Effect of high hydrostatic pressure on rheological and thermophysical properties of murtilla (*Ugni molinae* Turcz) berries

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Abstract Effects of high hydrostatic pressure (HHP) on rheological and thermophysical properties of murtilla berries were evaluated after pressure treatments for 5 min between 100 and 500 MPa. Differential scanning calorimetry was employed to measure specific heat capacity. HHP caused a significant decrease in specific heat and density, while thermal diffusivity did not change significantly. Thermal conductivity showed a slight increase upon HHP treatment. Apparent viscosity increased significantly above 200 MPa HHP treatment. Apparent viscosity of treated samples between 200 and 400 MPa did not differ significantly and the increase was significant at 500 MPa. Herschel–Bulkley, Bingham and Ostwald de Waele models were used to describe the rheological behaviour of murtilla purée, and Ostwald de Waele model gave the best fit for the experimental data.

Keywords Murtilla berry · High hydrostatic pressure · Thermal properties · Viscosity

Introduction

High pressure technology has been used to inactivate pathogenic microorganisms and produce novel food of high quality (Hurtado et al. 2000). Value-added, pressure

pasteurised foods are commercially available and the pressure-assisted thermal sterilisation process has been approved by Food and Drug Administration, FDA (2000) for production of low acid foods. HHP processing has many advantages. Its effect is independent on shape or size of sample. The natural quality of the processed product is maintained, since covalent bonds are not affected and alien flavour development is thus avoided (Ramaswamy et al. 2007).

Murtilla (*Ugni molinae* T.) berries, also known as murta or Chilean guava, are the fruits of a wild-growing native plant of southern Chile. It belongs to the Myrtaceae family and is found mainly in woodland edges of the coastal mountains of the Andes (Taboada et al. 2010). This plant is a perennial shrub that historically has been appreciated for the pleasant flavour of its edible fruits. Its potential in food manufacturing has seized the attention of Chilean farmers, who have cultivated new developed varieties of this plant on a large scale. At present, murtilla berries are industrially used for juices, nectars, ice creams, jam, jellies, tea and liquor. Furthermore, its beneficial effects on human health have been demonstrated (Speisky et al. 2008).

Murtilla berry purée is used as a basic raw material for many functional food products. Therefore the use of high hydrostatic pressure (HHP) processing to maintain the original quality characteristics of the berries is a promising technology. Processing of murtilla involves various unit operations, such as pumping, blending, mixing or separation processes. For such industrial processes to be technically and economically feasible, knowledge of thermophysical and rheological properties is required. Among these characteristics, rheological behaviour is very useful as a quality criterion, as well as for design, evaluation and operation of process equipment (Haminiuk et al. 2006; Fisher and Windhab 2010).

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Due to the importance of rheological characterisation and modelling of food formulations, the number of scientific studies published on this matter has significantly increased in the last decades (Haminiuk et al. 2006; Kechiniski et al. 2011). Focusing exclusively on the rheology of fruit pulps and purées, the great majority of the studies reported pseudoplastic behaviour, frequently combined with the occurrence of a yield stress and/or time dependent effects. Rheological properties of foods are strongly influenced by temperature, concentration, physical stage of dispersion, time as well as processing methods (Ahmed et al. 2007). The complex rheology of food products is a consequence of their biphasic nature, with non-Newtonian features being related to structural changes induced by shear (Tabilo-Munizaga and Barbosa-Cánovas 2005).

Regarding characterisation and modelling of the rheological behaviour of different fruit pulps and purées, some important studies can be mentioned. Ditchfield et al. (2004) determined the rheological behaviour of banana purée at temperatures from 30 to 120 °C using a dynamic stress rheometer, reporting that the Herschel–Bulkley model was the best fit for the experimental data at all temperatures. Sato and Cunha (2009), studying the rheology of jaboticaba or Brazilian grape under dynamic and steady state shear at different temperatures (5–85 °C), also identified the Herschel–Bulkley model as the one providing the best fit for their experimental data. Maceiras et al. (2007) studied the rheological behaviour of different fresh and cooked fruits (raspberry, strawberry, peach and prune) at temperatures ranging from 20 at 40 °C and reported that both Ostwald–de Waele and Herschel–Bulkley models provided a good fit of the experimental data. Therefore, the main objective of this study was to find out whether high hydrostatic pressure (HHP) processing causes any change in thermophysical and rheological properties of murtilla berry purée that should be further processed.

Materials and methods

Berries samples

Murtilla berries were purchased in the city of Valdivia, Chile, from merchants who sell the berries plucked from neighbouring coastal forests in the localities of Punucapa and Curiñanco. Fruits were selected to provide a homogeneous group, based on their colour, size and freshness according to visual analysis. They were kept at 4.5 ± 0.2 °C and relative humidity of 92.3 ± 0.4 % in a refrigerator (Samsung SR-34RMB, Seoul, South Korea). Before pressurising treatments, the fruit were triturated and homogenized using an electric blender (Phillips HR1720,

Amsterdam, Netherlands). The murtilla purée samples were then packed in 100 mL portion in polyethylene flexible pouches, and kept under chilling conditions at 4.5 ± 0.2 °C in a refrigerator (Samsung SR-34RMB, Seoul, South Korea) until high pressure processing. A proximal analysis was carried out on the fresh murtilla purée. Moisture content (gravimetric method), crude protein (Kjeldahl method), lipid (Soxhlet extraction), crude fibre (acid/alkaline hydrolysis), crude ash (incineration at 550 °C), as well as acidity (titration), pH (potentiometer), and soluble solids content (refractometer) were determined in triplicate according to AOAC (1990) methods, and expressed in g/100 g fresh product.

High pressure treatment (HHP)

Packaged samples of murtilla purée were pressurised at ambient temperature (15 ± 1 °C) in a 2 L processing unit (Avure Technologies Incorporated, Kent, WA, USA) at 100, 200, 300, 400 and 500 MPa for 5 min. Water was employed as the pressure-transmitting medium, and a ramp rate of 17 MPa/s was implemented; the decompression time was less than 5 s. After HHP-treatment samples were stored refrigerated (4.5 ± 0.2 °C) until further rheological and thermophysical characterization. All experiments were performed in triplicate.

Thermophysical measurements

Density

The density (ρ , kg/m³) of murtilla purée was determined in triplicate using a 50 mL pycnometer (Labor- und Messgeräte GmbH, Stützerbach, Germany) with volume calibrated at 20 °C. The purée sample was carefully introduced inside the pycnometer to about two-thirds of the whole volume and sample mass was then obtained by weight difference. Volume of purée sample was obtained by difference after filling the pycnometer with distilled water equilibrated at 20.00 ± 0.02 °C in a thermostatic bath (Haake DC10, Thermo Electron, Karlsruhe, Germany).

Specific heat

The specific heat (C_p , J/g °C) of pressure treated murtilla purée sample was determined by using a differential scanning calorimeter (DSC) (Model DSC823e, Mettler-Toledo, Schwerzenbach, Switzerland) equipped with DSC sensor HSS7. The instrument was calibrated with indium standard. A purée sample between 20–40 mg was weighed in a Mettler-Toledo DSC pan (ME-00026763), and hermetically sealed. An empty pan was used as reference (air). The sample was first cooled from room temperature to

10 °C at 5 K/min, and then scanned from 10 to 80 °C at a rate of 10 K/min to determine an average C_p value within the scanned temperature range using STARe software 9.01 (Mettler Toledo, Schwerzenbach, Switzerland).

Thermal diffusivity and conductivity

Thermal diffusivity (α , m²/s) was determined by a transient heat transfer method (Zanoelo et al. 2011). An infinite copper cylinder (32 mm interior diameter by 350 mm height and 0.7 mm thickness) filled with the murtilla purée was heated in a constant temperature water bath (JEIO Tech, Seoul, South Korea). Temperature in the geometric centre as well as on the surface of the copper cylinder was monitored using a 12-channel data logger (Scanning Thermocouple Thermometer DigiSense 92800-15, Cole-Parmer, USA) and T-type thermocouples (± 0.5 °C). Thermal diffusivity was calculated using Fourier equation under established conditions and solved by the variables separation method to obtain Eq. (1).

$$\frac{\Delta T}{\Delta T_o} = 1.6e^{-5.78Fo} - 1.06e^{-30.47Fo} + 0.85e^{-74.9Fo} - 0.73e^{-139Fo} + \dots \quad (1)$$

where Fo is Fourier number ($\alpha t/r^2$), ΔT_o and ΔT are temperature differences between geometric centre and surface of copper cylinder at time zero and time t respectively. For $Fo > 0.1$ only the first term of Eq. (1) is of relevant magnitude and the equation may be transformed to a linear function (Eq. 2) and thermal diffusivity is calculated from the gradient of the straight line obtained.

$$\log_{10}\left(1.6\frac{\Delta T_o}{\Delta T}\right) = \frac{1}{0.398} \frac{\alpha}{r^2} t \quad (2)$$

Thermal conductivity (k , W/m K) was calculated indirectly from the relationship of thermal diffusivity to thermal conductivity, density and specific heat ($\alpha = k/\rho C_p$).

Rheological measurements

The rheological behaviour of the purée sample was determined using a rotational viscometer equipped with disc spindle (Brookfield RVDV-II-Pro, Middleboro, USA). A cylindrical sample chamber with water jacket connected to a circulating temperature bath (Haake DC 10, Thermo Electron GmbH, Karlsruhe, Germany) was used to maintain constant temperature. Direct readout of sample temperature was provided using embedded temperature sensor connected to the RVDV-II-Pro viscometer. Measurements of viscosity and speed were taken at 15 °C, within a range between 15 and 100 % full scale torque of the Brookfield viscometer. Disc spindle R6 was used for the measurements. Shear stress and shear rate

were derived from these measurements, following Mitschka conversion method (Briggs and Steffe 1997). The rheological analysis was carried out, varying the shear rate through change of rotational speed from 1 to 200 rpm in ascending order, maintaining rotational speed constant during 5 min at each particular value. The readings were taken thrice, and for each measurement a new pressure treated sample was used. The average and standard deviation were estimated for all measurements at each temperature studied.

The Ostwald–de Waele (Eq. 3), Herschel–Bulkley (Eq. 4) and Bingham (Eq. 5) models were fitted to the rheological data obtained for control and treated samples of murtilla purée (Steffe 1996). The software SigmaPlot v.11.0 was used for the calculation (in triplicate).

$$\tau = K(\dot{\gamma})^n \quad (3)$$

$$\tau = \tau_o + K(\dot{\gamma})^n \quad (4)$$

$$\tau = \tau_o + \eta_{\infty}(\dot{\gamma}) \quad (5)$$

In Eqs. (3)–(5), τ is shear stress (Pa), τ_o yield stress (Pa); η_{∞} Bingham plastic viscosity (Pa s); $\dot{\gamma}$ shear rate (1/s); n flow behaviour index (dimensionless) and K consistency coefficient (Pa s ^{n}). For a Newtonian fluid, $n = 1$. If $n < 1$, the fluid shows pseudoplastic behaviour; if $n > 1$, the fluid is dilatant.

Statistical analysis

For modelling the rheological behaviour, the goodness of fit between predicted and experimental data was evaluated based on statistical analyses including sum squared error (SSE) (Eq. 6), root mean squared error (RMSE) (Eq. 7) and Chi square (χ^2) (Eq. 8) (Ozbek and Dadali 2007; Lemus-Mondaca et al. 2009). The temperature effect on thermo-physical and rheological parameters was estimated using Statgraphics Plus® 5.1 (Statistical Graphics Corp., Herndon, VA, USA). The results were analysed by an analysis of variance (ANOVA). Differences between the media were analysed using the least significant difference (LSD) test with a significance level of $\alpha = 0.05$ and a confidence interval of 95 % ($p < 0.05$). In addition, the multiple range test (MRT) was used to demonstrate the existence of homogeneous groups.

$$SSE = \frac{1}{N} \sum_{i=1}^N (\phi_{ei} - \phi_{ci})^2 \quad (6)$$

$$RMSE = \left[\frac{1}{N} \sum_{i=1}^N (\phi_{ci} - \phi_{ei})^2 \right]^{1/2} \quad (7)$$

$$\chi^2 = \frac{\sum_{i=1}^N (\phi_{ei} - \phi_{ci})^2}{N - z} \quad (8)$$

where ϕ is a dependent variable; ei is the experimental value, ci the calculated value, N the number of data values, z the number of constants and i the number of terms.

Results and discussion

Effect of HHP on thermophysical properties

Proximate analysis of fresh murtilla purée (treated at 0.1 MPa), presented moisture content of 77.40 ± 1.01 g/100 g, protein of 0.80 ± 0.30 g/100 g, lipids of 0.80 ± 0.10 g/100 g, fibre of 4.27 ± 0.51 g/100 g, ash of 0.63 ± 0.06 g/100 g and carbohydrates of 16.1 ± 0.52 g/100 g (by difference). Furthermore, soluble solids content, pH and titrimetric acidity were of $18.62 \pm 0.15^\circ$ brix, 3.82 ± 0.27 and 1.007 ± 0.141 %, respectively. Variation in the moisture content of the wild murtilla was reported (Scheuermann et al. 2008).

Knowledge of the thermophysical properties is essential for estimating thermal processing time and simulating variations in the temperature field all through the material under thermal treatment during processing or storage periods. In this study density, specific heat and thermal diffusivity of HHP treated murtilla purée has been determined. As shown in Fig. 1, a significant difference ($p < 0.05$) in density of fresh and HHP treated murtilla purées was observed. Surprisingly, HHP treated samples showed a decrease in density. This means that high pressure did not cause any permanent compacting of the solid material of the purée. Presumably the pressure exerted may have caused cell wall damage, leading to a loss of cellular water. After decompression the cells probably resumed its shape and volume and reabsorbed liquid, but did not return to the initial moisture content. Some volume expansion may also have occurred and on the whole a decrease in

density occurred as shown by experimental results. Above 400 MPa, a slight increase in density was observed (Fig. 1), which may be the result of a probable compaction of cell material.

Cellular water loss during HHP treatment may also explain the significant decrease ($p < 0.05$) in specific heat, since the latter is an additive physical property and water contributes greatly to its magnitude. Figure 2 clearly shows the significant difference ($p < 0.05$) in specific heat between fresh and HHP treated murtilla purée. Specific heat of HHP treated murtilla purée decreased as pressure level increased.

Barbosa (2003) reported decrease in specific heat values for 10 % sucrose solution from 3.95 to 3.64 J/g °C at 600 MPa pressure treatment. Bridgman (1912) evaluated the specific heat of 12 organic liquids under pressure and found a complex pressure and temperature dependence of specific heat. C_p at constant pressure decreased in the relatively low pressure range and increased when pressure surpassed a certain threshold limit. Pressure dependency of C_p was attributed to a change in potential of attractive forces between molecules, the association of molecules and partition of different components of internal energy with changing pressure. Therefore, HHP treated purée suffer structural change that may lead to lower water holding capacity and hence to a decrease in C_p as can be observed in Fig. 2.

On the other hand, the measured thermal diffusivity of fresh and HHP treated murtilla purée (Fig. 3) did not show any significant change. Thermal diffusivity being the relationship between thermal conductivity and the product of density by specific heat, showed congruency with the experimental measurements of density and specific heat. Decreasing values of these two latter properties may cause an increase in thermal diffusivity by a constant value of thermal conductivity. Since the measured thermal diffusivity did not significantly change, although slight

Fig. 1 Density of HHP processed murta berry puree

Fig. 2 Specific heat capacity of HHP processed murta berry puree

Fig. 3 Thermal diffusivity of murta berry puree after HHP Processing

increases at higher pressures (300 and 500 MPa) were observed, a relative increase of thermal conductivity probably occurred. This was in accordance with Nguyen et al. (2012) that increasing pressure linearly increased the thermal conductivity in some selected food (tomato purée, soy protein isolate, soybean oil, guacamole, honey, cream cheese, and sucrose solution). Conductivity values from 0.173 W/m K (at 0.1 MPa) to 0.752 W/m K (at 600 MPa) were also reported. Thermal diffusivity values were reported for cheddar cheese by Zhu et al. (2007) in the order of magnitude of $1.2\text{--}1.3 \times 10^{-7} \text{ m}^2/\text{s}$, for pressure treatment between 0.1 and 350 MPa at 25 °C. The authors also reported a positive pressure dependency of thermal diffusivity following a second order polynomial. For the murtilla purées the order of magnitude determined for thermal diffusivity is about 5–8 times higher (Fig. 3).

Increase in thermal conductivity values of foods with increasing pressure (Fig. 4) has also been reported earlier (Denys and Hendrickx 1999; Ramaswamy et al. 2007; Zhu et al. 2008; Werner et al. 2007, 2008). Pressure dependency of thermal conductivity seems to be a function of

Fig. 4 Thermal conductivity of murta berry puree after HHP processing

compressibility of materials (Bridgman 1923; Ross et al. 1984). Under pressure, the intermolecular distance may have decreased, hence reducing the mean free path of the molecules, and resulted in an increase in thermal conductivity. It also appeared that for aqueous solutions, change in thermal conductivity under pressure may be mainly a function of water fraction. Thermal conductivity of 10 % (w/v) sucrose solution and tomato purée (5.04 % solid content) closely followed the thermal conductivity values of water. Similar observations were also made by Werner et al. (2008) who reported that thermal conductivity of sugar solutions was primarily a function of applied pressure and mass fraction. In the case of honey, the main components were glucose (35.7 %), fructose (41.0 %), galactose (3.0 %) and water (17.1 %) (USDA, National Nutrient Data Base). Thus, the k values of honey were less influenced by pressure. Min et al. (2010) reported that honey had lower compressibility values than that of water and 10 % sucrose solutions, and that compressibility decreased with increasing sugar content (2.5–50 %). Shariaty-Niassar et al. (2000) determined thermal conductivity of gelatinized potato starches at 25–80 °C, 50–80 % moisture content and 0.2–10 MPa, and found that the thermal conductivity of the starch gel increased with temperature and moisture content, but only increased with pressure up to 1 MPa, above which it remained almost constant.

Effect of HHP on rheological behaviour

Murtilla purée made from whole berries contained seeds, skin and pulp in a proportion of 1:2:6 with the seeds, skin and pulp having approximate moisture content in the order of $16.5 \pm 0.3 \%$, $60.0 \pm 0.2 \%$ and $82.6 \pm 0.6 \%$ respectively. Taboada et al. (2010) showed that murtilla contained noticeable amount of pectic substances. Therefore, the major factors influencing the rheological properties of murtilla purée were granular structure and the presence of pectic substances. Change in molecular alignment took place within the substance and led to a decrease in viscosity. The experimental shear rate and shear stress for fresh (control) and HHP treated murtilla purée are shown in Fig. 5 in the range of shear rates from 0.97 to 252.54 s^{-1} .

The rheological parameters obtained from the Ostwald–de Waele and Herschel–Bulkley models (σ_0 , K , n) for the different HHP treatments are given in Table 1. The flow behaviour index (n) varied between 0.112 and 0.178, providing evidence of shear thinning (pseudo plastic) properties ($n < 1$). Therefore murtilla purée at 15 °C has a non-Newtonian character similar to gels like xanthan gum (Dolz et al. 2007) or blueberry purées (Kechiniski et al. 2011). This is also characteristic to foods with a high content of particles, as pectic substances or fine particles of

Fig. 5 Effect of HHP processing on rheological behaviour of murtilla berry purée

plant tissue in dispersion. Interactions between these particles will affect the response between the applied strain and contrary effort to flow. Shear thinning behaviour, very common in fruit and vegetable products, occurs as the molecules become less dependent on each other and offer less resistance to flow with increasing shear rate (Barbosa 2003).

Murtilla purée showed low yield stress (σ_o) ranging between 6.31×10^{-12} and 3.47×10^2 Pa in the Herschel–Bulkley model, being significantly higher ($p < 0.05$) in purée treated at 500 MPa. Therefore yield stress may be neglected and the Power Law or Ostwald–de Waele model may then be used. Yield stress is a minimum shear stress that must be achieved before the material starts to flow. Its occurrence in any food samples is attributed to the presence of the large number of particles in dispersion and its determination is important because of its relation to

suspension ability and to property of stabilizing agent in food products (Hibberd et al. 1987). In spite of the low yield stress murtilla purée showed high viscosity at very low shear rate (Fig. 5), which means initial flow difficulty due to large increase of shear stress for small changes in shear rate.

For non-Newtonian pseudoplastic fluids, viscosity decreases with shear rate and is modelled as consistency coefficient (K), which corresponds to the quotient of shear stress to shear rate. A significant increase ($p < 0.05$) in this apparent Newtonian viscosity of the HHP treated murtilla purée is first observed at 200 MPa. However, among samples treated between 200 and 400 MPa no significant differences were observed ($p > 0.05$). Compared with these treatments, apparent viscosity increased significantly at 500 MPa ($p < 0.05$). The increase in the consistency coefficient (K) of the HHP treated samples is probably due to an increase in pectic particle interactions, reported to be promoted by high pressure (Krebbes et al. 2003). Therefore, the increase in apparent viscosity may be the result of formation of larger structures of colloidal dimensions, formed by different associations between molecules and pectic particles. Furthermore, HHP may also have caused a change in the degree of hydration of these molecules and particles, which may lead to an increase in consistency in the HHP treated murtilla purées. HHP also affected the solid-gel transition of polysaccharide forming different gels depending on the level of pressurisation (Mozhaev et al. 1994).

Statistical analyses on rheological models

The method used for evaluation of the fit quality of the experimental data to the models tested employed four important statistics which are widely used in mathematical simulations of food processing (r^2 , SSE , $RMSE$ and χ^2). The rheological data of all examined purées were

Table 1 Parameter of the rheological models at different HHP treatments for murtilla berry purée

Models	Parameters		HHP treatment (MPa)					
			Control (0.1 MPa)	100	200	300	400	500
Ostwald–de Waele	K	Pa s ⁿ	296.27	368.50	277.89	325.93	520.13	301.07
	n	–	0.165	0.143	0.178	0.164	0.117	0.176
Herschel–Bulkley	τ_o	Pa	6.31×10^{-12}	9.09×10^1	1.05×10^{-9}	1.77×10^{-11}	3.47×10^2	3.31×10^{-10}
	K	Pa s ⁿ	303.28	360.89	282.00	330.50	193.80	305.30
	n	–	0.158	0.145	0.173	0.160	0.224	0.172
Bingham plastic	τ_o	Pa	387.00	464.90	363.50	421.40	636.50	393.70
	η_∞	Pa s	1.947	1.933	2.239	2.235	1.848	2.371

Table 2 Statistical parameters of rheological models after different HHP treatments for murta berry purée

Model	Statistical	Control (0.1 MPa)	HHP treatment (MPa)				
			100	200	300	400	500
Ostwald–de Waele	<i>SSE</i>	0.0121	0.0116	0.0043	0.0136	0.0277	0.0127
	<i>RMSE</i>	0.1100	0.1077	0.0658	0.1168	0.1667	0.1130
	χ^2	0.0128	0.0123	0.0046	0.0145	0.0295	0.0135
Herschel–Bulkley	<i>SSE</i>	0.0192	0.0123	0.0066	0.0168	0.0162	0.0182
	<i>RMSE</i>	0.1386	0.1112	0.0816	0.1297	0.1274	0.1352
	χ^2	0.0204	0.0131	0.0070	0.0178	0.0172	0.0194
Bingham plastic	<i>SSE</i>	0.2705	0.1864	0.2556	0.2403	0.0160	0.3232
	<i>RMSE</i>	0.5201	0.4317	0.5055	0.4902	0.1268	0.5685
	χ^2	0.2874	0.1980	0.2715	0.2553	0.0170	0.3434

adequately described by the Power-Law or Ostwald–de Waele (Eq. 3) and Herschel–Bulkley (Eq. 4) models with high regression coefficients (0.970–0.999). The models, with high values of r^2 (>0.90) and values close to zero for *SSE*, *RMSE* and χ^2 , show the closest fit to experimental data (Table 2). The model for a Bingham plastic was also examined, but proved to be less adequate to fit experimental data (Table 2). Thus, the best fit was obtained using the Ostwald–de Waele model ($SSE < 0.0278$, $RMSE < 0.1667$ and $\chi^2 < 0.0295$), since this model resulted in the lowest values compared with those resulting from Herschel–Bulkley and Bingham models. The results of mathematical modelling of the experimental rheological data made with the Ostwald–de Waele model is presented in Fig. 5.

Conclusions

HHP up to 500 MPa caused a significant change in thermal properties of murtilla purée. HHP treated purées showed a decrease in density and specific heat, but only slight increase in thermal conductivity. Murtilla purée retained non-Newtonian character after HHP treatment and rheological behaviour can be described by the Herschel–Bulkley model. However, yield stress was very low and the Power Law or Ostwald–de Waele model can be used to fit experimental data. HHP caused significant increase in apparent viscosity of murtilla purée after treatment at 500 MPa. The increase in consistency coefficient (*K*) of the HHP treated purées was probably due to an increase in pectic particle interactions and probable decrease in the degree of hydration of these molecules and its consequent increase in size.

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Compliance with ethical standards

Conflict of interest The authors have no conflict of interest to declare.

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