processes

Article

Rheological Characterization of Gofio and Aloe Vera Blended Juice

Francisco José Rubio-Hernández [1,*], Julia Rubio-Merino [2] and Elvira García-López [1]

[1] Departamento de Física Aplicada II, Universidad de Málaga, 29010 Málaga, Spain; elviralop88@gmail.com
[2] Hospital Clínico Universitario Virgen de la Victoria, 29010 Málaga, Spain; j_rubiomerino@hotmail.com
* Correspondence: fjrubio@uma.es; Tel.: +34-951952296

Abstract: Considering that gofio (Gf) and aloe vera juice (AVJ) have very good nutritional qualities, their combination is proposed because it is indicated as an easy and fast source of basic bio-elements. The texture of a food must be accepted by customers. This means that the rheological characteristics of the product must be known and controlled. Therefore, the influence of Gf concentration on the rheological behavior of Gf/AVJ suspensions must be determined. With continuous shear experiments, the purely viscous response of a material can be obtained. AVJ and Gf/AVJ suspensions showed shear-thinning behavior. The ability of Gf particles and aggregates to distort the flow field was quantified determining the intrinsic viscosity ($[\eta]$) of the suspensions at several shear rates using Krieger–Dougherty equation. The results indicated that the shape and size of Gf aggregates is not affected by the mechanical action due to shear. The power law (Ostwald–de Waele) model fitted the experimental steady viscosity versus shear rate values (steady viscosity curves). The flow index was less than 1, which corresponded to shear-thinning behavior. It was obtained that the flow index of AVJ maintained unaltered despite the presence of Gf particles. However, the viscosity value increased with the increasing amount of Gf as it was expected. The viscoelastic behavior of the microstructure at rest of the AVJ and Gf/AVJ suspensions was studied using oscillatory shear tests. First, linear viscoelastic response was confirmed in the relatively low amplitude shear region ($\gamma_0 < 0.001$) using an amplitude sweep shear test. After that, frequency sweep shear tests were conducted in the region where Gf/AVJ suspensions showed linear viscoelastic behavior. Varying the frequency, the response of the microstructure at rest of the suspensions when the mechanical action lasts from short to long time interval can be characterized. Jeffreys mechanical model was used for the analysis of the LVE response of Gf/AVJ suspensions. Using small amplitude oscillatory shear (SAOS) tests, it was obtained that Gf/AVJ suspensions are viscoelastic liquids that change their texture from chewy to creamy when the Gf concentration increases.

Keywords: cereals; fruit juices processing; rheology; mechanical properties; microstructure at rest

Citation: Rubio-Hernández, F.J.; Rubio-Merino, J.; García-López, E. Rheological Characterization of Gofio and Aloe Vera Blended Juice. *Processes* **2023**, *11*, 3315. https://doi.org/10.3390/pr11123315

Academic Editors: Diána Bánáti, Balázs P. Szabó and Antal Véha

Received: 6 November 2023
Revised: 19 November 2023
Accepted: 25 November 2023
Published: 28 November 2023

1. Introduction

Aloe vera juice (AVJ) blended with fruits or other juices has been shown as a clever way to develop functionally enriched low-calorie food products [1]. In addition, it has been used to fortify dairy products [2]. However, to the best of our knowledge, blends of aloe vera juice and cereals have still not been considered as a possible application in the food industry.

AVJ is obtained by crushing and centrifuging the leaf pulp of the plant aloe vera (L.) Burm. F. It has been included as a food product due to its beneficial content in vitamins, minerals, amino acids, enzymes, sugars, and bioactive compounds [3,4]. The list of aloe vera species is large, although the most widely used in nutritional applications is *Aloe Barbadensis miller* [5]. The use of aloe vera juice in food applications requires a comprehensive insight on its rheological behavior because the high content of insoluble polymer particles affects its storage, processing, and ingestion [6]. This kind of study is specifically indicated considering the variety of non-Newtonian behaviors observed in AVJ, referred to shear dependent viscosity [7] and viscoelastic properties [6].

Gofio canario [8] is a variety of flour made from toasted cereals (corn, wheat, spelled, or oats) mainly used in Canary Islands. It is a highly nutritious food, being the basis of the diet of Canary Island inhabitants even before Spanish colonization. It contains proteins; carbohydrates; fibers; vitamins B1, B2, B3, and C; and different trace elements [9].

Considering nutritional qualities of gofio (Gf) and AVJ, their combination supplies an easy and fast source of ingestion of basic bio-elements. As the texture of the final product must be accepted by customers, the aim of this study is to determine the influence of Gf concentration on the rheological behavior of Gf/AVJ suspensions.

2. Materials and Methods

Canary Gf, AVJ, and citric acid (CA) were used for the preparation of Gf/AVJ suspensions. Canary Gf is a mixture of corn, wheat, and oats fabricated in La Gomera (Canary Islands, Spain). AVJ was the supernatant, resulting from crushing and centrifugating aloe vera pulp, which was extracted from leaves of 3-year-old aloe vera plants. Three years is the minimum age of aloe vera plants containing enough polysaccharides and flavonoids to be optimum nutritionally [10]. Finally, citric acid (99.5% purity) was purchased from Panreac Química S.A. (Castellar del Vallès, Spain) and used as received. The addition of CA was justified by the necessity of avoid oxidation and degeneration of AVJ [11]. Despite these precautions, samples were rejected two days after their preparation to avoid misinterpretations of the results due to possible physical–chemical variations.

Gf/AVJ suspensions were prepared as follows. Aloe vera gel was carefully extracted from an adult leaf and vigorously crushed with a stirrer RZR1 (Heidolph Instruments, Nuremberg, Germany) at 800 rpm for 10 min, using a PR30 pitched-blade impeller. After that, it was centrifugated in a centrifuge (ALC Model4218, Alexandria, VA, USA) at maximum velocity (6000 rpm), and the supernatant was extracted. Then, 0.1% respect to supernatant weight was calculated, and this amount of CA was added to obtain the AVJ. Power law relationship between the viscosity value measured at 100 1/s and the concentration of AVJ [12] was used to estimate AVJ concentration used in this study. The estimated value was 1.11 °Bx at 25 °C. After that, different amounts of Gf were added to the AVJ and mixed with the same stirrer at 75 rpm until homogenization (≥15 min). The pH of the pastes increased from 3.6 to 4.4 when the amount of Gf increased. The density of Gf/AVJ suspensions was determined by weighting 1 mL of each suspension. These results are summarized in Table 1.

Table 1. Composition and properties of Gf/AVJ suspensions. Density and pH slightly increased with the amount of Gf. Viscosity vs. shear rate experimental data was fitted with a power law. The consistency of the suspension increases with the amount of Gf.

Gf (%w/w)	***pH***	**Density** ($\mathbf{kg/m^3}$)	***K*** ($\mathbf{Pa{\cdot}s^n}$)	***n*** $(-)$	R^2
0	3.6 ± 0.1	262 ± 1	0.045 ± 0.001	0.39 ± 0.01	0.9897
5	3.6 ± 0.1	273 ± 1	0.072 ± 0.001	0.38 ± 0.01	0.9988
10	3.8 ± 0.1	285 ± 1	0.191 ± 0.003	0.41 ± 0.01	0.9954
15	4.0 ± 0.1	296 ± 1	0.443 ± 0.005	0.41 ± 0.01	0.9965
20	4.2 ± 0.1	307 ± 1	1.15 ± 0.02	0.41 ± 0.01	0.9938
25	4.4 ± 0.1	319 ± 1	2.48 ± 0.04	0.41 ± 0.01	0.9944

Electron microscopy (JEOL JSM-840, JEOL Ltd., Tokyo, Japan) of canary Gf (SEM image) shows rounded particles (Figure 1) with high polydispersity; this last, probably due to Gf used in this study, was a mix of three different cereals. It is well known that starch resulting from different cereals conforms to different shape and size [13]. The average particle size (11.6 μm) and polydispersity (1.6 μm) of Gf particles were obtained by processing SEM images with a MATLAB tool (MathWorks®). The polydispersity index was calculated from the standard deviation of the initial distribution in units of $1/2\ (\sigma_M + \sigma_m)$, σ_M and σ_m being the maximum and minimum particle size, respectively [14]. The density of Gf $(489\ \mathrm{kg/m^3})$ was estimated as being the average of the density of the three cereals taken from the bibliography.

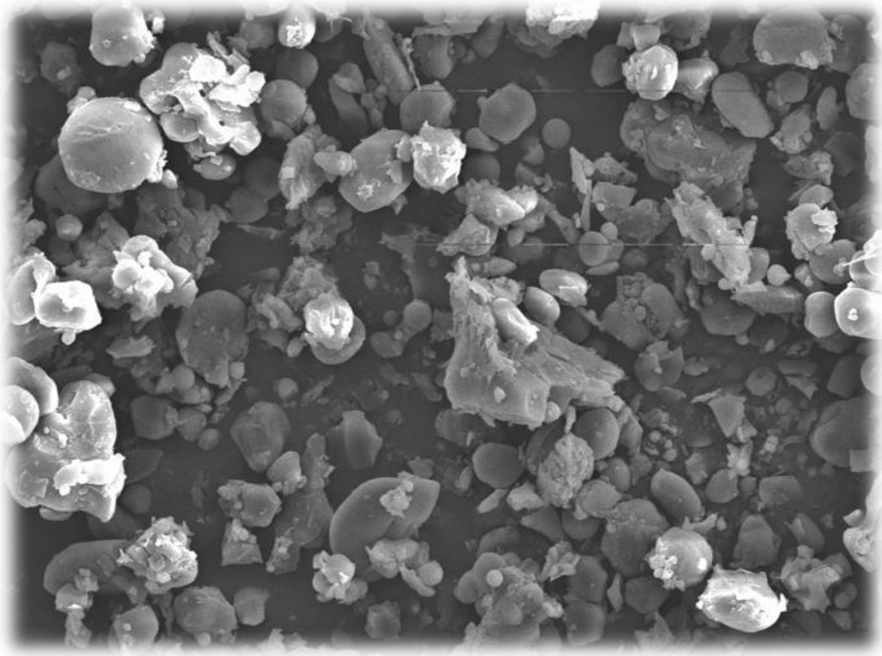


Figure 1. SEM image of Canary Gf (corn, wheat, and oats mixture). The average particle size was 11.6 μm with a polydispersity index of 1.6 μm.

Rheological measurements were performed with a stress-controlled rheometer Gemini 150 (Malvern Instruments Ltd., Malvern, UK). This device was equipped with a Peltier module for the temperature control. Each experiment was conducted on fresh samples. The temperature was fixed at 25.00 $\pm$ 0.05 °C. A double gap geometry was used to record rheometric data. The double gap geometry consisted of an inverted hollow cylinder, acting as the rotor, which is fixed in the space between two other concentric cylinders, acting as the stator. In this way, the cylindrical surface of the rotor duplicates and the gap between surfaces reduced. Then, the sensibility of the rheometric geometry increased, allowing us to measure lower viscosity values. Therefore, the main reason for the selection of double gap cylinders was that AVJ and Gf/AVJ suspensions were characterized by relatively small viscosity values, which demanded a more sensible rheometric geometry. Another remarkable characteristic of the double gap geometry when it was compared to the more conventional concentric cylinders was the reduced inertia of the rotor. This characteristic was achieved by eliminating great amount of mass of the original rotating cylinder. Therefore, double gap cylinders were also especially useful for oscillatory shear measurements.

All rheological tests were preceded by a pre-shear phase. This previous mechanical conditioning of samples was indicated to erase uncontrolled random or hazardous initial sample state due to stress samples that could be experimented on when they were placed into the double gap rheometric geometry. The pre-shear phase consisted of the application of a constant shear rate $(10\ \mathrm{s}^{-1})$ for 30 s. This time interval of shear was enough in all cases to achieve a steady state characterized by small relative variation of the recorded shear stress along some imposed time interval $\left(\frac{\Delta\tau}{\tau} \leq 1\% \text{ for } 10\ \mathrm{s}\right)$. After that, samples were allowed to rest for 60 s. In this way, complete structural rebuilding of samples was achieved. Then, the rheological test (steady flow curve, amplitude sweep or frequency sweep) was subsequently applied to the sample. The rheological tests were carried out in triplicate, and the results shown in figures were the average of those series of experimental data.

Two rheological tests were used to describe textural properties of Gf/AVJ suspensions. Steady viscous flow was characterized with the steady flow curve protocol. It consisted of the growing application of a shear rate ramp from 0.1 s^{-1} to 200 s^{-1}, logarithmically distributed. Logarithmic recording data allowed us to achieve information on the rheological behavior of suspensions just near the rest state. The value of the viscosity at very low shear rates was pompously named zero shear viscosity because it was clearly contradictory. Zero shear viscosity parameter was of great interest in the rheological characterization of suspensions because it supplied crucial information on their behavior when they were at rest, i.e., supplied information on the stability against the sedimentation of the suspended phase. Although theoretically predicted, zero shear viscosity is not always accessible due to limitations of the devices to apply extremely small shear rates. On the other hand, the rheological behavior of the suspensions away from the rest state can be properly characterized knowing the response of suspensions at a small number of increasing shear rates. Each shear rate was applied until a steady response was recorded. The condition to ensure that the steady response was achieved for every shear rate was the same as indicated before $\left(\frac{\Delta\tau}{\tau} \leq 1\% \text{ for } 10 \text{ s}\right)$. The viscoelastic behavior of Gf/AVJ suspensions was determined by applying oscillatory shear to samples. The linear viscoelastic response of the at-rest microstructure developed by Gf/AVJ suspensions was delimited with an amplitude sweep test. With this rheological test, the frequency was maintained constant while the amplitude of the harmonic signal increased from very small values. The objective was to determine the maximum amplitude of the oscillation that the microstructure at rest could withstand without breaking. As this maximum amplitude value is usually small, the subsequent test was considered a small amplitude oscillatory shear (SAOS) analysis. This second part of the oscillatory rheological test consisted of the application of a frequency sweep maintaining the strain amplitude as a constant in the linear viscoelastic regime, i.e., with a value smaller than the maximum amplitude found in the previous amplitude sweep rheological test. The objective of the frequency sweep test is to analyze the response of the microstructure at rest when the time of the experiment is large compared to its characteristic time (low frequency values), and the response of the microstructure at rest when the time of the experiment is small compared to its characteristic time (high frequency values). The behavior of the suspensions was quantified, determining the elastic (storage modulus) and viscous (loss modulus) components of the complex modulus as a function of the angular frequency.

3. Results and Discussion

3.1. Steady Viscous Behavior

Steady viscosity curves of Gf/AVJ suspensions showed that the viscosity increased with the increase in Gf amount (Figure 2). On the other hand, the viscosity of each Gf/AVJ suspension decreased with the shear rate, indicating (non-Newtonian) shear-thinning behavior. The decrease in viscosity of AVJ (black square symbols) has been previously reported [12] and justified by the rupture of structural units due to the shear [15]. This is a typical non-Newtonian behavior also found in fruit-based products [16–18].

The dependence of the viscosity (η) with the shear rate $(\dot{\gamma})$ was fitted with the power law model (Ostwald–de Waele),

$$\eta = K\dot{\gamma}^{n-1} \tag{1}$$

In Equation (1), K and n are consistency and flow indexes, respectively. As can be seen, good correlation between experimental and predicted values was found for the liquid phase (AVJ) and Gf/AVJ suspensions (Table 1). It is worthy to note that the "strange" units of the consistency index (Pa·s^n) can become a handicap for the comparison of the value of this magnitude taken by different materials. Fortunately, in this specific case, n-values coincide (∼0.40) for all the suspensions, and therefore, we can affirm that the consistency of Gf/AVJ suspensions increases with Gf content. In addition, the abrupt shear-thinning behavior characterized by a relatively small n-value is not affected by Gf concentration. Consequently, the shear-thinning behavior of Gf/AVJ suspensions should be justified by the shear-thinning behavior shown by the carrier liquid (AVJ). In other words, Gf/AVJ suspensions are non-Newtonian systems resulting from the dispersion of a solid phase

(Gf) in a non-Newtonian carrier liquid (AVJ). Therefore, the fact that the n-value was independent of Gf content allows us to conclude that the shear-thinning behavior of the liquid phase (AVJ) is the main cause of the shear-thinning behavior observed in Gf/AVJ suspensions. AVJ is a dispersion of high molecular weight insoluble polysaccharides entangled at rest. Increasing the shear disentangles polysaccharide molecules and tends to align them along the flow direction. Consequently, the flow field distortion is less at a high shear, and the viscosity is lower.

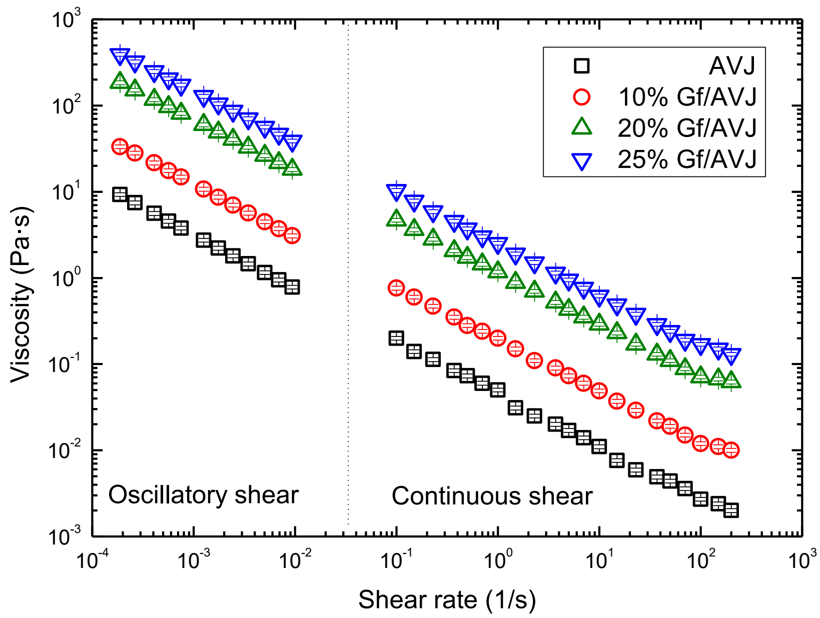


Figure 2. Viscosity vs. shear rate. Note the consistency of the results obtained using continuous and oscillatory shear tests.

The presence of Gf particles places an additional flow field distortion (higher viscosity) at each shear rate value. The ability of Gf particles and aggregates to distort the flow field can be quantified with the intrinsic viscosity $([\eta])$ of the suspensions [19]. The Krieger–Dougherty equation [20] relates the viscosity of the suspension with the volume fraction (ϕ) occupied by the solid phase.

$$\eta = \eta_{\updownarrow}\left(\frac{1}{1-\frac{\phi}{\phi_m}}\right)^{[\eta]\phi_m} \tag{2}$$

In Equation (2), $\eta_{\updownarrow}$ is the viscosity of AVJ, and ϕ_m is the maximum packing fraction achieved by Gf particles dispersed in Gf/AVJ suspensions. Although the Krieger–Dougherty equation was formulated assuming Newtonian behavior of the suspension, its utility for the estimation of the flow field distortion in non-Newtonian suspensions has also been shown to be valid [21]. Experimental relative viscosity values corresponding to four different shear rate values $\left(0.1,\ 1,\ 10,\ 100\ \mathrm{s}^{-1}\right)$ against Gf volume fraction overlapped within the experimental error, indicating that the shape and size of Gf aggregates are not significantly affected by the shear rate. To confirm this result, the Krieger–Dougherty equation was fitted to these experimental data. The resulting values of the parameters of the Krieger–Dougherty equation confirmed that the intrinsic viscosity does not practically vary when the shear rate increases (15.9 to 17.1). This means that the shape and size of Gf aggregates is not affected by the mechanical action due to the shear. In addition, the maximum packing fraction was the same independent of the shear rate value (0.25). In conclusion, the shear-thinning behavior observed in Gf/AVJ suspensions is mainly due to the shear-thinning behavior shown by the AVJ solvent.

3.2. Viscoelastic Behavior

The viscoelastic flow of G/AVJ suspensions was characterized using Small Amplitude Oscillatory Shear (SAOS strain) tests. With this rheological technique, the linear viscoelastic response of the microstructure at rest developed by the suspensions is analyzed. The importance of this study is justified by the fact that it helped determine the stability of the storage suspension against sedimentation. With this rheological study, the variation of the deformation (γ) imposed by the suspension is sinusoidal.

$$\gamma(t) = \gamma_o \, sin \, \omega t \tag{3}$$

Therefore, first, an amplitude (γ_o) sweep is applied to the sample, maintaining a constant angular frequency (ω) of the oscillation. The aim of this first part of the SAOS strain test is to determine the maximum γ_o-value delimiting the linear viscoelastic (LVE) behavior of the suspension.

The LVE response of suspensions to the sinusoidal deformation is an out-of-phase sinusoidal shear stress (τ).

$$\tau(t) = \tau_o \, sin \, (\omega t + \delta) = (\tau_o cos\delta) sin \, \omega t + (\tau_o sin\delta) cos \, \omega t \tag{4}$$

In Equation (4), τ_o is the stress amplitude, and δ is the phase difference between input (deformation) and output (stress) signals. From Equation (4), two viscoelastic moduli are defined.

$$G'(\omega) = \frac{\tau_o}{\gamma_o} cos\delta \tag{5}$$

$$G''(\omega) = \frac{\tau_o}{\gamma_o} sin\delta \tag{6}$$

G' is the elastic or storage modulus, and G'' is the viscous or loss modulus. The accomplishment of the LVE behavior condition implies that both moduli must be independent on γ_o. Results corresponding to amplitude of deformation sweep tests showed that the viscoelastic moduli do not depend on γ_o (LVE behavior) when the amplitude of the oscillatory shear is lower than 0.01.

After the LVE region was detected, the behavior of Gf/AVJ suspensions at short and long experimental times was tested while varying the frequency of the SAOS strain and maintaining a constant amplitude in the LVE regime. This second rheological test is named frequency sweep. More concretely, to be sure that responses of Gf/AVJ suspensions to frequency sweep rheological tests were recorded in the LVE region, an amplitude $\gamma_o = 0.001$ was maintained constant during oscillatory shear. The results of frequency sweeps in the LVE regime obtained with Gf/AVJ suspensions are shown in Figure 3. As can be seen, Gf/AVJ is a viscoelastic gel in all cases [22]. This qualification results from the fact that booth moduli are practically independent on the frequency. This is an indication of the existence of a relatively strong microstructure, which gives the suspensions a gel appearance. This gel-microstructure is mainly built by polymeric molecules dispersed in the AVJ. We arrive at this conclusion because G' and G'' dependence with angular frequency is qualitatively similar for the AVJ solvent and Gf/AVJ suspensions. Certainly, the value of both moduli increases with Gf concentration, which is an indication of some additional effect due to the increase in the solid phase.

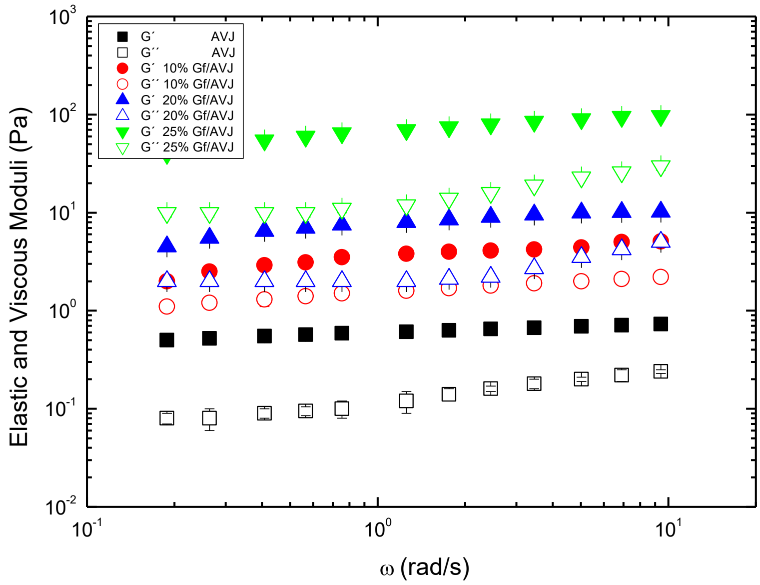


Figure 3. Frequency sweeps in the LVE region. $\gamma_o = 0.001$. Gf/AVJ is a stronger viscoelastic gel when the Gf amount increases in the Gf/AVJ suspension.

For the analysis of $G'(\omega)$ and $G''(\omega)$, experimental data Jeffreys model (Figure 4) will be used. Jeffreys mechanical analog is the simplest equivalent encompassing the entire spectrum of mechanical behaviors [23]. Therefore, it is indicated for the analysis of the general LVE response of non-Newtonian fluids.

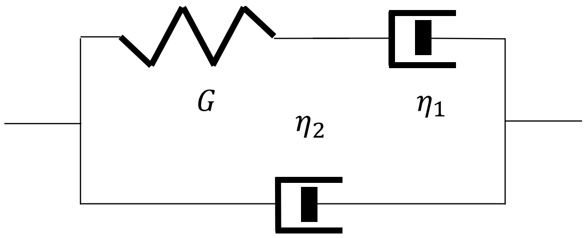


Figure 4. The Jeffreys mechanical analog.

The constitutive equation that corresponds to the mechanical analog shown in Figure 4 is as follows:

$$\tau + \frac{\eta_1}{G}\dot{\tau} = (\eta_1 + \eta_2)\dot{\gamma} + \eta_1 \frac{\eta_2}{G}\ddot{\gamma} \tag{7}$$

In Equation (7), $\eta = \eta_1 + \eta_2$ is the steady-state shear viscosity, and G is the elastic modulus. With the definitions $\lambda_1 = \frac{\eta_1}{G}$ and $\lambda_2 = \frac{\eta_1 \eta_2}{\eta G}$ for relaxation and retardation times, respectively, Equation (7) can be re-written as follows:

$$\tau + \lambda_1 \dot{\tau} = \eta \dot{\gamma} + \eta \lambda_2 \ddot{\gamma} \tag{8}$$

Jeffreys material functions can be expressed in terms of the experimentally accessible magnitudes G' and G'', enhancing its utility for the physical interpretation of the LVE behavior of Gf/AVJ suspensions. Substituting Equations (3)–(6) in Equation (8), the following relationships are obtained:

$$\lambda_1 = \frac{\eta}{G'} - \frac{G''}{G'\omega} \tag{9}$$

$$\lambda_2 = \frac{G''}{G'\omega} - \frac{G'^2 + G''^2}{G'\eta\omega^2} \tag{10}$$

$$\eta_2 = \frac{G''}{\omega} - \frac{G'^2}{\eta\omega^2 - G''\omega} \tag{11}$$

$$\eta_1 = \eta - \frac{G''}{\omega} + \frac{G'^2}{\eta\omega^2 - G''\omega} \tag{12}$$

$$G = G'\left[1 + \frac{G'^2}{(\eta\omega - G'')^2}\right] \tag{13}$$

To obtain the function $\eta(\omega)$, the experimental dependence of the steady-state viscosity with the shear rate given by Equation (1) was re-written using the relationship $\dot{\gamma}_o = \gamma_o\omega$ with $\gamma_o = 0.001$,

$$\eta(\omega) = K(\gamma_o\omega)^{n-1} \tag{14}$$

Therefore, the dependence of the Jeffreys-based material functions (η_1, η_2, G) and characteristic times (λ_1, λ_2) with angular frequency can finally be obtained. The results are shown in Figure 5a–c.

As can be seen, η_1 is highly dependent on the frequency and Gf content. More specifically, it decreases with frequency and increases with Gf content. Although, as in the ideal Jeffreys model, η_2 represents the viscosity of the completely unstructured material, i.e., theoretically, it should be independent of the frequency, we can see that it decreases with frequency. However, it is worth noting that $\eta_1 \gg \eta_2$ by some orders of magnitude. The results from Figure 5a correspond to a very low shear rate range after using the relationship $\dot{\gamma}_o = \gamma_o\omega$. Specifically, the shear rate interval $\left[10^{-4} - 10^{-2}\ \mathrm{s}^{-1}\right]$ is accessible with the use of oscillatory rheological tests. Therefore, these results can be combined with results obtained in the shear rate range $\left[10^{-1} - 10^{2}\ \mathrm{s}^{-1}\right]$ using continuous rheological tests to obtain information on the viscosity dependence with the shear rate in a much wider range. As can be seen in Figure 2, the results obtained using both methods are consistent.

The shear modulus G increases only very slightly with frequency (Figure 5b). This means that Gf/AVJ suspensions only stiffen a little bit when the experimental time decreases. It is worth noting that this material function raised a saturation value when the Gf concentration was 20% w/w, i.e., the microstructure achieved the stiffer state with this Gf concentration.

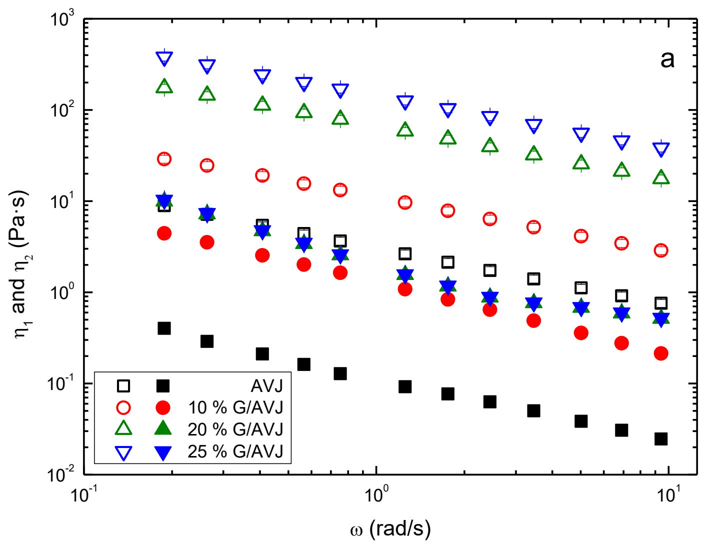
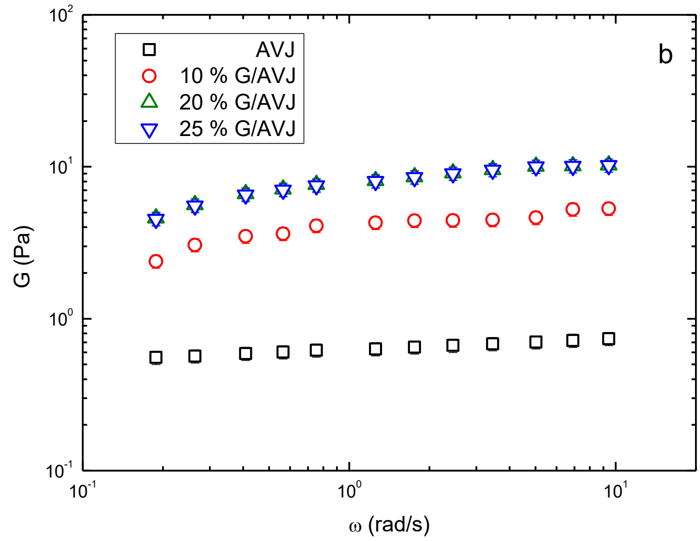


Figure 5. *Cont.*



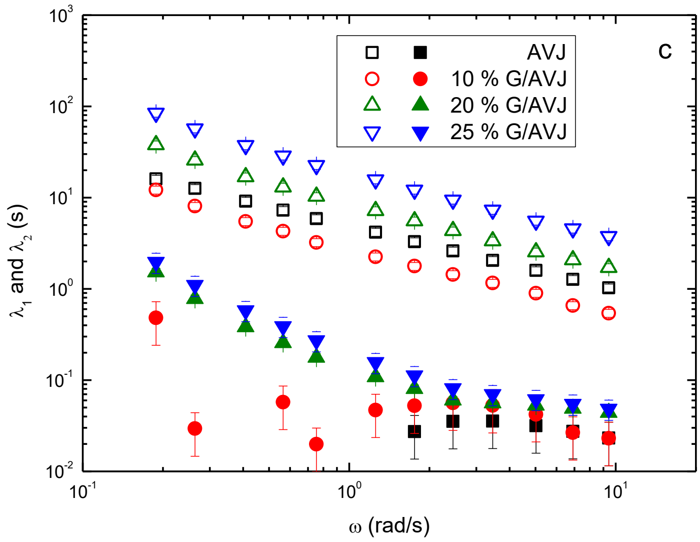


Figure 5. Jeffreys material functions of Gf/AVJ suspensions vs. angular frequency: (**a**) η_1 open symbols, η_2 full symbols; (**b**) G; and (**c**) λ_1 open symbols, λ_2 full symbols. See text for interpretation.

The relaxation time λ_1 and the retardation time λ_2 decrease with frequency (Figure 5c). As the retardation time λ_2 is much lower than the relaxation time λ_1, liquid-like behavior is dominant in the full frequency range. On the other hand, λ_1 increases with Gf content, suggesting liquid-like behavior due to a higher presence of Gf particles in the suspension. In other words, the presence of a higher Gf content in the suspension results in a higher dissipation of energy (viscous effect, liquid-like behavior). Note that, from the data shown in Figure 3, the relative increase in the viscous modulus G'' is higher than the relative increase in the elastic modulus G' when the amount of Gf in suspensions increases. Therefore, it is apparent that the elastic behavior of the AVJ solvent, due to the entanglement of polysaccharide molecules, is diminished by the presence of Gf particles, probably due to the breaking of links, reducing the extent and stiffness of the network formed by polysaccharide molecules. From a sensorial point of view, this means that increasing the addition of Gf to AVJ changes the texture of the suspension from chewy to creamy.

4. Conclusions

A Gf/AVJ suspension is proposed as a liquid food that facilitates the ingestion of bio-elements. Considering that the texture of food products must be accepted by customers, the influence of Gf concentration on the rheological (purely viscous and viscoelastic) behavior of Gf/AVJ suspensions was consequently studied.

Rheological measurements were performed with a stress-controlled rheometer using a double gap geometry to record rheometric data. In this way, the inertia of the rotor was reduced, which is especially useful for oscillatory shear (viscoelastic) measurements.

Steady flow curves showed abrupt shear-thinning behavior of Gf/AVJ suspensions independently of the Gf content. Therefore, the shear-thinning behavior of Gf/AVJ suspensions was mainly justified by the shear-thinning behavior of the non-Newtonian carrier liquid (AVJ). Certainly, the presence of Gf particles results in an additional flow field distortion, which increases the viscosity of the resulting suspension at each shear rate value. The ability of Gf particles and aggregates to distort the flow field was quantified, determining the intrinsic viscosity ($[\eta]$) of the suspensions at several shear rates using the Krieger–Dougherty equation. The results indicated that the shape and size of Gf aggregates is not affected by the mechanical action due to the shear. Therefore, it was confirmed that the shear-thinning behavior observed in Gf/AVJ suspensions is mainly due to the shear-thinning behavior shown by the AVJ solvent.

A small amplitude oscillatory shear (SAOS) was applied to Gf/AVJ suspensions to characterize the microstructure at rest. A gel appearance of the suspensions was confirmed measuring the dependence of linear viscoelastic moduli with the experimental time using frequency sweep tests. Jeffreys mechanical model was used for the analysis of the LVE response of Gf/AVJ suspensions. It was obtained that liquid-like behavior is dominant in the full frequency range despite gel appearance of suspensions. In addition, increasing the Gf content enhances the liquid-like behavior of the suspensions or diminishes the elastic response, i.e., from a sensorial point of view, an increasing presence of Gf particles changes the texture of Gf/AVJ suspensions from chewy to creamy.

Author Contributions: Conceptualization, F.J.R.-H.; methodology J.R.-M. and E.G.-L.; data curation, J.R.-M. and E.G.-L.; writing—original draft preparation, F.J.R.-H.; writing—review and editing, F.J.R.-H., J.R.-M. and E.G.-L.; supervision, F.J.R.-H. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The figures and tables used to support the findings of this study are included in the article.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Sharma, R.; Burang, G.; Kumar, S.; Sharma, Y.P.; Kumar, V. Optimization of apricot (*Prunus armeniaca* L.) blended Aloe vera (*Aloe barbadensis* M.) based low-calorie beverage functionally enriched with aonla juice (*Phyllanthus emblica* L.). *J. Food Sci. Technol.* **2021**, *59*, 2013–2024. [CrossRef] [PubMed]
2. Mugdil, D.; Barak, S.; Darji, P. Development and characterization of functional cultured buttermilk utilizing Aloe vera juice. *Food Biosci.* **2016**, *15*, 105–109.
3. Hes, M.; Dziedzic, K.; Górecka, D.; JedrusekGolinska, A.; Gujska, E. *Aloe vera* (L.) Webb.: Natural Sources of Antioxidants—A Review. *Plant Foods Hum. Nutr.* **2019**, *74*, 255–265. [CrossRef] [PubMed]
4. Chhikara, N.; Kaur, A.; Mann, S.; Garg, M.K.; Sofi, S.A.; Panghal, A. Bioactive compounds, associated health benefits and safety considerations of Moringa oleifera L.: An updated review. *Nutr. Food Sci.* **2020**, *51*, 255–277. [CrossRef]
5. Domínguez-Fernández, R.N.; Arzate-Vázquez, I.; Chanona-Pérez, J.J.; Welti-Chanes, J.S.; Alvarado-González, J.S.; Calderón-Domínguez, G.; Garibay-Febles, V.; Gutiérrez-López, G.F. Aloe vera gel: Structure, chemical composition, processing, biological activity, and importance in pharmaceutical and food industry. *Rev. Mex. Ing. Quim.* **2012**, *11*, 23–43.
6. Sonowane, S.K.; Gokhale, J.S.; Mulla, M.Z.; Kandu, V.R.; Patil, S. A comprehensive overview of functional and rheological properties of aloe vera and its applications in foods. *J. Food Sci. Technol.* **2021**, *58*, 1217–1226. [CrossRef] [PubMed]
7. Matabura, V.V.; Rweyemamu, L.M.P. Effects of Xanthan gum on rheological properties of Aloe-vera-Moringa leaf juice blends. *Tanzan. J. Sci.* **2021**, *47*, 583–596. [CrossRef]

8. Diario Oficial de la Unión Europea (DOUE). Reglamento de Ejecución (U.E.) n° 128/2014. Available online: https://eur-lex.europa.eu/legal-content/ES/TXT/PDF/?uri=CELEX:32014R0128&rid=1 (accessed on 6 November 2023).
9. Caballero-Mesa, J.M. Estudio Toxicológico, Higiénico-Sanitario y Nutricional Del Gofio Canario. Ph.D. Thesis, Universidad de La Laguna, Canary Island, Spain, 2010.
10. Hu, Y.; Xu, J.; Hu, Q. Evaluation of antioxidant potential of aloe vera (*Aloe vera barbadensis* Miller) extracts. *J. Agric. Food Chem.* **2003**, *51*, 7788–7791. [CrossRef] [PubMed]
11. He, Q.; Liu, C.; Kojo, E.; Tian, Z. Quality and safety assurance in the processing of aloe vera gel juice. *Food Control* **2005**, *16*, 95–104. [CrossRef]
12. Hulle, N.R.S.; Patruni, K.; Rao, P.S. Rheological properties of aloe vera (*Aloe barbadensis* Miller) juice concentrates. *J. Food Process Eng.* **2014**, *37*, 375–386. [CrossRef]
13. Prieto-Méndez, J.; Rubio-Hinojosa, C.U.; Román-Gutiérrez, A.D.; Méndez-Marzo, M.A.; González-Ramírez, A.; Prieto-García, F. Degradación física del almidón de cebada (hordeum sativun Jess). Correlación entre la gelatinización y el tamaño de gránulos. *Multiciencias* **2009**, *9*, 115–125.
14. Masoero, E.; Delgado, E.; Pellenq, R.M.; Ulm, F.J.; Yip, S. Nanostructure and nanomechanics of cement: Polydisperse colloidal packing. *Phys. Rev. Lett.* **2012**, *109*, 155503. [CrossRef] [PubMed]
15. Rao, M.A. *Rheology of Fluid and Semisolid Foods. Principles and Applications*; Springer: New York, NY, USA, 2007.
16. Dak, M.; Verma, R.C.; Sharma, G.P. Flow characteristics of juice of "Totapuri" mangoes. *J. Food Eng.* **2006**, *76*, 557–561. [CrossRef]
17. Sesmero, R.; Mitchell, J.; Mercado, J.; Quesada, M. Rheological characterization of juices obtained from transgenic pectate lyase-silenced strawberry fruits. *Food Chem.* **2009**, *116*, 426–432. [CrossRef]
18. Rubio-Merino, J.; Rubio-Hernández, F.J. Activation energy for the viscoelastic flow: Analysis of the microstructure-at-rest of (water- and milk-based) fruit beverages. *Food Chem.* **2019**, *293*, 486–490. [CrossRef] [PubMed]
19. Rubio-Hernández, F.J.; Ayúcar-Rubio, M.F.; Velázquez-Navarro, J.F.; Galindo-Rosales, F.J. Intrinsic viscosity of SiO_2, Al_2O_3, and TiO_2 aqueous suspensions. *J. Colloid Interface Sci.* **2006**, *298*, 967–972. [CrossRef] [PubMed]
20. Krieger, I.M.; Dougherty, T.J. Concentration dependence of the viscosity of suspensions. *Trans. Soc. Rheol.* **1959**, *3*, 137–152. [CrossRef]
21. Gómez-Merino, A.I.; Rubio-Hernández, F.J.; Velázquez-Navarro, J.F.; Aguiar, J.; Jiménez-Agredano, C. Study of the aggregation state of anatase-water nanofluids using rheological and DLS methods. *Ceram. Int.* **2014**, *40*, 14045–14050. [CrossRef]
22. Sánchez, A. Colloidal Gels of Fumed Silica: Microstructure, Surface Interactions, and Temperature Effects. Ph.D. Thesis, North Carolina State University, Raleigh, NC, USA, 2006.
23. Leite, R.T.; de Souza-Mendes, P.R.; Thompson, R.L. A simple method to analyze materials under quasilinear large amplitude oscillatory shear flow (QL-LAOS). *J. Rheol.* **2019**, *63*, 305–317. [CrossRef]