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Research Article

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Rheological Properties of Green and Gold Kiwifruit Purees at Different Temperatures

Lemuel M. Diamante* **and Hang Liu**

Department of Wine, Food and Molecular Biosciences, Lincoln University, Lincoln, Canterbury, New Zealand

***Correspondence to:**
Lemuel M. Diamante, PhD
Department of Wine, Food and Molecular Biosciences, Lincoln University
Lincoln, Canterbury, New Zealand
Tel: +64 211793772
E-mail: Lemuel.Diamante@lincoln.ac.nz

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Abstract

A study was conducted to determine the rheological properties of green and gold kiwifruit purees with total soluble solids of 16 to 17 °Brix at different temperatures (25, 35 and 45 °C). The rheological properties of the samples were determined using a rotational rheometer at a shear range of 32 to 4835 s^{-1}. The green and gold kiwifruit purees were found to be Non-Newtonian fluids following the Herschel-Bulkley model. The yield stress and consistency coefficient of the green kiwifruit puree at different temperatures were higher than those of the gold kiwifruit purees but the opposite was observed for the flow behavior index. Moreover, all rheological properties of the green and gold kiwifruit purees decreased with increasing temperature. The consistency coefficient was related to temperature using an Arrhenius-type relationship. The gold kiwifruit puree (8.96 kJ/mol) has higher activation energy than the green kiwifruit puree (5.82 kJ/mol). The yield stress values of the green and gold kiwifruit purees can be related to temperature by linear regression equations and the flow behavior index values by exponential regression equations.

Keywords

Kiwifruit, Temperatures, Herschel-Bulkley fluid, Yield stress, Consistency coefficient, Flow behavior index

Introduction

Kiwifruit (*Actinidia chinensis,* Planch and *Actinidia deliciosa, A. chev.*) is a native of the mountains of southern China but the commercial development of the fruit took place in New Zealand. There are two well-known cultivars, green kiwifruit (Hayward) and gold kiwifruit (Hort16A) [1]. The green kiwifruit has a hairy skin that is brown in colour, has a vibrant green pulp, with small white core and black seeds with a tangy, sweet-sour taste and combination of flavors. The gold kiwifruit has a smooth hairless skin that is bronze in colour, a golden flesh interior, and a white core with black seeds [2]. Kiwifruits are highly perishable in their fresh state and therefore need to be processed, for example, by drying, canning, freezing, into stable products. The fruits are usually peeled, sliced and blended with other ingredients before processing.

Fruit purees can be used as raw material in the food industry to make various products, such as nectars, jams, ice creams, etc., or they can be sold directly to consumers in canned or frozen forms. Knowledge of the rheological properties of these fruit purees is needed to evaluate their quality and also for use in engineering to calculate flow rates, the selection of pumps, determination of the pressure loss in pipes, etc. [3, 4].

Fruit purees are generally characterized as Non-Newtonian fluids due to the complex interactions of their components. These kinds of fluids are generally described by empirical rheological models that give the best curve fitting rheograms [5]. The most widely used models for fruit purees are the Power Law and Herschel-Bulkley models [5-10]. At present, there have been limited studies on the rheological properties of kiwifruit puree and none for the gold kiwifruit.

Goula and Adamopoulos [11] studied the rheological properties of kiwifruit juice with different soluble solid concentrations (13.5-30 ˚Brix) and at different temperatures (25-65 ˚C). They reported that the kiwifruit juice samples exhibited pseudo plastic behavior and were characterized by the power law model. The fluid consistency index decreased with an increase in temperature and a decrease in soluble solids concentration, whereas there was no significant effect of temperature and concentration on the flow behavior index. At low shear rates, kiwifruit juice samples exhibited thixotropic behavior, which turned into a rheopectic behavior at high shear rates. The effects of blanching and osmotic dehydration on the dynamic behavior and tissue structure of kiwifruit was reported by Gerschenson et al. [12]. They found that kiwifruit tissue behaved as an elastic solid with storage moduli (G') dominating the viscoelastic response (G"/G'≈0.2). Both storage (G') and loss (G") moduli were frequency independent and a clear linear range was evident. In general, G' and G" decreased upon blanching and osmotic dehydration due to tissue damage.

The objective of this study was to determine the rheological properties of green and gold kiwifruit purees with total soluble solids of 16-17 ˚Brix at different temperatures (25 to 45 ˚C).

Materials and Methods

Materials

About 2 kg of each green and gold kiwifruits were bought from a local supermarket in Christchurch, New Zealand. Some of the green and gold kiwifruits were stored in a chiller (about 5 ˚C) and some samples were kept at room temperature (about 20 ˚C) to ripen the fruits.

Sample preparation

Green and gold kiwifruits were taken from either the chiller or room temperature. The bottom end of the fruit was cut off and the juice was squeezed out and placed in the prism of the refractometer (Eclipse, Bellingham and Stanley, UK). The total soluble solids (TSS) of the fruit were measured and the fruits of 16 to 17 ˚Brix were used. The kiwifruits were peeled and cut into 2 cm x 2 cm x 2 cm cubes before putting them into a blender (Breville, China). The blender was set at speed no. 3 and was blended for three minutes until achieving smooth kiwifruit puree. About 400 g of kiwifruit puree for each specific TSS were prepared for both kiwifruits.

Measurement of pH

The pH values of the blended samples were measured by LabX® direct pH meter (Mettler Toledo, China) at 20.1 ˚C. The meter electrode was washed first with distilled water, then patted dry with a soft tissue. The electrode was placed inside a container of the sample. The pH was recorded when a stable reading was reached. Three measurements were done for each sample.

Total solids content determination

The total solids contents of the kiwifruit puree were determined using an air oven (Clayson, Laboratory Apparatus Ltd., New Zealand) at 105 ˚C for 16 hours. Three sets of each sample were measured. The weight of the container (Wc), the weight of container with the sample (Ws) and the weight of container with the dried sample (Wd) were measured using Mettler Toledo AB 204 balance (Mettler Toledo, Switzerland) with an accuracy of 0.0001 g. The total solids content of the sample was calculated using the following equation,

$$\text{Total solids content\%} = \frac{\text{Wd-Wc}}{\text{Ws-Wc}} \times 100 \quad \text{--------} \quad (1)$$

Rheological properties measurements

The rheological properties of the samples were determined using a rotational rheometer (RM100, Lamy, France) [13]. The available accessories that has been used were DIN 1 tube and MK Din-9 bob. The temperature of sample during measurement was controlled with the aid of a thermostating cell and attached to a recirculating water bath. Measurements were done at 25, 35 and 45 ˚C. The rheometer was first zero adjusted before measurements. About 25 ml of the kiwifruit sample was poured into the tube. Then the bob and the tube with the sample were attached to the rheometer. The conditions of the measurement were inputted to the rheometer control panel. Ten shear rates ranging from 32 to 4835 s^{-1} were chosen and set from low speed to high speed then doing in opposite direction. A measuring time of 60 seconds was used for all experiments. The mean values of the temperature, torque and apparent viscosity for the two replicated shear rates was used in all the data obtained. The diameters of bob and tube, the length of bob were 0.031 m, 0.0325 m and 0.054 m, respectively. The shear stress for each data was calculated using the equation below,

$$\tau = \left(1 + \left(\frac{R_i}{R_o}\right)^2 \div \left(2\left(\frac{R_i}{R_o}\right)^2\right)\right) \times \left(\frac{\frac{\Omega}{1000}}{2\pi L R_0^2}\right) \quad \text{--} \quad (2)$$

where: τ = shear stress (Pa)

Ro = the diameter of bob (m)

Ri = the diameter of tube (m)

Ω = torque (mNm)

L = length of bob (m)

δ = ratio of diameters = $R_i/R_o \geq 0.92$

The shear stress (τ) and shear rate (γ) for the range of measurement for each sample was plotted on arithmetic scales for both x and y axis and on logarithmic scales for both x and y axis. If the plot of the data is approximately a straight line in the arithmetic scales and passing thru the origin then the sample is a Newtonian fluid and the absolute viscosity (μ) can be obtained from the slope of the regression line, as shown in the equation below,

$$\tau = a_1 + b_1 \gamma \text{- - - - - - - - - - - - - - - - - - (3)}$$

where: a_1 = intercept ≈ 0 b_1 = slope = μ = absolute viscosity

If the approximate straight line did not pass thru the origin, then the fluid is a Bingham fluid where the intercept was the yield stress, as shown below,

$$\tau = a_2 + b_2 \gamma \text{- (4)}$$

where: a_2 = intercept = τ_y = yield stress
b_2 = slope = μ = absolute viscosity

However, if the plot is approximately a straight line in the logarithmic scales and passing thru the origin then the sample is a Non-Newtonian Power Law Fluid and the rheological properties can be obtained from the regression line of the data, as shown in the equation below,

$$\log \tau = a_3 + b_3 \log \gamma \text{- - - - - - - - - - - - - - (5)}$$

where: a_3 = intercept
k = consistency coefficient = 10^{a3}
b_3 = slope = n = flow behavior index

If the approximate straight line did not pass thru the origin, then this is a Herschel-Bulkley fluid and can be represented using the equation as shown below,

$$\log (\tau - \tau_y) = a_4 + b_4 \gamma \text{- - - - - - - - - - - - - - (6)}$$

where: τ_y = yield stress obtained from the antilogarithm of the intercept of the regression of log τ against log γ

a_4 = intercept
k = consistency coefficient = 10^{a4}
b_4 = slope = n = flow behavior index

Temperature dependency of the rheological properties of kiwifruit purees

From the literatures [5, 14, 15], the consistency coefficient of a Non-Newtonian fluid can be related to temperature using an Arrhenius-type relationship,

$$k = k_o \exp [E_a/(R_g.T_K)] \qquad \text{- - - - - - - (7)}$$

which can be written in a regression form as shown below,

$$\ln k = \ln k_o + (E_a/R_g)\left(\frac{1}{T_k}\right) \qquad \text{- - - - - - - (8)}$$

where: k = consistency coefficient (Pa.s)

k_o = pre-exponential constant (Pa.s)

E_a = activation energy (J/mol)

R_g = gas constant (8.314 J/(mol.K))

T_K = absolute temperature (K)

The yield stress and flow behavior index data were related to temperature by doing linear, logarithmic, exponential and power regressions. The regression equations which gave the highest coefficient of determination were selected.

Data analysis

The shear stress and shear rate data for green and gold kiwifruit purees at different temperatures were fitted with various linear regression equations (Equations 3 to 6) using the Minitab 16 software. The consistency coefficient was related to temperature using Equation 7 while the yield stress and flow behavior index data were regressed with temperature using also the Minitab 16 software.

The mean relative percentage error (MRPE) was used to evaluate the adequacy of the derived Herschel-Bulkley equations and Arrhenius-type equations in predicting the shear stress values and consistency coefficients of green and gold kiwifruit purees at different temperatures, respectively, as outlined in Diamante et al. [16].

Results and Discussion

Selected properties of kiwifruit purees

The mean pH of the green and gold kiwifruit purees with total soluble solids (TSS) of 16 to 17 °Brix were 3.455 and 3.580, respectively so were both acidic. The results obtained were comparable to the pH of the green kiwifruit juice of 3.55 as reported by Goula and Adamopoulos [11] and within the pH range of 3.1-3.8 according to Luh and Wang [17]. The results showed that the green kiwifruit puree was slightly more acidic than the gold kiwifruit puree.

The mean total solids content (TSC) of the green and gold kiwifruit purees with TSS of 16 to 17 °Brix were 16.36 and 14.63%, respectively. The results suggested that the green kiwifruit puree had more solids than the gold kiwifruit puree and so will be expected to be more viscous.

Rheograms of green and gold kiwifruit purees

A number of studies have shown that many of fruit purees behave either as a power law fluid or as a Herschel-Bulkley fluid [6-9, 18-20].

Figure 1 shows a representative rheogram for the green kiwifruit puree with a TSS of 16-17 °Brix at 35 °C in logarithmic scale. The data fell on an approximately straight line but not passing through the origin which means that the sample was not a power law fluid. The intercept of the regression equation for the data was 0.9682 and the antilogarithm of this value was 9.294 Pa which is the yield stress of this data. Using this yield stress, the plot of the Herschel-Bulkley fluid was done on the same data and shown in Figure 2. The rest of the data were processed in the same way and revealed that the green kiwifruit puree behaved as a Herschel-Bulkley fluid at the different temperatures. Figure 3 shows a representative rheogram for the gold kiwifruit puree with a TSS of 16-17 °Brix at 25 °C in logarithmic scale. The intercept of the regression equation was 0.08588 and the antilogarithm of this value was 1.2184 Pa which is also the yield stress for this data. Using this yield stress, the plot of the Herschel-Bulkley fluid was also done on the same data and shown in Figure 4. Again the rest of the data were processed in the same way and revealed that the gold kiwifruit puree behaved as a Herschel-Bulkley fluid at the different temperatures. A number of other fruit purees had been fitted as well with the Herschel-Bulkley model including banana puree [7], blackberry pulp [8], raspberry, strawberry, prune and peach purees [19], mango pulp [21], blueberry puree [22], acai pulp [23] and siriguela pulp [24].

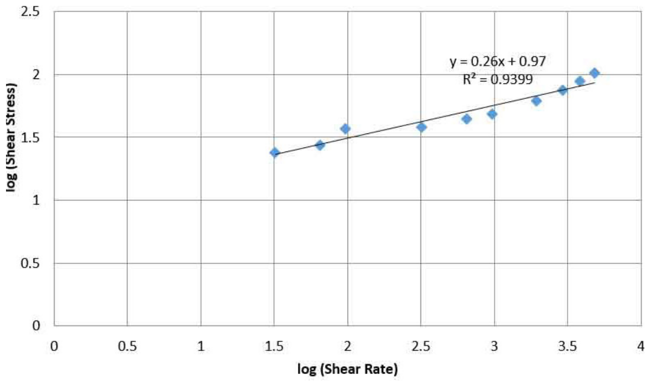

Figure 1: Representative rheogram of logarithm of shear stress versus logarithm of shear rate for green kiwifruit puree with total soluble solids of 16 to 17 °Brix at 35 °C.

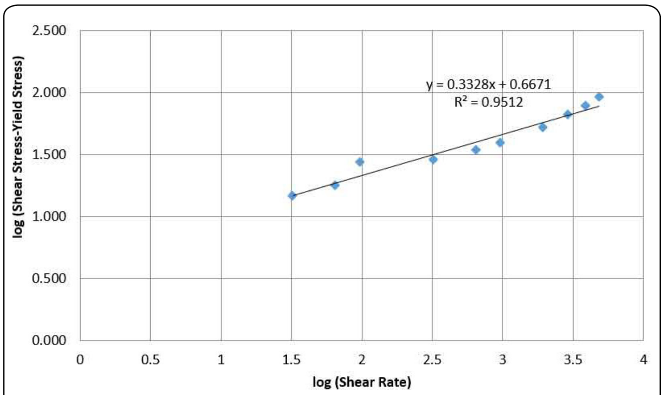

Figure 2: Representative rheogram of logarithm of (Shear Stress-Yield Stress) versus logarithm of shear rate for green kiwifruit puree with total soluble solids of 16 to 17 °Brix at 35 °C.

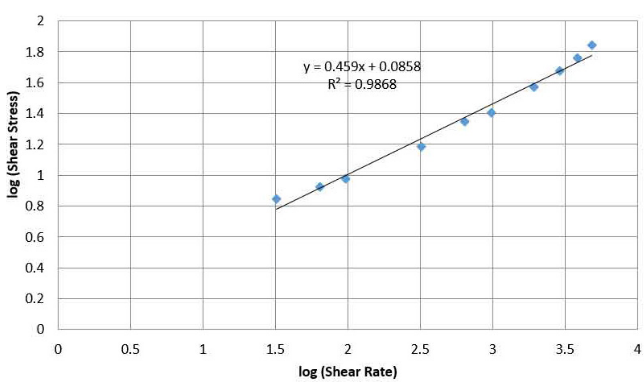

Figure 3: Representative rheogram of logarithm of shear stress versus logarithm of shear rate for gold kiwifruit puree with total soluble solids of 16 to 17 °Brix at 25 °C.

Rheological of properties green and gold kiwifruit purees

From the slope and intercept of the Herschel-Bulkley regression equation for all data, the consistency coefficient (k) and flow behavior index (n) values were derived. Table 1 shows the rheological properties and the range of coefficient of determination (r^2) of regression for the green and gold

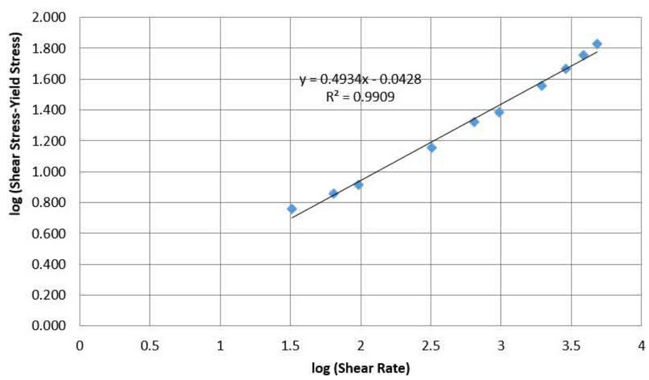

Figure 4: Representative rheogram of logarithm of (shear stress-yield stress) versus logarithm of shear rate for gold kiwifruit puree with total soluble solids of 16 to 17 °Brix at 25 °C.

kiwifruits at different temperatures. The results suggest that there were better fits on the data of the gold kiwifruit puree at different temperatures because of their higher r^2 values but all data were acceptable since all r^2 values were above 0.90.

The yield stress and consistency coefficient of the green kiwifruit puree at different temperatures were higher than those of the gold kiwifruit purees. However, the flow behavior index of the gold kiwifruit puree at different temperatures were higher than those of the green kiwifruit puree. All of these rheological properties indicate that green kiwifruit puree was more viscous than gold kiwifruit puree. This was due to the higher solids content of green kiwifruit puree compared with the gold kiwifruit puree as shown previously. In addition, the yield stress, consistency coefficient and flow behavior index of the green and gold kiwifruit purees decreased with increasing temperature. The yield stress and consistency coefficient values of Brazilian cherry pulp [5], banana puree based baby food [18] and raspberry, strawberry, prune and peach purees [19] also behaved in the same way. The flow behavior index also decreased with increasing temperature for papaya puree [6], mango pulp [21] and acai pulp [23].

Using the rheological properties in Table 1, the shear stress values for green and gold kiwifruit purees at different temperatures were predicted using the Herschel-Bulkley equation. Figures 5 and 6 shows the plots of the experimental and predicted shear stress for the green and gold kiwifruits at different temperatures. Generally, the predicted curves for both green and gold kiwifruit purees encompassed most of the data points except for data above a shear rate of 3000 s^{-1}. In order to evaluate the goodness of fit of the equation, the mean relative percentage error (MRPE) were calculated between the experimental and predicted shear stress. Table 2 shows the mean percentage error for green and gold kiwifruit purees at different shear rate and 25 °C. There was higher percentage error (10% or more) occurring at the shear rates of 32.2, 645, 967 and 4835 s^{-1}, however the MRPE values for both were all less than 10% which were very acceptable. The rest of the data were subjected to the same evaluation and the MRPE values were summarized in Table 3. The results shows that the rest of the data were all closed to 10% which were acceptable for most engineering purposes [25].

Table 1: Mean rheological properties and the range of coefficient of determination of regression for the green and gold kiwifruit purees with total soluble solids of 16 to 17 °Brix and different temperatures (number of replications = 3).

Variety	T (°C)	τ_y (Pa)	k (Pa s^n)	n (no units	Range of r^2
Green kiwifruit puree	25	9.5243	4.9043	0.3332	0.92-0.96
	35	9.1287	4.4807	0.3281	0.94-0.96
	45	8.6247	4.2321	0.3251	0.91-0.97
Gold kiwifruit puree	25	1.2532	0.9293	0.4924	0.98-0.99
	35	1.1576	0.8431	0.4809	0.98-0.99
	45	1.0186	0.7400	0.4757	0.97-0.98

where: T = temperature; τ_y = yield stress; k = consistency coefficient; n = flow behavior index; r^2 = coefficient of determination

Table 2: Mean relative percentage error (MRPE) for the shear stress values of green and gold kiwifruit purees with total soluble solids of 16 to 17 °Brix at different shear rate and 25 °C as predicted by the Herschel-Bulkley equation and using the derived rheological properties.

Shear Rate (s^{-1})	Green Kiwifruit Puree Shear Stress (Pa)		% Error	Gold Kiwifruit Puree Shear Stress (Pa)		% Error
	Experimental	Predicted		Experimental	Predicted	
32.2	30.165	26.023	13.73	6.947	6.244	10.12
64.5	31.102	30.561	1.74	8.464	8.299	1.95
96.7	30.692	33.755	9.98	9.413	9.864	4.80
322	42.290	46.362	9.63	15.463	16.871	9.10
645	49.904	56.421	13.06	22.258	23.270	4.55
967	61.912	63.501	2.57	25.538	28.147	10.22
1934	73.860	78.175	5.84	37.311	39.127	4.87
2901	89.675	88.538	1.27	47.620	47.523	0.20
3868	104.025	96.823	6.92	57.987	54.585	5.87
4835	119.371	103.841	13.01	68.999	60.796	11.89
		MRPE	7.78		MRPE	6.36

Table 3: Summary of the mean relative percentage error for the different shear stress values of green and gold kiwifruit purees at different temperatures.

Variety	Temperature (°C)	Mean Relative Percentage Error (%)
Green Kiwifruit Puree	25	7.78
	35	10.26
	45	11.44
Gold Kiwifruit Puree	25	6.36
	35	11.00
	45	8.64

Temperature dependency of the consistency coefficient of kiwifruit purees

The consistency coefficient was related to temperature using an Arrhenius-type relationship. From the slope and intercept of the Arrhenius regression the pre-exponential constant (k_o) and the activation energy (E_a) were obtained and the results are summarized in Table 4. The gold kiwifruit puree (8.96 kJ/mol) had a higher activation energy than the green kiwifruit puree (5.82 kJ/mol). This indicated that the consistency coefficient of the gold kiwifruit puree was more temperature sensitive, since it needs greater energy over the temperature range to effect a change in the property. The derived activation energies for green and gold kiwifruit purees compared well with that of "Kesar" mango juice of 3.18 to 13.70 kJ/mol [15], peach puree of 9.35 kJ/mol [19], acai pulp of 4.18-6.21 kJ/mol [23] and blueberry puree of 9.36 kJ/mol [26].

Using the Arrhenius-type equation and the values from Table 4, the predicted consistency coefficients for green and gold kiwifruit purees were obtained. The mean relative percentage error (MRPE) values for the green and gold kiwifruit purees are shown in Table 5 which yielded values of less than 1%. The results therefore suggest that these equations are excellent for predictive purposes.

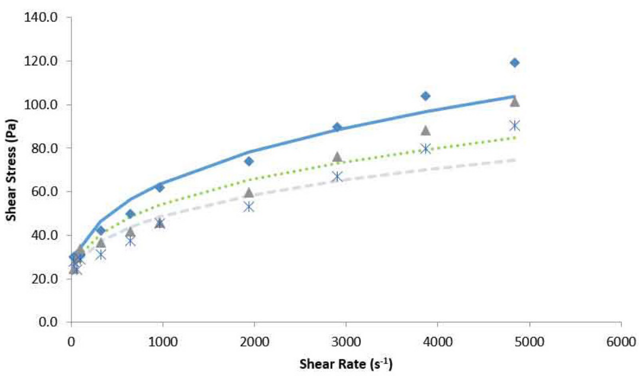

Figure 5: Rheograms of the experimental and predicted shear stresses versus shear rate for green kiwifruit puree with total soluble solids of 16 to 17 °Brix at different temperatures (♦ representative experimental at 25 °C, — predicted at 25 °C, ▲ representative experimental at 35 °C, ... predicted at 35 °C, * representative experimental at 45 °C, ---- predicted at 45 °C).

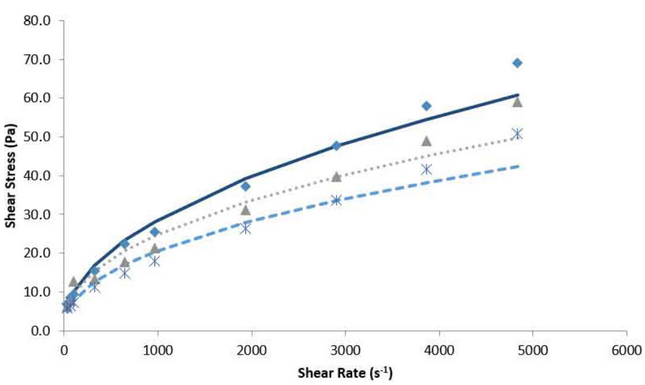

Figure 6: Rheograms of the experimental and predicted shear stresses versus shear rate for gold kiwifruit puree with total soluble solids of 16 to 17 °Brix at different temperatures (♦ representative experimental at 25 °C, — predicted at 25 °C, ▲ representative experimental at 35 °C, ... predicted at 35 °C, * representative experimental at 45 °C, ---- predicted at 45 °C).

The yield stress values of green and gold kiwifruit purees can be related to temperature using linear regression equations as shown below,

Green Kiwifruit Puree, τ_y = 10.667 - 0.04498 (r^2 = 0.995) - - (9)

Gold Kiwifruit Puree, τ_y = 1.5537 - 0.01173 T (r^2 = 0.989) - - (10)

On the other hand, the flow behavior index values of green and gold kiwifruit purees can be related to temperature

Table 4: Pre-exponential constants (k_o), activation energies (E_a) and coefficient of determination (r^2) of regression for the consistency coefficients of green and gold kiwifruit purees with total soluble solids of 16 to 17 °Brix.

Variety	k_o (Pa.s)	Ea (J/mol)	r^2
Green Kiwifruit Puree	0.46563	5824.94	0.988
Gold Kiwifruit Puree	0.02514	8964.57	0.990

Table 5: Mean relative percentage error (MRPE) for the consistency coefficient of green and gold kiwifruit purees with total soluble solids of 16 to 17 °Brix using the predictive equations.

Variety	Temperature	Experimental Consistency Coefficient ($Pa.s^n$)	Predicted Consistency Coefficient ($Pa.s^n$)	% Error
Green Kiwifruit Puree	25	4.9043	4.8818	0.46
	35	4.4807	4.5234	0.95
	45	4.2321	4.2114	0.49
			MRPE	0.63
Gold Kiwifruit Puree	25	0.9293	0.9354	0.66
	35	0.8431	0.8318	1.34
	45	0.7400	0.7451	0.69
			MRPE	0.90

using exponential regression equations as shown below,

Green Kiwifruit Puree, log n = -0.41862 – 0.042087 log T (r^2 = 0.996) ---- - (11)

which can be simplified into,

$n = 0.38140\ T^{-0.042087}$ - - - - - - - - - - - - - - - - - - (12)

Gold Kiwifruit Puree, log n = -0.22521 – 0.059335 log T (r^2 = 0.984) - - - - - (13)

which can also be simplified into,

$n = 0.59537\ T^{-0.059335}$ - - - - - - - - - - - - - - - - - - (14)

Using equations 9 and 10, the predicted yield stress values for green and gold kiwifruit purees were obtained. While the predicted flow behavior index values for green and gold kiwifruit purees were calculated using equations 12 and 14. The mean relative percentage error values for the yield stress and flow behavior index for the green and gold kiwifruit purees are shown in Table 6 which also yielded values of less than 1%. The results therefore also mean that these equations are excellent for predictive purposes.

Table 6: Mean relative percentage error (MRPE) for the yield stress and flow behavior index of green and gold kiwifruit purees with total soluble solids of 16 to 17 °Brix using the predictive equations.

Variety/ Temperature (°C)	Yield Stress (Pa)			Flow Behavior Index (no units)		
	Experimental	Predicted	% Error	Experimental	Predicted	% Error
Green Kiwifruit						
25	9.5243	9.5424	0.19	0.3332	0.3331	0.03
35	9.1287	9.0926	0.40	0.3281	0.3284	0.09
45	8.6247	8.6428	0.21	0.3251	0.3249	0.06
		MRPE	0.27		MRPE	0.06
Gold Kiwifruit						
25	1.2532	1.2604	0.57	0.4924	0.4919	0.10
35	1.1576	1.1431	1.25	0.4809	0.4821	0.25
35	1.0186	1.0258	0.71	0.4757	0.4750	0.15
		MRPE	0.84		MRPE	0.17

Conclusions

The rheological properties green and gold kiwifruit purees at different temperatures (25, 35 and 45 °C) were found to be Non-Newtonian fluids following the Herschel-Bulkley model.

The yield stress and consistency coefficient of the green kiwifruit puree at different temperatures were higher than those of the gold kiwifruit purees. However, the flow behavior index of the gold kiwifruit puree at different temperatures were higher than those of the green kiwifruit puree. In addition, the yield stress, consistency coefficient and flow behavior index of the green and gold kiwifruit purees decreased with increasing temperature.

The consistency coefficient was related to temperature using an Arrhenius-type relationship. The gold kiwifruit puree (8.96 kJ/mol) has higher activation energy than the green kiwifruit puree (5.82 kJ/mol).

The yield stress values of green and gold kiwifruit purees can be related to temperature by linear regression equations while the flow behavior index values by exponential regression equations.

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