BROMATOLOGICAL COMPOSITION AND EFFECT OF TEMPERATURE ON THE RHEOLOGY OF EGGPLANT PULP

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ABSTRACT

This study aimed to determine the bromatological composition and the behavior of rheological parameters on the pulp eggplant (*Solanum melongena)*. Bromatological analyzes were performed according to the reference methods, in which a percentage of moisture 90.98%, total carbohydrates 6.86%, crude fiber 1.94%, crude protein 1.19%, Fat 0.31% and 0.49% of ash has been obtained. Viscous flow curves were calculated in the steady state over a temperature range of 10-80ºC, and the rheological properties of the pulp were evaluated as a function of temperature. The pulp showed pseudoplastic behavior (shear thinning type) at all temperatures, and the relationship between viscosity and the Carreau-Yasuda model (R^2>0.99). The Arrhenius equation was fitted to the data for the apparent viscosity of the pulp with respect to temperature, with activation energy E_a=1081.61 J/mol. The results provide information on bromatological composition and the rheological behavior of eggplant pulp and may have applications in the design of processes using this raw material.

Keywords: Carreau-Yasuda model, eggplant (*Solanum melongena*), bromatological analysis, pulp, rheological behavior, shear thinning

1. INTRODUCTION

Eggplant or aubergine (*Solanum melongena*) is an economically important crop that is widely cultivated in tropical and subtropical areas of the world, and its cultivars produce a wide variety of fruits with different shapes, sizes and colors (SALUNKHE and DESAI, 1984; SAN JOSÉ *et al.*, 2013; NIÑO-MEDINA *et al.*, 2017). The global consumption of eggplant has increased in recent years, due to the numerous benefits of this crop, such as the presence of metabolites that contribute significantly to a healthy diet (SUN *et al.*, 2015). It has also been found that extracts of eggplant can successfully suppress the development and growth of tumors, metastasis, inflammation and heart disease (NISHA *et al.*, 2009). Eggplant is one of the vegetables on which great importance is placed in the Colombian Caribbean, due to its strong suitability for export, the aforementioned health benefits, its high content of phenols and antioxidant activity, and its contribution to the diet in terms of low calorie content, very low sodium content and high fiber content (ARAMENDIZ-TATIS *et al.*, 2010).

According to Food and Agriculture Organization - FAO (2015) data from 2015, eggplants used for consumption were fresh (more common), or in industrial processes, mainly frozen. In industrial processes, this vegetable can be used as cubes or dice, such as in slices, jams and jellies. The products of fruits and vegetables contain pulps as basic raw materials, which in most cases are transported via pipes and tanks and are agitated and mixed with other raw materials, pasteurized and evaporated in heat exchangers and continuous evaporators. In addition, other operations are applied such as sieving, snubbing, mixing and various thermal treatments. In order for these operations to be technically and economically feasible, it is important to have a knowledge of the properties of the pulp (IBARZ *et al*., 1996; ORTEGA-QUINTANA *et al*., 2015).

The rheological behavior is one of the most important properties in the development of new products, and is very useful in the design of unit operations, guarantees of high-quality food and beverages, and process optimization. In addition, rheological approaches are essential tools for food engineering, since rheology is linked to the processing and stability of food as well as its sensory qualities. Physical properties such as density, specific heat and thermal conductivity are of great importance for food and beverages, as they are closely related to their sensory and rheological characteristics (AUGUSTO *et al.*, 2012; DE CASTILHOS *et al*., 2017).

Several factors affect the rheological behavior of fruit and vegetable pulps, and temperature is the most likely to affect the viscosity of the pulp (HOLDSWORTH, 1971). An understanding of the influence of temperature on viscosity is therefore fundamental in obtaining better knowledge of the rheological behavior of fruit and vegetable derivatives during processing at high temperatures (IBARZ *et al.*, 1996).

Various studies have been carried out on the rheological behavior of pulps from different botanical sources; most of these do not comply with Newton's law of viscosity, and it is said that they behave like non-Newtonian fluids. Their behavior can be described by a power law (HOLDSWORTH, 1971) or by the Herschel-Bulkley model in the case where they have a non-zero yield stress (STEFFE, 1996). The main objective of this research is to determine the effect of temperature on the behavior of the rheological parameters of eggplant pulp.

2. MATERIALS AND METHODS

The eggplants used were acquired from a food supply center in Cartagena, Bolivar-Colombia, and were in a state of commercial maturity and free from mechanical damage.

2.1. Pulp extraction

The selected fruits were weighed, washed and blanched at 80ºC for five minutes. Pulp was obtained using a refining 1.5 mm opening mesh, giving a pulp to facilitate rheological measurements. This was then packed in hermetic bags and stored in refrigeration at 4ºC for 24 hours for further rheological analysis.

2.2. Bromatological evaluation

Bromatological analyses were performed on the eggplant pulp. Moisture content, ash, protein, fat, total carbohydrates and raw fiber were determined using the methods described by the Association of Official Analytical Chemists (AOAC) (2000): moisture: Dehydration in an oven at 105ºC AOAC 33.7.03 Method 926.08; ash: y combustion at 450ºC for 12 hours AOAC 33.7.07 Method 935.42; crude protein: Using the method of Macro Kjeldahl, AOAC 33.7.12 Method 926.123; fat: AOAC 972.28 ethereal extraction method; total carbohydrates: AOAC 923.03; Crude fiber: A.O.A.C. 985.29.

2.4. Rheological evaluation

Steady flow tests were carried out to give viscosity curves at temperatures of 10ºC, 20ºC, 25ºC, 40ºC, 60ºC and 80ºC for samples without a previous history of shear, using a controlled-stress rehometer (Modular Advanced Rheometer System Mars 60, Haake, Thermo-Scientific, Germany), equipped with Peltier temperature control and measuring system, using a stainless steel plate-plate geometry (rough surface Ø 35 mm) with 1 mm gap, over a range of shear rates between 0.001 and 1000 s^{-1} (Franco *et al*., 1998). Prior to measurement, all samples were left at rest for 600 s to allow for relaxation, and the temperature of the samples was kept constant at 20±0.1°C using a Peltier system, following the methodology used by QUINTANA *et al.* (2017).

2.4. Statistical analysis

The data were analyzed with a unidirectional ANOVA using SPSS software (version 17.0 for Windows) in order to determine statistically significant differences ($p < 0.05$) between the samples. All tests were performed in triplicate.

3. RESULTS AND DISCUSSION

3.1. Bromatological analysis

Table 1 shows the average values for moisture, total carbohydrates, total fiber, protein, fat and ash, obtained in triplicate. The results show that the eggplants used in this study mostly contained water at a percentage of 90.98±0.016%, a carbohydrate content of

6.86±0.17% and a fiber content of 1.94±0.07%, fairly close to the values reported by GARCÍA *et al*. (2003), MOREIRAS *et al*. (2013) and ICBF (2015).

Table 1. Bromatological analysis.

Sample (%)	Moisture	Total carbohydrates	Crude fiber	Crude protein	Fat	Ash
Eggplant	90.98±0.16	6.86±0.17	1.94±0.07	1.19 ±0.04	0.31±0.02	0.49±0.02

Eggplant represents an important source of dietary fiber, and therefore has health benefits in terms of its effects on digestive regularity and the prevention of diseases such as constipation, hypercholesterolemia, hyperglycemia and obesity, which are partly related to intake of fiber (ALVES DOS SANTOS *et al*., 2002). Its beneficial physiological effects lie in its texture and consistency, since it acts as a sponge that binds to foods rich in cholesterol, releasing accumulated wastes from the intestinal wall, which would otherwise be difficult to expel. It also increases the fecal mass, which results in a reduction in carcinogenic risk and faster elimination from the body (CAÑAS-ÁNGEL *et al* 2011.)

3.2. Rheological evaluation

The variation of the viscosity with the deformation speed was observed using steady flow tests at different temperatures. Fig. 1 shows the viscous flow curves for the eggplant pulp as a function of the deformation speed, at temperatures of 10°C, 20°C, 25°C, 40°C, 60°C and 80°C. These curves show the characteristics of a non-Newtonian fluid of rheofluidifying (shear thinning) type, since they combine the characteristic properties of elastic and both solid-like and liquid-like properties, characterized by a potential decrease in viscosity with respect to the shear rate (MÜLLER, 1973). On the other hand, a constant viscosity value η_0 and at high deformation η_∞ velocities are observed at low deformation speeds.

This behavior can be explained by the breaking of the reticular structure of polysaccharide molecules during shearing, as explained by BHANDARI *et al.* (2002). In a reticular system, the speed at which existing molecular interactions break becomes higher than the speed at which they reform, with increasing shear rate. The result is a lower intermolecular resistance to the flow, and hence a lower viscosity (DÍAZ-OCAMPO *et al.,* 2012). Similar behaviors have been observed in several fruit pulps, such as squash pulp (*Cucurbita moschata*) (QUINTANA[a] *et al.,* 2018); papaya pulp (*Carica papaya*) (QUINTANA *et al.*, 2017); borojó pulp (*Borojoa patinoi cuatrec*) (DÍAZ-OCAMPO *et al.,* 2012); nispero pulp (*Achras sapota L.*) (ANDRADE *et al.,* 2009) and mango, papaya and peach purees (GUERRERO and ALZAMORA, 1998).

Among the models most often used to describe the rheological behavior of fruit pulps is the Ostwald de Waele power law (TORALLES *et al.,* 2006). Numerous authors have successfully described the flow behavior of various pulps using this model, for example, peach pulp (MUÑOZ *et al.,* 2012) and mango pulp of different varieties (VIDAL *et al.,*2004; ORTEGA-QUINTANA *et al.,* 2015; FIGUEROA-FLÓREZ *et al.,* 2017). In this case, the experimental data for the viscosity and shear rate were fitted to the Carreau-Yasuda model (CARREAU, 1972), which gave us the best statistical parameters including a minimum correlation coefficient R^2>0.99282:

$$\eta = \eta_\infty + (\eta_0 - \eta_\infty)[1 + (\lambda_c\dot{\gamma})^a]^{\frac{n-1}{a}} \quad (1)$$

This model represents a fluid that follows Newton's law of viscosity at low deformation speeds and obeys a power law at high shear rates (MÉNDEZ-SÁNCHEZ *et al.*, 2010). It uses five parameters: η_0 corresponds to the Newtonian viscosity at low shear rates; η_∞ is the Newtonian viscosity at high deformation speeds; λ_c is the Carreau time constant; a is the transition control factor, which is a dimensionless constant; and n is the parameter of the power law model. In the case where n=1, the model is reduced to the linear Newtonian model, for example, the Navier-Stokes equations. For fluidifying liquids (n<1), the viscosity decreases with an increase in the shear rate.

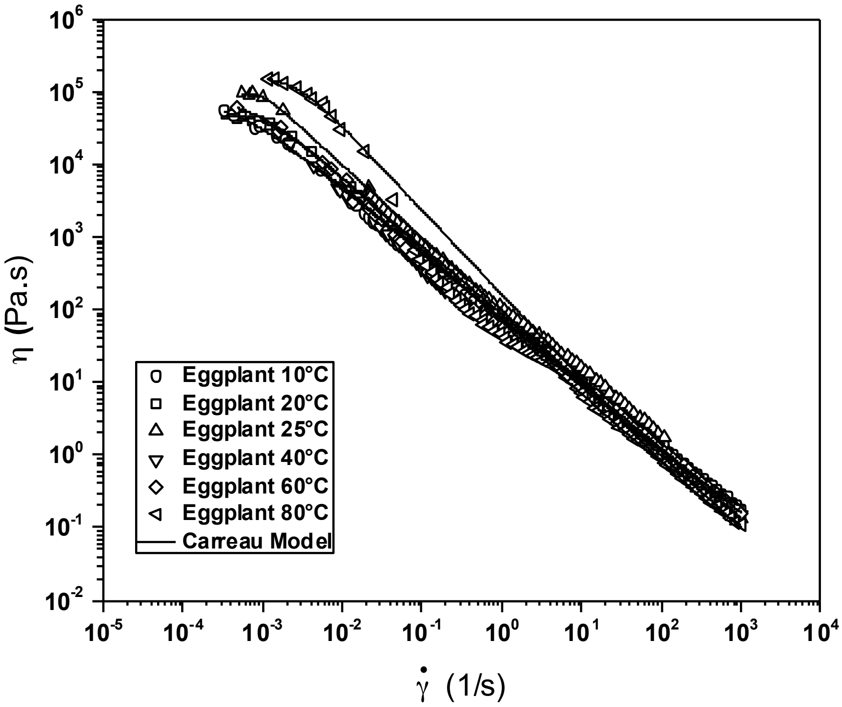

Figure 1. Viscous flow curves for *S. melongena* pulp at different temperatures (10ºC, 20ºC, 25ºC, 40ºC, 60ºC, 80ºC) fitted to the Carreau-Yasuda model.

Fig. 1 shows the experimental data (viscosity vs. shear rate) fitted to the Carreau-Yasuda model. At the initial points, the apparent viscosity tends to be constant, and is represented as the null viscosity η_o. It subsequently begins to decrease, and the viscosity curve enters a logarithmic drop phase, where at high deformation speeds it tends to behave like a Newtonian fluid, following the behavior of the Carreau model. This decrease in viscosity with an increase in shear rate is called shear thinning, and similar results have been obtained in rheological studies of papaya pulp (QUINTANA *et al.*, 2017).

The fitting parameters of the Carreau-Yasuda model are shown in Table 2. The results demonstrate rheofluidifying (shear-thinning) behavior, with values for the flow behavior index of less than unity (n<1) for the different conditions of temperature. The viscosity decreases with the shear rate, and hence it is not considered an increase or decrease in the fluidifying character of the pulps. However, changes in temperature affect the viscosity, since an increase in temperature produces greater intermolecular interaction in the aqueous phase of the pulp, causing repulsion between the suspended particles, lower resistance to flow, and consequently a decrease in the apparent viscosity (FIGUEROA-FLÓREZ *et al.*, 2017). This effect was also found by QUINTANA (2016), who showed that the results depended strongly on the heat treatment applied to the pulp before rheological analyses were carried out.

Table 2. Rheological parameters of the Carreau-Yasuda model for the viscosity of eggplant pulp with variation in shear rate, at temperatures of 10-80°C.

Temp.	η_0	η_∞	λ_c	a	n	R^2
10°C	70390.99±1495.38	4.31E-47±0.01	2129.66±136.20	1.50±0	0.10±0.02	0.99
20°C	48987.00±751.80	0.02±0.01	882.40±23.87	2.15±0.14	0.06±0.01	0.99
25°C	96193.78±583.63	5.14E-37±0	980.64±0	5.00±0.33	0.02±0.01	0.99
40°C	23964.83±654.76	0.08±0	643.23±10.68	17.61±5.43	0.08±0.01	0.99
60°C	83051.70±5478.35	0.13±0.3	1222.66±48.54	1.25±0.13	0.05±0.02	0.99
80°C	164922.94±5552.34	0.05±0.01	39.73±8.43	2.09±0.21	0.16±0.01	0.99

The effect of temperature on the apparent viscosity of fluid foods (at constant shear rate) can be explained by the Arrhenius equation (DAK *et al.*, 2007; RAO and TATTIYAKUL, 1999), expressed as:

$$\eta = Aexp\left(\frac{E_a}{RT}\right) \quad (2)$$

where A is the pre-exponential factor; Ea is the activation energy, a parameter used to evaluate the thermal dependence (J/mol); R is the gas constant (8.314 J/mol K); and T is the temperature absolute (K). In this model, the apparent viscosity decreases in an exponential way with temperature. A shear rate of 15 s^{-1} was selected, since operations such as flow in pipes, mixing and agitation involve a range of shear speed of 10–1000 s^{-1} (STEFFE, 1996).

The experimental data for η can be well modeled by the Arrhenius equation, as shown in Fig. 2, and the values for R^2 are found to be greater than 0.9387. The effect of temperature on apparent viscosity (at a constant shear rate) can also be observed in Fig. 2.

In this case, the activation energy E_a=1081.61894 J/mol was lower than the values reported for squash pulp (E_a= 1229.46 J/mol) (QUINTANA *et al.*, 2018); acerola pulp (E_a=12637.89-14292.45 J/mol) (PEREIRA *et al.*, 2014); sapodilla pulp (E_a=12637.89 J/mol) (ANDRADE-PIZARRO *et al.*, 2010) and tomato paste (E_a=8600-13000 J/mol) (DAK *et al.*, 2008), indicating that eggplant pulp has a higher sensitivity to changes in temperature in a food transpiring process; in other words, the internal structure of eggplant pulp is more affected by temperature than the other pulps or food products mentioned above.

The activation energy is a very important parameter in terms of the movement of the molecules, as it influences when the temperature increases in the liquids, allowing them flow more easily, due to a high activation energy at high temperatures (MEMNUNE *et al.*, 2005). In this case, an increase in temperature causes a decrease in the viscosity of the liquid phase, thus increasing the movement of the suspended particles and causing a decrease in the viscosity of the pulp (PELEGRINE *et al.*, 2002).

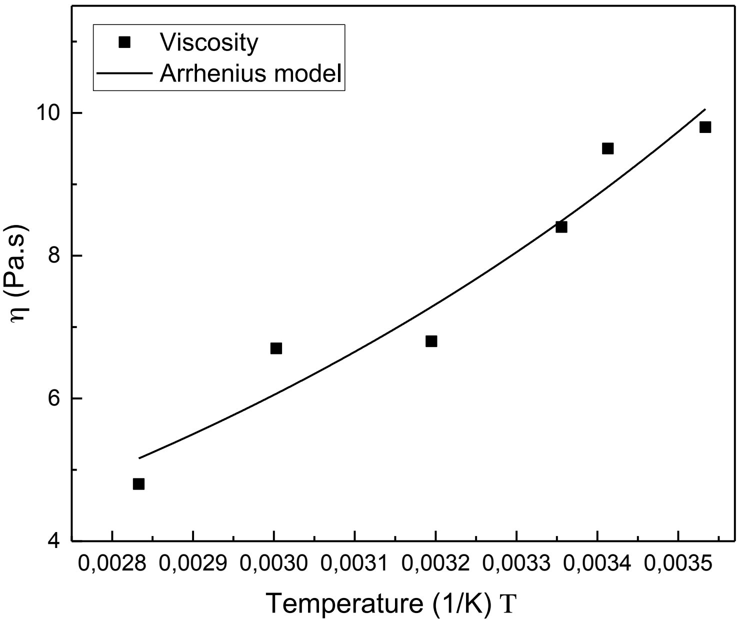

Figure 2. Variation in the values of η obtained at 15 s^{-1} as a function of temperature and fit to the Arrhenius model.

4. CONCLUSIONS

Based on the results obtained in this investigation, the eggplant pulp have a the mayor content expressed in percentage for moisture and carbohydrates, 90.98 and 6.86±0.17 respectively. The rheological properties of the pulp behave like a non-Newtonian fluid of rheofluidifying type (shear thinning). All samples showed a decrease in viscosity with shear rate, which was fitted to the Carreau-Yasuda model with R^2>0.99. The influence of temperature on the behavior of the pulp was observed, and the eggplant pulp was found to lose pseudoplasticity and become less consistent as the temperature increases and its rheological parameters are affected. The relationship between the temperature and the apparent viscosity of the pulp can be represented by the Arrhenius equation, where an increase in temperature causes a decrease in viscosity. Finally, by examining the rheological and flow properties of eggplant pulp, this study may encourage new applications and may help in the design of new food products from this raw material of national interest.

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