the opposite trend. Then, the λ and β are related to the differences in behavior between η_{ss} and η^* in relation to the shear rate ($\dot{\gamma}$) and oscillatory frequency (ω), while α is related to the magnitude of the difference between the apparent (η_{ss}) and complex viscosities (η^*) [6]. The results obtained were similar to potato puree (α = 0.90–1.35 and β = 2.15–39.83) [77], baby apricot food (α = 1.16–1.44 and β = 0.41–1.26), and ketchup (α = 0.94 and β = 0.41–13.97) [2], and lower than tomato juice (λ = 3.73–4.76) and sweet potato baby food (λ = 7.14) [78].

The parameters of the linear regression (Equation (9)) of the data could be used to evaluate the description of the experimental values by the models:

$$\eta^*_{model} = A \times \eta^*_{experimental} + B \quad (9)$$

Table 4 shows the parameters of Equations (7) and (8). The adjustment coefficient (R^2) was 0.99. The results show that parameter A is very close to 1 and parameter B is 0 for both models, which indicates that the complex viscosity values are very close to the steady viscosity values [6], confirming that the data obeyed the Cox–Merz rule. Similar behavior has been reported by different authors, i.e., Ishi and Nakamura [79] reported that concentrated suspension obeys the modified Cox–Merz rule, and Augusto et al. [6] correlated two modified Cox–Merz rules for tomato juice consistency processed by high-pressure homogenization.

Table 4. Parameters of linear regression (Equation (9)) of modified Cox–Merz rule parameters of mayonnaise enriched with *A. carambola* extracts.

Sample Code	$\eta^*(\omega)=\lambda\eta(\dot{\gamma})\big\vert_{\dot{\gamma}=\omega}$			$\eta^*(\omega)=\alpha\left[\eta(\dot{\gamma})\right]^{\beta}\big\vert_{\dot{\gamma}=\omega}$		
	A	**B**	$\mathbf{R^2}$	**A**	**B**	$\mathbf{R^2}$
Mayo−AEt50−0%	0.995 [a]	0.0 [a]	0.99	0.995 [a]	0.0 [a]	0.99
Mayo−AEt50−0.1%	0.998 [a]	0.0 [a]	0.99	0.998 [a]	0.0 [a]	0.99
Mayo−AEt50−0.2%	0.999 [a]	0.0 [a]	0.99	0.999 [a]	0.0 [a]	0.99
Mayo−AEt50−0.3%	0.999 [a]	0.0 [a]	0.99	0.999 [a]	0.0 [a]	0.99
Mayo−AEt50−0.4%	0.997 [a]	0.0 [a]	0.99	0.994 [a]	0.0 [a]	0.99

Data present CV < 0.05. Different letters in the same column express statistically significant differences ($p < 0.05$).

The results obtained indicate that the rheological properties of mayonnaise-type emulsion enriched with the phenolic extract of *A. carambola* can be determined by oscillatory or steady-state shear experiments, indicating that the noted solidity of the gels could be related to limited dynamic viscosity alterations rather than extensive loss of shear viscosity. Furthermore, the addition of extracts modified the consistency of mayonnaise more than it modified its internal structure and highlighted the possible applications of phenolic extract as a valuable ingredient for the development of healthy products.

4. Conclusions

The steady-state assays show that the flow properties of mayonnaise determine non-Newtonian behavior. Mayonnaise has a shear thinning behavior and was adjusted to the Herschel–Bulkley model ($R^2 > 0.96$). The addition of *A. carambola* extracts decreases the yield stress and flux index and increases the consistency index, which could be attributed to polysaccharide–phenolic complexation.

The viscoelasticity properties of mayonnaise exhibited frequency-dependent behavior and could be considered a weak gel, as both G' and G'' increase with the frequency, dominating the elastic component, which is characteristic of typical weak gel, confirming the Tan δ values.

The steady shear properties were correlated with the dynamic properties, checking the applicability of the Cox–Merz rule ($R^2 = 0.99$) when the complex viscosity values are very close to the steady viscosity values, suggesting that the solidity of the gel is related to limited dynamic viscosity changes rather than large losses of deformation viscosity.

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