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Research Article

Effect of High-Pressure with Temperature on Mango Pulp: Rheology Evaluation in Comparison with Thermal Process

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Abstract: Effect of High-Pressure with Temperature (HPP+T) and Thermal Processing (TP) were evaluated on the rheological characteristics of mango pulp. Samples were subjected to an equivalent condition of a 5D (5 log reduction) process for HPP+T (600 MPa/6.3 min at 90 °C) and TP (95 °C/10.5 min) to be compared. Storage-modulus (G') and loss-modulus (G'') were modeled according to the oscillatory frequency using the Power-Law. TP and HPP+T showed G' > G'' at all evaluated times. Both processes did not result in significant increases in the elastic and viscous behavior of the mango pulp. The flow behavior of the mango pulp presented a pseudoplastic characteristic with relevant residual tension. The Herschel-Buckley model was used to model the flow curves fitted well ($R^2 \geq 0.99$) and both processes increased the consistency index of the mango pulp. HPP+T proved to be a promising technology, which in addition to increasing the consistency of the product uses reduced time and temperature.

***Keywords*:** high-pressure process, thermal process, rheology, mango pulp

1. Introduction

Mango (*Mangifera indica* L.) is one of the main tropical and subtropical fruits commercialized worldwide due to its nutritional value, aroma, and pleasant taste [1]. It is present in many tropical and subtropical countries, such as Brazil, the 3rd largest fruit producer in the world [2] and especially in Asia, which represents 76.39% of the world production [3]. Source of fibers, β-carotene and ascorbic acid, the fruits are super versatile and used for the development of many products, such as pulps, juices, jellies, nectar, pickles, mango powder, and salads [4].

The use of heat is still very frequent for fruit pulp processing; however, it is known that high temperatures contribute to the reduction of nutritional value and sensory quality [5] and for this reason, an alternative that is being studied is the use of non-thermal technologies or reduced use of heating to minimize the negative effects.

One of these technologies is High-Pressure Process (HPP), initially studied in 1889 by Hite [6]. However, after a century, thermal processing still dominates the market [7] since HPP alone presents limitations in the sterilization of food, (low spore inactivation under process conditions commonly used at the industrial level) [8]. Therefore, the use of high-pressure process combined with temperature appeared in an attempt to fill this gap and to offer products that are microbiologically safe, nutritious, and sensorially attractive.

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With the development of new processes, it is necessary to assess the changes in the technological properties of these fruit-based products after processing, for example, changes in viscosity evaluated through rheological analysis. Rheology comprises the study of material deformation and it is an analysis that must be performed for the development and dimensioning of industrial processes, as well as to evaluate the impact of these processes on the sensory characteristics of the product. High-pressure process can change the rheological characteristics of fruit and vegetable products, such as mango puree [4], mango pulp [9], mango nectar [10], murtilla berries [11], and aloe vera juice [12]. The treatment can also cause long-term changes in flavor and color [13]. However, the effect of high-pressure process combined with temperature in comparison to a conventional thermal process on the rheological properties of mango pulp is still scarce in the literature.

Based on the above, the aim of this work was to evaluate two equivalent processes for 5D reduction (HPP+T and TP) of *Alicyclobacillus acidoterrestris* spores, a target bacterium in acidic fruits [14] through the rheological properties of mango pulp, once as a fluid product, the rheological characteristics of mango pulp are extremely important for the processing industry.

2. Material and methods

2.1 *Mango pulp*

Mangos Palmer (*Magnifica indica* L.) was collected in local commerce in the city of Campinas, São Paulo/Brazil. The mangos were washed with clean water to eliminate impurities and dirt, and immersed in a chlorinated solution (200 mg L^{-1}) for 20 min at 5 °C [15]. After sanitization, the mangoes were manually peeled, cut (the seed was discarded), and subjected to stirring (using a home blender-model B1000, Britânia, Brazil-1200 W at low velocity for 8 min). The mango pulp (°Brix: 12.8 ± 0.8 and pH: 4.1 ± 0.04) was stored at -18 °C until used. The term "*in natura*" was used to describe the mango pulp not subjected to thermal or HHP+T treatments.

The physicochemical characterization of the mango pulp was performed by determining the pH value (Mettler-Toledo GmbH, Schwerzenbach, Switzerland) and soluble solids content in °Brix (r2i300 Automatic refractometer-Reichert Technologies, NY, USA).

2.2 *High-pressure process*

Experiments were conducted on a pilot-scale high-pressure equipment (QFP-2L-700, Avure Technologies, OH, USA). The equipment reaches a maximum pressure of 690 MPa, a maximum temperature of 90 °C and 2 L of capacity. The machine is equipped with two thermocouples (type K) placed in the top and bottom of the pressure vessel, responsible for controlling the temperature during the process. The process chosen (600 MPa/90 °C/6.3 min) was a condition capable of promoting 5 decimal reductions (5D) in the *Alicyclobacillus acidoterrestris* spores count [14]. The chamber temperature and initial water temperature were adjusted to the process conditions, taking into account the rate of temperature increase (3 °C/100 MPa) under adiabatic conditions predicted for the equipment. The measured temperature in the chamber was 89.26 °C ± 0.82 and the come up time (min) was 2.09 ± 0.07. The samples were packaged in bags (LDPE-nylon-LDPE, Brazil) and submitted to process. A control (*in natura*) sample was not submitted to any pressurization or heating. At the end of the process, there was an instantaneous depressurization (< 1 second). After treatment, samples were stored at 20 °C.

2.3 *Thermal process*

Mango pulp (200 mL) was packaged and sealed in heat-resistant plastic packaging (LDPE-nylon-LDPE, Brazil). The beginning of the experiment was the immediate moment after immersing the sample in an ultra-thermostatic bath with water at 95 °C and mechanical agitation (Cole Parmer Instrument, Co. Chicago, IL, USA). A calibrated T-type thermocouples connected to a data logger (Testo 176 T2, ComSoft Basics, Brazil) was inserted at the cold spot of the package to measure the sample temperature, and to determine the come up time and the thermal history of the process [15]. After reaching the proposed processing time (10.5 min at 95 °C), the samples were removed and placed in a cold-water bath until reaching 30 °C, the temperature continued to be recorded during the cooling period. This process was based on a 5D reduction process of *Alicyclobacillus acidoterrestris* spores, a target microorganism in mango pulp [14]. After treatment, the samples were stored at 20 °C.

2.4 *Rheological analysis*

The rheological analysis was performed using a controlled voltage rheometer (AR2000ex, TA Instruments, USA), using a stainless steel plate geometry with 40 mm of diameter. A Peltier system was used to maintain the temperature of the sample at 25 °C. For *in natura* samples (without any process), the analysis was performed only on day 1 for the reason that after 5 and 10 days of storage at 20 °C, these samples were plenty deteriorated and would not be a reliable comparison, in addition to being unfit for consumption human.

2.4.1 *Dynamic rheological assay*

This test is a non-destructive analysis that maintains the integrity of the sample, allowing the evaluation of interactions between the food constituents. To perform this test, it was necessary to determine the Linear Viscoelasticity Zone (LVZ). For this, an oscillatory stress sweep was performed between 0.01 to 10 Pa at a fixed frequency of 1 Hz, to determine the linear viscoelastic range [16]. The frequency sweep under fixed shear stress was obtained in the LVZ test (1 Pa) and through it, the viscoelastic parameters G' and G" were obtained and modeled using the Power Law (Equations 1 and 2).

$$G' = K' \cdot \omega^{n'} \tag{1}$$

$$G'' = K'' \cdot \omega^{n''} \tag{2}$$

Where G' is the storage modulus; G'' is the loss modulus; ω is the oscillatory frequency; n' and n'' are behavior index in the power law model of viscoelasticity properties; K' and K'' are consistency coefficients in power law model of viscoelasticity properties.

2.4.2 *Steady-state test*

2.4.2.1 *Thixotropy and flow curves*

The samples were placed in a tension-controlled rheometer (AR2000ex, TA Instruments, USA) with a steel plate geometry (40 mm of diameter). The gap (1000 μm) was determined by the procedure described by Tonon et al. [17]. The samples were kept at rest for 5 min before the analysis started and the temperature was kept constant at 25 °C using a Peltier system. After this time, the sample was subjected to a constant shear rate (300 s^{-1}), while the shear stress was measured to assess the time dependence for 15 min (thixotropy). Thixotropy was modeled using the Figoni and Shoemaker model (Eq. 3).

$$\sigma = \sigma_e + (\sigma_i - \sigma_e) \cdot \exp(-K_{FS} \cdot t) \tag{3}$$

The samples were also evaluated in relation to the steady-state flow behavior, using flow ramps corresponding to the shear rate of 0.1 to 300 s^{-1}. The Herschel-Bulkley model (Eq. 4) was the one used to assess the steady-state flow behavior.

$$\sigma = \sigma_0 + K \cdot \dot{\gamma}^n \tag{4}$$

Where σ is the shear stress (Pa); σ_0 is the yield stress (Pa); K is the consistency coefficient; $\dot{\gamma}$ is the shear rate [s^{-1}], and n is the behavior index.

2.5 *Statistical analysis*

All the experiments were conducted in duplicate of process and triplicate of analysis. The rheological parameters of the models were obtained by non-linear regression using the CurveExpert Professional v.1.2.3 software, with a significant probability level of 95%. For comparative evaluation between samples, Tukey test with 95% confidence level was performed using the XLSTAT software (version 2015.2.02, Microsoft, Inc., USA).

3. Results and discussion

3.1 *Study of the gap and linear viscoelasticity zone*

For the proper conduction of studies on rheological analysis, it is essential that the rheometer is adequately adapted to the conditions of the samples to avoid reading errors. One of these important conditions is the adequate gap (µm).

Generally, larger gaps are indicated for samples that contain large particles in suspension, however, larger gaps can cause precipitation and consequently slide the sample through phase separation and part of the sample constituents can decant [18, 19] since plant products are complex dispersions composed of two phases: the pulp (dispersed phase) and the serum (dispersing phase) [20].

Figure 1 shows the shear rate (s^{-1}) versus shear stress (Pa), measurements were performed to observe the flow curves to choose the gap. The chosen gap was that in which the curves overlapped in the tests. The 1,000 µm and 1,500 µm gaps overlapped, indicating that there were no major differences between them and, therefore, the one that used the least sample volume was chosen. Thus, as shown in Figure 1, both gap's 1,000 and 1,500 µm were suitable for the studied mango pulp.

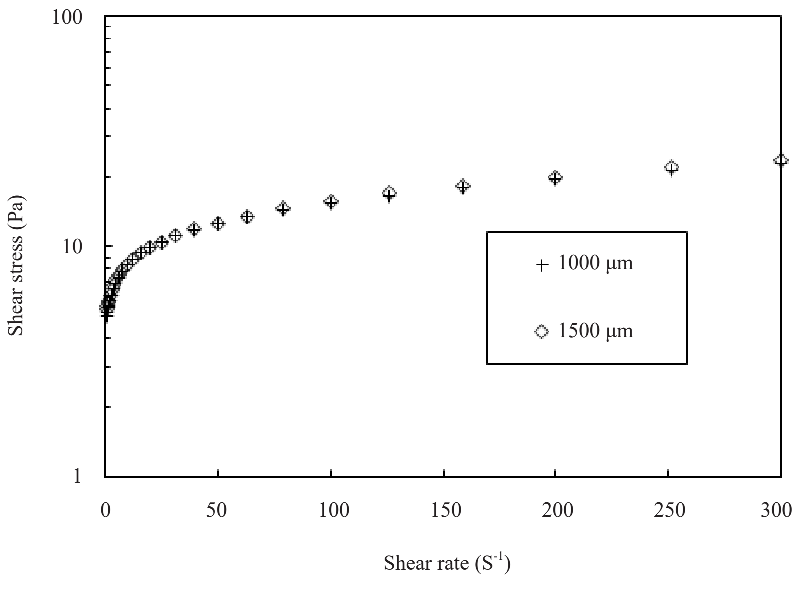

Figure 1. Shear stress (Pa) x shear rate (s^{-1}): determination (µm) of the gap better suited for the mango pulp characteristics

Figure 2 shows G' (Pa) versus oscillation stress (Pa). Through this curve, the linearity zone (represented in red) was determined and as shown in Figure 2, values between 0.01 and 1 Pa were adequate for the sample characteristics and for the test conduction; thus, the chosen value was 1 Pa. Dynamic tests during manufacture and storage can be useful in product quality control. In addition, dynamic rheological tests in the linear region of viscoelasticity also provide fundamental information about the three-dimensional structure that may be present in fruit pulp and jams, such as the pectin network in the pulp-sucrose-acid system [21].

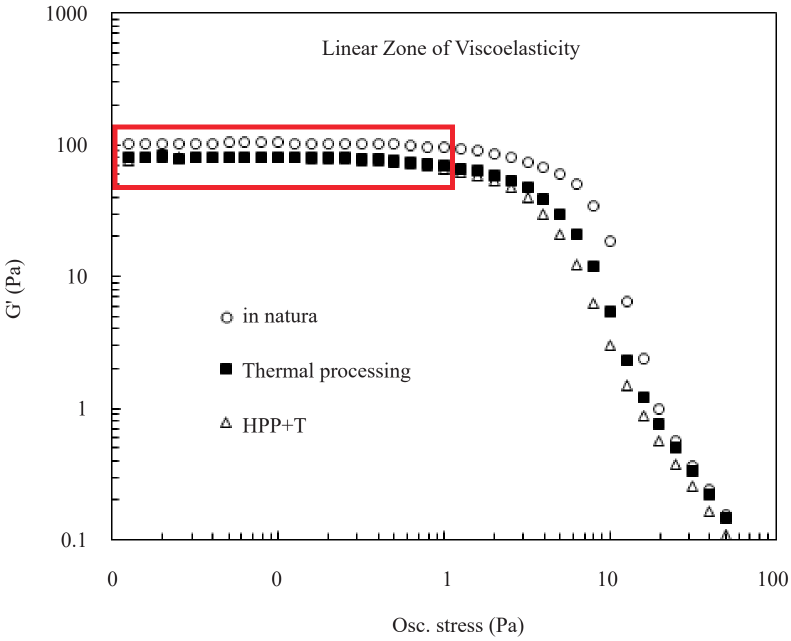

Figure 2. G' (storage modulus) versus oscillation stress: determination of the linear zone of viscoelasticity in mango pulp *in natura*, submitted to thermal processing, and submitted to HPP+T

3.2 *Thixotropy*

The study of thixotropy is important once it is a rheological parameter that can be correlated with the structure of the material/sample under test. Analyzing the characteristic of the curves (shear stress x time) it is possible to predict the effect of some process on the sample, as well as its own characteristic.

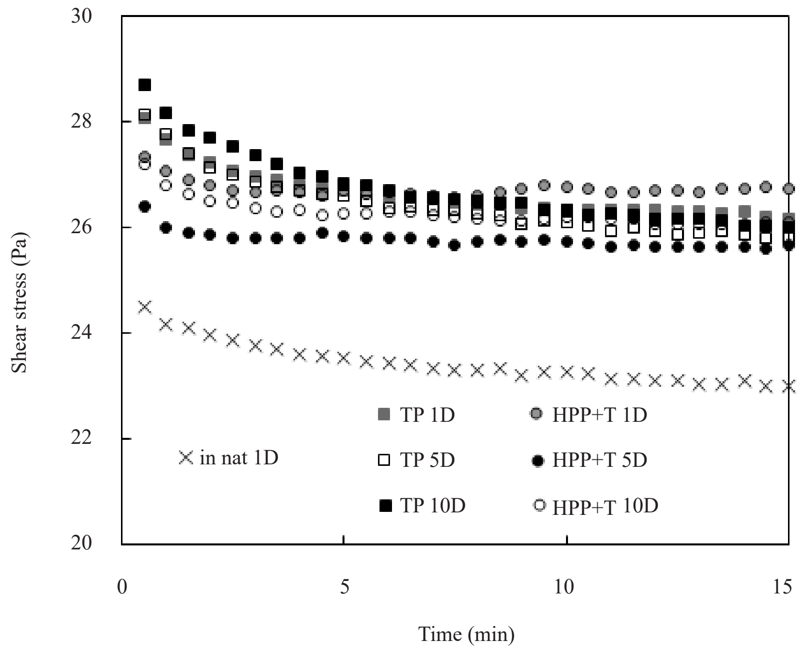

Figure 3. Thixotropy of mango pulp *in natura*, submitted to thermal processing, and submitted to HPP+T after 1, 5, and 10 days of storage

The mango pulp exhibited thixotropy at all evaluated storage times (1, 5, and 10 days) (Figure 3), this behavior can be seen with the reduction of the shear stress (Pa) over time. This appears to be a common behavior in different fruit-based products, as already reported for tomato juice [22], concentrated orange juice [23], mango juice [24], açaí pulp [17] and as well for mango pulp in this study.

From Figure 3, it is clearly noticeable that the TP and HPP+T processes caused an increase in the value of shear stress (Pa) in the mango. Compared to the *in natura* sample, it is also noticeable that the HPP+T process (600 MPa/90 °C/6.3 min) and the thermal processing (95 °C/10.5 min) affected the thixotropy at all evaluated storage times. Table 1 shows the effect of HPP+T and TP compared to the *in natura* sample on the parameters of the Figoni and Shoemaker model. Through these parameters, the thixotropy of the samples was modeled.

The thixotropic behavior is related to the structural changes caused by shear [25], and for a better understanding of the changes that can occur during the process, a time-dependent rheological characterization is necessary [23]. In the Figoni and Shoemaker model, σ_e represents the equilibrium shear stress, that is, its value after sufficient shear time to complete the breakdown of the product's internal structure. The parameter σ_i represents the initial shear stress, and K_{FS} is related to its stress decay during the time [26].

As shown in Table 1, by the parameters of the Figoni and Shoemaker model, samples TP and HPP+T significantly altered the shear stress compared to the *in natura* samples. However, between the processed samples at 1, 5, and 10 days no difference was observed. Similar behavior occurred for the initial shear stress ($p > 0.05$) over 10 days. For the K_{FS} parameter, the processes did not show a significant difference between the samples at 1 and 5 days, only on day 10 the sample processed by HPP+T was statistically different from the others. No considerable tend was observed for this parameter, which appears to be a common characteristic for K_{FS} in the Figoni and Shoemaker model. Similar results were found by Leite et al. [23]. Over storage time and in the same process, the TP and HPP+T samples showed similar behavior, with the only exception for HPP+T at 10 days. This shows that after the initial change, the samples remained stable during the 10 days of storage.

Table 1. Values for the parameters of Figoni and Shoemaker model for mango pulp submitted to thermal processing (95 °C/ 10.5 min) and HPP+T (600 MPa/ 90 °C/ 6.3 min)

$$\sigma = \sigma_e + (\sigma_i - \sigma_e) \cdot \exp(-K_{FS} \cdot t)$$

Treatment	Day	σ_e (Pa)	σ_i (Pa)	K_{FS} (s $^{-1}$)
in natura	1	$22.97^{a} \pm 0.25$	$24.61^{a} \pm 0.34$	$0.21^{a} \pm 0.04$
Thermal Processing	1	$26.07^{Ab} \pm 0.07$	$28.61^{Ab} \pm 0.34$	$0.45^{Aa} \pm 0.35$
	5	$25.71^{Aa} \pm 0.74$	$28.21^{Aa} \pm 0.74$	$0.24^{Aa} \pm 0.03$
	10	$26.01^{Aa} \pm 0.24$	$28.85^{Aa} \pm 0.57$	$0.25^{Aa} \pm 0.07$
HPP+T	1	$26.44^{Ab} \pm 0.42$	$27.43^{Ab} \pm 1.05$	$0.87^{Aa} \pm 0.66$
	5	$25.72^{Aa} \pm 0.42$	$26.77^{Aa} \pm 0.34$	$1.03^{Aa} \pm 1.00$
	10	$26.14^{Aa} \pm 0.54$	$27.45^{Ab} \pm 0.61$	$0.59^{Ab} \pm 0.12$

Different lowercase letters in the same column represent different processes (for the same days), being significantly different at $p < 0.05$
Different uppercase letters in the same column represent the same processes (1, 5 and 10 days), being significantly different at $p < 0.05$

The parameter σ_e relates to the mango pulp consistency; therefore, it is possible to conclude that both processes (HPP+T and TP), significantly increased ($p < 0.05$) the consistency of the pulp compared to the *in natura* pulp without treatment, and positively maintained this behavior during storage time. We can also conclude that this characteristic is advantageous since it is expected that during a certain product processing in the industrial production line, the mango pulp remains stable, without the need for major changes during processing.

3.3 *Analysis of viscoelasticity*

Within the linear region of viscoelasticity, the frequency dispersions of the storage modulus (G') and loss modulus (G") of the *in natura* mango pulp (without treatment), TP (thermally processed), and HPP+T (high-pressure process with temperature) exhibited similar behavior.

Figure 4 shows G' and G" of *in natura* mango pulp on day 1, and it can be seen that the mango pulp had a weak gel characteristic (G' > G"). Both processes (TP and HPP+T) reduced the storage (G') and loss (G") modules on day 1 and maintained their behavior until day 10 of storage (Figure 5). The slope value of the curve when different is indicative of the different nature of the sample linkage [21], however, as the samples came from the same mango pulp batch, different slopes were not observed.

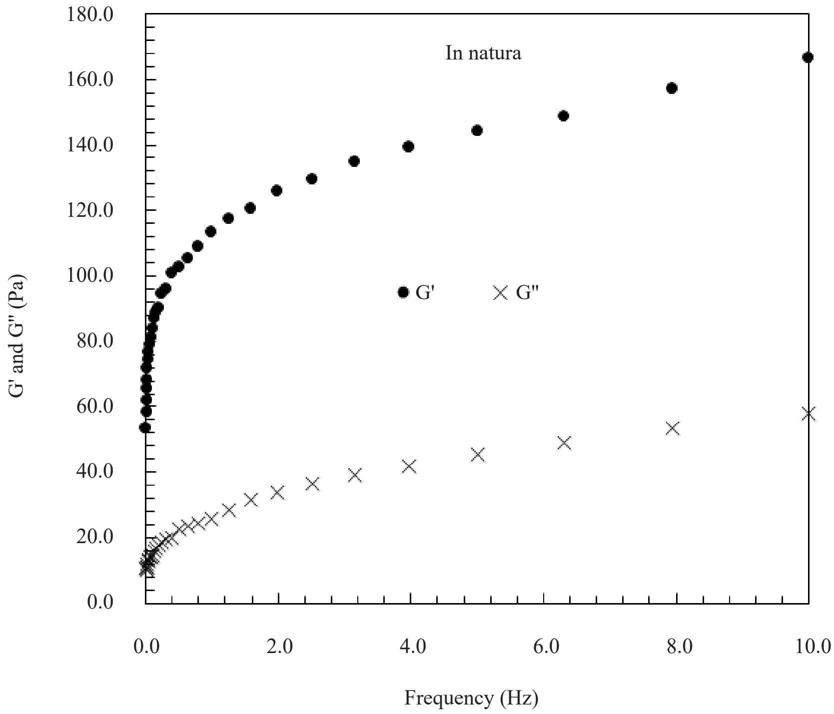

Figure 4. Storage modulus (G') and loss modulus (G") of *in natura* mango pulp on day 1

Based on the frequency sweep tests, it can be concluded that the mango pulp in all evaluated processes presented weak gel characteristic since G' was always greater than G" [24, 27]. That is, the elastic component (G') of the mango pulp predominated over the viscous component (G") for the *in natura* samples, as for the TP and HPP+T. The storage modulus is the elastic component of a gel and the loss modulus is the viscous component apparent in a gel. The processes (TP and HPP+T) did not result in significant increases in the viscous and elastic behavior of the mango pulp (Table 2).

In another study within *in natura* mango pulp, Ahmed et al. [9] found that after treatment with HPP (200 MPa/30 min), G' and G" increased linearly with angular frequency as for canned mango a steady downward trend was found. Liu et al. [13] reported that treatments at different pressures (300 to 600 MPa/1 to 20 min) showed similar values of G' and G", however, the heat-treated samples (HTST) showed slightly higher G' and G" values than the samples treated with HPP, but there were no significant differences, similarly to what was found in this study.

With these results, it was possible to model the storage and loss modules by the Power Law as a function of the oscillatory frequency (Table 2). R^2 values were always ≥ 97%, showing a good fit and accuracy of the data. Table 2 shows that values of n" were always higher than n', demonstrating that the viscous behavior of the mango pulp became important at high frequencies. The values of k' were always higher than k", and both k' and k" were statistically equal between processes and over time ($p > 0.05$), demonstrating that TP and HPP+T did not significantly affect the viscoelasticity of mango pulp.

Table 2. Values for the Power Law model of the storage modulus (G') and loss modulus (G") of mango pulp as a function of the oscillatory frequency (Hz)

$G' = k' \cdot \omega^{n'}$				
Treatment	Day	k'	n'	R^2
in natura	1	$115.00^{a} \pm 10.06$	$0.15^{ab} \pm 0.01$	0.99
Thermal Processing	1	$107.23^{Aa} \pm 5.15$	$0.13^{Aa} \pm 0.01$	0.97
	5	$109.87^{Aa} \pm 9.90$	$0.15^{Aa} \pm 0.01$	0.97
	10	$115.97^{Aa} \pm 7.85$	$0.14^{Aa} \pm 0.02$	0.99
HPP+T	1	$104.35^{Aa} \pm 12.15$	$0.16^{Ab} \pm 0.01$	0.97
	5	$104.84^{Aa} \pm 3.38$	$0.16^{Aa} \pm 0.01$	0.99
	10	$105.46^{Aa} \pm 10.94$	$0.15^{Aa} \pm 0.01$	0.99

$G'' = k'' \cdot \omega^{n''}$				
Treatment	Day	k''	n''	R^2
in natura	1	$28.51^{a} \pm 2.38$	$0.29^{ab} \pm 0.02$	0.99
Thermal Processing	1	$24.98^{Aa} \pm 1.69$	$0.31^{Aa} \pm 0.01$	0.99
	5	$25.90^{Aa} \pm 2.28$	$0.32^{Aa} \pm 0.00$	0.99
	10	$28.13^{Aa} \pm 1.58$	$0.30^{Aa} \pm 0.00$	0.99
HPP+T	1	$30.52^{Aa} \pm 4.20$	$0.27^{Ab} \pm 0.02$	0.98
	5	$26.33^{Aa} \pm 0.52$	$0.29^{Ab} \pm 0.00$	0.99
	10	$27.89^{Aa} \pm 3.02$	$0.29^{Aa} \pm 0.01$	0.99

Different lowercase letters in the same column represent different processes (for the same days), being significantly different at $p < 0.05$
Different uppercase letters in the same column represent the same processes (1, 5 and 10 days), being significantly different at $p < 0.05$

The reduction of the elastic behavior (solid component) can be correlated with the reduction of initial stress (σ_i, thixotropic behavior) and with the consistency index (k, flow behavior). In addition, the viscous behavior (liquid component) can be correlated with the reduction in the consistency index (k, flow behavior) and in the flow behavior index (n) and, consequently, with the apparent viscosity [20]. The storage and loss modules were then evaluated using the Power Law model, whose parameters are shown in Table 2.

It is important to note that the study of viscoelastic properties is very useful for the design and prediction of product stability, through this information we can better understand the product's behavior during processing, storage, and transportation [28].

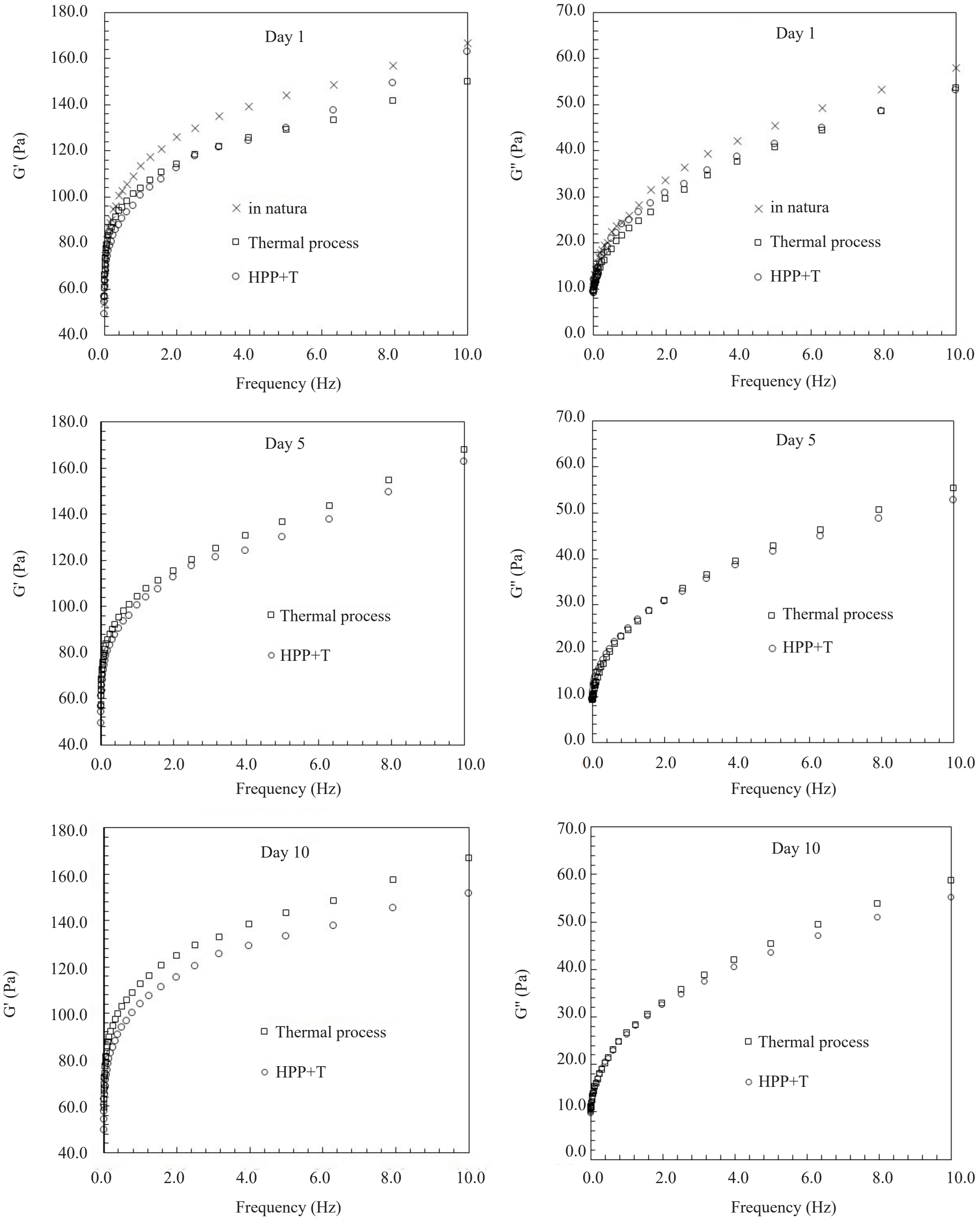

Figure 5. Mechanical spectra of mango pulp over storage time (1, 5, and 10 days): effect of thermal processing and HPP+T on the storage modulus (G') and on the loss modulus (G")

3.4 *Flow curves test*

The flow curves of *in natura* (without treatment) and treated mango pulp (TP and HPP+T) are shown in Figure 6. The data was modeled by the Herschel-Bulkley model (Table 3) and presented an excellent adjustment ($R^2 \geq 0.99$). The mango pulp showed shear thinning behavior ($n < 1$) in all evaluated times and processes (Figure 6). This behavior is common in products based on fruits and vegetables as already reported in the literature for mango juice [29], tomato juice [30], apple juice [31] and aloe vera juice [12].

Table 3. Values for the parameters of Herschel-Bulkley model for mango pulp treated by thermal processing (95 °C/10.5 min) and HPP+T (600 MPa/6.3 min/90 °C)

$$\sigma = \sigma_0 + K \cdot \dot{\gamma}^n$$

Treatment	Day	σ_0	k	n
in natura	1	$1.35^{a} \pm 0.23$	$3.27^{a} \pm 0.01$	$0.32^{a} \pm 0.22$
Thermal Processing	1	$0.95^{aA} \pm 0.07$	$4.79^{bA} \pm 0.00$	$0.30^{bA} \pm 0.07$
	5	$1.16^{aA} \pm 0.66$	$4.15^{aA} \pm 0.02$	$0.31^{aA} \pm 0.47$
	10	$1.18^{aA} \pm 0.34$	$4.05^{aA} \pm 0.33$	$0.33^{aA} \pm 0.01$
HPP+T	1	$0.97^{aA} \pm 0.22$	$4.26^{cA} \pm 0.01$	$0.31^{abAB} \pm 0.22$
	5	$0.90^{aA} \pm 0.08$	$4.29^{aA} \pm 0.00$	$0.29^{aA} \pm 0.17$
	10	$1.40^{aA} \pm 0.14$	$3.74^{aA} \pm 0.26$	$0.31^{aB} \pm 0.01$

Different lowercase letters in the same column represent different processes (for the same days), being significantly different at $p < 0.05$
Different uppercase letters in the same column represent the same processes (1, 5 and 10 days), being significantly different at $p < 0.05$

The mango pulp had a pseudoplastic character with relevant residual tension and the data was modeled using the Herschel-Bulkley model. The yield stress is the minimum shear stress required to initiate product flow and can be related to the material's internal structure which must be broken [32, 33]. The presence of yield stress is a typical characteristic of multiphase materials, i.e., the mango pulp used in this study, which is formed by a dispersion of insoluble components (materials of cellular walls) in a water solution (serum, containing sugars, minerals, proteins, and soluble polysaccharides) [34].

The processes caused an increase in the consistency index (k) of the mango pulp on day 1 compared to the *in natura* sample (Table 3). After 5 and 10 days, no significant difference was observed, which can be positive, since HPP+T maintained the stability over the storage time without change of its characteristics in this period. According to Ribeiro & Cristianini [14] applying the same process to mango pulp, there was an increase in consistency (k value was not calculated, it was a visual difference) considerable at the end of 10 days of processing, but in this study, the increase was verified only on day 1 ($p < 0.05$). Several factors can contribute to this hypothesis, such as the variations in the mango pulp itself, level of maturation and concentration of starch, sugar (reducing and non-reducing) and amylase activity [35, 36] furthermore small processing variations (not noticeable) can also be influenced.

The residual stress (σ_0) in the Herschel-Buckley model (Table 3), showed no significant difference regardless of the process and storage time evaluated. This behavior may be related to the fact that viscoelasticity (k' and k") also did not show significant differences (Table 2). Several other fruit and fruit products derived from pulp fruit and vegetables such as murtila berries [11], gabiroba jam [37], aloe vera [12], peach juice [38], as well as mango pulp products [39] have already been reported in the literature as being pseudoplastic fluids with residual tension. Residual stress is an important rheological parameter that can be used to assess the force required for fluid to come out of the package or make it difficult to settle suspended particles [40] and because dynamic analysis are performed without sample flow, the residual stress results corroborate the viscoelasticity results.

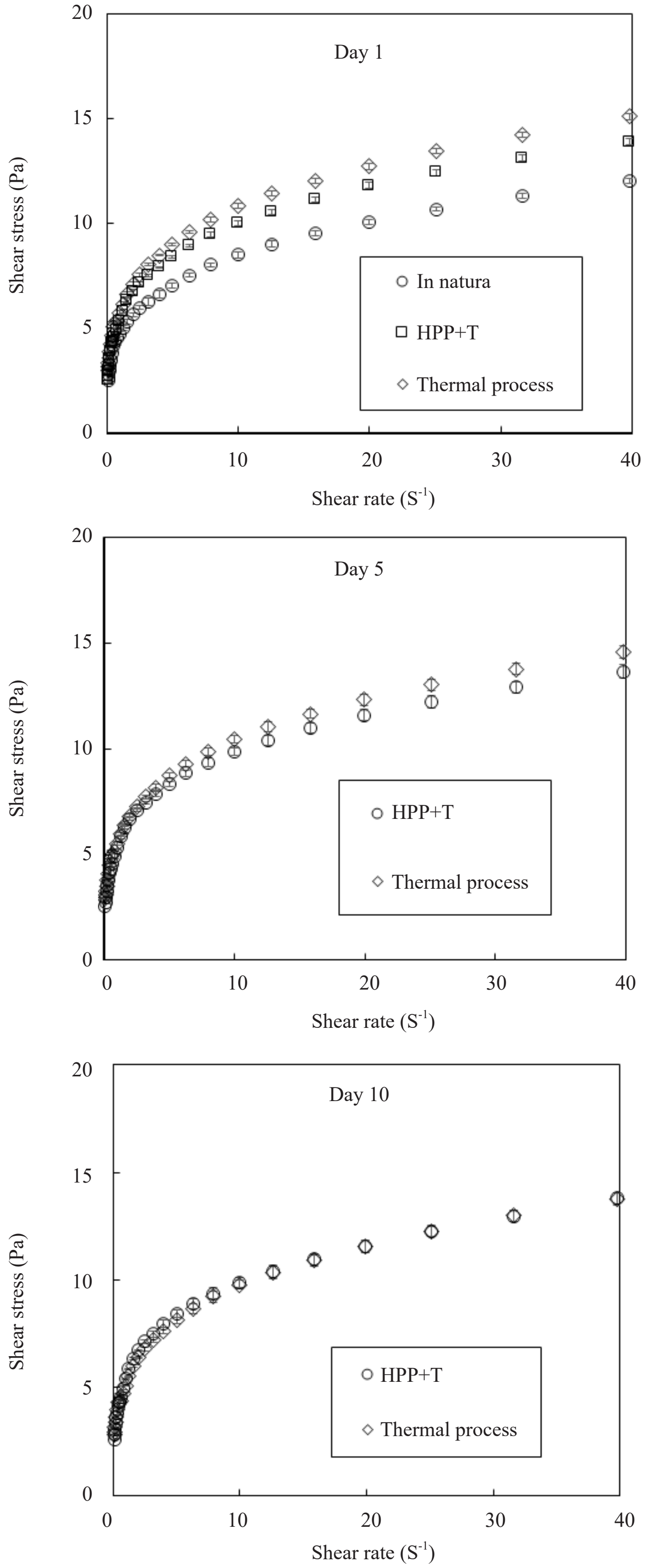

Figure 6. Flow curves of mango pulp treated by thermal processing (95 °C/10.5 min) and HPP+T (600 MPa/6.3 min/90 °C) after 1, 5, and 10 days of storage. Mean of three replicates; vertical bars represent the standard deviation for each value

As shown in Table 3, thermal processing and HPP+T did not affect ($p > 0.05$) the shear stress (σ_0) compared to the *in natura* sample at all evaluated storage times. For the consistency index (k) there was a significant increase ($p < 0.05$) for HPP+T and TP samples on day 1 compared to *in natura* sample. Over storage time (5 and 10 days), the increase of k for the processed samples maintained their behavior without significant difference. The increase in the consistency index (k) may be related to the presence of high molecular weight carbohydrates, such as sugar and starch. In addition, there are other factors that can affect k such as the maximum conversion of sugar and starch, enzymatic inactivation, and heat treatment temperature [9].

Another factor that may be related to the consistency increase is the disruption of cellular structures (by heat treatment and/or HPP+T), releasing more components to the serum phase of the pulp, which consequently causes an increase in the intermolecular interaction and in the interaction between the serum phase and the dispersed phase. Cell disruption and subsequent fragmentation not only increase the surface area of the suspended particles but can also alter the properties of the particles and the serum [28]. In addition, with cell fragmentation, the release of constituents from the cell wall such as pectin and protein can occur, improving particle-particle interactions and resulting in aggregates [22], this is a strong indication to explain the consistency increase (Table 3).

In Table 3, it can also be observed that the flow behavior index (n) for the TP sample was significantly different from the *in natura* sample on day 1, there was a reduction from 0.32 to 0.30, indicating an increase in the pseudoplasticity. As for the sample HPP+T, the increase in pseudoplasticity did not differ significantly from the *in natura* sample, which may be related to the fact that this sample was submitted to milder conditions of time and temperature (600 MPa/90 °C/6.3 min) when compared to the sample submitted to conventional thermal treatment (95 °C/10.5 min). Similar results were observed by Ahmed et al. [9] in mango pulp processed at up to 400 MPa/ 30 min, with a reduction in the flow behavior index (n) from 0.34 to 0.25, and an increase in pseudoplasticity.

It is also worth mentioning that HPP+T improves other aspects such as color, water holding capacity and turbidity [14], besides that the reduction of time and temperature lead to less thermal degradation in food constituents [5]. The results corroborate with the use of HPP+T technology, in addition to using lower time and temperature, it can also increase the consistency of the mango pulp and bring less energy cost to the industry.

4. Conclusion

In this research, the comparative effect of HPP+T and TP was studied on the rheological properties of mango pulp. This kind of comparison is important since the direct evaluation was made under a considerate safe process condition (minimum 5D reduction of a target microorganism) that can be useful for industry. In all evaluated processes the samples had shown a thixotropic characteristics. Observing the frequency sweep tests, the elastic component (G') showed to be always greater than the viscous component (G"), demonstrating a weak gel behavior. In addition, the mango pulp showed shear thinning behavior ($n < 1$), in all evaluated times and processes. HPP+T can be a promising technology in the processing of mango pulp using reduced time and temperature in the process. In addition, a reduction in the time-temperature binomial can lead to a reduction in energy costs for industry, which is extremely important nowadays (environment and economy).

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Conflict of interest

The authors declare no conflicts of interest.

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