ChemEngineering

Article

Physicochemical Factors Affecting the Rheology and Stability of Peach Puree Dispersions

Smaro Kyroglou [1], Christos Ritzoulis [2], Athina Theocharidou [2] and Patroklos Vareltzis [1,*]

[1] Chemical Engineering Department, Laboratory of Food and Agricultural Industries Technologies, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece; kyrosmar@cheng.auth.gr
[2] Department of Food Science and Technology, International Hellenic University, Alexander Campus, 57400 Thessaloniki, Greece; critzou@ihu.gr (C.R.); theocharidou.athina@gmail.com (A.T.)
* Correspondence: pkvareltzis@cheng.auth.gr; Tel.: +23-10996162

Abstract: The rheological properties and sedimentation phenomena in fruit purees are of particular importance for the food industry and product acceptance by consumers. The aim of this study was to correlate the phase separation with the underlying mechanisms. First, the influence of soluble solids content and temperature on the flow properties of peach puree was determined. Furthermore, considering the fruit puree matrix as a colloidal dispersion, the sedimentation rate, particle size and zeta potential were also determined. The peach puree samples exhibited pseudoplastic behavior, which was effectively described by the power law model. Both the flow consistency coefficient and apparent viscosity increased as the concentration rose. On the contrary, viscosity decreased as temperature increased. In addition, there was no significant effect of temperature on the flow behavior index. Low zeta potential values resulted in sedimentation as expressed by the phase separation index, and the highest sedimentation rate was observed for the sample with the lowest sucrose content.

Keywords: rheological properties; sedimentation; peach puree; colloidal dispersion; viscosity; zeta-potential; particle size

check for updates

Citation: Kyroglou, S.; Ritzoulis, C.; Theocharidou, A.; Vareltzis, P. Physicochemical Factors Affecting the Rheology and Stability of Peach Puree Dispersions. *ChemEngineering* **2024**, *8*, 119. https://doi.org/10.3390/chemengineering8060119

Academic Editor: José P. Coelho

Received: 4 October 2024
Revised: 8 November 2024
Accepted: 19 November 2024
Published: 22 November 2024

1. Introduction

Fruit purees are mainly produced by fruits that do not meet trade and/or consumers' standards, and are widely used in dairy, jams, syrups, jellies, and confectionery products [1]. Furthermore, fruit purees are now recognized by the consumers as valuable commodities, particularly for infants, as they can play a vital role in their nutrition and provide a convenient option for the caregivers [2,3].

Specifically, the Global Peach Puree Market is expected to grow at a Compound Annual Growth Rate (CAGR) of 5.5% from 2022 to 2030 [4]. Peach puree is industrially produced during the summer season, the harvest period of peaches and nectarines, and is stored in aseptic tanks and drums at ambient temperature. The major quality problem is the phase separation and sedimentation that can occur during the storage and transportation of the product. This phenomenon may lead to quality deterioration and loss of value, with direct economic consequences to the industry, including the loss of a stable customer base [5,6].

Recent studies have shown that stability and consistency of fruit purees are affected by the viscosity and rheological properties of product, the particle size distribution, and the microstructure [7–9]. The effect of concentration, temperature and processing on the rheological properties of a number of fruit purees and juices such as peach [10,11], apple [12,13], apricot [14], banana [15,16], strawberry [17,18], and mango puree [19], as well as apple [20], orange [21,22] and tomato juice [13,23] have been studied. Specifically, it was found that, as with all colloidal dispersions, viscosity is significantly affected by concentration and temperature. Furthermore, viscosity decrease was observed in cloudy juices as a function of storage time, because of pulp precipitation and pectin degradation [24,25]. At a physicochemical level, fruit purees and concentrated juices are complex polydisperse colloidal dispersions. They are composed of an insoluble phase (the pulp) and a viscous solution (the serum) [26]. The main components of the pulp are fruit tissue cells and their fragments, cell walls and insoluble polymer clusters, while the serum is an aqueous solution of soluble polysaccharides, sugars, salts, and acids [27,28]. The solid-insoluble particles are of various shapes and of multimodal size distributions. The fruit puree behavior is partially due to the interaction of particles contained in cells and cell wall materials [9]. The stability of these suspensions primarily depends on factors like zeta potential and pH [29,30]. Suspensions with an absolute zeta potential value exceeding 30 mV are considered stable, since they exhibit sufficient electrostatic repulsive force between particles, preventing them from flocculating and forming aggregates. Moreover, dispersion stability improvement has also been correlated to mixing entropy, as demonstrated by mixing attractive and unstable particles [31].

However, there is little information available that analyzes the separation phenomena and at the same time relates them to the internal mechanisms of dispersion of fruit puree and peach puree in particular. Several studies have investigated the application of high-pressure treatment (HPP) to cloudy juices, highlighting its effectiveness in preventing pulp sedimentation and maintaining turbidity stability [32–34]. It was found that HPP was efficient at improving particle uniformity, reducing the particle diameter, and modulating the rheological characteristics of juices. However, high HPP intensity could alter the particle interaction patterns, resulting in aggregation and reduction of the Brownian motion. Other researchers studied the application of ultrasound to stabilize fruit juices [28,35]. A recent experiment combined HPP with a natural kiwifruit pectin methylesterase inhibitor, yielding satisfactory results in orange-based juice [36].

Therefore, to gain insight of peach puree destabilization and quality loss, it is important to understand the correlations between particle size, rheology and phase separations in such systems. Consequently, this study aims to explore the impact of colloidal particles and temperature on the stability and rheology of peach puree dispersions. A noteworthy aspect of this research is the correlation of sugars content with the phase separation and sedimentation rate of peach puree, marking a novel approach. The outcomes of this study can offer valuable insights, potentially providing solutions that enhance the consistency and stability of industrial peach products.

2. Materials and Methods

2.1. Raw Materials and Reagents

Peach puree samples were supplied packaged in aseptic bags in concentrated (30° Brix) and non-concentrated (10° Brix) form by a local industry (Hellenic Juice Industry C. Dedes ASPIS S.A., Imathia, Greece).

Moreover, sucrose, citric acid and sodium hydroxide were of analytical grade and obtained from Merck & Co (Kenilworth, NJ, USA).

2.2. Percentage of Total Dissolved Solids TDS%

Total soluble solids were measured using an electronic refractometer (ATAGO, PAL-1, Tokyo, Japan) at room temperature (20 °C) and were expressed as ° Brix. In fruit purees and juices, total soluble solids are mainly made up of sugars and the Brix measurement corresponds to the sugar content of the product. In addition to the sugar content, the Brix value is also used in this study to express the concentration of colloidal particles.

2.3. Rheological Behavior

2.3.1. Sample Preparation for Rheological Measurements

The peach puree samples were prepared by diluting the concentrated puree (30° Brix) with distilled water (Hydrolab, R10, Straszyn, Poland) at different concentrated peach puree to water ratios ranging from 1:6 to 5:1 (*w*/*w*). Samples with lower soluble solids (5, 10, 15, 20 and 25° Brix) were obtained and stored in refrigerator at 4 °C until their use.

2.3.2. Rheological Measurements

The experimental process took place in two phases: First, the influence of the soluble solids content on the rheological behavior under constant temperature conditions was investigated; then, the influence of temperature at constant soluble solids content was explored. The samples with soluble solids of 15, 20, 25 and 30° Brix were analyzed using a Brookfield HBDV-II+P viscometer (Brookfield, Middleboro, MA, USA). The rheological behavior of the samples at different temperatures (10, 15, 25, 30, 35, 40, 45, 55 °C) was investigated for each Brix value. The temperature was controlled during the entire test procedure by using a thermostated water bath.

Enough sample (about 400 g) in a 500 mL beaker was used for viscosity measurements. The spindles found to be suitable for rheology determination were of disk geometry with different diameters ranging from 27.3 mm to 47.12 mm. Measurements were taken at increasing rotor speeds until a maximum speed was reached.

2.3.3. Rheological Calculations

The apparent viscosity, the rotational speed (RPM) and Torque% were obtained by the viscometer and used for rheological measurements. Afterwards, shear rate, shear stress, consistency coefficient and flow behavior index were determined using the following equations [37,38]:

$$\tau = k_{\alpha\sigma} \times (C \times Torque\%) \quad (1)$$

where τ is shear stress (Pa), $k_{\alpha\sigma}$ is a constant that depends on the spindle number and C is a constant that depends on the viscometer model.

$$\gamma = \left(0.263 \times n^{-0.771}\right) \times N \quad (2)$$

where γ is shear rate (s^{-1}), n is the flow behavior index and N the rotational speed of spindle (RPM).

The flow behavior index was equal to the slope of diagram depicting the logarithm of shear stress as a function of rotational speed. Moreover, consistency coefficient was equal to the slope of diagram that illustrates the shear stress as a function of shear rate.

The rheological behavior of non-Newtonian fluids like fruit purees and juices can be described by the models presented in Table 1.

Table 1. Rheological models for the description of non-Newtonian behavior.

Rheological Models	Equation	References
Power-law	$\tau = K\gamma^n$ (3)	[13,17]
Herschel-Bulkley	$\tau = \tau_0 + K\gamma^n$ (4)	[13,17]
Bingham	$\tau = \tau_0 + \mu_B\gamma$ (5)	[39,40]
Casson	$\sqrt{\tau} = \sqrt{\tau_0} + K\sqrt{\gamma}$ (6)	[2,7]

τ: shear stress, K: consistency coefficient, γ: shear rate, n: flow behavior index, τ_0: yield stress, μ_B: Bingham plastic viscosity.

2.4. Particle Size

The particle size of the peach puree samples was determined using a particle size analyzer (Ambivalue, EyeTech, Dussen, The Netherlands) based on the principle of laser obscuration. The samples were diluted with deionized water in a sample-to- water ratio (1:1, *w*/*w*) and placed in a cuvette cell. A magnetic stirrer was also used during measurements to ensure homogeneity of colloidal dispersions. Each measurement was repeated three times.

2.5. Zeta-Potential

Zeta potential of peach colloidal dispersions was measured using a Brookhaven Zeta-Plus apparatus (Brookhaven, Holtsville, NY, USA). The peach puree samples were diluted with deionized water in a sample-to- water ratio (1:1, w/w) and placed in cuvette cell. Afterwards the electrode was placed inside and connected to the device. The parameters of refractive index (1.43 for dispersion) and viscosity (1.0 mPa·s) were set and zeta-potential was determined. The measurement was conducted at room temperature (20 °C).

2.6. Mechanical and Ultrasonic Homogenization Process

Four grams of concentrated peach puree at 30° Brix were diluted with water at a ratio of 1/20 (w/w). The sample was then homogenized for 10 min (2 cycles × 5 min) using the IKA T18 ULTRA-TURRAX® disperser (IKA, Staufen, Germany). Another sample of peach puree with the same ratio was homogenized for 10 min (2 cycles × 5 min, amplitude setting: 40%) using the SONOPLUS HD 4200 ultrasonic homogenizer (BANDELIN, Berlin, Germany). The particle size and zeta potential were then determined and compared.

2.7. Determination of Sedimentation Phenomena

For sedimentation experiments, the peach puree dispersions were prepared by mixing equal volumes of sucrose stock solutions with either peach puree solution of 1° Brix or 3° Brix (Table 2). Specifically, the stock solution was an aqueous buffer solution containing of 0.01 M citric acid. pH was determined using a digital pH-meter (HANNA, pH 211, Woonsocket, RI, USA) and adjusted to 3.95 using 0.1M sodium hydroxide solution. Different sucrose quantities were diluted to the stock solution and seven solutions with different Brix concentration were obtained (0 to 30° Brix). The rheological properties of the reconstituted samples were subsequently examined immediately after formulation of each colloidal dispersion, at 20 °C using a cone plate viscometer (Lamy Rheology, RM 100 CP2000 PLUS, Champagne au Mont d'Or, France). Sixty milliliters of each dispersion were sealed in a test tube and stored at 20 °C under quiescent conditions. The phases separation of these samples was recorded as the ratio: $\frac{\textit{discernible serum height}}{\textit{total dispersion height}}$ ("phases separation index") at set time intervals with variable frequency.

Table 2. Reconstituted peach puree dispersions for sedimentation kinetics.

Sucrose Stock Solution (° Brix)	Reconstituted °Brix 1/1 Mix with:	
	Non Concentrated Puree 10° Brix	Concentrated Puree 30° Brix
0	5	15
5	7.5	17.5
10	10	20
15	12.5	22.5
20	15	25
25	17.5	27.5
30	20	30

2.8. Statistical Analysis

Data were analyzed by ANOVA (one way analysis of variance) with Tukey's test to compare means. Significance was reported at the $p < 0.05$ level. Data are presented as mean values ± standard deviation (SD) obtained from three independent analyses ($n = 3$). Minitab® 21 (Minitab, Ltd., Coventry, UK) statistical software was used for the statistical analysis.

3. Results

3.1. Rheological Properties of Peach Puree

3.1.1. Effect of Soluble Solids Content

First, the influence of the soluble solids content on the rheological behavior of peach puree at constant temperature was investigated. The variation in viscosity as a function of shear stress is shown in Figure 1 for all °Brix concentrations investigated. The effects of the soluble solids content on the parameters of consistency coefficient K and flow behavior index n are also shown in Figure 2.

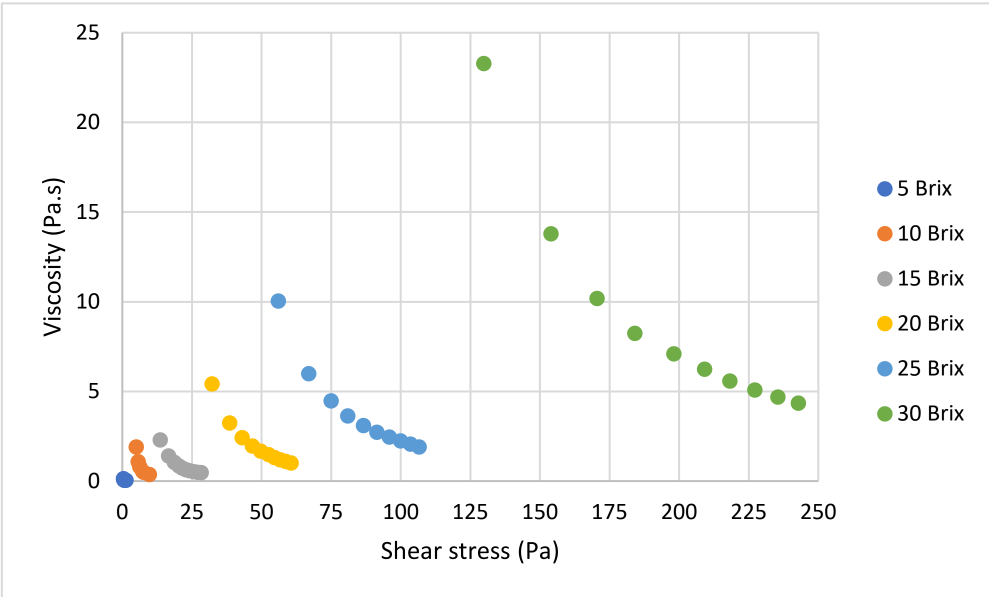
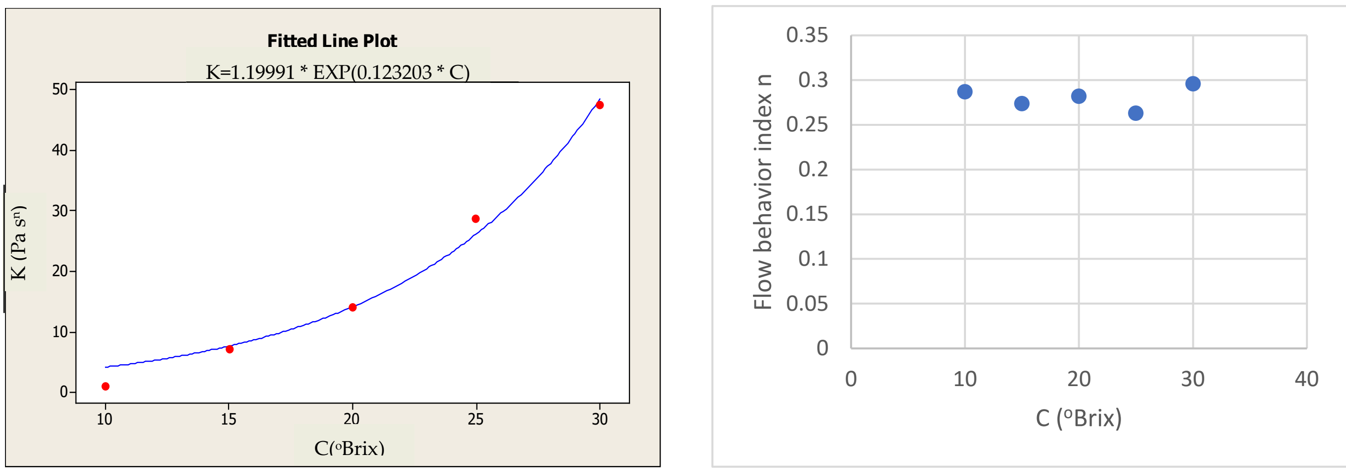


Figure 1. Viscosity curves of peach puree at different °Brix concentration (T = 10 °C).



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

Figure 2. Variation of consistency coefficient (K) (**a**) and flow behavior index (n) (**b**) at 10 °C as a function of soluble solids content.

The equation that describes adequately the variation of K as a function of soluble solids content at constant temperature (10 °C) is:

$$K = 1.2 \times exp(0.1232 \times C) \quad (7)$$

with R^2: 0.987.

According to Figure 2a, increase in soluble solids content led to the increase of consistency coefficient K, as is expected from a colloidal dispersion. On the other hand, no significant effect was observed to the flow behavior index (Figure 2b).

3.1.2. Effect of Temperature

The effect of temperature on the rheological properties of peach puree was examined at constant concentration. The variation of consistency coefficient K and flow behavior index n as a function of temperature for each concentration are presented in Figure 3.

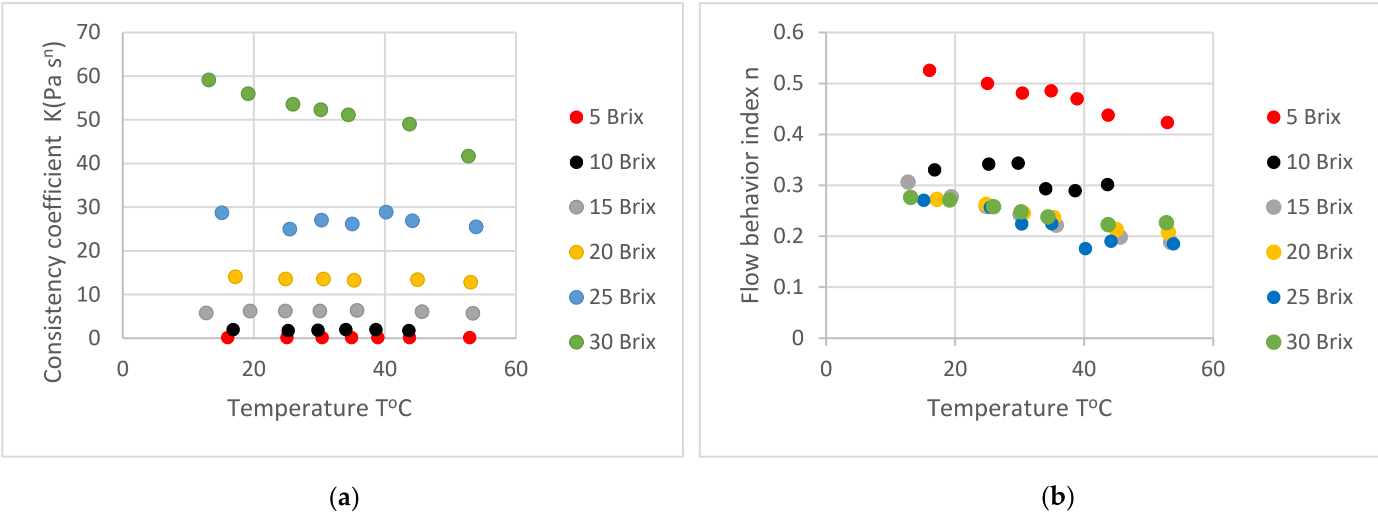


Figure 3. Variation of consistency coefficient (K) (**a**) and flow behavior index (n) (**b**) as a function of temperature.

According to Figure 3a, the consistency coefficient K was not significantly affected by temperature for concentrations ranging from 5 to 25° Brix, whereas the consistency coefficient showed a significant dependence on the temperature for the 30° Brix concentration (a decreasing trend, as expected from a dispersion of noninteracting colloidal particles [17]). The same tendency was observed for the flow behavior index (Figure 3b).

The equation that describes adequately the variation of K as a function of temperature at constant concentration 30° Brix is:

$$K = 3.7 \times exp\left(\frac{797.3}{T}\right) \quad (8)$$

The Equation (8) is of Arrhenius type and was derived from plotting the consistency coefficient against the inverse absolute temperature (1/T) (Supplementary Materials, Figure S1). It was used for the determination of the activation energy at 30° Brix, and was found equal to 6630 J/mol, while the activation energy calculated by fitting the viscosity data at a shear rate of 100 s^{-1} to an Arrhenius equation for the same concentration was found equal to 9536 J/mol.

Furthermore, the apparent viscosity decreased at all shear stresses and strain rates, as the temperature was increased throughout the entire range of the examined concentrations. This was depicted in Figure 4 for the concentration ranging from 5 to 30° Brix.

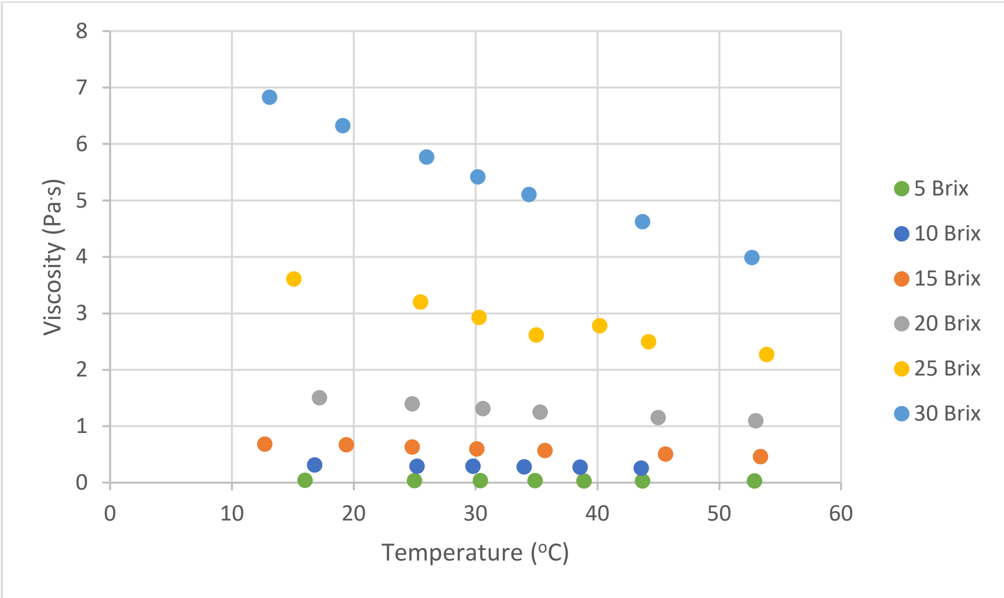


Figure 4. Variation of viscosity at a shear rate of 100 s^{-1} as a function of temperature for different °Brix concentration.

In addition, the rheological data for peach puree were well fitted with the power-law model for concentration ranging from 5 to 30° Brix with $R^2 \geq 95\%$. Additionally, the Herschel-Bulkley, Casson and Bingham models were used for data fitting, and results are presented in Supplementary Materials (Tables S2–S4).

3.2. Particle Size and Zeta-Potential

As explained in the Section 1, the peach puree behavior is determined by its colloidal properties; so, the measurements of particle size and zeta potential were necessary to understand the stability and rheology of the samples. The results of particle size and zeta-potential measurements are presented in Table 3.

Table 3. Particle size, zeta-potential and mobility of samples with different sucrose content (avg ± SD, *n* = 3).

Brix	Particle Size D [3,2] μm	Zeta Potential (mV)	Mobility (μ/s)/(V/cm)
5 Brix	8.8 ± 4.7	0 ± 1.6	0 ± 0.1
10 Brix	7.4 ± 3.4	−1.1 ± 1.4	−0.1 ± 0.1
15 Brix	8.3 ± 4.3	0 ± 1.6	0 ± 0.1
20 Brix	10.1 ± 5.9	0.1 ± 1.4	0 ± 0.1
25 Brix	9.5 ± 5.7	−0.3 ± 2.7	0 ± 0.2
30 Brix	8.4 ± 4.9	−1.5 ± 3.3	−0.1 ± 0.3

According to Table 3, the particle size D [3,2] did not differ significantly among the samples examined. Furthermore, no significant difference was recorded for the zeta-potential values of the samples. Specifically, zeta potential values were lower than 30 mV for all the sucrose concentrations tested.

3.3. Effect of Mechanical and Ultrasonic Homogenization

The effect of mechanical and ultrasonic homogenization on the particle size and the zeta potential of the samples is presented in Table 4.

Table 4. Particle size and zeta potential of processed peach puree samples (5° Brix and T = 25 °C, avg ± SD, n = 3).

Processing	Particle Size D [3,2] μm	Zeta Potential (mV)
Mechanical homogenization	1.8 ± 1.0	−8.8 ± 1.1
Ultrasonic homogenization	1.9 ± 1.3	−7.6 ± 0.7

Both mechanical and ultrasound homogenization significantly reduced the particle size of the samples ($p < 0.05$) i.e., when compared to Table 3 values, and increased the absolute value of zeta potential.

3.4. Sedimentation Kinetics

The sedimentation kinetics were monitored in terms of the ratio of the visually discernible serum height to the total dispersion height (this ratio is here called the "phases separation index") at set time intervals. Figures 5 and 6 present the evolution of sedimentation in non-concentrated and concentrated purees respectively. Moreover, Table 5 shows the viscosities at 500 s^{-1}, measured immediately after the formulation of colloidal dispersions.

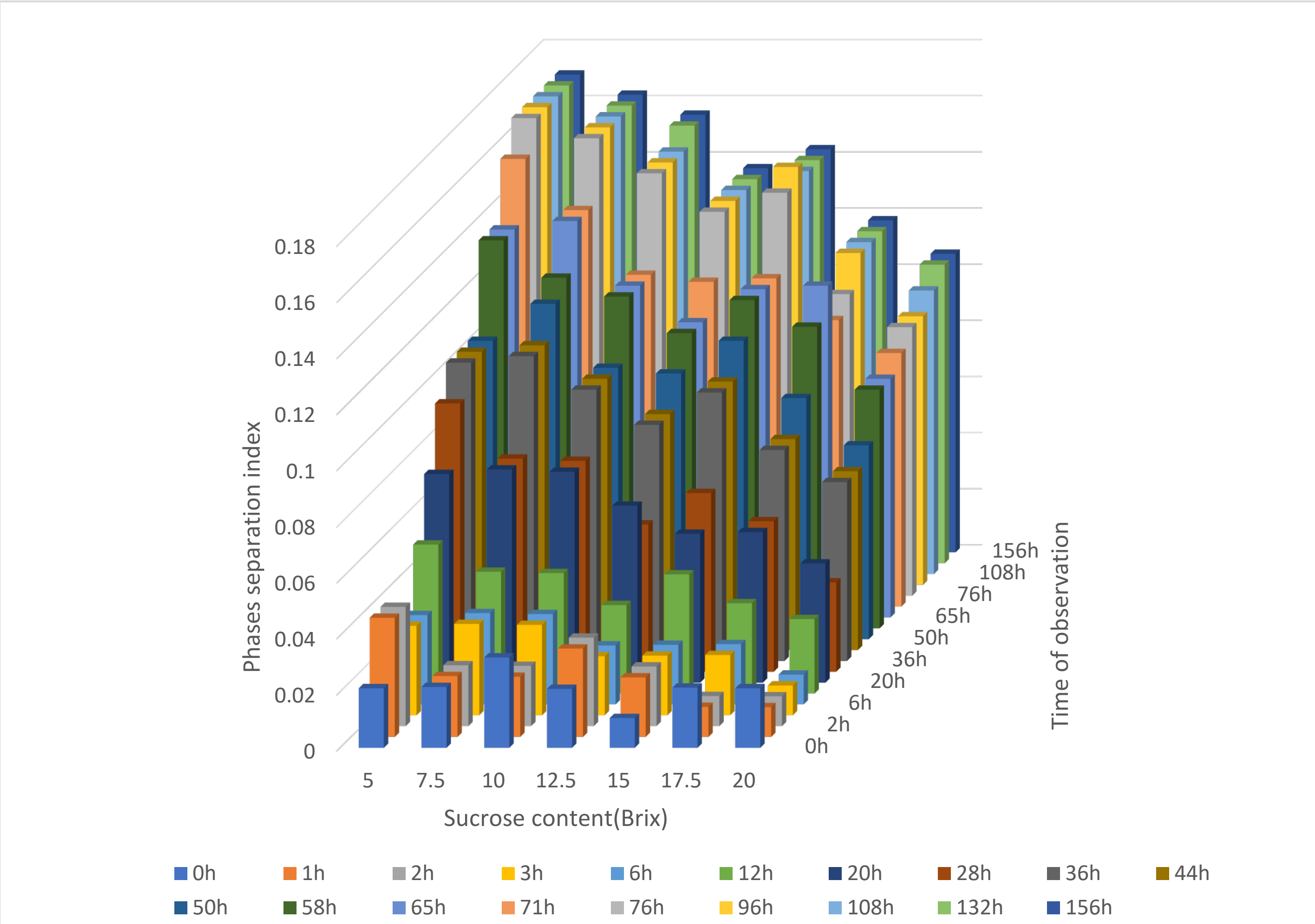


Figure 5. Evolution of sedimentation in dispersions containing increasing Brix levels in non-concentrated puree. x-axis: sucrose content (Brix); y-axis: phases separation index (serum height: dispersion height); z-axis: hours of observation.

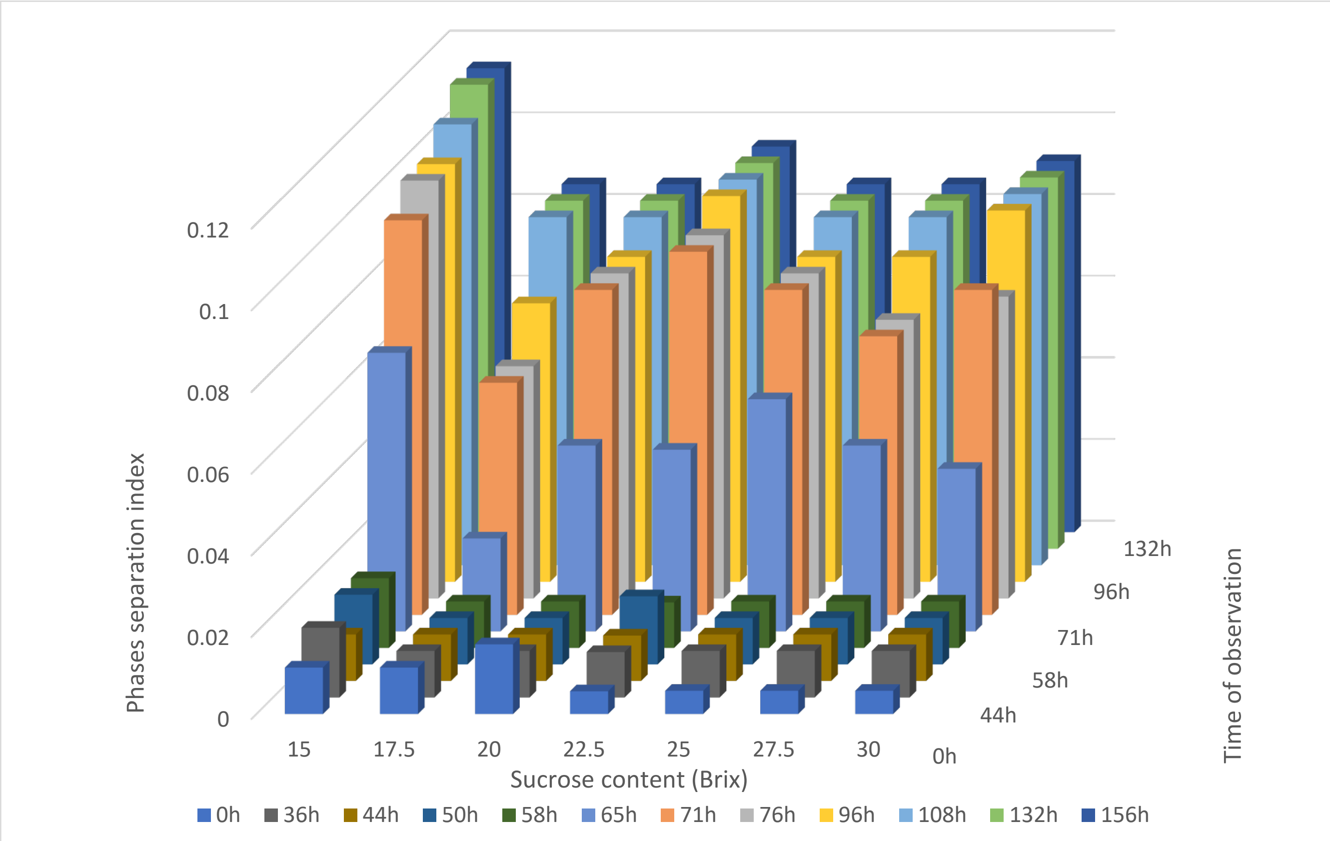


Figure 6. Evolution of sedimentation in dispersions containing increasing Brix levels in concentrated puree. *x*-axis: sucrose content (Brix); *y*-axis: phases separation index (serum height: dispersion height); *z*-axis: hours of observation.

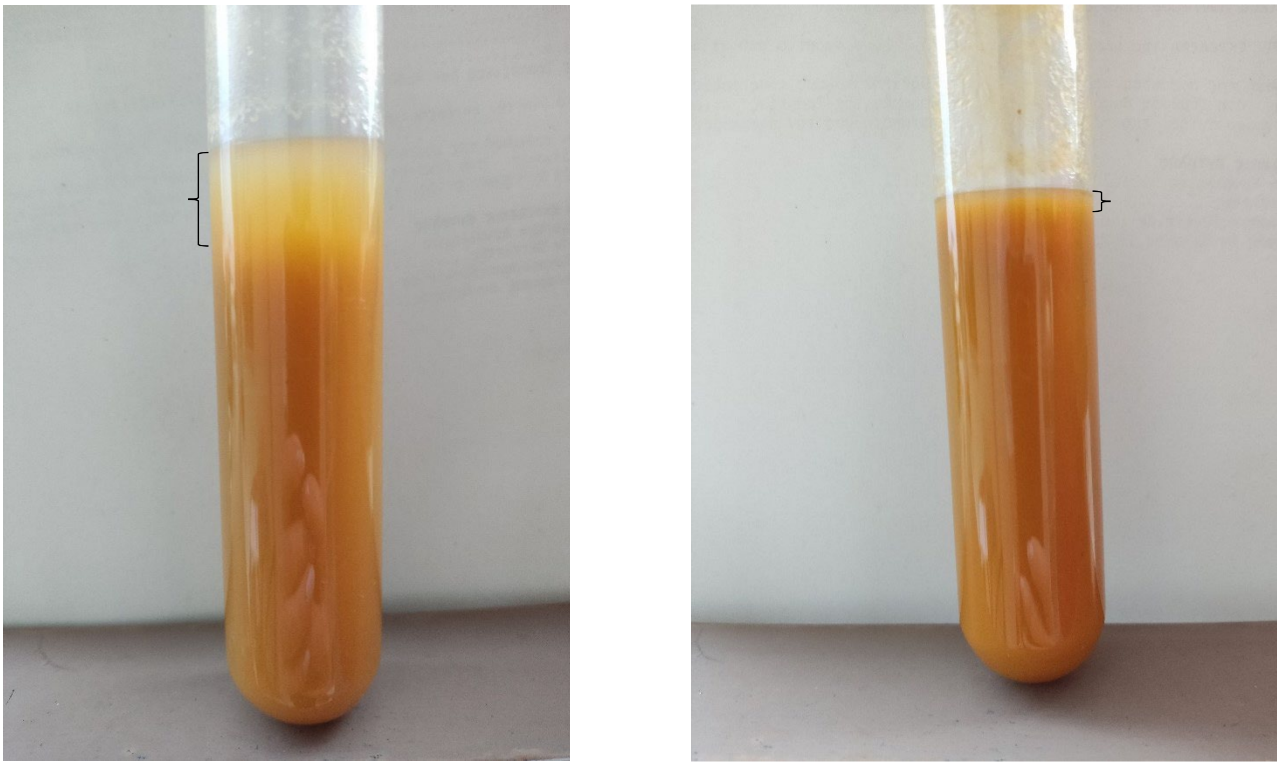
Table 5. Viscosity of samples with increasing amount of sucrose at shear rate of 500 s^{-1} containing (a) non-concentrated and (b) concentrated puree (avg ± SD, $n = 3$) [1].

(a) Sucrose Content (°Brix) Non-Concentrated Puree	Viscosity (mPa·s)	(b) Sucrose Content (° Brix) Concentrated Puree	Viscosity (mPa·s)
5	167 ± 3.1 ^{B}	15	201 ± 3.1 ^{BC}
7.5	232 ± 3.6 ^{A}	17.5	204 ± 4.5 ^{BC}
10	126 ± 5.1 ^{D}	20	148 ± 7.2 ^{D}
12.5	167 ± 4.6 ^{B}	22.5	221 ± 5.9 ^{A}
15	145 ± 5.0 ^{C}	25	216 ± 3.9 ^{AB}
17.5	88 ± 3.7 ^{E}	27.5	161 ± 3.8 ^{D}
20	133 ± 2.5 ^{CD}	30	200 ± 2.5 ^{C}

[1] Different superscript letter (A, B, etc.) corresponds to significant differences, $p < 0.05$.

Sedimentation was noticed for all sucrose concentrations throughout the duration of the experiment. According to Figure 5, all samples show a typical two-phase sedimentation profile, consisting of an initial lag phase up to 6 h, followed by a rapid sedimentation. One can note that, in general terms, the size of the clear layer at the top of samples, increased faster for the samples of lower brix, which is in line with the lower viscosities of these samples (as viscosity inhibits particle movement, hence sedimentation).

According to Figure 6, all the samples suffered sedimentation throughout the observation time because of their low zeta-potential values (Table 3). A lag phase is also encountered, this time extending up to 58 h. Furthermore, the sample with the lowest sucrose content presented the highest sedimentation rate, as it was also recorded in Figure 5 for the non-concentrated puree. Moreover, the phases separation index of samples with sucrose content ranging from 17.5° Brix to 3° Brix did not show significant differences for 108, 132 and 156 h. Another major observation is the delay of the first sedimentation phenomena for the samples containing the concentrated puree in contrast to those containing the non-concentrated. Specifically, the samples depicted in Figure 6 showed the first significant sedimentation at 65 h. On the other hand, only 6–20 h were needed for the sedimentation of non-concentrated samples (Figure 5). Comparing the highest phases separation index that was recorded in both cases, it can be concluded that sedimentation rate was higher in the non-concentrated puree. In Figure 7, the difference in sedimentation rate at the same observation time between non-concentrated and concentrated peach puree is obvious.



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

Figure 7. Development of sedimentation in sample containing (**a**) non-concentrated puree with 5° reconstituted Brix and (**b**) concentrated puree with 30° reconstituted Brix at 76th observation hour.

4. Discussion

4.1. Rheological Properties of Peach Puree

4.1.1. Effect of Soluble Solids Content

The consistency coefficient and viscosity of peach puree dispersions both increase with the increase in soluble solids content. Similar results have been reported by other researchers for the effect of soluble solids content [13,14]. This can be attributed to an increase in interactions between particles, as the number of particles coming into contact with each other increases with a higher soluble solids content [3]. Not only sugars, but also dissolved solids, including cellulose and pectin, form hydrogen bonds with water molecules. These bonds restrict the movement of the solids inside the fruit dispersion and the puree becomes more viscous [41]. In addition, water activity decreases as the number of soluble solids increases, so that less free water is available, resulting in a thicker consistency [1,10,11,42–44]. On the contrary, the flow behavior index was not significantly affected [1,44]. Specifically, the flow behavior index calculated for 20 and 30° Brix was comparable with the index determined by other researchers for peach puree. Relevant values equal to 0.34 and 0.32 for 30.5° Brix and 21° Brix respectively have been reported [10,11]. Moreover, it was quite lower than 1 for all the concentrations examined and consequently the peach puree can be characterized as a pseudoplastic material. The non-Newtonian behavior of peach puree dispersions can be attributed to complex interactions among soluble sugars, pectic substances and suspended solids contained in peach puree and fruit dispersion [28,43].

4.1.2. Effect of Temperature

Incremental temperature increases significantly affected the consistency coefficient for the 30° Brix concentration because of the formation of a less developed structure at higher temperatures as a result of an increase in Brownian motion [10]. The flow behavior index was not affected by temperature, which was confirmed by other studies [1,44].

The calculated activation energies from the viscosity values were significantly higher than those calculated by the Arrhenius type Equation (8). Luz et al. (2021) found that the values for activation energy calculated from the apparent viscosity were higher than those obtained from the consistency index. For the concentration of 30.5° Brix, the viscosity-based activation energy was 5556 J/mol, whereas the corresponding one based on consistency index was 2963 J/mol [11].

Furthermore, apparent viscosity decreased by temperature incremental changes for the range of the examined concentrations. This could be attributed to the increased molecular motion, which results to more effectively overcoming intermolecular forces and reducing the internal friction within the peach puree [45,46]. Consequently, the peach dispersion can flow easier encountering reduced resistance. Similar results were underlined by other researchers not only for peach puree but also for most fruit purees and juices [1,11,15,43].

4.2. Particle Size and Zeta-Potential

Particle size of peach puree dispersions expressed as D [3,2] did not differ significantly among the different sucrose content examined. This could be attributed to the fact that all the samples were prepared by adding the same quantity of peach puree and comprise of essentially the same colloidal particles (the components that are responsible for the modification of particle size, such as tissue cells and their fragments, cell walls, insoluble polymer clusters, proteins and polysaccharides were the same in all the samples). However, other researchers claimed that sugar addition may lead to particle size reduction, because sugars can draw water out of the fruit particles through osmosis, causing the cells to lose water and shrink [47–49]. Consequently, the particles in the puree could become more concentrated and smaller, leading to a finer dispersion with smaller visible particles.

Moreover, zeta potential was lower than 10 mV for the samples tested; this lack of effective electrostatic stabilization can result in rapid coagulation or flocculation, because attractive forces may exceed electrostatic repulsion between similarly charged particles in the dispersions. Higher zeta potential values could be achieved by applying high pressure homogenization. Homogenization at 20 Mpa resulted to higher zeta potential values, more uniform particle size and higher stability in cloudy apple juice [34].

4.3. Mechanical and Ultrasonic Homogenization

According to the results presented in Table 4, no significant difference was recorded for the particle size and zeta potential of mechanical and ultrasonic homogenized samples. This could be attributed to the operating conditions (intensity and homogenization time) that used during the treatments. However, both mechanical and ultrasound homogenization significantly reduced the particle size of the samples compared to the unprocessed samples. This reduction led to an increase in the absolute value of zeta potential. Since particles of small diameter are easily affected by the random movement of fluid flow and other particles, then the absolute value of zeta-potential of small particles is greater than that of large particles. Similar pattern was observed by other researchers when colloidal dispersions were treated with ultrasound [50].

4.4. Analysis of Sedimentation Phenomena

The peach puree dispersion with a high sucrose concentration is more stable than the one with a lower sucrose content (Figure 5), even though all samples show a low zeta potential (Table 3). This could be explained by the hygroscopicity of the sugar and the attraction of more water molecules at high sucrose content. As a result, the free water was reduced, leading to an increase in viscosity and a low sedimentation rate. The highest phase separation index in the non-concentrated puree compared to the concentrated puree (Figures 5 and 6, respectively) means that the sedimentation rate was higher in the non-concentrated puree. Georgiadis et al. (2011) and Manoj et al. (1998) claim that viscosity is an important factor in retarding phase separation in emulsions and colloidal dispersions [51,52]. Other researchers found that the specific energy of cohesion increased continually as the soluble solids content increased. Therefore, particles–particles interactions became much important enhancing the build-up of a tight network of particles with higher strength, which prevented sedimentation [21].

Recent studies showed that sedimentation was reduced by applying sonication to peach juice and non-dairy functional beverage emulsion [28,53]. Ultrasound caused reduction to particle size and according to Stokes law the sonicated samples would sediment slower with gravity in contrast with the non-sonicated ones.

Future research should be conducted to investigate the variation in particle size and microstructure of peach puree and the possible effects on rheology. The microstructure could be modified by applying ultrasonic homogenization at higher intensity than that tested in the present study or high-pressure homogenization (HPH). In addition, the zeta potential should be further investigated. The variation of pH and the addition of surfactants could possibly lead to higher zeta potential values and a more stable colloidal dispersion. The fruit processing industry could improve the consistency and quality of their products by choosing the optimal combination of processing factors including temperature, sucrose content, particle size and zeta potential.

5. Conclusions

Among the factors investigated in the experimental procedure, the concentration of soluble solids and temperature had a significant effect on the rheological properties. In addition, the sucrose content influenced the sedimentation rate. The samples prepared with the concentrated puree showed a slower sedimentation rate than those prepared with the non-concentrated puree. However, sedimentation was evident in all colloidal dispersions due to the low zeta potential values. The correlation of sedimentation kinetics with the concentration of colloidal particles, the size and the zeta potential could contribute to the quality and consistency of fruit-based products.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/chemengineering8060119/s1, Figure S1: Arrhenius curve of peach puree at 30° Brix concentration; Table S1: Rheological parameters and R^2 of Power-law model; Table S2: Rheological parameters and R^2 of Herschel-Bulkley model; Table S3: Rheological parameters and R^2 of Casson model; Table S4: Rheological parameters and R^2 of Bingham model.

Author Contributions: Conceptualisation, C.R. and P.V.; methodology, C.R., S.K. and P.V.; software, S.K. and A.T.; validation, S.K. and A.T.; formal analysis, S.K.; investigation, S.K. and P.V.; resources, C.R. and P.V.; data curation, S.K. and A.T.; writing—original draft preparation, S.K.; writing—review and editing, C.R. and P.V.; supervision, C.R. and P.V.; project administration, P.V. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in the study are included in the article/Supplementary Materials, further inquiries can be directed to the corresponding author.

Acknowledgments: The authors would like to thank the Hellenic Juice Industry C. Dedes ASPIS S.A for providing the non-concentrated and concentrated peach puree.

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

References

1. Goula, A.M.; Adamopoulos, K.G. Rheological Models of Kiwifruit Juice for Processing Applications. *J. Food Process. Technol.* **2011**, *2*, 1–106. [CrossRef]
2. Álvarez, E.; Cancela, M.A.; Delgado-Bastidas, N.; Maceiras, R. Rheological Characterization of Commercial Baby Fruit Purees. *Int. J. Food Prop.* **2008**, *11*, 321–329. [CrossRef]
3. Wani, S.; Bakshi, R.A.; Khan, Z.S.; Fayaz, S.; Muzaffar, K.; Dar, B.N. Physiochemical, Sensorial and Rheological Characteristics of Puree Developed from Kashmiri Peaches: Influence of Sugar, KMS and Storage Conditions. *Heliyon* **2021**, *7*, e07781. [CrossRef]
4. More, A. Global Peach Puree Sales Market. Available online: https://dataintelo.com/report/global-peach-puree-sales-market/ (accessed on 12 December 2023).
5. Zou, B.; Xu, Y.J.; Wu, J.J.; Yu, Y.S.; Xiao, G.S. Phenolic Compounds Participating in Mulberry Juice Sediment Formation during Storage. *J. Zhejiang Univ. Sci. B* **2017**, *18*, 854–866. [CrossRef] [PubMed]
6. Sinchaipanit, P.; Kerr, W.L. Effect of Reducing Pulp-Particles on the Physical Properties of Carrot Juice. *Int. Food Res. J.* **2007**, *14*, 205–214.
7. Balestra, F.; Cocci, E.; Marsilio, G.; Rosa, M.D. Physico-Chemical and Rheological Changes of Fruit Purees during Storage. *Procedia Food Sci.* **2011**, *1*, 576–582. [CrossRef]
8. Colin-Henrion, M.; Cuvelier, G.; Renard, C.M.G.C. Texture of Pureed Fruit and Vegetable Foods. *Stewart Postharvest Rev.* **2007**, *5*, 3. [CrossRef]
9. Abson, R. Factors Contributing to the Rheology of Tomato Puree. Ph.D. Thesis, University of Nottingham, Bonington Campus, Loughborough, UK, 2012.
10. Massa, A.; GonzÁLez, C.; Maestro, A.; Labanda, J.; Ibarz, A. Rheological Characterization of Peach Purees. *J. Texture Stud.* **2010**, *41*, 532–548. [CrossRef]
11. de Sousa Luz, A.; Berto, M.I. Rheological Behavior of Concentrated Peach Puree and Its Dilutions in a Stationary State/Comportamento Reológico Em Estado Estacionário de Purê de Pêssego Concentrado e Suas Diluições. *Braz. J. Dev.* **2021**, *7*, 80697–80715. [CrossRef]
12. Espinosa, L.; To, N.; Symoneaux, R.; Renard, C.M.G.C.; Biau, N.; Cuvelier, G. Effect of Processing on Rheological, Structural and Sensory Properties of Apple Puree. *Procedia Food Sci.* **2011**, *1*, 513–520. [CrossRef]
13. Krokida, M.K.; Maroulis, Z.B.; Saravacos, G.D. Rheological Properties of Fluid Fruit and Vegetable Puree Products: Compilation of Literature Data. *Int. J. Food Prop.* **2001**, *4*, 179–200. [CrossRef]
14. Sharoba, A.M.; Bahlol, H.; El-Mansy, H.A.; Senge, B. Rheological and Mechanical Properties of Apricot Fruit. In Proceedings of the 3rd International Conference for Food Science and Technology, Cairo, Egypt, 22–24 February 2005.
15. Ditchfield, C.; Tadini, C.C.; Singh, R.; Toledo, R.T. Rheological Properties of Banana Puree at High Temperatures. *Int. J. Food Prop.* **2004**, *7*, 571–584. [CrossRef]
16. Ibarz, A.; Falguera, V.; Garvín, A. Rheological and Thixotropic Behavior of Banana (*Musa cavendishii*) Puree. *Afinidad* **2010**, *67*, 415–420.
17. Maceiras, R.; Álvarez, E.; Cancela, M.A. Rheological Properties of Fruit Purees: Effect of Cooking. *J. Food Eng.* **2007**, *80*, 763–769. [CrossRef]
18. Osorio, O.; Martínez-Navarrete, N.; Moraga, G.; Carbonell, J.V. Effect of Thermal Treatment on Enzymatic Activity and Rheological and Sensory Properties of Strawberry Purees. *Food Sci. Technol. Int.* **2008**, *14* (Suppl. 5), 103–108. [CrossRef]
19. Gundurao, A.; Ramaswamy, H.S.; Ahmed, J. Effect of Soluble Solids Concentration and Temperature on Thermo-Physical and Rheological Properties of Mango Puree. *Int. J. Food Prop.* **2011**, *14*, 1018–1036. [CrossRef]
20. Benítez, E.I.; Genovese, D.B.; Lozano, J.E. Effect of Typical Sugars on the Viscosity and Colloidal Stability of Apple Juice. *Food Hydrocoll.* **2009**, *23*, 519–525. [CrossRef]
21. Dahdouh, L.; Wisniewski, C.; Ricci, J.; Vachoud, L.; Dornier, M.; Delalonde, M. Rheological Study of Orange Juices for a Better Knowledge of Their Suspended Solids Interactions at Low and High Concentration. *J. Food Eng.* **2016**, *174*, 15–20. [CrossRef]
22. Ibarz, A.; Gonzalez, C.; Esplugas, S. Rheology of Clarified Fruit Juices. III: Orange Juices. *J. Food Eng.* **1994**, *21*, 485–494. [CrossRef]
23. Bot, F.; Calligaris, S.; Cortella, G.; Nocera, F.; Peressini, D.; Anese, M. Effect of High Pressure Homogenization and High Power Ultrasound on Some Physical Properties of Tomato Juices with Different Concentration Levels. *J. Food Eng.* **2017**, *213*, 10–17. [CrossRef]
24. Laaksonen, O.; Mäkilä, L.; Jokinen, M.; Metz, T.; Kallio, H.; Yang, B. Impact of Storage on Sensory Quality of Blackcurrant Juices Prepared with or without Enzymatic Treatment at Industrial Scale. *Eur. Food Res. Technol.* **2020**, *246*, 2611–2620. [CrossRef]
25. Cao, X.; Bi, X.; Huang, W.; Wu, J.; Hu, X.; Liao, X. Changes of Quality of High Hydrostatic Pressure Processed Cloudy and Clear Strawberry Juices during Storage. *Innov. Food Sci. Emerg. Technol.* **2012**, *16*, 181–190. [CrossRef]

26. Dundar Kirit, B.; Akyıldız, A. Rheological Properties of Thermally or Non-Thermally Treated Juice/Nectar/Puree: A Review. *J. Food Process. Preserv.* **2022**, *46*, e17075. [CrossRef]
27. Kubo, M.; Atribst, A.A.L.; Augusto, P. High Pressure Homogenization in Fruit and Vegetable Juice and Puree Processing: Effects on Quality, Stability and Phytochemical Profile. In *Reference Module in Food Science*; Elsevier: Amsterdam, The Netherlands, 2020. [CrossRef]
28. Rojas, M.L.; Leite, T.S.; Cristianini, M.; Alvim, I.D.; Augusto, P.E.D. Peach Juice Processed by the Ultrasound Technology: Changes in Its Microstructure Improve Its Physical Properties and Stability. *Food Res. Int.* **2016**, *82*, 22–33. [CrossRef]
29. Pochapski, D.J.; Carvalho dos Santos, C.; Leite, G.W.; Pulcinelli, S.H.; Santilli, C.V. Zeta Potential and Colloidal Stability Predictions for Inorganic Nanoparticle Dispersions: Effects of Experimental Conditions and Electrokinetic Models on the Interpretation of Results. *Langmuir* **2021**, *37*, 13379–13389. [CrossRef]
30. Sharaf, O.Z.; Taylor, R.A.; Abu-Nada, E. On the Colloidal and Chemical Stability of Solar Nanofluids: From Nanoscale Interactions to Recent Advances. *Phys. Rep.* **2020**, *867*, 1–84. [CrossRef]
31. Mo, S.; Shao, X.; Chen, Y.; Cheng, Z. Increasing Entropy for Colloidal Stabilization. *Sci. Rep.* **2016**, *6*, 36836. [CrossRef]
32. Salehi, F. Physicochemical Characteristics and Rheological Behaviour of Some Fruit Juices and Their Concentrates. *J. Food Meas. Charact.* **2020**, *14*, 2472–2488. [CrossRef]
33. Li, M.; Liu, Q.; Zhang, W.; Zhang, L.; Zhou, L.; Cai, S.; Hu, X.; Yi, J. Evaluation of Quality Changes of Differently Formulated Cloudy Mixed Juices during Refrigerated Storage after High Pressure Processing. *Curr. Res. Food Sci.* **2021**, *4*, 627–635. [CrossRef]
34. Zhu, D.; Kou, C.; Wei, L.; Xi, P.; Lv, C.; Cao, X.; Liu, H. Effects of High Pressure Homogenization on the Stability of Cloudy Apple Juice. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *358*, 022059. [CrossRef]
35. Ferrari, G.; Mohapatra, D.; Prabhakar, P.K.; Freitas, J.; de São José, J.F.B. Stability Parameters during Refrigerated Storage and Changes on the Microstructure of Orange-Carrot Blend Juice Processed by High-Power Ultrasound. *Front. Sustain. Food Syst.* **2022**, *6*, 891662.
36. Zhang, W.; Li, Y.; Jiang, Y.; Hu, X.; Yi, J. A Novel Strategy to Improve Cloud Stability of Orange-Based Juice: Combination of Natural Pectin Methylesterase Inhibitor and High-Pressure Processing. *Foods* **2023**, *12*, 581. [CrossRef] [PubMed]
37. Mitschka, P. Simple Conversion of Brookfield RVT Readings into Viscosity Functions. *Rheol. Acta* **1982**, *21*, 207–209. [CrossRef]
38. Briggs, J.L.; Steffe, J.F. Research/Application Note Using Brookfield Data and the Mitschka Method to Evaluate Power Law Foods. *J. Texture Stud.* **1997**, *28*, 517–522. [CrossRef]
39. Diamante, L.; Umemoto, M. Rheological Properties of Fruits and Vegetables: A Review. *Int. J. Food Prop.* **2015**, *18*, 1191–1210. [CrossRef]
40. Phaokuntha, S.; Poonlarp, P.B.; Pongsirikul, I. Rheological Properties of Mango Puree and Process Development of Mango Sheet. *Acta Hortic.* **2014**, *1024*, 373–380. [CrossRef]
41. López-Esparza, R.; Balderas Altamirano, M.A.; Pérez, E.; Gama Goicochea, A. Importance of Molecular Interactions in Colloidal Dispersions. *Adv. Condens. Matter Phys.* **2015**, *2015*, 683716. [CrossRef]
42. Sato, Y.; Kawabuchi, S.; Irimoto, Y.; Miyawaki, O. Effect of Water Activity and Solvent-Ordering on Intermolecular Interaction of High-Methoxyl Pectins in Various Sugar Solutions. *Food Hydrocoll.* **2004**, *18*, 527–534. [CrossRef]
43. Haminiuk, C.W.I.; Sierakowski, M.R.; Vidal, J.R.M.B.; Masson, M.L. Influence of Temperature on the Rheological Behavior of Whole Araçá Pulp (*Psidium cattleianum* Sabine). *LWT-Food Sci. Technol.* **2006**, *39*, 427–431. [CrossRef]
44. Dak, M.; Verma, R.C.; Jaaffrey, S.N.A. Effect of Temperature and Concentration on Rheological Properties of "Kesar" Mango Juice. *J. Food Eng.* **2007**, *80*, 1011–1015. [CrossRef]
45. Wei, S.; Li, X.; Shen, Y.; Zhang, L.; Wu, X. Study on Microscopic Mechanism of Nano-Silicon Dioxide for Improving Mechanical Properties of Polypropylene. *Mol. Simul.* **2020**, *46*, 468–475. [CrossRef]
46. Wu, X.-J.; Wang, Y.; Yang, W.; Xie, B.-H.; Yang, M.-B.; Dan, W. A Rheological Study on Temperature Dependent Microstructural Changes of Fumed Silica Gels in Dodecane. *Soft Matter* **2012**, *8*, 10457–10463. [CrossRef]
47. Branca, C.; Magazù, S.; Maisano, G.; Migliardo, F.; Migliardo, P.; Romeo, G. α,α-Trehalose/Water Solutions. 5. Hydration and Viscosity in Dilute and Semidilute Disaccharide Solutions. *J. Phys. Chem. B* **2001**, *105*, 10140–10145. [CrossRef]
48. Lerbret, A.; Bordat, P.; Affouard, F.; Guinet, Y.; Hédoux, A.; Paccou, L.; Prévost, D.; Descamps, M. Influence of Homologous Disaccharides on the Hydrogen-Bond Network of Water: Complementary Raman Scattering Experiments and Molecular Dynamics Simulations. *Carbohydr. Res.* **2005**, *340*, 881–887. [CrossRef] [PubMed]
49. Ellis, A.L.; Mills, T.B.; Norton, I.T.; Norton-Welch, A.B. The Effect of Sugars on Agar Fluid Gels and the Stabilisation of Their Foams. *Food Hydrocoll.* **2019**, *87*, 371–381. [CrossRef]
50. Nakatuka, Y.; Yoshida, H.; Fukui, K.; Matuzawa, M. The Effect of Particle Size Distribution on Effective Zeta-Potential by Use of the Sedimentation Method. *Adv. Powder Technol.* **2015**, *26*, 650–656. [CrossRef]
51. Georgiadis, N.; Ritzoulis, C.; Sioura, G.; Kornezou, P.; Vasiliadou, C.; Tsioptsias, C. Contribution of Okra Extracts to the Stability and Rheology of Oil-in-Water Emulsions. *Food Hydrocoll.* **2011**, *25*, 991–999. [CrossRef]

52. Manoj, P.; Fillery-Travis, A.J.; Watson, A.D.; Hibberd, D.J.; Robins, M.M. Characterization of a Depletion-Flocculated Polydisperse Emulsion. I. Creaming Behavior. *J. Colloid Interface Sci.* **1998**, *207*, 283–293. [CrossRef]
53. Vallath, A.; Shanmugam, A. Study on Model Plant Based Functional Beverage Emulsion (Non-Dairy) Using Ultrasound—A Physicochemical and Functional Characterization. *Ultrason. Sonochem.* **2022**, *88*, 106070. [CrossRef]