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Modelling of rheological behaviour of macaíba pulp at different temperatures[1]

Modelagem do comportamento reológico da polpa de macaíba em diferentes temperaturas

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HIGHLIGHTS:

The rheological behaviour of macaíba pulp can be represented by the Mizrahi-Berk equation.
The fluid behaviour index (n) was below unity, characterizing a pseudoplastic behaviour for the macaíba pulp.
The effect of temperature can be evaluated using the Arrhenius-type equation for the viscous flow of the macaíba pulp.

ABSTRACT: Fruit pulps undergo temperature variations during processing, leading to viscosity changes. This study aimed to analyse the rheological behaviour of macaíba pulp at different temperatures (10 to 50 °C, with 5 °C increments) and speeds (2.5 to 200 rpm, totalling 17 speeds). Experimental measurements were performed in a Brookfield viscometer, fitting the Ostwald-de-Waele, Mizrahi-Berk, Herschel-Bulkley, and Casson models to the experimental data of shear stress as a function of shear rate. Among the models used, the Mizrahi-Berk model ($R^2 > 0.9656$ and average percentage deviation - $P \leq 4.1\%$) was found to best fit the rheogram data. Macaíba pulp exhibited a non-newtonian behaviour and was characterised as pseudoplastic. It showed fluid behaviour indexes below unity under the studied conditions, with decreases in apparent viscosity as temperature and shear rate increased. Such behaviour could be described by the Arrhenius equation. The Mizrahi-Berk and Falguera-Ibarz models ($R^2 > 0.99$ and $P \leq 10\%$) best fitted the data and were used to represent the viscosity behaviour of macaíba pulp. The activation energy values of macaíba pulp ranged between 17.53 and 25.37 kJ mol^{-1}, showing a rheological behaviour like other fruit pulps.

Key words: *Acrocomia intumescens*, apparent viscosity, non-newtonian fluid, pseudoplastic, Arrhenius equation

RESUMO: As polpas de frutas estão sujeitas a mudanças de temperatura durante o processo de fabricação que podem alterar a viscosidade. Este estudo objetivou avaliar o comportamento reológico da polpa de macaíba em diferentes condições de temperatura (10 a 50 °C, com incrementos de 5 °C) e velocidades de rotação (2,5 a 200 rpm, totalizando 17 velocidades). As medições experimentais foram realizadas em viscosímetro Brookfield e os modelos Ostwald-de-Waele, Mizrahi-Berk, Herschel-Bulkley e Casson foram ajustados aos dados experimentais de tensão de cisalhamento em função da taxa de deformação. Dentre os modelos testados, o modelo que descreveu com maior precisão os reogramas foi o modelo de Mizrahi-Berk ($R^2 > 0,9656$ e desvio percentual médio $P \leq 4,1\%$). A polpa de macaíba comportou-se como fluido não-newtoniano com características pseudoplásticas apresentando valores de índice de comportamento menores que a unidade, nas condições estudadas, apresentando diminuição da viscosidade aparente com o aumento da temperatura e taxa de deformação, podendo ser expressa através da equação de Arrhenius. Os modelos de Mizrahi-Berk e Falguera-Ibarz ($R^2 > 0,99$ e $P \leq 10\%$) foram os que obtiveram melhores ajustes podendo ser utilizados na predição do comportamento da viscosidade da polpa de macaíba. A polpa apresentou valores de energia de ativação variando entre 17,53 a 25,37 kJ mol^{-1}, tendo características reológicas similares a outras polpas de frutas.

Palavras-chave: *Acrocomia intumescens*, viscosidade aparente, fluido não-newtoniano, pseudoplástico, equação de Arrhenius

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Introduction

Macaíba (*Acrocomia intumescens*) is considered the palm tree with the widest dispersion throughout Brazil compared to other species. It occurs naturally in the northeast of the country and has unique characteristics (Amaral et al., 2011).

Macaíba fruit pulp is edible and yellow in colour and has a light flavour at the beginning of ripening, which gets stronger and sweeter as it ripens. It presents a unique physicochemical composition rich in lipids, fibre, and starch. These characteristics provide a distinctive rheological behaviour when compared to other fruit pulps (Ramos et al., 2008).

Although its production chain has evolved towards the biofuel sector, macaíba has been applied in the food industry. However, one of the bottlenecks still found for its use in this sector is its unsuitable processing. Therefore, new technologies are needed at all stages of its production chain.

Fruit pulps can be used as raw materials for several products such as juices, nectars, jams, syrups, jellies, and ice cream. As a lot of equipment and unit operations are involved in pulp processing, its physical and chemical properties must be known to ensure the process technical and economic feasibility. One of these properties is rheological behaviour, which is used for quality control of equipment design and operation, new product development, and correlation with sensory analysis (Quintana et al., 2015).

The rheological behaviour of macaíba pulp at different temperatures should be studied to predict its behaviour in production processes such as pasteurisation. In this sense, major parameters may be estimated, namely: shear stress, apparent viscosity, and activation energy. Thereby, equipment, pipelines, among others can be designed as a function of processing and storage conditions.

Plenty of models have been used to represent fruit pulp rheological behaviour in terms of shear stress and rate relationship. For instance, one can cite the Bingham, Ostwald-de-Waele (or Power Law), Herschel and Bulkley, Casson and Mizrahi-Berk models, among others. Most of the fruit-derived liquid food exhibit non-newtonian behaviour, as their apparent viscosity varies with time (Quintana et al., 2015; Silva et al., 2017).

Given the importance of describing the rheological behaviour of fruit pulps for production on an industrial scale, the lack of data for exotic fruits, and macaíba potential as a food source, this study aimed to analyse the rheological behaviour of its pulp at different temperatures and rotation speeds.

Material and Methods

Mature macaíba fruits (*Acrocomia intumescens*) were collected from the city of Alagoa Nova, Paraíba State (Brazil). The city is located at the geographical coordinates of 07º 04' 15" S, 35º 45' 30" W, and 463 m of altitude. The fruits were initially selected, washed, and sanitised. Afterwards, they were manually peeled and pulped in a mechanical pulper. The pulp was then homogenised in a blender and diluted in mineral water until reaching a total soluble solids concentration of 7 °Brix for full homogenisation, as defined in preliminary tests. Lastly, the pulp was packed in low-density polyethylene bags and stored in a freezer (-18 ºC) until analyses were performed.

Stationary rheological analyses were carried out with macaíba pulp using a viscometer (Brookfield DV-II+PRO, Massachusetts, USA), equipped with a small sample adapter and a thermostatically controlled water bath, with an accuracy of 0.1 ºC over a range from 10 to 50 ºC. Readings were taken at varying rotation speeds from 2.5 to 200 rpm, which are available on the viscometer model, totalizing 17 speeds with increments every 30 s. Apparent viscosity, shear rate, and shear stress were determined for each rotation speed. The measurements were made in triplicate at temperatures of 10, 15, 20, 25, 30, 35, 40, 45, and 50 ºC, using spindle 29, using a new sample for each measurement.

Table 1 shows the four rheological models fitted to the curves of shear stress as a function of shear rate (rheograms), with a non-linear fit using the Quasi-Newton method through Statistica® version 7.0 software. This was used to describe the rheological behaviour of macaíba pulp and determine the best-fitted model.

Table 1. Rheological models fitted to the curves of shear stress as a function of shear rate to describe the rheological behaviour of macaíba pulp

Model	Equation	
Casson	$\tau^{0.5} = K_{0C} + K_C \dot{\gamma}^{0.5}$	(1)
Herschel-Bulkley	$\tau = \tau_{0H} + K_H \dot{\gamma}^{n_H}$	(2)
Mizrahi-Berk	$\tau^{0.5} = K_{0M} + K \dot{\gamma}^{n}$	(3)
Ostwald-de-Waele	$\tau = K \dot{\gamma}^{n}$	(4)

τ - Shear stress (Pa); γ - Shear rate (s^{-1}); K - Consistency index (Pa s^n); n and n_H - Flow behaviour indexes (non-dimensional); K_{0M} - Square root of initial stress; τ_{0H} - Initial shear stress (Pa); K_H - Consistency index (Pa); $K^2_{0C} = \tau_{0C}$ - Initial shear stress (Pa); K_C - Casson's plastic viscosity (Pa s)

Model adequacy was checked by the coefficient of determination (R^2) and average percentage deviation (P), which was calculated according to Eq. 5.

$$P = \frac{100}{n} \sum \frac{\tau_{exp} - \tau_{pred}}{\tau_{exp}} \quad (5)$$

where:

P - average percentage deviation, %;
τ_{pred} - shear stress predicted by the model;
τ_{exp} - experimental shear stress; and,
n - number of observations.

Pulp rheological behaviour was investigated by plotting a curve of apparent viscosity versus shear rate (0.7 to 56 s^{-1}), using experimental data and values from the rheological models (Mizrahi-Berk, Power Law, Sisko and Faguelra-Ibarz). These are described in Table 2, using non-linear regression by the Quasi-Newton method through Statistica® version 7.0 software.

Temperature influence on apparent viscosity (η) at speeds between 2.5 and 200 rpm was assessed by adjusting the Arrhenius equation, using linear regression, as in Eq. 10.

Table 2. Rheological models utilised to describe the rheological behaviour of macaíba pulp related to the apparent viscosity and shear rate

Model	Equation	
Mizrahi-Berk	$\eta_{ap} = \frac{(K_{0M} + K\dot{\gamma}^{n})^2}{\dot{\gamma}}$	(6)
Power Law	$\eta_{ap} = K\dot{\gamma}^{n-1}$	(7)
Sisko	$\eta_{ap} = \eta_{\infty} + K_s\dot{\gamma}^{n_s-1}$	(8)
Faguelra-Ibarz	$\eta_{ap} = \eta_{\infty} + (\eta_0 - \eta_{\infty})\dot{\gamma}^{-k}$	(9)

η_{ap} - Apparent viscosity (Pa s); η_{∞} - Viscosity at infinite shear rate (Pa s); η_0 - Static apparent viscosity (Pa s); γ - Shear rate (s^{-1}); K - Consistency index (Pa s); K_s and K_{0M} - Consistency index (Pa s); n and n_s - Flow behaviour index (non-dimensional); k - Constant of fluid behaviour (non-dimensional)

$$\eta = \eta_0 \exp\left(\frac{E_a}{RT_a}\right) \qquad (10)$$

where:

- η - apparent viscosity, Pa s;
- η_0 - pre-exponential factor, Pa s;
- E_a - activation energy, kJ mol^{-1};
- R - universal gas constant, 0.008314 kJ mol^{-1}; and,
- T_a - absolute temperature, K.

Results and Discussion

Table 3 displays the rheological parameters used to describe the rheological behaviour of macaíba pulp at different temperatures, with total soluble solids at 7 °Brix and water content of 54.78 g per 100 g. Among the models studied, the Mizrahi-Berk was the one that best fit the experimental data on the curve of shear stress versus shear rate, at the temperatures evaluated. Its coefficient of determination (R^2) ranged between 0.9656 and 0.9945, with low average percentage deviations (1.52-4.11%). Thus, this model can be used to satisfactorily estimate the rheological behaviour of macaíba pulp. In turn, the consistency indexes K_{0M} and K_M followed no defined trend.

The Casson, Herschel Bulkley, and Ostwald-de-Waele (power-law) models can also describe the rheological behaviour of macaíba pulp, given their high R^2 values (0.8778-0.9929) and P values (below 14%). The consistency indexes of the Casson and Ostwald-de-Waele models (K_{0C}, K_C, and K) decreased as temperature increased. Pereira et al. (2014) evaluated acerola fruit pulp at 5.5-13.5 °Brix and 20 to 60 °C temperatures and observed the same behaviour for consistency index. Quintana et al. (2015) found similar values, ranging from 4.03 to 31.9 Pa s^n by applying the power-law model in mango pulp.

On the other hand, negative values were found for some parameters by the Herschel-Bulkley and Mizrahi-Berk models, but with no physical significance.

Other studies on fruit pulp rheological behaviour testing different models can be found in the literature to explain such performance. For instance, Sousa et al. (2014) tested pequi pulp at different total soluble solid concentrations (6, 8, 10, and 12 °Brix) and temperatures (25-50 °C) and found that the Mizrahi-Berk model best fitted the rheogram, with R^2 of about 0.99, P below 1%, and K_{0M} and K_M also not following any defined trend. In turn, Tonon et al. (2009), when studying the

Table 3. Parameters of nonlinear regression models adjusted for shear stress as a function of shear rate of macaíba pulp

Casson

Temperature (°C)	K_{0C} (Pa)	K_C (Pa s)	R^2	P (%)
10	5.52	0.94	0.8778	13.97
15	5.35	0.83	0.9183	5.15
20	3.19	1.06	0.9766	3.15
25	3.30	0.90	0.9902	2.30
30	3.35	0.80	0.9826	2.65
35	3.87	0.93	0.9282	7.07
40	3.07	0.85	0.9458	6.30
45	2.64	0.72	0.9749	4.26
50	2.58	0.72	0.9788	3.59

Herschel Bulkley

Temperature (°C)	τ_{0H} (Pa)	K_H (Pa^n)	n	R^2	P (%)
10	-667.78	693.99	0.0372	0.9846	5.87
15	-72.41	100.69	0.1613	0.9843	3.59
20	6.49	9.26	0.6219	0.9675	8.56
25	7.22	8.49	0.5832	0.9929	3.12
30	5.98	9.13	0.5285	0.9858	4.14
35	-30.23	45.96	0.2698	0.9781	6.38
40	-0.30	12.64	0.4692	0.9447	8.28
45	-2.66	11.22	0.4257	0.9917	5.29
50	3.56	5.99	0.5613	0.9769	5.23

Mizrahi-Berk

Temperature (°C)	K_{0M} (Pa)	K_M (Pa s^n)	n	R^2	P (%)
10	-145.97	151.40	0.0105	0.9799	2.57
15	-1166.01	1171.34	0.0012	0.9865	1.76
20	2.83	1.34	0.4517	0.9771	3.50
25	2.22	1.76	0.3637	0.9945	1.52
30	2.04	1.88	0.3298	0.9894	2.02
35	-48.04	51.97	0.0285	0.9833	3.07
40	-0.79	4.25	0.2097	0.9656	4.11
45	0.24	2.78	0.2470	0.9919	2.39
50	1.34	1.75	0.3253	0.9860	2.69

Ostwald-de-Waele

Temperature (°C)	K (Pa s)	n	R^2	P (%)
10	38.52	0.3278	0.9567	10.27
15	33.56	0.3232	0.9770	6.37
20	13.02	0.5483	0.9661	10.60
25	13.17	0.4898	0.9909	5.73
30	13.32	0.4505	0.9843	5.74
35	20.44	0.4145	0.9729	10.09
40	12.43	0.4727	0.9447	8.28
45	9.27	0.4638	0.9913	4.98
50	8.33	0.4912	0.9758	5.94

K_{0C}, K_c and K_M - Consistency index; K_C - Casson's plastic viscosity; n - Flow behaviour index; R^2 - Coefficient of determination; P - Average percentage deviation; τ_{0H} - Initial shear stress; K_H - Consistency index; K_{0M} - Square root of initial stress

rheological properties of açaí pulp at temperatures between 10 and 70 °C, observed that the Herschel Bulkley model best described the pulp rheological behaviour. Conversely, Balestra et al. (2011) considered the Casson model (R^2 = 0.84-0.97) as the most suitable for describing the rheological behaviour of fruit purees.

Macaíba pulp exhibited the rheological behaviour of a non-newtonian fluid, that is, a non-linear relationship between shear stress and shear rate, with pseudoplastic behaviour. This is because the behaviour indexes (n) were below unity at all temperatures studied, ranging between 0.0012 and 0.6219. Such a classification has been reported in most fruit fluids such as pequi pulp (Sousa et al., 2014); mango pulp (Quintana et al., 2015); buriti juice (Rodrigues et al., 2016); mixed nectars of pineapple skin juice and tropical fruit pulp (Silva et al., 2017); cashew, acerola and mango pulps (Silva et al., 2012); and pitanga pulp (Lopes et al., 2013).

Figure 1 illustrates the influence of temperature on the rheological behaviour of macaíba pulp. It shows that, at a fixed shear rate, shear stress decreases with an increase in temperature. This is a characteristic behaviour of a non-newtonian fluid. According to Alpaslan & Hayta (2002), this behaviour stems from the structural collapse of the pulp due to the hydrodynamic force generated and better orientation of molecules towards the applied force. Moreover, as temperature increases, thermal energy and molecular distances increase due to a reduction in intermolecular forces.

Table 4 exhibits the rheological parameters of the Mizrahi-Berk, Power Law, Sisko, and Falguera-Ibarz models fitted to the experimental data on apparent viscosity as a function of shear rate of macaíba pulp at the temperatures studied. Among these models, the best-fitted ones were the Mizrahi-Berk and Falguera-Ibarz models, which had R^2 above 0.99 and P below 10%, which can be deemed suitable to describe the rheological behaviour of macaíba pulp. Similar behaviour was found by Feitosa et al. (2015), in which the Falguera-Ibarz model best fitted to the rheological data of myrtle pulp (*Eugenia gracillima* Kiaersk) at temperatures of 15, 25, and 35 °C and rotation speeds of 20-200 rpm. In turn, Braga et al. (2013) observed that the Mizrahi-Berk model ($R^2 > 0.98$) best fitted the rheological data of pineapple juice (*Ananas comosus* L. Merr.) at 10, 25, 50, and 65 °C.

The negative values of some parameters have no physical meaning. The flow behaviour indexes (n) below unity ($n < 1$) observed in the Mizrahi-Berk, Power Law, and Sisko models at most temperatures confirm the pseudoplastic characteristic of the macaíba pulp.

Reductions in the consistency index (K) were observed with increasing temperatures in the Mizrahi-Berk and Power Law models. The static apparent viscosity (η_0) in the Falguera-Ibarz model decreased with increasing temperatures, similar to what was observed by Feitosa et al. (2015) for myrtle pulp. The viscosity values at the infinite shear rate observed in the Sisko and Falguera-Ibarz models did not show a definite trend in behaviour.

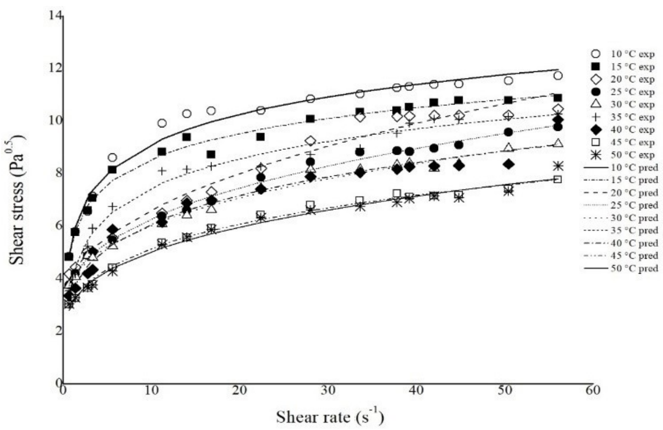

Figure 1. Shear stress as a function of shear rate of macaíba pulp at different temperatures with adjustments by the Mizrahi-Berk model

Table 4. Parameters of the nonlinear regression models adjusted to the apparent viscosity of macaíba pulp as a function of shear rate

Mizrahi-Berk

Temperature (°C)	K_{0M} (Pa)	K (Pa s)	n	R^2	P (%)
10	-184.71	352.45	0.1248	0.9928	9.96
15	-465.84	632.95	0.0680	0.9942	7.85
20	113.75	22.94	0.5853	0.9982	6.02
25	65.73	60.80	0.3405	0.9993	3.31
30	71.69	52.56	0.3527	0.9980	4.51
35	-3.19	123.39	0.1920	0.9958	5.41
40	69.73	41.59	0.4010	0.9980	6.59
45	69.29	30.18	0.4595	0.9973	6.68
50	69.52	29.77	0.4535	0.9979	6.19

Power Law

Temperature (°C)	K (Pa s)	n	R^2	P (%)
10	27658.44	0.4320	0.9908	14.64
15	27969.69	0.4587	0.9904	15.19
20	19002.87	0.3488	0.9819	18.51
25	16131.87	0.3941	0.9968	8.66
30	15576.38	0.3691	0.9952	9.19
35	14444.42	0.3922	0.9958	5.25
40	12510.83	0.3946	0.9922	9.11
45	10005.24	0.4013	0.9869	12.03
50	9973.82	0.3887	0.9887	12.57

Sisko

Temperature (°C)	η_∞ (Pa s)	K_s (Pa s)	n	R^2	P (%)
10	-3102.36	31018.97	0.5705	0.9947	5.67
15	4169171.46	-4144439.37	1.0015	0.9245	34.52
20	1820.69	16929.56	0.1154	0.9981	6.06
25	786.72	15304.08	0.3067	0.9994	3.38
30	738.65	14783.40	0.2788	0.9979	4.85
35	125.55	14313.67	0.3786	0.9958	4.78
40	817.33	11647.95	0.2693	0.9970	7.81
45	866.61	9084.41	0.2238	0.9962	8.01
50	2254253.31	-2245794.79	1.0009	0.8293	35.08

Falguera–Ibarz

Temperature (°C)	η_∞ (Pa s)	η_0 (Pa s)	k	R^2	P (%)
10	-3102.36	27916.61	0.4295	0.9947	5.67
15	-2698.87	27650.35	0.4602	0.9950	7.55
20	1820.69	18750.25	0.8846	0.9981	6.06
25	786.72	16090.79	0.6933	0.9994	3.38
30	738.65	15522.06	0.7212	0.9979	4.85
35	125.55	14439.22	0.6214	0.9958	4.78
40	817.33	12465.28	0.7307	0.9970	7.81
45	866.61	9951.02	0.7762	0.9962	8.01
50	801.24	9915.94	0.7773	0.9970	7.64

K_{0M}, K and K_S - Consistency index; n - Flow behaviour index; R^2 - Coefficient of determination; P - Average percentage deviation; η_∞ - Viscosity at infinite shear rate; η_0 - Static apparent viscosity; k - Constant of fluid behaviour

Figure 2 shows the relationship between the apparent viscosity and shear rate fitted to the Mizrahi-Berk model, which was considered the best-fitted model. The apparent viscosity of macaíba pulp ranged between 1 and 33 Pa s for shear rates from 0.7 to 56 s^{-1}, with flow behaviour varying with shear rate and temperature changes. Furthermore, viscosity decreased with increasing shear rates and temperatures, confirming the non-newtonian (pseudoplastic) behaviour of macaíba pulp. Similar values were found by Zhou et al. (2017) when analysing mango juice submitted to high-pressure treatments, with a viscosity between 5-25 Pa s for shear rates between 0.1 and 100 s^{-1}. Conversely, these results were lower than those found by Sousa et al. (2014) for pequi pulp (60-375 Pa s), with

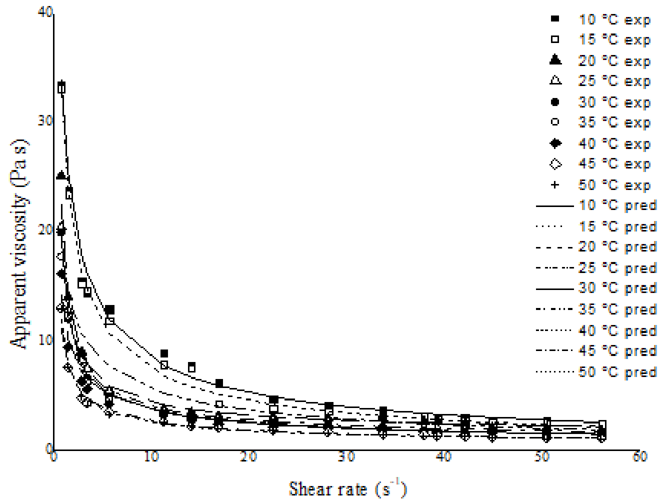

Figure 2. Apparent viscosity as a function of shear rate of macaíba pulp at different temperatures with adjustments by Mizrahi-Berk model

changes in viscosity between 60 and 375 Pa s for shear rates from 0.45 to 1.25 s^{-1}. These results were also higher than those of Quintana et al. (2015) for mango pulp (0.5-4.5 Pa s) with 25 °Brix total soluble solids, those of Pereira et al. (2014) for acerola pulp (1-7 Pa s) with 13.5 °Brix, and those of Huang et al. (2018) for polysaccharides extracted from lychee pulp with changes in viscosity between 0.010 and 1 Pa s for shear rates from 1 to 1000 s^{-1}.

Increasing temperatures reduce liquid phase viscosity due to greater increased mobility of particulate material. From an industrial and economic perspective, lower viscosity favours the pumping of fruit pulps along the pipes and heat exchange during processing (Silva et al., 2017).

The temperature had a significant effect on macaíba pulp rheological properties. This can be supported by the good fit of the linearized Arrhenius equation to apparent viscosity as a function of the inverse of temperature. Therefore, temperature influenced macaíba pulp apparent viscosity at the different rotation speeds (between 2.5 and 200 rpm; Figure 3), with high coefficients of determination ($R^2 > 0.86$). It was observed a positive correlation between the natural logarithm of apparent viscosity and the inverse of absolute temperature. Accordingly,

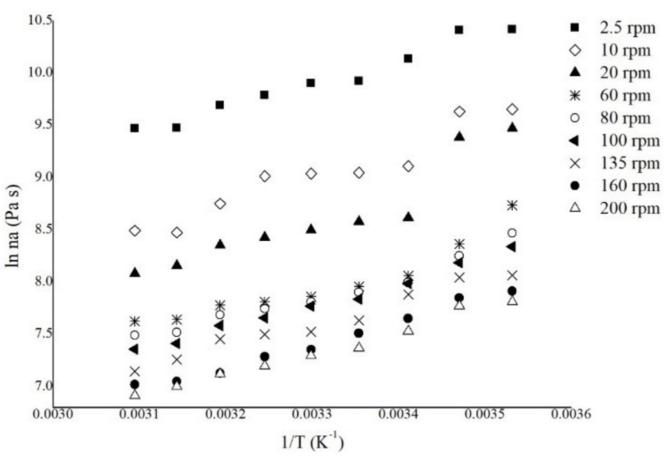

Figure 3. Effect of temperature on the apparent viscosity of macaíba pulp at 2.5 to 200 rpm rotational speeds with fits by the Arrhenius equation

temperature increases led to pulp apparent viscosity reductions at the studied rotational speeds (from 2.5 to 200 rpm). Such behaviour is typical of pseudoplastic fluids. For Deshmukh et al. (2015), this behaviour can be explained by structural changes in fluid samples subjected to increasing temperatures, which enhances the mobility of molecules and inter-molecular spacing, decreasing flow resistance and hence viscosity.

Pereira et al. (2014) reported good fits of the Arrhenius equation to the temperature effect on the apparent viscosity of acerola pulp concentrate, with R^2 between 0.89 and 0.99 and apparent viscosity reductions with temperature increases.

Table 5 shows the activation energy (E_a) and pre-exponential factor (μ_0) values for macaíba pulp at rotation speeds between 2.5 and 200 rpm. These values were obtained from linear fits of the apparent viscosity data as a function of the inverse of temperature, with fits by the Arrhenius equation. Activation energy is indicative of apparent viscosity sensitivity to changes in temperature (Quintana et al., 2015). As for this parameter, macaíba pulp had values between 17.53 and 23.37 kJ mol^{-1} at rotation speeds from 2.5 to 200 rpm. However, the highest activation energy values (19.40-25.37 kJ mol^{-1}) were related to lower velocities. This indicates that temperature had a greater effect on apparent viscosity at lower shear rates. In this sense, there was a decreasing trend in theoretical initial apparent viscosity with increasing rotation speeds.

However, activation energy decreased with increasing rotation speeds (20 to 80 rpm), as reported by Sousa et al. (2017). These authors studied noni pulp (5-65 °C) with activation energy ranging between 14.01 and 1.13 kJ mol^{-1} at rotation speeds from 5 to 200 rpm.

Pereira et al. (2014) observed activation energy values close to the results obtained in this research (11.09-15.71 kJ mol^{-1}) for temperatures between 20 and 60 °C when analysing the rheological characteristics of acerola pulp. Likewise, Augusto et al. (2012) reported an E_a of 17.51 kJ mol^{-1} for seriguela pulp.

In short, apparent viscosity and activation energy may be related to insoluble solid contents, as reduced levels can lead to lower apparent viscosity and activation energy values (Karwowski et al., 2013; Murillo et al., 2017).

Table 5. Activation energy (Ea) values for macaíba pulp at rotation speeds between 2.5 and 200 rpm

Rotation speed (rpm)	μ_0 (mPa s)	E_a (kJ mol^{-1})	R^2
2.5	9.0322	19.3957	0.9686
10	1.0660	22.5343	0.9181
20	0.2300	25.3743	0.8624
60	1.6967	18.7464	0.8738
80	2.4368	17.5666	0.9535
100	1.6051	18.4104	0.9872
135	1.6883	17.8294	0.9665
160	1.0846	18.4554	0.9848
200	1.4405	17.5284	0.9809

μ_0 - Pre-exponential factor; E_a - Activation energy; R^2 - Coefficient of determination

Conclusions

1. Macaíba pulp exhibited a non-newtonian fluid behaviour, showing pseudoplastic characteristics.

2. The rheological models of Casson, Herschel Bulkley, Mizrahi-Berk, and Ostwald-de-Waele (Power Law) were

suitable to describe the rheological behaviour of macaíba pulp, with the fit by the Mizrahi-Berk (coefficient of determination [R^2] > 0.9656 and average percentage deviation [P] < 4.11%).

3. Temperature has a significant effect on the rheological characteristics of macaíba pulp, which can be satisfactorily described by the Arrhenius equation.

4. The apparent viscosity of macaíba pulp decreases with increasing temperatures and shear rates.

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