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Research Article

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Rheological Models of Kiwifruit Juice for Processing Applications

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Abstract

Rheological behavior of kiwifruit juice at different solids concentrations (13.5–30 °Brix) and different temperatures (25–65°C) was studied with the objective of defining suitable mathematical models for use in evaporation and other processing procedures. Kiwifruit juice samples exhibited pseudoplastic behavior and were characterized by the power law model. The flow consistency index decreased with an increase in temperature and a decrease in concentration, whereas there was no significant effect of temperature and concentration on flow behavior index. The apparent viscosity at a reference shear rate of 1.0 s^{-1} ($\mu_{\alpha 1}$) was used instead of the flow consistency index. The temperature and concentration effects on $\mu_{\alpha 1}$ were expressed with a single equation. At low shear rates, kiwifruit juice samples exhibited a thixotropic behavior, which turned to rheopectic at high shear rates. In addition, the Bostwick consistency levels were related to the apparent viscosity measurements and the flow consistency index values.

Keywords: Consistency; Flow properties; Kiwifruit; Rheological characteristics; Shear rate; Thixotropy; Viscosity

Introduction

Kiwi fruit (*Actinidia chinensis*, Planch and *Actinidia deliciosa*, A. Chev.) is a native of the mountains of southern China. Commercial development of the fruit took place in New Zealand, with a number of cultivars being selected from seeds of *Actinidia deliciosa* [1]. Kiwifruit presents a high nutritional value, rich mainly in vitamin C and fibers, calcium, iron, and phosphorus, which turn it into an excellent nutritional option with an important association between quality attributes and flavor [2]. The fruit that does not meet export standards and is not sold in the domestic fresh-fruit market may be processed as a food ingredient for industrial use. In this sense, kiwi fruits are either canned or frozen, whereas different kinds of drying processes may also be used. In addition, concentrated kiwi fruit juices are used extensively as fruit ingredients in many foods such as dairy products, jams and jellies, syrups, confectionery, etc.

The rheological behavior of kiwifruit juice plays an important role not only as a measurement of its quality, but also for designing processes such as pumping, agitation, transport in tubes, evaporation and others. The type of evaporator, direction of feed, and heat transfer in a kiwifruit juice processing plant are all affected by viscosity. High shear rates are utilized in modern evaporators to reduce the viscosity, increase the heat transfer rate, and thus save energy. If the viscosity of the concentrate exceeds a threshold value then the output products concentration must be reduced or the concentrate will "burn on" the inside of the evaporator. This would cause a loss of energy and product [3].

In addition, information of the viscosity of kiwifruit juice as influenced by concentration and temperature is of particular importance to the design and operation of evaporation processes. For example, for improving the design of an evaporation system in which fluids flow by forced circulation through pipes and by gravity over an inclined evaporation surface, a good understanding of how the evaporation is influenced by viscosity at different concentrations and temperatures is required. Mathematical models that express the dependence of rheological properties on temperature and water content are a very appealing alternative to experimentation and a useful tool for Equationuipment selection.

There is a number of research works published about rheological properties of fruit juices [3-20]. However, the scientific literature lacks information on the rheological characteristics of kiwifruit juice. One study is only concerned with the rheological behavior of kiwi juice with a high solids concentration (22.5–63.0°Brix) [21]. However, that juice was clarified by centrifugation and thus has rheological properties different from these of the whole kiwifruit juice.

In addition, many authors have studied the influence of temperature and moisture content on the rheological parameters of fruit juices. According to Cepeda and Villaran [22], temperature influence on viscosity has been found to be related to soluble solids content, and experimental data for fixed concentrations can be related to the temperature using the Arrhenius-Guzman equation. Many researchers reported that flow behavior index (n) of juices varies only slightly with temperature and moisture content and used a combined model (Equation (1)) to describe their effect on flow consistency index (K) values [20,23,24]:

$$K = AC^{B}\exp\left(\frac{E_a}{RT}\right) \tag{1}$$

where C is the solids content, E_a is the activation energy, R is the universal gas constant, T is the absolute temperature, and A and B are constants. Krokida, Maroulis and Saravacos [25] indicated that an Arrhenius relationship can be used to describe the effect of temperature and concentration on K values:

$$K = K_0\exp\left(\frac{E_a}{RT} + DC\right) \tag{2}$$

where K_0 is the frequency factor and D is a constant. Similar equations

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have been derived for the viscosity of juices presenting Newtonian behavior [22].

Generally, many researchers have studied the temperature and moisture content effects on the rheological characteristics of fruit juices, but they have not taken into account that the flow consistency index cannot be compared independently from the flow behavior index, as it has dimensions related to *n* value. Since *n* varies, *K* dimensions change too. To deal with this problem, we propose the use of the apparent viscosity at a reference shear rate of 1.0 s^{-1} ($\mu_{\alpha 1}$) and the development of suitable mathematical models describing the effect of temperature and concentration on $\mu_{\alpha 1}$ values. In order to present some practical utility, this apparent viscosity should be useful in modeling the hydrodynamic behavior of kiwifruit juice flow. For example, to calculate the pressure drop in the laminar flow of kiwifruit juice in circular pipes, Equations. (3)–(5) could be used:

$$\mathrm{Re}_M = \frac{D \cdot u \cdot \rho}{\mu_{a1}} \quad (3)$$

$$f = \frac{16}{\mathrm{Re}_M} \quad (4)$$

$$\Delta P = \frac{2 \cdot f \cdot L \cdot u^2 \cdot \rho}{D} \quad (5)$$

where Re_M is the modified Reynolds number, *D* is the pipe diameter, *u* is the fluid velocity, ρ is the fluid density, *f* is the friction factor, ΔP is the pressure drop, and *L* is the pipe length.

Thus, the objectives of this work were to study the rheological properties of whole kiwi juice with solids concentrations usually met in the kiwi juice processing and to define suitable mathematical models for use in designing kiwi juice processes such as evaporation, pumping, agitation and others.

Materials and Methods

Sample preparation

Kiwi fruits were supplied by a local producer. After washing and peeling, juice was extracted. The kiwi juice was concentrated to 30°Brix using a rotary vacuum evaporator (Model R II, Buchi Laboratoriums-Technik, Flawil, Switzerland) at 60°C and immediately stored in refrigerator at 4°C till used. Samples with lower soluble solids (13.5, 15, 20, and 20°Brix) were obtained by diluting the concentrated juice with distilled water.

Analysis of kiwifruit juice

Kiwifruit juice was analyzed by using standard methods for soluble solids, acidity, pH, pectin, and density. The soluble solids content was measured using a universal laboratory refractometer (ATC-1E, Atago Co., Ltd, Tokyo, Japan) at room temperature (20°C) and expressed as °Brix. Total acidity was determined by potentiometric titration with NaOH 0.1 N until pH 8 [26]. The pH was measured with a digital pH-meter (HI 2210, Hanna Instruments, Inc., Rhode Island, USA) at 20°C. The pectic substances were precipitated by alcohol. The total residue was used for the determination of the total pectin. An alcoholic carbazole solution in acidic medium was added to provide a colour [27], which was measured at 525 nm by a Helios UV-Visible spectrophotometer (Helios gamma, Thermo Spectronic, Madison, USA). The pectin was estimated quantitatively by using a standard curve of galacturonic acid. The relative density was determined in capillary tube pycnometers of 10 mL capacity; the water and juice weight were recorded in analytical balance with 0.0001 g precision after stabilization in a thermostatic bath (±0.1°C). Table 1 refers to physical-chemical characteristics of kiwifruit juice.

Soluble solids (°Brix)	13.5
Acidity (eq/L)	0.146
pH	3.55
Pectins (g galacturonic acid/L)	0.729
Density (g/mL)	1.054

Table 1: Physicochemical characteristics of kiwifruit juice.

Rheological measurements

The rheological behavior of kiwifruit juice samples having soluble solids contents of 13.5, 15, 20, 25, and 30°Brix and temperatures of 25, 35, 45, 55, and 65°C was studied using a Brookfiled rotational viscometer (LVDV-II+, Brookfield Engineering Laboratories, Inc., Stoughton, Massachusetts, USA). Enough sample (about 400g) in a 500 mL beaker was used for viscosity measurements. Rotor speed was variable in the range 0.3–100 rpm. Readings were taken at increasing rotor speeds until a maximum speed was reached, after which it was gradually decreased. The viscometer temperature was controlled using an Edmund Buhler thermostatic circulating water bath (Model 7400, Edmund Buhler GmbH & Co., Tuebingen, Germany) and the samples were maintained at rest for 5min in the viscometer to equilibrate at the set temperature before the shear rate sweeps were performed. Silicone oil was applied to the exposed surface of the sample to prevent evaporation. All experiments were performed on duplicate samples.

Consistency measurements were also taken for each sample with a Bostwick Consistometer. Bostwick value (*BC*) was taken as the distance in meters the juice traveled in 30 s.

Flow behavior was described by the fitting of the experimental data with the following power law model [18]:

$$\log(\mu_\alpha) = (n-1)\log(4\pi N) + \log(K) - n\log(n) \quad (6)$$

where μ_α is the apparent viscosity (Pa s), *n* is the flow behavior index, *N* is the spindle speed (rps), and *K* is the flow consistency index (Pa s^n).

However, the flow consistency index cannot be compared independently from the flow behavior index, as it has dimensions related to *n* value. Thus, the apparent viscosity predicted by the power law model (Equation (7)) at a reference shear rate of 1.0 s^{-1} was used instead of *K*.

$$\mu_\alpha = \mu_{\alpha 1} \dot{\gamma}^{n-1} \quad (7)$$

where $\dot{\gamma}$ is the shear rate (s^{-1}) and $\mu_{\alpha 1}$ is the apparent viscosity (Pa s) at a shear rate of 1.0 s^{-1}.

The effect of temperature on $\mu_{\alpha 1}$ was described by the Arrhenius-Guzman equation:

$$\mu_{\alpha 1} = \mu_{\alpha 10} \exp\left(\frac{E_a}{RT}\right) \quad (8)$$

where $\mu_{\alpha 10}$ is the frequency factor (Pa s), E_a is the activation energy (J/mol), *R* is the universal gas constant (8.314 J/mol K), and *T* is the absolute temperature (K).

The effects of temperature and solids concentration on $\mu_{\alpha 1}$ can be combined in a single logarithmic model:

$$\mu_{\alpha 1} = \exp(a + b/T + cC) \quad (9)$$

where *a*, *b*, and *c* are constants and *C* is the solids concentration (°Brix).

To study the time-dependence of kiwifruit juice rheological properties, samples with solids concentrations of 15 and 30°Brix were sheared at constant shear rates, namely at 20, 30, 60, and 100 s^{-1} (at 25°C), and the apparent viscosity was measured as a function of shearing time until an equilibrium state was reached. The measured time-dependent flow properties of samples were modeled by the structural kinetic model [28]:

$$\left(\frac{\mu_\alpha - \mu_{\alpha\infty}}{\mu_{\alpha 0} - \mu_{\alpha\infty}}\right)^{1-n'} = (n'-1)kt + 1 \qquad (10)$$

where t is the shearing time (s), $\mu_{\alpha 0}$ is the initial apparent viscosity (Pa s) at $t = 0$ (structured state), $\mu_{\alpha\infty}$ is the steady state apparent viscosity (Pa s) at $t \to \infty$ (non-structured state), n' is the order of the structure breakdown reaction, and k is the breakdown rate constant (s^{-1}). Many authors reported that among the models usually used to describe the time-dependent flow properties, the second-order structural kinetic model ($n' = 2$) is well fitted to the experimental data compared to the first-order stress decay and Weltman models [29-31].

Results and Discussion

Flow curves

Figure 1 shows the values of $\log(\mu_\alpha)$ against $\log(4\pi N)$ for two

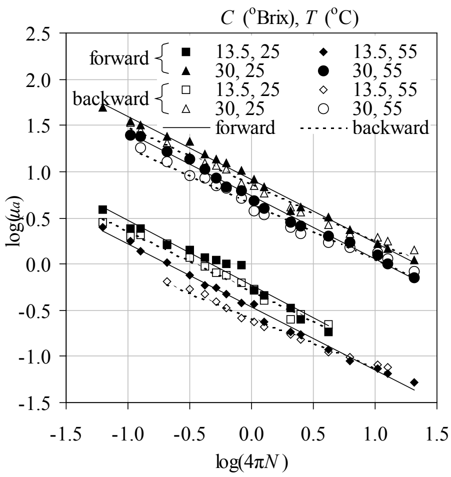

Figure 1: Flow curves of kiwifruit juice of 13.5 and 30 °Brix at 25 and 55 °C measured by increasing (forward) and decreasing (backward) the shear rate.

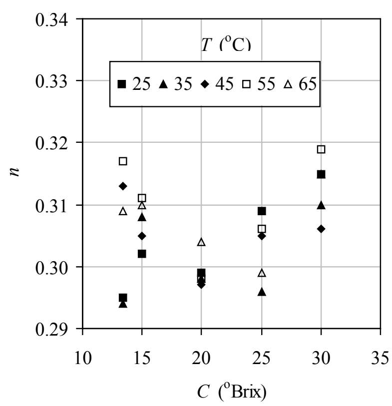

Figure 2: Variation of flow behavior index of kiwifruit juice with solids concentration at various temperatures.

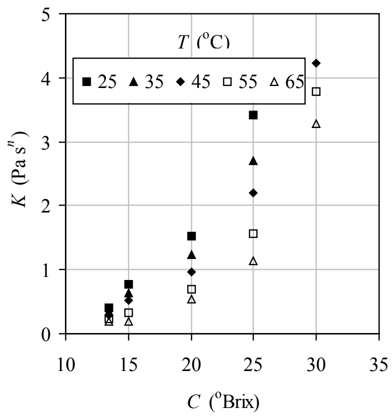

Figure 3: Variation of consistency index of kiwifruit juice with solids concentration at various temperatures.

solids concentrations and two temperatures. From the distribution of the points we can see that the plots are approximately linear ($R^2 = 0.965$–0.998). The slope and the intercept of the straight line fitting the values of $\log(\mu_\alpha)$ against $\log(4\pi N)$ for each solids concentration and each temperature give the n and K values, which are given in Figures 2–3 for all C and T values. As it can be drawn from Figure 2, the flow behavior index was lower that 1.0 for all C and T values showing that kiwifruit juice exhibits pseudoplastic behavior. This observation is similar to that obtained by Telis-Romero et al. [32], Dak et al. [18], Ibarz et al. [27], and Pelegrine, Silva, and Gasparetto [33] for clarified orange juice with different moisture content (0.34–0.73 w/w), whole mango juice with a solids concentration varying from 7.6 to 26%, whole sloe (*Prunus spinosa*) fruit juice (25–58.5 °Brix), and both whole and centrifuged pineapple juice, respectively. On the contrary, Belibagli and Dalgic [17], Altan and Maskan [14], Nindo et al. [15], Khalil, Ramakrishna, Nanjundaswamy and Patwardhan [34], and Rao, Cooley, and Vitali [35] reported that clarified sour-cherry, pomegranate, blueberry, raspberry, and banana juices and depectinized clarified apple juice exhibit Newtonian behavior at all concentrations and temperatures. According to Zuritz et al. [16], the clarified juice concentrates have a Newtonian behavior, although Ibarz et al. [21] have found a small pseudoplasticity in the flow of various fruit concentrates due to the presence of some soluble solids, mostly pectins and tartrates.

The pseudoplastic behavior of kiwifruit juice concentrates can be attributed to discontinuous phase substances, such as fibrous materials, when water acts as a continuous phase. Insoluble solids consist mainly of proteins and pectic substances. According to Sharma, LeMaguer, Liptay and Poysa [36], who studied the rheological properties of tomato thin pulp, pectin is the major factor that increases the viscosity of a food product, whereas protein plays a minor role. Bhattacharya and Rastogi [37] reported that the pectinaceous substances possess a high water holding capacity and develop a cohesive network structure.

Dak et al. [18] reported a n value varying from 0.21 to 0.33 for mango juice with a solids concentration of 7.6–26.0% at 20–70°C, whereas Telis-Romero et al. [32] found that orange juice with different moisture content (0.34–0.73 w/w) at a wide range of temperatures (0.5–62°C) has a n value of 0.47–0.68. The chemical characteristics, especially pectin content and sugar composition, and the processing procedures (such as finishing and clarification) for juices are likely factors that can explain the differences in rheological properties [15].

Statistical analysis indicated that there is no significant effect of

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temperature and solids concentration on flow behavior index. This observation is similar to that obtained by Dak et al. [18], who studied the rheological properties of mango juice. The flow consistency index decreased as temperature increased (Figure 3). This tendency was also obtained in other studies [20,38]. In addition, *K* increased with an increase in concentration. This effect can be attributed to an increase in the interactions between the particles, because the number of particles that come into contact increases. However, the consistency indices could not be compared because of changing flow behavior indices, which varied from 0.294 to 0.319. This implies that *K* units vary from Pa $s^{0.294}$ to Pa $s^{0.319}$, when comparisons of parameters with the same units would be expected. Thus, the apparent viscosity $\mu_{\alpha 1}$ predicted by the power law model (Equation (7)) at a reference shear rate of 1.0 s^{-1} was used instead of *K*.

As it can be seen in Figure 4, the viscosity $\mu_{\alpha 1}$ decreased with an increase in temperature and a decrease in solids concentration. The effect of temperature on $\mu_{\alpha 1}$ follows the Arrhenius-Guzman equation (Equation (8)) with R^2 values greater than 0.95. Magnitudes of activation energy for flow, relating the apparent viscosity to temperature, ranged from 24.727 to 34.297 kJ/mol (Table 2) and are within the reported values for fruit juices [22]. The general tendency is for the activation energy to increase with the soluble solids concentration. In the present work, it was found that the value of E_a did not change significantly between 13.5 and 20°Brix. Thereafter, beyond 20°Brix, the value of E_a increased with concentration, the largest value of 34.297 kJ/mol corresponding to the highest concentration, 30°Brix. This observation indicates that the effect of temperature in decreasing the viscosity of kiwifruit juice concentrates is more pronounced at higher solids concentrations. Saravacos [4] and Khalil et al. [34] observed a similar trend for clarified apple and banana juices. The experimental data have been fitted to a polynomial equation:

$$E_a = 0.004C^3 - 0.199C^2 + 3.213C + 7.791 \quad (R^2 = 0.999) \tag{11}$$

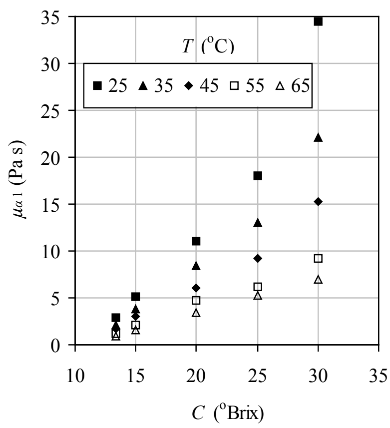

Figure 4: Variation of apparent viscosity (at a reference shear rate of 1.0 s^{-1}) of kiwifruit juice with solids concentration at various temperatures.

C (°Brix)	μ_{a10} (Pa s)	E_a (kJ/mol)	R^2
13.5	1.373×10^{-4}	24.777	0.997
15	2.214×10^{-4}	24.974	0.994
20	5.270×10^{-4}	24.727	0.992
25	3.380×10^{-4}	26.990	0.996
30	0.340×10^{-4}	34.297	0.996

Table 2: The parameters of Arrhenius-Guzman equation for the apparent viscosity (at a reference shear rate of 1.0 s^{-1}) of kiwifruit juice samples.

C (°Brix)	T (°C)	n	K (Pa s^n)	μ_{a1} (Pa s)
13.5	25	0.359	0.357	1.351
	35	0.357	0.298	0.980
	45	0.394	0.233	0.791
	55	0.402	0.189	0.619
	65	0.387	0.145	0.456
15	25	0.374	0.713	1.671
	35	0.385	0.586	1.350
	45	0.379	0.475	0.981
	55	0.390	0.276	0.710
	65	0.389	0.152	0.602
20	25	0.367	1.471	2.381
	35	0.362	1.186	1.842
	45	0.362	0.917	1.456
	55	0.362	0.653	1.102
	65	0.377	0.487	0.800
25	25	0.387	3.373	4.615
	35	0.360	2.660	2.780
	45	0.380	2.147	1.940
	55	0.379	1.514	1.381
	65	0.367	1.086	1.081
30	25	0.399	5.560	7.753
	35	0.389	4.972	5.412
	45	0.380	4.171	3.801
	55	0.406	3.726	2.650
	65	0.399	3.240	1.910

Table 3: The parameters of power-law model for the completely destructed kiwifruit juice samples.

The effects of temperature and solids concentration on $\mu_{\alpha 1}$ can be combined in a single logarithmic model (Equation (9)). Similar equations have been derived for the viscosity and the flow consistency index of Newtonian and non-Newtonian fruit juices, respectively [19,22]. Experimental data have been fitted to Equation. (9) and the equations obtained were:

Forward direction: $\mu_{\alpha 1} = \exp(-12.626 + 3766.791/T + 0.117C)$ ($R^2 = 0.987$) (12)

Backward direction: $\mu_{\alpha 1} = \exp(-12.307 + 3431.336/T + 0.102C)$ ($R^2 = 0.982$) (13)

In addition, the flow curves of the completely destructed kiwifruit juice samples were measured on samples that had been subjected to a long pre-shearing period (~ 1.5 h) to ensure that material reached a completely destructed structure at which the rheological behavior is no longer dependent on shearing time. Once the structure responsible for thixotropy was destroyed, kiwifruit juice samples showed a pseudoplastic behavior, which was characterized by the power law model (Equation (6)) (Table 3). Similar trends, as in forward and backward measurements, were observed for the apparent viscosity $\mu_{\alpha 1}$, which decreased with an increase in temperature and a decrease in solids concentration. These effects can be expressed by the following equation:

$$\mu_{\alpha 1} = \exp(-12.178 + 3356.226/T + 0.098C) \quad (R^2 = 0.989) \tag{14}$$

As it can be concluded, the temperature dependence is exponential and the term of Equation (14) corresponding to the temperature effect is similar to an Arrhenius-type equation and gives an activation energy for flow equal to 27.904 kJ/mol, lower than those of forward and backward measurements. According to Telis-Romero et al. [32], high values of activation energy mean that there is a large effect of temperature on the considered property. Akbulut et al. [20], who used a similar to Equation (14) model for the viscosity of *Juniperus drupacea* fruit juice with a total soluble solids concentration varying from 62.8 to 75.2%, reported an activation energy value of 70.37 kJ/mol, whereas

E_a values of 15.20 and 38.71 kJ/mol was found for pomegranate juice (17.5–75.0°Brix) and sour-cherry juice (40–70°Brix), respectively [14,17]. In addition, once the structure responsible for thixotropy was destroyed, there was also a lower effect of solids concentration on the viscosity than that in forward and backward measurements. Figure 5 shows the response surface obtained from Equation (14).

Time dependent flow

The measurements of increasing and decreasing shear rates showed a hysterisis loop (Figure 1), which indicates that the samples exhibited thixotropic behavior. Altan and Maskan [14] and Abu-Jdayil, Banat, Jumah, Al-Asheh and Hammad [39] also reported thixotropic behavior for cranberry juice and tomato pulp, respectively. The thixotropic effect might be due to the internal structure of the juice, formed by physical interactions between the soluble solids, sugars, and in particular the protein. However, the hysterisis loops indicate that the degree of thixotropy is small.

Kiwifruit juice samples with solids concentrations of 15 and 30°Brix were sheared at different values of constant shearing rate at 25°C and the apparent viscosity was measured as a function of shearing time until an equilibrium state was reached. Figure 6 presents the effect of shear rate on the time-dependent behavior of the juice at 15°Brix solids concentration. As it can be seen, apparent viscosity varies with time. At low shear rates, 20 and 30 s^{-1}, the apparent viscosity decreased rapidly with time of shearing within the first 100–300 s and approached a constant value corresponding to a steady state after approximately 600 s (thixotropic behavior), while at higher values of shear rate, 60 and 100 s^{-1}, the apparent viscosity increased with time before it became steady (rheopectic behavior). Such behavior was more obvious at the high solids contents than at the lower ones (see Figure 7) and can be attributed to a possible break down of the cells. Similar observations were reported by De Kee, Code, and Turcotte [40] and Abu-Jdayil et al. [39], who mentioned that the plant cells are broken down at high shear rates, whereas at low shear rates particles agglomeration and dissociation occur. On the contrary, Abu-Jdayil [30] and Razavi and Karazhiyan [28] reported that the apparent viscosity of milled sesame and salep, which decreased rapidly with time of shearing within the first 100–300 s and approached a constant value after approximately 2400 s, tended to decrease more rapidly at high shear rates. The difference in the time-dependent behavior of the kiwi juice can be attributed to its composition. According to Abu-Jdayil [30], the food products containing polymers exhibit a high degree of thixotropy, such as for milled sesame and salep.

The apparent viscosity data could be correlated with Equation (10)

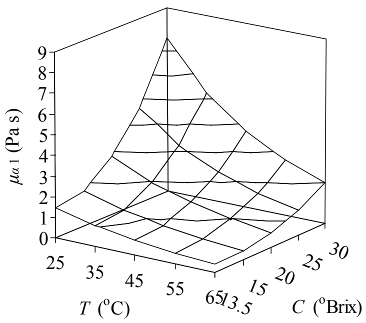

Figure 5: Response surface presenting the effect of temperature and solids concentration on the apparent viscosity (at a reference shear rate of 1.0 s^{-1}) of kiwifruit juice.

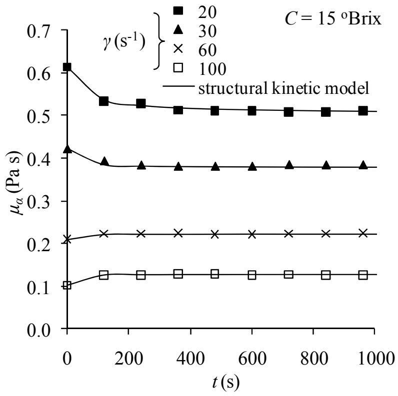

Figure 6: Viscosity of kiwifruit juice with a solids concentration of 15 °Brix as a function of shearing time at different shear rates.

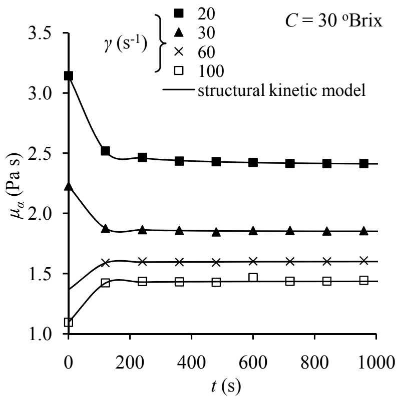

Figure 7: Viscosity of kiwifruit juice with a solids concentration of 30 °Brix as a function of shearing time at different shear rates.

C (°Brix)	$\dot{\gamma}$ (s^{-1})	k (s^{-1})	$\mu_{\alpha 0}/\mu_{\alpha\infty}$	R^2
15	20	1.992×10^{-2}	1.221	0.992
	30	4.690×10^{-2}	1.116	0.938
	60	9.713×10^{-2}	0.944	0.950
	100	14.203×10^{-2}	0.802	0.946
30	20	4.325×10^{-2}	1.312	0.998
	30	9.985×10^{-2}	1.205	0.988
	60	12.658×10^{-2}	0.852	0.967
	100	16.135×10^{-2}	0.762	0.974

Table 4: The parameters of second-order structural kinetic model for kiwifruit juice samples.

using $n' = 2$ (second-order structural kinetic model). Table 4 shows the parameters of the structural kinetic model. The high R^2 values indicate that the specific model gave a good fit to the experimental data, as it can be also seen in Figures 6–7. The rate constant k, which is a measure of the thixotropic breakdown rate, increased with increasing shear rates. This observation implies that the breakdown rate of kiwifruit juice samples under a shear field accelerated at high shear rates. According to Abu-Jdayil and Mohameed [29], the ratio of initial to steady state viscosity, $\mu_{\alpha 0}/\mu_{\alpha\infty}$, can be considered as a relative measure of the amount of structure breakdown or as a relative measure of the extent of thixotropy. As it can be seen in Table 4, the ratio $\mu_{\alpha 0}/\mu_{\alpha\infty}$ decreased with shear rate and varied between 0.762 and 1.312. These values are much lower than that reported by other researchers [28,30,41]. The much

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lower $\mu_{\alpha 0}/\mu_{\alpha\infty}$ values found in this work are due to the lower thixotropy degree of the kiwi juice concentrates.

Bostwick consistency

The consistencies of kiwifruit concentrates at each temperature and solids concentration are shown in Figure 8. As it can be seen, the Bostwick value decreased as juice concentration increased. In addition, as temperature increased from 25 to 65°C, the Bostwick consistency increased. This observation is similar to that obtained by Tehrani and Ghandi [42], who used the Bostwick method to determine tomato concentrate consistency. The results showed that the consistency measured by the Bostwick method depends highly on the solids concentration and the temperature of kiwifruit juice. To estimate the consistency of kiwifruit juice at each value of absolute temperature and concentration, Equation (15) can be used:

$$BC = -0.586 - 0.325 \cdot 10^{-2} T + 0.246 \cdot 10^{-2} C \quad (R^2 = 0.941) \tag{15}$$

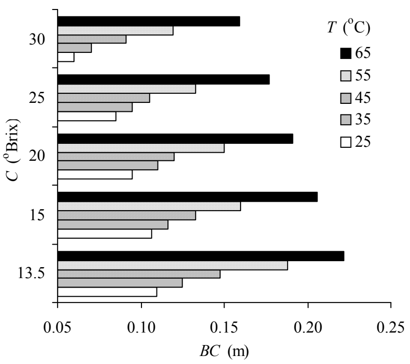

Figure 8: Variation of Bostwick consistency of kiwifruit juice with solids concentration at various temperatures.

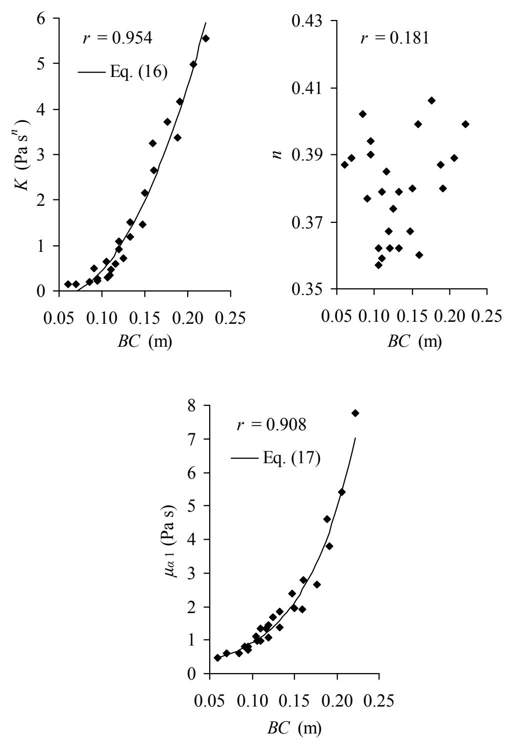

Figure 9: Correlation between Bostwick consistency and rheological parameters (consistency index, flow behavior index, and apparent viscosity) of kiwifruit juice.

The correlation between consistency and rheological parameters was evaluated (Figure 9). The correlation coefficient between the Bostwick consistency levels and the flow consistency index, the flow behavior index, and the apparent viscosity (at a reference shear rate of 1.0 s^{-1}) was found to be 0.954, 0.181, and 0.908, respectively. Thus, the Bostwick consistency levels can be related to the viscosity measurements and the flow consistency index values, whereas the flow behavior index showed no correlation with the consistency. This observation is similar to that obtained by Hoffman, Nicosia, and Robbins [43], who related consistency values obtained on the line spread test to apparent viscosity values of certain Newtonian and non-Newtonian liquids. Steele, Van Lieshout, and Goff [44] also reported that the apparent viscosity of four industrial thickened beverages (three honey-like and one nectar-like) and of regular products such as water, apple juice, applesauce, yogurt, chocolate milk, and chocolate pudding could be related to the consistency levels. On the contrary, Germain, Dufresne, and Ramaswamy [45], who used various binding agents to obtain a wide range of refrigeration stable products, reported a moderate to limited correlation between apparent viscosity or flow consistency index and the consistency levels established with the Bostwick consistometer (r = 0.60–0.83).

The relation between Bostwick consistency and flow consistency index and apparent viscosity values can be described by the following equations:

$$K = 197.160 BC^2 - 18.402 BC + 0.316 \quad (R^2 = 0.964) \tag{16}$$

$$\mu_{\alpha 1} = 0.171 \exp(16.793 BC) \quad (R^2 = 0.963) \tag{17}$$

Conclusions

The flow curves and time-dependent flow properties of kiwifruit juice concentrates were assessed at different solids concentrations (13.5, 15, 20, 25, 30°Brix) and different temperatures (25, 35, 45, 55, 65°C). Kiwifruit juice concentrates exhibit pseudoplastic behavior and are characterized by the power law model. The flow behavior index varies between 0.357 and 0.406 and is not significantly dependent on juice temperature and solids concentration, whereas the flow consistency index varies between 0.145 Pa $s^{0.387}$ and 5.560 Pa $s^{0.399}$ and decreases with an increase in temperature and a decrease in solids concentration. However, the flow consistency index cannot be compared independently from the flow behavior index, as it has dimensions related to flow behavior index value. Thus, the apparent viscosity at a reference shear rate of 1.0 s^{-1} ($\mu_{\alpha 1}$) can be used instead of the flow consistency index. This apparent viscosity varies between 0.456 and 7.753 Pa s and decreases with an increase in temperature and a decrease in solids concentration. In addition, at low shear rates, kiwifruit juice concentrates exhibit a thixotropic behavior, which turns to rheopectic at high shear rates. The Bostwick consistency varies between 0.06 and 0.22 m and decreases with a decrease in temperature and an increase in solids concentration. The Bostwick consistency levels can be related to the apparent viscosity measurements and the flow consistency index values, whereas the flow behavior index shows no correlation with the consistency.

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