Modeling the rheological behavior of thermosonic extracted guava, pomelo, and soursop juice concentrates at different concentration and temperature using a new combination model

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Abstract
This study has modeled the rheological behavior of thermosonic extracted pink-fleshed guava, pink-fleshed pomelo, and soursop juice concentrates at different concentrations and temperatures. The effects of concentration on consistency coefficient (K) and flow behavior index (n) of the fruit juice concentrates was modeled using a master curve which utilized the concentration-temperature shifting to allow a general prediction of rheological behaviors covering a wide concentration. For modeling the effects of temperature on K and n, the integration of two functions from the Arrhenius and logistic sigmoidal growth equations has provided a new model which gave better description of the properties. It also alleviated the problems of negative region when using the Arrhenius model alone. The fitted regression using this new model has improved coefficient of determination, $R^2$ values above 0.9792 as compared to using the Arrhenius and logistic sigmoidal models alone, which presented minimum $R^2$ of 0.6243 and 0.9440, respectively.

Practical applications
In general, juice concentrate is a better form of food for transportation, preservation, and ingredient. Models are necessary to predict the effects of processing factors such as concentration and temperature on the rheological behavior of juice concentrates. The modeling approach allows prediction of behaviors and determination of processing parameters. The master curve model introduced in this study simplifies and generalized rheological behavior of juice concentrates over a wide range of concentration when temperature factor is insignificant. The proposed new mathematical model from the combination of the Arrhenius and logistic sigmoidal growth models has improved and extended description of rheological properties of fruit juice concentrates. It also solved problems of negative values of consistency coefficient and flow behavior index prediction using existing model, the Arrhenius equation. These rheological data modeling provide good information for the juice processing and equipment manufacturing needs.

1 | INTRODUCTION

Fruit juice contains low-molecular-weight solutes such as sugars, organic acids, flavors, aromas, and vitamins, and high-molecular-weight solutes such as pectins, proteins, enzymes, and microorganisms (DasGupta & Sarkar, 2012; Sharoba & Ramadan, 2011). Its total soluble solids content is mainly constituted by the low-molecular-weight sugars, giving it a sticky behavior and often referred for sweetness estimation in fruits and fruit-based products including fruit powders and juices (Jha & Gunasekaran, 2010; Pereira, Carvalho, Cabeça, & Colnago, 2013; Quek, Chok, & Swedlund, 2007). The total soluble solids content is also known to give rheological characteristics to fruit juices (Kaya & Sözer, 2005) where it plays an essential role in determining the magnitude of viscosity. Information on viscosities of concentrated fruit juice
is important to ensure it is pumpable and provides desired final product properties including the mouth feel properties for fruit juice.

Due to high water content in fruit juice, concentrating fruit juice in industrial processing is necessary to reduce packaging, storage, and transportation costs. Fruit juice concentrates are usually reconstituted at the time of usage by adding water. In producing juice concentrates, the water removal must be sufficient to increase its total soluble solids content until its °Brix level is at least 50% greater than its established reconstituted juice (Codex, 2005). Most food concentrates used in food industry are in the range of 30 to 40°Brix (Sharoba & Ramadan, 2011). Since fruit juice is a thermally sensitive product, concentrating by heating could develop a cooked taste in the final product and fouling in the pipe wall. The nutrient content in the fruit juice are also degraded by heat. These losses are serious processing and marketing problems. The freeze-drying process is introduced to concentrate fruit juice to produce the highest end product quality in terms of taste, aroma, nutritive value, and a longer shelf life. This process involves crystallization of water at low temperature and then sublimation from solid to vapor without passing through the liquid phase. In extracting heat-sensitive and starchy or creamy fruit juices, the use of thermosonic method has helped to increase juice yield at reduced heat levels (Abdullah, 2015; Chemat, Zill, & Khan, 2011).

Temperature is the most important control parameter in fruit juice processing because fruit juice concentrates are very heat-sensitive. Excessive heat and viscosity of fruit juice concentrates cause loss of energy and lower juice amount produced. Fruit juice may also overheat where less nutritious fruit juice is produced and its flavor and aroma degrade. The effect of temperature on rheological properties of fruit juices such as pomegranate and pear juice concentrates (Magerramov, Abdulagatov, Azizov, & Abdulagatov, 2007), untreated and pasteurized carrot juice (Vandresen, Quadri, de Souza, & Hotza, 2009), clarified pear and apple juices (Falguera, Vicente, Garvín, & Ibarz, 2013), and aloe vera juice concentrates (Swami Hulle, Patruni, & Rao, 2014) have been well described using the Arrhenius model. The Arrhenius model is based on temperature change, which causes thermal expansion by the magnitude of flow activation energy. The thermal energy results in the changes of intermolecular distances by the intermolecular forces (Vandresen et al., 2009). The flow activation energy is defined as sensitivity of sample viscosity to temperature changes (Juszczak, Witzczak, Fortuna, & Solarz, 2014; Kaya & Sözer, 2005). The activation energy parameter in the Arrhenius model explains the minimum amount of energy that is enough for collision of molecules to initiate bonds breakage. Strong intermolecular forces and weak molecules mobility of the high viscosity fruit juices require a high amount of energy to be broken for starting the flow of fruit juices.

The aim of this study was to model rheological behavior of thermosonically extracted guava, pomelo, and soursop juice concentrates using the concentration-temperature superposition principle where a master curve is developed to display a single smooth line to express its rheological behavior. The present work has also developed and proposed a new mathematical model, which combines the Arrhenius and logistic growth models for modeling the effect of temperature on the rheological behavior of guava, pomelo, and soursop juice concentrates.

## 2 MATERIALS AND METHODS

### 2.1 Preparation of fruit juice concentrates

2.5 kg of each fruit pulp, the pink-fleshed guava (*Psidium guajava* L.), pink-fleshed pomelo (*Citrus maxima* M.), and soursop (*Annona muricata* L.) was blended in a commercial food blender (300 W, Model XB409, Cecado, Italy) at 28,000 rpm for 1 min, pulsed for 30 s and another 1 min at 22,000 rpm to get homogenized pulp. The pulp was then mixed with distilled water at ratio of 1:1 by weight before thermosonic treatment. Table 1 lists the conditions for thermosonic treatment for all three juices where it has been optimized priory for the highest juice yield with maximum ascorbic acid and total soluble solids content (Abdullah, 2015). Direct thermosonic treatment was carried out using a 400 W digital ultrasonic processor (S-450D, Branson Ultronics Corporation, Danbury, CT) with its probe tip immersed to a depth of 25 mm into a 150 mL beaker containing soursop pulp mixture. For indirect thermosonic treatment, a glass bottle of the guava or pomelo pulp mixture was partially immersed in an ultrasonic water bath (Chin, Tan, Che Pa, & Yusof, 2013), which contained water. The thermosonic treatment temperature was maintained using a temperature probe where cold water was added into the surrounding water of beaker containing sample for direct thermosonication or applying continuous flow of water into the bath for indirect thermosonication.

The thermosonic treated pulp mixture was centrifuged at 4,000 rpm for 20 min at 4 °C using a refrigerated centrifuge (Mikro 22R, Hettich Zentrifugen, Germany) to separate the fruit precipitate and liquid supernatant. The supernatant was collected as the thermosonic extracted juice and filled into plastic containers (100 mL), frozen in a freezer at ~20 °C prior to freeze-drying. Ten containers of each frozen guava, pomelo, and soursop juice were concentrated in a freeze-dryer (FreeZone, Labconco) at vacuum pressure of 0.06 mbar for 72 hr where the average final concentration of guava, pomelo, and soursop juices produced were 47.8 ± 0.7°Brix, 73.1 ± 0.4°Brix, and 73.8 ± 0.7°Brix, respectively. The guava juice concentrate was diluted using distilled water to concentrations of 5, 15, 30, and 45°Brix, while the pomelo and soursop juice concentrates to concentrations of 5, 15, 30, 45, and 70°Brix for rheological measurements. Each concentrated juice was diluted in duplicate. The whole process of blending, homogenization, thermosonic treatment, concentration, and dilution of each fruit juice was repeated twice. The concentration was measured using a digital refractometer (PAL-Alpha, Atago) and expressed in °Brix.

### TABLE 1 Optimized conditions for fruit juice extraction

| Factors         | Guava Indirect thermosonication | Pomelo Indirect thermosonication | Soursop Direct thermosonication |
|-----------------|---------------------------------|----------------------------------|---------------------------------|
| Intensity       | 1                               | 2.5                              | 10                              |
| Time (min)      | 30                              | 23                               | 10                              |
| Temperature (°C)| 55                              | 54                               | 55                              |

*Intensity in amplitude (%) for direct thermosonication and in power (kW) for indirect thermosonication.*
2.2 | Rheological measurements

The rheological properties were measured using a rheometer (ARG2, TA Instruments) with the 40-mm cone and diameter plate geometry for shear rate range of 0–400 s⁻¹. Steady-state flow test was conducted for each juice concentrate samples at temperatures of 0, 4, 10, 25, 40, 60, and 80 °C. Shear stress versus shear rate data were fitted to the power law model (Equation 1) to obtain values of consistency coefficient (K) and flow behavior index (n) in studying the flow behavior of the juice concentrates. Its viscosity (η) is reported as a function of shear rate (Equation 1a) (Steffe, 1996).

\[ \sigma = K \gamma^n \]  
\[ \eta = K(\dot{\gamma})^{n-1} \]  

where, \( \sigma \) is the shear stress (Pa), K is the consistency coefficient, \( \gamma \) is the shear rate (s⁻¹), and n is the flow behavior index.

2.3 | Modeling the effect of concentration on the juice concentrates flow behavior

The effect of concentration (C) on the variation of K or n can be described by the exponential (Equations 2a and 2b) and power law (Equations 3a and 3b) models. The exponential (Dak, Verma, & Jaaffrey, 2007; Yilmaz, Sert, & Demir, 2010) and power law (Barbana & El-Omri, 2012; Dak et al., 2007; Yilmaz et al., 2010) are the most widely fitted empirical models for predicting values of K and n.

\[ K = k_c \exp(\beta C) \]  
\[ n = n_c \exp(\beta C) \]  
\[ K = k_c C^n \]  
\[ n = n_c C^n \]  

where \( k_c, n_c, \) and \( \beta \) is the constants and \( C \) is the concentration.

The dimensionless concentration-temperature shift factors, \( \alpha_T \) at each temperature were calculated using Equation 4 to make a horizontal shift of other temperatures at the concentration axis to make an overlapped smooth curve. 25 °C was chosen as the reference temperature (Quek, Chin, & Yusof, 2013).

\[ \alpha_T = C_T / C_{\text{ref}} \]  

where \( \alpha_T \) is the dimensionless shift factor, \( C_T \) is the concentration at defined temperature, and \( C_{\text{ref}} \) is the concentration at reference temperature of 25 °C.

A master curve was then plotted as \( K \) or \( n \) versus \( C/\alpha_T \), where exponential model (Equations 5a and 5b) or power law model (Equations 6a and 6b) was fitted to find the best regressed master curve model for each fruit concentrate.

\[ K = k'_c \exp \left[ \beta' \left( \frac{C}{\alpha_T} \right) \right] \]  
\[ n = n'_c \exp \left[ \beta' \left( \frac{C}{\alpha_T} \right) \right] \]  
\[ K = k'_c \left( \frac{C}{\alpha_T} \right)^{b'} \]  
\[ n = n'_c \left( \frac{C}{\alpha_T} \right)^{b'} \]  

where \( k'_c, n'_c, \) and \( b' \) are the constants, K is the consistency coefficient, n is the flow behavior index, C is the concentration, and \( \alpha_T \) is the dimensionless shift factor.

2.4 | Modeling the effect of temperature on the juice concentrates flow behavior

The variation of K or n as function temperature was modeled using the Arrhenius model in Equations 7a and 7b, logistic sigmoidal growth model (Augusto, Soares, Chiu, & Gonçalves, 2012) in Equations 8a and 8b, and also the proposed new model in Equations 9a and 9b. The original logistic sigmoidal model, \( dN/dt = N(1−N/H) \) is based on approximation of population growth in the United States, where \( N \) is the number of population, \( t \) is the time, \( r \) is the growth parameter, and \( H \) is the carrying capacity (Pearl & Reed, 1920). The equation is integrated to get logistic model as in Equation 8a. The separable of variable method, \( \int dN/[N(1−N/H)] = ∫ r \ dt \) is applied to the original logistic sigmoidal model prior to the integration step to bring together \( N \) variable on left side and \( t \) variable on right side. The integration gives \( \ln[D(N(t))/H−N(t)] = rt \). All terms at both sides of this integrated equation were then exponent to eliminate the logarithm term, which is written as \( D(N(t))/[H−N(t)] = \exp(rt) \). By rearranging and adding fractions into the equation, a sigmoidal growth model \( N(t) = H/\left[\exp(-rt)+1\right] \) with positive value of \( r \) is obtained. In this study, \( N \) as function of time is replaced with K as function of temperature and decay function is suitable to be used because K reduces by temperature increment. Therefore, \( r \) is a negative value to make it a decay function and logistic sigmoidal models for this study are as in Equations 8a and 8b. Cross product of the Arrhenius (Equations 7a and 7b) and logistic sigmoidal growth (Equations 8a and 8b) models yields the proposed new model as in Equations 9a and 9b.

\[ K = k_T \exp \left( -\frac{E_a}{RT} \right) \]  
\[ n = n_T \exp \left( -\frac{E_a}{RT} \right) \]  
\[ K(T) = \frac{H}{\exp(-rt)+1} \]  
\[ n(T) = \frac{H}{\exp(-rt)} \]  
\[ K = \frac{Hk_T \exp \left( \frac{E_a}{RT} \right)}{\exp(-rt)+1} \]  
\[ n = \frac{Hn_T \exp \left( \frac{E_a}{RT} \right)}{\exp(-rt)+1} \]  

where K is the consistency coefficient, n is the flow behavior index, T is temperature in Kelvin, \( k_T \) and \( n_T \) are the pre-exponential factor, \( E_a \) is the activation energy in kJ mol⁻¹, \( R \) is the universal gas constant of 8.314 J mol⁻¹ K⁻¹, \( H \) is the maximum value of the asymptotic curve, \( k_T, n_T, \) and D are constants and \( r \) is the growth parameter.
FIGURE 1 Effect of concentration on consistency coefficient, K of (a)(i) guava, (b)(i) pomelo, and (c)(i) soursop at temperatures of 0 °C (Δ), 4 °C (■), 10 °C (▲), 25 °C (▲), 40 °C (▲), 60 °C (◆), and 80 °C (○) and their respective master curve (a)(ii), (b)(ii), and (c)(ii)

2.5 Statistical analysis

The coefficient of determination, \( R^2 = 1 - \frac{SSE}{SST} = \sum \frac{(Y_{\text{experimental}} - Y_{\text{model}})^2}{\sum (Y_{\text{experimental}} - \bar{Y}_{\text{experimental}})^2} \), was determined for each temperature or the master curve in choosing the best fitted model, where SSE is the sum of square error, SST is the total sum of squares, \( Y_{\text{experimental}} \) is the experimental value of dependent variable, \( Y_{\text{model}} \) is the model value of dependent variable, and \( \bar{Y}_{\text{experimental}} \) is the mean of experimental value of dependent variable. Curve fitting was
done using the solver function in Microsoft Excel 2007 (XP Edition, Microsoft Corporation). Root mean square error, RMSE = \( \sqrt{\frac{1}{N} \sum_{i=1}^{N} (Y_{\text{experimental}} - Y_{\text{model}})^2} \) was used to assess the variation in dependent variable that the model did not explain, where \( N \) is the number of data. The highest \( R^2 \) and the lowest RMSE values determined the best fitted model. The goodness of model fitting was also determined by a plot of the model values of \( K \) or \( n \) (\( Y_{\text{model}} \)) versus the experimental values of \( K \) or \( n \) (\( Y_{\text{experimental}} \)) as \( Y_{\text{model}} = V \cdot Y_{\text{experimental}} - W \), where \( V \) is the line slope, and \( W \) is the \( Y_{\text{model}} \)-intercept. A straight line with slope (\( V \)) value near to one, \( Y_{\text{model}} \)-intercept (\( W \)) near to zero and \( R^2 \) near to one was considered as the best fitted model (Augusto, Falguera, Cristianini, & Ibarz, 2012). The analysis and comparison of
TABLE 2

|                | Guava                        |              | Pomelo                      |              | Sourso                      |              |
|----------------|------------------------------|--------------|----------------------------|--------------|----------------------------|--------------|
|                | $T$ (°C)                     | $n_c$        | $b$                        | $R^2$        | $RMSE$                     | $n_c$        | $b$                        | $R^2$        | $RMSE$                     |
| Exponential    |                              |              |                            |              |                            |              |                            |              |                            |
| 0              | 0.8382                       | −0.0462      | 0.9492                     | 0.0467       | 1.0246                     | −0.0047      | 0.9627                     | 0.0184       | 0.9043                     | −0.0060      | 0.9879                     | 0.0110       |
| 4              | 0.8515                       | −0.0459      | 0.9491                     | 0.0474       | 1.0255                     | −0.0046      | 0.9583                     | 0.0190       | 0.9160                     | −0.0057      | 0.9944                     | 0.0073       |
| 10             | 0.8794                       | −0.0459      | 0.9453                     | 0.0508       | 1.0284                     | −0.0044      | 0.9576                     | 0.0185       | 0.9232                     | −0.0053      | 0.9911                     | 0.0087       |
| 25             | 0.9448                       | −0.0442      | 0.9384                     | 0.0576       | 1.0254                     | −0.0036      | 0.9683                     | 0.0133       | 0.9466                     | −0.0046      | 0.9924                     | 0.0074       |
| 40             | 0.9969                       | −0.0397      | 0.9378                     | 0.0602       | 1.0265                     | −0.0027      | 0.9327                     | 0.0154       | 0.9756                     | −0.0041      | 0.9816                     | 0.0216       |
| 60             | 1.0358                       | −0.0326      | 0.9235                     | 0.0628       | 1.0121                     | −0.0009      | 0.8959                     | 0.0070       | 0.9947                     | −0.0027      | 0.9838                     | 0.0072       |
| 80             | 0.9913                       | −0.0247      | 0.9420                     | 0.0502       | 1.0095                     | −0.0006      | 0.8238                     | 0.0061       | 1.0116                     | −0.0014      | 0.9768                     | 0.0049       |
| Power law      |                              |              |                            |              |                            |              |                            |              |                            |
| 0              | 1.9630                       | −0.6430      | 0.9977                     | 0.0096       | 1.2079                     | −0.1010      | 0.8121                     | 0.0413       | 1.1298                     | −0.1328      | 0.9227                     | 0.0278       |
| 4              | 1.9867                       | −0.6399      | 0.9977                     | 0.0109       | 1.2057                     | −0.0988      | 0.8183                     | 0.0397       | 1.1271                     | −0.1243      | 0.9071                     | 0.0295       |
| 10             | 2.0545                       | −0.6402      | 0.9977                     | 0.0103       | 1.1988                     | −0.0938      | 0.8090                     | 0.0392       | 1.1226                     | −0.1165      | 0.9082                     | 0.0279       |
| 25             | 2.1647                       | −0.6222      | 0.9951                     | 0.0163       | 1.1633                     | −0.0769      | 0.8097                     | 0.0326       | 1.1239                     | −0.1021      | 0.8983                     | 0.0270       |
| 40             | 2.2180                       | −0.5769      | 0.9983                     | 0.0100       | 1.1215                     | −0.0575      | 0.7057                     | 0.0322       | 1.1377                     | −0.0909      | 0.8909                     | 0.0260       |
| 60             | 2.0867                       | −0.5005      | 0.9973                     | 0.0125       | 1.0416                     | −0.0187      | 0.6156                     | 0.0135       | 1.1034                     | −0.0610      | 0.8755                     | 0.0198       |
| 80             | 1.7507                       | −0.3959      | 0.9965                     | 0.0124       | 1.0262                     | −0.0112      | 0.5114                     | 0.0101       | 1.0672                     | −0.0321      | 0.8068                     | 0.0142       |

3 | RESULTS AND DISCUSSION

3.1 | Modeling the effect of concentration on flow behavior of juice concentrates

Figure 1 illustrates the effect of concentration on consistency coefficient, $K$ at seven different temperatures ranging from 0 to 80°C. Generally, guava juice concentrates are thicker and has the widest range of $K$ while the pomelo juice concentrates are thinner and has the lowest $K$ values. The value of high $K$ at high concentration is attributed to the formation of a highly viscous gel-type layer on the membrane surface by pectin (Sharoba & Ramadan, 2011). Based on graphical and statistical analysis (Table 2), it was found that the power law model (Equation 3a) fitted better for the guava juice concentrates ($R^2 = 0.9995; RMSE = 0.2835−2.6278$) as compared to the exponential model ($R^2 = 0.9932−0.9995; RMSE = 0.7454−13.0210$). However, the exponential model (Equation 2a) is better fitted for pomelo ($R^2 = 0.9973; RMSE = 0.0022−0.0348$) and soursop juice concentrates ($R^2 = 0.9986−1.0; RMSE = 0.0048−0.0386$) as the power law model fit was poorer for pomelo ($R^2 = 0.9244−0.9653; RMSE = 0.0124−1.0297$) and soursop ($R^2 = 0.9631−0.9756; RMSE = 0.0264−2.9382$). ANOVA results show that the means of $K$ for all three juices at temperatures range of 0 to 80°C have no significant difference as large $p$ values of .3302, .2343, and .2769, respectively, for guava, pomelo, and soursop.
were obtained. This supports the approach of consolidating the K values from different temperatures into a single line in the form of a master curve.

Figure 2 shows the relationship of n and C, which was also fitted to the exponential and power law models. The fruit juice concentrates tend to be more shear-thinning when concentrations increased. The guava juice concentrates have a more prominent shear thinning behavior than the pomelo and soursop. This is due to low starch content in guava, around 13% (Chek Zaini, Zaiton, Zanariah, & Sakinah, 2012) as compared to 27.3% starch content in soursop (Nwokocha & Williams, 2009). Non-starchy (Economos & Clay, 1999) and low pulp content causes the pomelo fruit is close to Newtonian behavior. Table 3 shows that the power law model (Equation 3b) was best fitted for guava juice concentrate with R² values of 0.9951 and 0.9983. The n for pomelo and soursop juice concentrates fitted the exponential model (Equation 2b) well with R² values of 0.8238–0.9683 for pomelo and 0.9768–0.9944 for the soursop. The ANOVA results indicate that means of n for pomelo and soursop with different temperature levels were significantly different with p = .0046 and p < .0001, respectively. However, means of n for guava was not significantly different with p = .3342. The DMRT results for pomelo and soursop shows that the average n at 80°C was higher than n at 0°C, thus suggest that shear-thinning behavior more prominent at lower temperature.

Figures 1a(ii),b(ii),c(ii) show a well superimposed smooth curve when K values are plotted against C/αT. By fitting Equations 5a or 6a, the master curve can be used to predict the K at for its respective concentration range for each juice concentrate. Figures 2a(ii),b(ii),c(ii) show the master curve for n for guava, pomelo, and soursop, respectively, suitable to be modeled using either Equations 5b or 6b for n prediction purposes. Table 4 lists the best fitted master curve models for K and n with their constants selected by the highest R² and lowest RMSE values. These master curve models have acceptable R² values of more than 0.93, and can be used for predicting rheological properties, K and n of respective fruit juice concentrates. The negative constants suggest the decrement of n with increment of concentration.

Figure 3 shows the relationship of viscosity (Equation 1a) with concentration and shear rate. Viscosity is higher at lower shear rates because due to higher forces in breaking agglomerated molecules (Genovese & Lozano, 2001). The aggregation between molecules is attributed to pectinaceous substances, which have a high water holding capacity that develops a cohesive network structure (Bhattacharya & Rastogi, 1998). Lower viscosity is low at high shear rate was due to the molecules orientation and alignment, which reduced friction between molecules (Sun-Waterhouse, Bekkour, Wadhwa, & Waterhouse, 2014). The reduction in juice viscosities gives benefit to the high-shear processes like pumping and filling. Increase in viscosity with concentration is due to the increment of hydrated molecules and hydrogen bonding with the hydroxyl groups (Sharoba, Manikantan, Ranote, & Singh, 2014). Cell wall debris such as cellulose and pectin which is usually made up by small amounts of hemicelluloses and hydroxyproline-rich protein may also be the main interference for juice to flow (Sharoba & Ramadan,

![Figure 3](image_url)
TABLE 5

| Arthusen model | E₀ (kJ/mol) | H | D | R² | RMSE |
|----------------|-------------|---|---|----|------|
| New model      |             |   |   |    |      |
| Guava          |             |   |   |    |      |
| 5              | 1.36E-05    | 0.9833 | 0.7722 | 0.8145 | 0.0485 | 0.9956 | 0.0037 | 1.3241 | 1.49E-03 | 1.2316 | 5.77E-05 | 0.2488 | 0.9967 |
| 15             | 1.87E-01    | 0.9955 | 0.6614 | 0.5190 | 0.0750 | 0.9957 | 0.0027 | 1.2570 | 1.38E-01 | 1.84E-05 | 1.1926 | 2.44E-05 | 0.1228 | 0.9989 |
| 30             | 1.62E-02    | 0.9972 | 0.7814 | 0.6297 | 0.0504 | 0.9973 | 0.0028 | 1.3506 | 1.84E-02 | 1.96E-05 | 1.2196 | 2.46E-05 | 0.1128 | 0.9963 |
| 45             | 2.37E-02    | 0.9981 | 0.6614 | 0.5190 | 0.0750 | 0.9957 | 0.0027 | 1.2570 | 1.38E-01 | 1.84E-05 | 1.1926 | 2.44E-05 | 0.1228 | 0.9989 |
| Pomelo         |             |   |   |    |      |
| 5              | 5.89E-08    | 0.9133 | 0.0442 | 0.381E-05 | 0.0027 | 0.9890 | 0.0001 | 1.09E-04 | 1.54E-04 | 1.36E-04 | 1.04E-03 | 5.77E-05 | 0.9957 | 0.00001 |
| 15             | 1.66E-01    | 0.9952 | 0.2076 | 0.713E-05 | 0.0035 | 0.9973 | 0.0002 | 1.24E-04 | 1.54E-04 | 1.36E-04 | 1.04E-03 | 5.77E-05 | 0.9957 | 0.00001 |
| 30             | 2.22E-02    | 0.9986 | 0.3846 | 0.83E-05 | 0.0043 | 0.9978 | 0.0003 | 1.31E-04 | 1.54E-04 | 1.36E-04 | 1.04E-03 | 5.77E-05 | 0.9957 | 0.00001 |
| 45             | 5.49E-02    | 0.9981 | 0.3846 | 0.83E-05 | 0.0043 | 0.9978 | 0.0003 | 1.31E-04 | 1.54E-04 | 1.36E-04 | 1.04E-03 | 5.77E-05 | 0.9957 | 0.00001 |
| Soursop        |             |   |   |    |      |
| 5              | 2.11E-01    | 0.9957 | 0.0442 | 0.381E-05 | 0.0027 | 0.9890 | 0.0001 | 1.09E-04 | 1.54E-04 | 1.36E-04 | 1.04E-03 | 5.77E-05 | 0.9957 | 0.00001 |
| 15             | 3.89E-02    | 0.9952 | 0.2076 | 0.713E-05 | 0.0035 | 0.9973 | 0.0002 | 1.24E-04 | 1.54E-04 | 1.36E-04 | 1.04E-03 | 5.77E-05 | 0.9957 | 0.00001 |
| 30             | 6.75E-02    | 0.9986 | 0.3846 | 0.83E-05 | 0.0043 | 0.9978 | 0.0003 | 1.31E-04 | 1.54E-04 | 1.36E-04 | 1.04E-03 | 5.77E-05 | 0.9957 | 0.00001 |
| 45             | 1.55E-01    | 0.9957 | 0.0442 | 0.381E-05 | 0.0027 | 0.9890 | 0.0001 | 1.09E-04 | 1.54E-04 | 1.36E-04 | 1.04E-03 | 5.77E-05 | 0.9957 | 0.00001 |

TABLE 6

| Arthusen model | E₀ (kJ/mol) | H | D | R² | RMSE |
|----------------|-------------|---|---|----|------|
| New model      |             |   |   |    |      |
| Guava          |             |   |   |    |      |
| 5              | 1.01E-08    | 0.9961 | 0.9485 | 0.9487 | 0.0211 | 0.9882 | 0.0004 | 1.50E-04 | 1.89E-04 | 1.50E-04 | 1.89E-04 | 1.50E-04 | 1.89E-04 | 1.50E-04 | 1.89E-04 |
| 15             | 1.11E-01    | 0.9953 | 0.6765 | 0.6769 | 0.0769 | 0.9709 | 0.0019 | 1.50E-04 | 1.89E-04 | 1.50E-04 | 1.89E-04 | 1.50E-04 | 1.89E-04 | 1.50E-04 | 1.89E-04 |
| 30             | 1.03E-02    | 0.9934 | 0.6765 | 0.6769 | 0.0769 | 0.9709 | 0.0019 | 1.50E-04 | 1.89E-04 | 1.50E-04 | 1.89E-04 | 1.50E-04 | 1.89E-04 | 1.50E-04 | 1.89E-04 |
| 45             | 2.76E-02    | 0.9981 | 0.6765 | 0.6769 | 0.0769 | 0.9709 | 0.0019 | 1.50E-04 | 1.89E-04 | 1.50E-04 | 1.89E-04 | 1.50E-04 | 1.89E-04 | 1.50E-04 | 1.89E-04 |
| Pomelo         |             |   |   |    |      |
| 5              | 1.83E-02    | 0.9953 | 0.6765 | 0.6769 | 0.0769 | 0.9709 | 0.0019 | 1.50E-04 | 1.89E-04 | 1.50E-04 | 1.89E-04 | 1.50E-04 | 1.89E-04 | 1.50E-04 | 1.89E-04 |
| 15             | 2.34E-02    | 0.9953 | 0.6765 | 0.6769 | 0.0769 | 0.9709 | 0.0019 | 1.50E-04 | 1.89E-04 | 1.50E-04 | 1.89E-04 | 1.50E-04 | 1.89E-04 | 1.50E-04 | 1.89E-04 |
| 30             | 7.34E-02    | 0.9953 | 0.6765 | 0.6769 | 0.0769 | 0.9709 | 0.0019 | 1.50E-04 | 1.89E-04 | 1.50E-04 | 1.89E-04 | 1.50E-04 | 1.89E-04 | 1.50E-04 | 1.89E-04 |
| 45             | 1.74E-01    | 0.9953 | 0.6765 | 0.6769 | 0.0769 | 0.9709 | 0.0019 | 1.50E-04 | 1.89E-04 | 1.50E-04 | 1.89E-04 | 1.50E-04 | 1.89E-04 | 1.50E-04 | 1.89E-04 |
Goula and Adamopoulos (2011) mentioned that the fibrous materials influenced the shear-thinning behavior of kiwi fruit juice.

### 3.2 Modeling the effect of temperature on the flow behavior of juice concentrates

Results from Tables 5 and 6 on the Arrhenius model for describing the effect of temperature on rheological behavior of fruit juice suggest a poor fit. The values of $K$ should be positive because negative $K$ values result in negative shear rates and will not give a viscosity value (Dealy & Wang, 2013). As all three juices are shear-thinning, it is necessary to make sure the $n$ values remain between 0 and 1. A negative $n$ value is also meaningless and it occurs due to sample slipping out during rheological testing (Fraiha, Biagi, & Ferraz, 2011). In overcoming the limitations of the Arrhenius model, a S-shaped curve, which is the logistic sigmoidal model, was applied to predict the effect of temperature on $K$ and $n$. Originally, the logistic sigmoidal model is most widely used to describe the growth of population, such as tumor cell growth (Kozusko & Bourdeau, 2007). The sigmoidal decay model has also been used to evaluate the effect of temperature on lipid solid fat content (Augusto, Soares, et al., 2012). Modeling the current rheological data for juice concentrates using the logistic sigmoidal model, however, did not give a good fit as seen in Tables 5 and 6. A newly proposed model (Equations 9a and 9b) which integrated the Arrhenius and sigmoidal growth models from combined functions of Equation 7a with Equation 8a, and Equation 7b with Equation 8b have provided the highest $R^2$ ($R^2 = 0.9792−1.0$ and the lowest RMSE (RMSE = 0.0001−8.2749) values of all as compared with the Arrhenius model ($R^2 = 0.6243−0.9978$; RMSE = 0.0002−10.6811) and the logistic sigmoidal growth models ($R^2 = 0.9440−0.9984$; RMSE = 0.0001−25.8989) individually. Statistical analysis in Table 6 also shows that the proposed model is the best fitted model to describe the effect of temperature on $n$. The negative values of $r$ denote the decay pattern of $K$ by increment of temperature. Activation energy values ranged between $3.23 \times 10^{-5}$ and $1.20 \times 10^{-2}$ $kJ \cdot mol^{-1}$, and $7.57 \times 10^{-6}$ and $9.37 \times 10^{-5}$ $kJ \cdot mol^{-1}$ for $T$-$K$ and $T$-$n$ relationships, respectively. The sensitivity of viscosity to
temperature is shown by its activation energy (Quek et al., 2013). Guava juice concentrate had the lowest range of activation energy as it is less sensitive to a temperature change.

Figures 4 and 5 show a trend of $K$ decaying and growing with increasing temperature. The $K$ value of fruit juice concentrates reduced at high temperature because heat energy applied has loosened the molecules bonding until they could move fast and random, and leads to less resistance to flow. Figure 4 shows that the guava has the highest range of $K$, while the pomelo has the lowest range of $K$. The guava juice concentrate is the most viscous juice compared to the pomelo and soursop. Statistical analysis using ANOVA show that means of $K$ of guava, pomelo, and soursop at different temperatures was significant with $p < .0001$. From DMRT analysis, the highest concentrations at 45°C for guava and 70°C for the pomelo and soursop lead to a higher $K$ values and this reflected higher juice viscosity. Figure 5 shows that the increment of temperatures caused all the juice concentrates to be more Newtonian. The guava juice concentrates are more shear-thinning, while pomelo juice concentrates are close to Newtonian behavior. The ANOVA results indicate that means of $n$ for all guava, pomelo, and soursop juice concentrates at different concentrations were significantly different with $p < .0001$. From DMRT analysis, the lower means of $n$ at low concentrations of 5°Brix explains the shear-thinning behavior in all juice concentrates.

4 | CONCLUSIONS

The shifting of rheological data to a single reference temperature in developing a master curve model to predict the overall effect of juice concentration on rheological properties of $K$ and $n$ is useful when statistical analysis supports that the data are not significantly different at different temperatures. The master curve models of $K$ or $n$ as function of concentration shows an increasing trend for $K$ and decreasing trend for $n$. The modeling of $K$ and $n$ with respect to temperature using the Arrhenius and logistic sigmoidal growth models was improved using a new model proposed from the integration of both the Arrhenius and logistic sigmoidal functions. The modeling of fruit juice concentrate properties is potentially useful for the juice processing and equipment industry as it provide avenue to fast, easy, and efficient references on rheological properties for operations and equipment design.

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