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MODELING OF THE OVERAL KINETIC EXTRACTION FROM *Maytenus aquifolia* USING COMPRESSED CO_2

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Abstract - In Brazil, the species *Maytenus aquifolia* and *Maytenus ilicifolia* are widely used in popular medicine in the form of teas for stomach and ulcer illness treatment. Despite the great interest in *Maytenus aquifolia* therapeutic properties and the fact that it is an abundant and native plant growing in Brazil, there is a lack of information in the literature concerning the extraction at high pressures. In this context, this work is focused on the mathematical modelling of the packed-bed extraction of *Maytenus aquifolia* with compressed CO_2. Three mathematical models were used to represent the experimental data. The experiments were performed in a laboratory-scale unit, evaluating the effects of temperature (293 to 323 K), pressure (100 to 250 bar), and extraction time on the yield of the extracts. Results show that the extraction temperature and solvent density exerted a pronounced effect on yield. The mathematical model of Sovová was the most suitable to represent the experimental extraction data of *M. aquifolia*.

Keywords: High-pressure extraction; Extraction kinetics; *Maytenus aquifolia*; Mathematical modeling.

INTRODUCTION

The extraction of products by super/sub-critical fluids (SFE) is based on the contact between a solid raw material and a pressurized solvent, which removes the compounds of interest from the solid phase. In this technique, after removal, the extract is separated from the solvent through pressure reduction (Martínez *et al*., 2003). The operating temperature, pressure and solvent flow rate generally determine the solubility and the selectivity of the target components, and their diffusion capacity across the fluid (Brunner, 1994).

The use of SFE to obtain extracts from plants with pharmaceutical or food properties has received increased interest nowadays (Carvalho *et al*., 2012; Paviani *et al*., 2012; Barroso *et al*., 2011; Mazutti *et al*., 2008; Pavaiani *et al*., 2006; Santos *et al*., 2007). Among these medicinal plants are the species *Maytenus aquifolia* and *Maytenus ilicifolia*, which are widely used in popular medicine, being known as "espinheira-santa". Both species are native growing plants, with natural occurrence in South Brazil where they are used in the form of teas for stomach ulcer illness treatment. For instance, Souza-Formigori *et al*., (1991) have demonstrated the antiulcerogenic

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*To whom correspondence should be addressed property of *Maytenus aquifolium* and *Maytenus ilicifolia*, which seems to be closely related to the presence of two classes of substances, namely, phenols and triterpenes (Pereira *et al*., 1995; Pereira *et al*., 2003). The antiulcerogenic activity of aqueous extracts of *Maytenus ilicifolia* and *Maytenus aquifolium* has also been confirmed in laboratory tests with rats (Oliveira *et al*., 1991).

The use of pressurized carbon dioxide for extraction and characterization of extracts of *Maytenus ilicifolia* has been previously reported (Mossi *et al*., 2004; Lanças *et al*., 1997). For example, Mossi *et al*. (2004) evaluated the influence of particle size, temperature, pressure and carbon dioxide flow rate on the yield and chemical profile of the extracts obtained. In the work of Lanças *et al*. (1997), the investigation focused only on the characterization of the triterpene fraction and no evaluation of the effects of process extraction parameters was provided.

Although *Maytenus ilicifolia* and *Maytenus aquifolia* belong to the Celestraceae family they comprise different species. The different chemotypes of *M. aquifolia* and *M. ilicifolia* could influence the yield and chemical profile of the extracts. For medicinal purposes, an interesting possibility is to obtain an extract rich in the desired compounds, like the triterpenes and phenols. As SFE already was employed successfully for extraction of *M. ilicifolia*, it may also be relevant to evaluate the SFE of *M. aquifolia*. For scale-up purposes it may be important to carry out kinetic modeling of the extraction curves to determine the proper operating conditions, making feasible SFE processes (Silva *et al*., 2008; Martínez *et al*., 2003).

The present report is part of a broader project aiming at the extraction and total characterization of some species of the Celestraceae family. Here, the goal is to investigate the influence of temperature (293 to 323 K), pressure (100 to 250 bar), and extraction time on the yield of the extracts obtained from high-pressure carbon dioxide extraction of *Maytenus aquifolia*. Three mathematical models available in the literature were used to represent the experimental extraction kinetic data.

EXPERIMENTAL METHODS

Material

Leaves of *Maytenus aquifolia* were collected in Erechim county (Rio Grande do Sul State, Brazil, 27° 37' 54") from plants growing in full sunlight. After the collection, the samples were immediately dried at room temperature during 3 days, ground and sieved, collecting the particles that passed through a sieve of 100 mesh and were retained in a sieve of 200 mesh. The samples were then stored at room temperature under nitrogen atmosphere prior to the extraction. The carbon dioxide (99.9% purity) was purchased from White Martins S.A. (Brazil).

Characterization of the Raw Material

The real density of the raw material (ρ_p) was determined by helium picnometry (Micrometrics, model Multivolume Pycnometer 1305, Norcross, EUA). The apparent bed density (ρ_{ap}) was determined by the ratio of mass of raw material and the volume of the extractor, whereas the bed porosity (ε) was determined according to the following equation:

$$\varepsilon = 1 - \frac{\rho_{ap}}{\rho_p} \tag{1}$$

The particle mean diameter was calculated by the equation presented by Gomide (1983) and also used in the work of Mezzomo *et al*. (2009).

Apparatus and Experimental Procedure

The experiments were performed in a laboratory scale unit, schematically presented in Figure 1, which consists basically of a CO_2 reservoir, two thermostatic baths, a syringe pump (ISCO 260D), a 0.1 dm^3 jacketed extraction vessel, an absolute pressure transducer (Smar, LD301) equipped with a portable programmer (Smar, HT 201) with a precision of $\pm$ 0.12 bar, a collector vessel with a glass tube and a cold trap. Amounts around 25 g of dried *Maytenus aquifolia* leaves were charged into the extraction vessel. The CO_2 was pumped into the bed, which was held by two 300 mesh wire disks at both ends, and was kept in contact with the herbaceous matrix for at least one hour to allow system stabilization at the same condition of the experiment. Afterwards, the essential oil was collected by opening the micrometering valve and the CO_2 mass flow was accounted for by the pump recordings. The experiments were accomplished isothermally, at constant pressure using a mass CO_2 flow rate of 2 g/min, as suggested by Mossi *et al.* (2004). The experimental range investigated was 293 - 323 K in temperature and from 100 to 250 bar in pressure. Triplicate extraction runs were accomplished for all conditions.

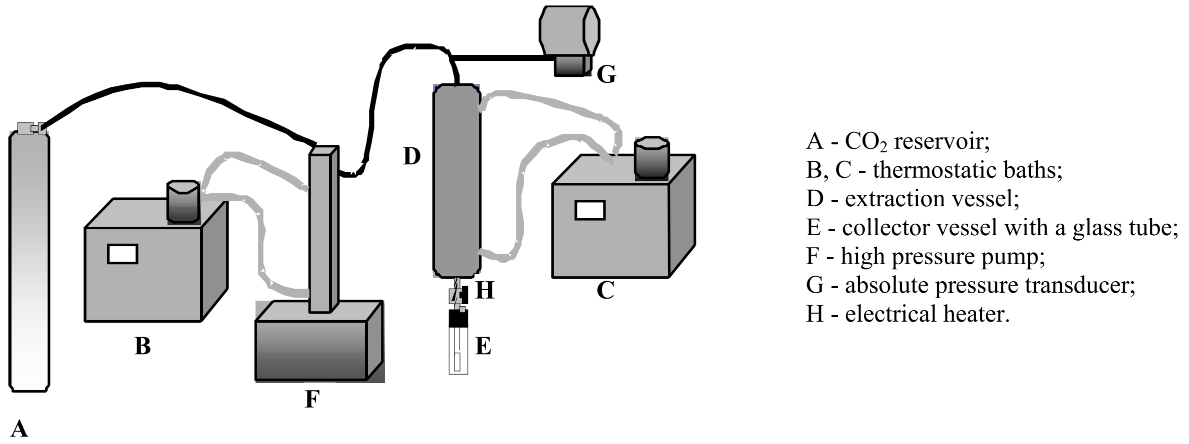


Figure 1: Schematic diagram of the high-pressure extraction apparatus.

Mathematical Modelling

Many mathematical models for the extraction of substances from solid material using supercritical fluids were already presented in the literature (Sovová, 1994; França and Meirelles, 2000; Martínez *et al*., 2003). SFE is usually treated as a cylindrical bed of solid particles, and the pressurized fluid flows axially through it, removing the soluble compounds from the solid phase. Both phases involved in the process, solid and fluid phases, are considered to occupy all the volume of the extraction bed. The mathematical models of Crank (1975), Sovová (1994) and Martínez *et al*. (2003) were applied here to represent the experimental extraction data of *M. aquifolia*, considering the extract as a single pseudo-compound.

The data concerning the overall extraction curves were used to estimate the model parameters using software developed in Fortran 90 language, which uses the Particle Swarm Optimization (PSO) heuristic method for the parameter estimation (Schwaab *et al*., 2008). The objective function used was the sum of least squares. The parameters of the PSO algorithm, namely the number of particles, inertial weight, cognition and social parameters were set as: 40, 0.7, 1.0 and 1.0, respectively. These parameters were fixed based on previous works of the group concerning parameter estimation.

Crank Model

The Crank model supposes that the soluble extracts are uniformly distributed in the spherical solid particles. Based on the Fick law of diffusion, the equation that predicts the mass of extract obtained in the process is given by (Crank, 1975):

$$m_{ext} = m_0 \left[1 - \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(\frac{-n^2 \cdot \pi^2 \cdot D_{eff} \cdot t}{r^2} \right) \right] \quad (2)$$

where m_{ext} is the mass of extract (g), m_0 is the initial solute mass (g), t is the extraction time (min), D_{eff} is the effective diffusivity of solute in the solid particle (m^2/min), r is the particle radius and n is the number of the series expansion; in the above equation, the parameter D_{eff} is estimated using the extraction kinetic data.

Sovová Model

This model describes a situation when solvent flows axially through the bed of milled plant material in a cylindrical extractor. The solvent is solute-free at the entrance of the extractor, and the temperature and pressure are regarded as constants. The solid bed is homogeneous with respect to both the particle size and the initial distribution of solute. The solute is deposited in plant cells and protected by cell walls. However, a part of the walls has been broken, opened by milling, so that a part of the solute is directly exposed to the solvent (Sovová, 1994). The mass of solute contained initially in the solid phase consists of the mass of easily accessible solute. According to Sovová (1994) the extraction curves could be calculated using the extended Lack's plug-flow model:

$$m_{ext} = q \cdot Y^* \cdot \left[1 - \exp(-Z)\right] \cdot t \tag{3}$$

for $t < t_{CER}$

$$m_{ext} = q \cdot Y^* \cdot \left[(t - t_{CER}) \exp(Z_w(t) - Z)\right] \tag{4}$$

for $t_{CER} < t \le t_{FER}$

$$m_{ext} = N\left[x_0 - \frac{Y^*}{W} \ln\left\{1 + \left[\exp\left(\frac{W \cdot x_0}{Y^*}\right) - 1\right] \exp\left[\frac{W \cdot q}{N}(t_{CER} - t)\right]\left(\frac{x_k}{x_0}\right)\right\}\right] \tag{5}$$

for $t > t_{FER}$

where,

$$t_{CER} = \frac{N \cdot (x_0 - x_k)}{Y^* \cdot Z \cdot q} \tag{6}$$

$$t_{FER} = t_{CER} + \frac{N}{W \cdot q} \ln\left[\frac{x_k + (x_0 - x_k) \cdot \exp\left(\frac{W \cdot x_0}{Y^*}\right)}{x_0}\right] \tag{7}$$

$$Z_w = \frac{Z \cdot Y^*}{W \cdot x_0} \ln\left\{\frac{x_0 \cdot \exp\left[\frac{W \cdot q}{N}(t - t_{CER})\right] - x_k}{x_0 - x_k}\right\} \tag{8}$$

where t is the extraction time (min), N is the initial mass of inert material (g), x_0 is the mass fraction of extract in the inert material (g/g), Y^* is the solubility of the extract in the CO_2 (g/g), q is the mass flow rate of CO_2 (g/min), t_{CER} and t_{FER} are the time related to the steps of constant extraction rate and falling extraction rate, respectively (min), and x_k is the mass fraction of easily accessible solute in the inert material (g/g), which is an estimated parameter in the model.

Parameter Z is directly proportional to the solvent-phase mass transfer coefficient and inversely proportional to the specific solvent flow rate:

$$Z = \frac{k_f a \cdot \rho}{q \cdot \rho_p \cdot (1 - \varepsilon)} \tag{9}$$

where ρ e ρ_p are the density of CO_2 and of the particles (g/cm^3), respectively, ε is the bed porosity and $k_f a$ is the solvent-phase mass transfer coefficient (min^{-1}), a fitted parameter.

Similarly, parameter W is directly proportional to the solid-phase mass transfer coefficient and inversely proportional to the specific solvent flow rate:

$$W = \frac{k_s a \cdot \rho}{q \cdot \rho_p \cdot (1 - \varepsilon)} \tag{10}$$

where $k_s a$ is the solid-phase mass transfer coefficient (min^{-1}), another adjusted parameter.

Martínez Model

The model proposed by Martínez *et al.* (2003) neglects the accumulation and the dispersion in the fluid phase as these phenomena are less important for the process compared with the convection effect, which leads to:

$$m_{ext} = \frac{m_0}{\exp(b_i \cdot t_{mi})} \left\{\frac{1 + \exp(b_i \cdot t_{mi})}{1 + \exp\left[b_i \cdot (t_{mi} - t)\right]} - 1\right\} \tag{11}$$

where m_{ext} is the mass of extract (g), m_0 is the initial solute mass (g), t is the extraction time (min), and b_i and t_{mi} are parameters estimated from extraction kinetic data (min^{-1} and min, respectively).

RESULTS AND DISCUSSION

Characteristics of the Raw Material

The dried *M. aquifolia* particles had a mean diameter of 1.02±0.01 x 10^{-3}m and a real density of 1390±43 kg/m^3. The extraction bed apparent density was 292 kg/m^3 and its porosity was 0.79. The values of CO_2 density at each condition of pressure and temperature, presented in Table 1, were estimated from the Angus *et al.* (1976) correlation. In addition, Table 1 presents other relevant information to be used in the mathematical modeling of the extraction curves, such as the mass-transfer rate of the constant extraction rate period (M_{CER}), the mass flow rate of CO_2 and the extract solubility (Y^*).

Table 1: Experimental data and kinetic parameters used for modeling SFE of *M. aquifolia*[*]

Run	P (bar)	T (K)	CO_2 density (kg/m^3)	$M_{CER} \times 10^3$ (g/min)	t_{CER} (min)	t_{FER} (min)	$Y^* \times 10^3$ (kg/kg)	Yield (% m/m)
1	100	293	865	1.38	90	90	0.80	0.74^{fdehh}
2	250	293	970	1.82	90	120	0.94	$0.92^{abcdefg}$
3	100	323	375	0.29	90	90	0.39	0.12^{i}
4	250	323	842	1.36	240	nv	0.81	1.10^{abc}
5	100	308	718	0.84	90	90	0.59	0.62^{fgh}
6	250	308	912	2.34	60	120	1.07	1.02^{abcd}
7	175	293	930	1.83	60	120	0.98	0.78^{cdefgh}
8	175	323	756	1.60	60	120	0.11	0.85^{bcefg}
9	175	308	853	1.74	60	120	1.02	0.80^{cdfg}
10	175	308	853	1.72	60	120	1.01	0.81^{cdfg}
11	175	308	853	1.78	60	120	1.01	0.84^{cdfg}

[*] P - pressure; T - temperature; Y^*- solubility of solute in CO_2; M_{CER} - constant extraction rate; t_{CER} – time of constant extraction rate; t_{FER} – time of falling extraction rate.
[a, b, c, d, e, f, g, h, i] different letters represent a difference significant at 95% ($p<0.05$ - Tukey test).

Extraction of *Maytenus aquifolia* Samples

Table 1 presents the yield along with the experimental conditions investigated in this work. Here, the yield is defined as the weight percentage of the oil extracted with respect to the initial charge of the raw material in the extractor. The general analysis of the results of Table 1 reveals that the extraction obtained in this work ranged from 0.116% (m/m) in run 3 (100 bar and 50 °C) to 1.104% (m/m) in run 4 (250 bar and 50 °C), which are in good agreement with the work of Mossi *et al*. (2004) for the SFE of *M. ilicifolia.*

The increase in temperature at the lowest extraction pressure (100 bar) led to a sharp decrease in the extraction yield whereas a considerable increase (two time higher) was verified at the highest pressure (250 bar) due to large solvent density changes. The increase of solvent density caused an enhancement of the solvent power, increasing the yield. However, comparing runs 2, 4, and 6 (same pressure, increasing temperature, decreasing solvent density), it is seen that the extraction yield increased with temperature.

This behavior is due to the competition between temperature (vapor pressure of essential oil) and extraction pressure (solvent power) in the range investigated, which is clearly verified in the eighth column of Table 1 (solubility of solute in CO_2). It is seen that the solubility decrease with increasing temperature at low pressure (100 bar), since the density of the solvent decreases sharply. For pressures higher than 175 bar, the change in the density with temperature is less expressive, in a manner that the increase in the vapor-pressure caused by the increase in the temperature is more important than density of the solvent. The thermodynamic solubility is dependent on temperature and pressure (solvent density) and, thus, the appreciable decrease in density observed at 100 bar from 20 to 50°C is responsible for the slight reduction in solubility, implying a low extraction yield.

Data of Table 1 were used to compute linear (L), quadratic (Q) and interaction effects of temperature and pressure (1Lx2L) on the extraction yields, which are presented in Figure 2 in the form of a Pareto Chart. It is seen that the pressure exerts the most significant effect on the extraction yield due to the enhancement in the solvent power of CO_2 as a consequence of the solvent density increase, whereas the temperature did not present a significant effect on the extraction yield in the variable range evaluated. The positive effect of the interaction between temperature and pressure is clearly verified from Figure 2, which was already expected on the basis of the vapor pressure of volatile compounds and CO_2 solvent power, as discussed in the previous paragraph.

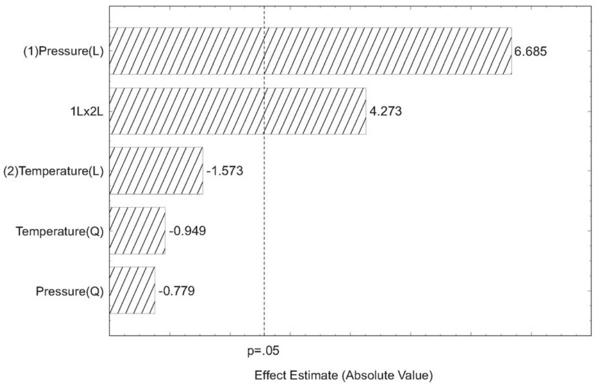
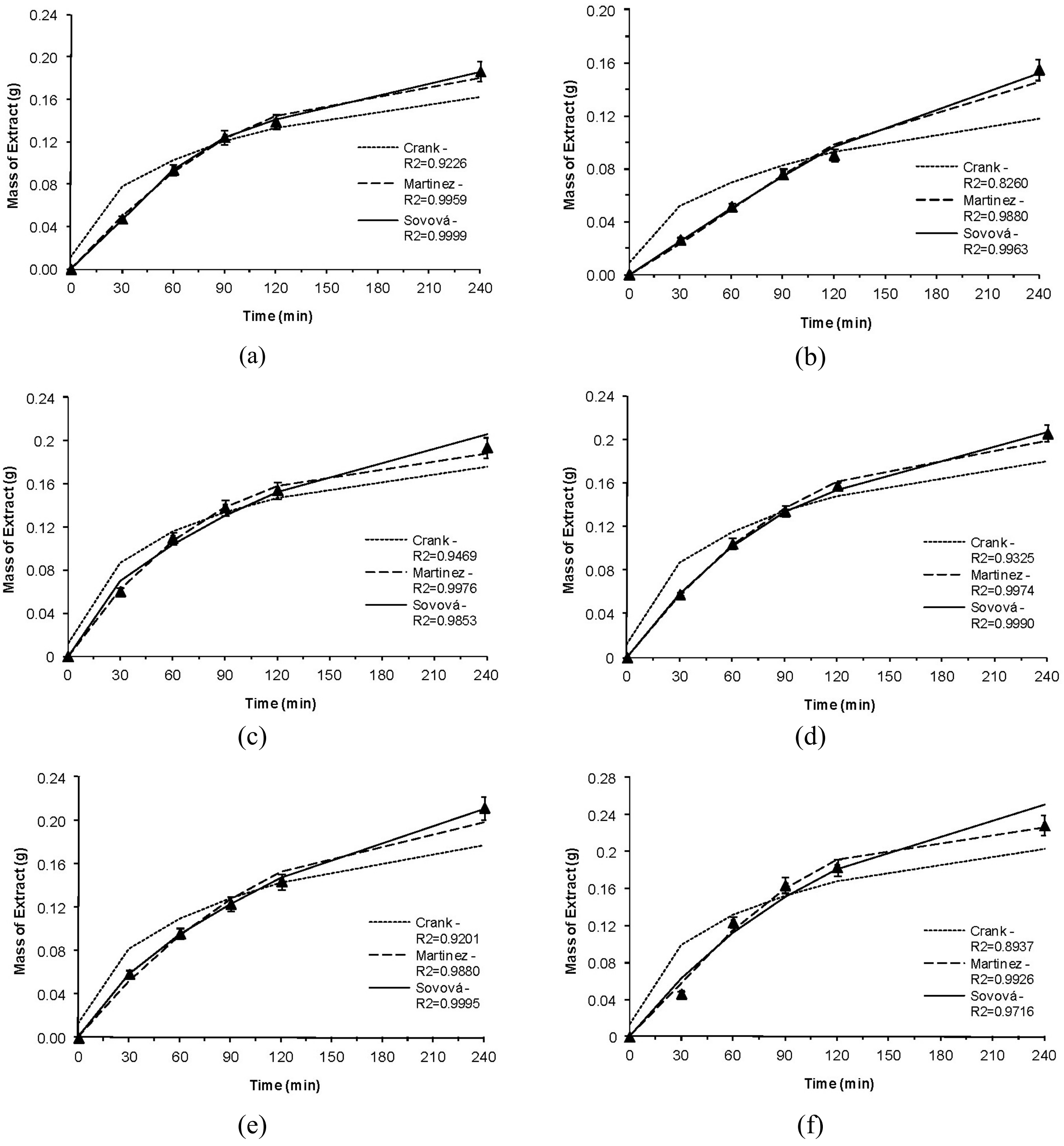


Figure 2: Pareto Chart presenting the effects of pressure and temperature on the extracts yield. L – linear effect; Q – quadratic effect; 1Lx2L – interaction effect.

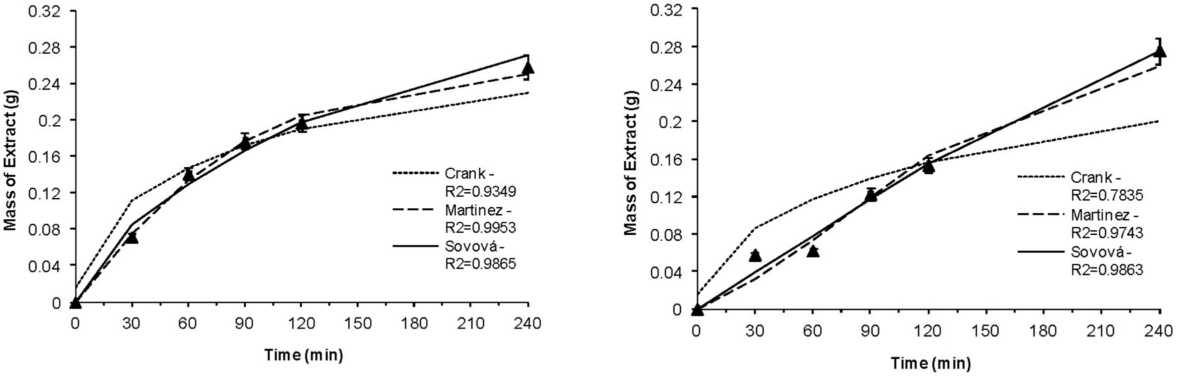
Figure 3 presents the experimental extraction curves for all conditions shown in Table 1. From this figure it is seen that, for the pressure of 100 bar, the constant extraction rate (M_{CER}) decreases with the increase of temperature (runs 1, 5 and 3 concerning the temperatures of 20, 35 and 50°C, respectively), whereas for a pressure of 175 bar M_{CER} was practically constant around $1.75x10^{-3}$ g/min. At 100 bar, a great variation in density was verified, affecting the M_{CER}, whereas at 175 bar the density was nearly constant among the experiments. At 250 bar and temperatures of 20 and 50 °C, it was verified that the temperature increase promoted a decrease in M_{CER}, due to the decrease in the density, but at 35 °C the greatest value of M_{CER} ($2.340x10^{-3}$ g/min) was verified. Although the density of the solvent is lower than run 2 (250 bar and 20 °C), at this point the interaction between pressure and temperature was more favorable, since the temperature increases the vapor-pressure of extracts but has little effect on the density decrease. This result is confirmed in Figure 2, which clearly shows the influence of interaction between pressure and temperature on extraction yield.



(a) (b)

(c) (d)

(e) (f)



(g) (h)

Figure 3: Experimental and predicted overall extraction curves for *M. aquifolia* under different experimental conditions: a) 100 bar and 293 K; b) 100 bar and 308 K; c) 175 bar and 293 K; d) 175 bar and 308 K; e) 175 bar and 323 K; f) 250 bar and 293 K; g) 250 bar and 308 K; h) 250 bar and 323 K.

From Figure 2 it is also verified that the time of constant extraction (t_{CER}) was around 90 minutes for a pressure of 100 bar, independent of temperature, and for another pressure t_{CER} was 60 minutes. For run 4 (250 bar and 50 °C) we verified only the constant extraction rate through the extraction time due to the high vapor-pressure of the extract. The falling extraction rate, when present, was short and it is related with the diffusion of the extract from the center of the particle to its surface. Concerning Figure 2, it is important to point out that the extraction yield after 240 minutes was still increasing, but extraction was not extended because the most important stage in supercritical fluid extraction is the constant extraction stage and the parameters associated with this step should be carefully determined in this work. About 80-90% of the extracts are obtained in the constant and falling extraction stages. In addition, the final stage of extraction is characterized by the extraction of wax that presents little interest in the extracts. This information is now provided in the manuscript.

Modeling of Extraction Curves

For the evaluation of experimental data, extraction curves were expressed in terms of mass of extract of *M. aquifolia* as a function of extraction time. Figure 3 shows the experimental and simulated data for all runs using the three models: Crank, Sovová and Martínez. Figure 3 also gives the determination coefficient (R^2) for each model. The models of Sovová and Martínez presented good agreement with the experimental data, with values of R^2 higher than 0.97 for all conditions, whereas the Crank model showed unsuitable results because of its lower values of R^2. If R^2 is calculated considering all experimental points the values obtained are 0.9912, 0.9897 and 0.8504 for the models of Sovová, Martínez and Crank, respectively. A Tukey test ($p<0.05$) indicated that there are no significant differences between the predictions of the Martínez and Sovová models.

In the Sovová model, the transport phenomena that occur during the process are properly explained, such as the characteristics of the solid substrate (particle size, porosity, and relative amount of broken cells). Although the values of the parameters were not presented here, the fluid-phase mass transfer parameter was always higher than that exhibited by the solid-phase mass transfer. The appreciable difference between the two parameters indicates that, in the *M. aquifolia* SFE process, the effect of fluid phase convection is much more important than the diffusion in the solid substrate. Of course, at the end of the extraction process, when the solute from broken cells is depleted, diffusion becomes the most important mass-transfer mechanism, hence controlling the extraction process.

Although the model of Martínez provided a satisfactory representation of the experimental data during all the steps of the extraction process, its applicability is affected due to the fact that the values of the parameter t_{mi} that corresponds to the instant in which the extraction rate reaches its maximum were negative for some experimental conditions, which lacks physical meaning. The model of Crank was the least effective to simulate the SFE of *M. aquifolia* because of two reasons: first, the extraction process is controlled by convection and not by a diffusion mechanism in the solid substrate as discussed above; second, the model of Crank had only one adjustable parameter, which makes representation of the experimental data more difficult.

CONCLUSIONS

This work presented experimental and predicted data concerning the supercritical extraction of *M. aquifolia*. From the experimental results, it can be concluded that the extraction yield at low pressure is affected by the pressure or, in other words, by the fluid density. For pressures above 175 bar, the temperature variation of the density of fluid is less accentuated and the extraction yield is influenced by the temperature or, more precisely, by the increase in the vapor-pressure of the extract. The highest extraction yield was 1.10 wt% at 250 bar and 308K. The models of Sovová and Martínez showed satisfactory results concerning the fitting of experimental kinetic data for SFE of *M. aquifolia*. However, the modeling results obtained here should be evaluated in subsequent studies to verify their capability of predicting extraction curves on larger scales, and to evaluate whether the estimated parameters vary with operational conditions, such as the solvent flow rate, particle diameter, size, and geometry of the extraction bed.

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