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Supercritical fluid and pressurized liquid extractions of phytonutrients from passion fruit by-products: Economic evaluation of sequential multi-stage and single-stage processes

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ABSTRACT

This work presents the economic evaluation of two processes to obtain: *i*) four extract fractions from passion fruit bagasse by sequential multi-stage process comprising three steps of supercritical fluid extraction (SFE) and one step of pressurized liquid extraction (PLE); *ii*) one extract from passion fruit rinds by single-stage PLE process. The economic simulation and sensitivity study were performed for plants containing two extraction vessels of 1, 5, 50 and 500 L. The scale-up led to a decrease in the cost of manufacturing (COM). COMs of extracts from sequential multi-stage and single-stage processes decreased from US$ 220.51/kg to US$ 26.33/kg and US$ 71.03/kg to US$ 11.96/kg, respectively, when the system capacity increased from 2×1 L to 2×500 L. Itemized costs related to materials, facilities, labor and utilities are also presented. Both processes are economically promising, especially when the extracts are produced in large scale and sold by the current market price.

1. Introduction

The passion fruit production is an important part of the fruit marketing in Brazil. One of the most cultivated species is the yellow passion fruit (*Passiflora edulis*), which grows in 95% of orchards. Passion fruit by-products are generated in the industrial processes during the pulp separation. It is estimated that the residues from the production of passion fruit juice reach 40–60% of the mass of processed fruits. About 90% of the by-products are composed of rinds and bagasse [1].

Some works point out that passion fruit by-products are rich sources of phytonutrients such as fatty acids [1,2], carotenoids [3], tocopherols and tocotrienols (tocols) [4], and phenolic compounds [5–8]. Some studies have concentrated their efforts in performing extraction processes to obtain such compounds. Viganó et al. [9] and Viganó et al. [10] developed a sequential multi-stage process to obtain four extract fractions from passion fruit bagasse. Such fractions were concentrated in tocotrienols, fatty acids, carotenoids and phenolic compounds, in which piceatannol was the major compound. The sequential multi-stage process consisted of three supercritical fluid extraction (SFE) steps followed by one pressurized liquid extraction (PLE) step. Similarly, Viganó et al. [11] performed a single-stage process to obtain phenolic compounds from passion fruit rind using PLE. The extracts obtained in both works presented antioxidant capacity. Thus, the recovery of the aforementioned compounds can lead to a variety of commercial products, either feedstock for secondary processes, substitutes for ingredients or ingredients for new products. In addition, sequential extraction processes are inserted in the concept of bio-refinery, which uses the entire raw material through combined processes. However, there are major technical and economic challenges to overcome before the full potential of bio-refineries can be realized at industrial scale [12].

Indeed, phytonutrients are gaining market importance around the world. It is estimated that the phytonutrients market may reach $ 4.63 billion with a compound annual growth rate of 7.2% between 2015 and 2020 [13]. The major influencing factors for the global phytonutrients market are health issues, such as cardiovascular diseases, cancer, and type 2 diabetes. In addition, the aging population and increased awareness about health and wellness are also contributing to the market growth [13].

Based on the mentioned information, the knowledge of the costs involved for obtaining extracts from passion fruit by-products is required in order to overcome some of the challenges associ-

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Table 1
Experimental data used to simulate the single-stage and sequential multi-stage extraction processes.

Parameter	Value[a]
Tocols-rich extract (TRE) [a] – 1st step	
Extraction yield	6.56 g/100 g bagasse[b]
Extraction time	4.8 h
Temperature	60 °C
Pressure	17 MPa
S/F	150 kg CO_2/kg feed
Fatty-acids-rich extract (FARE) [a] – 2nd step	
Extraction yield	13.84 g/100 g bagasse[b]
Extraction time	4.8 h
Temperature	50 °C
Pressure	17 MPa
S/F	150 kg CO_2/kg feed
Carotenoids-rich extract (CRE) [a] – 3rd step	
Extraction yield	3.15 g/100 g bagasse[b]
Extraction time	3.2 h
Temperature	60 °C
Pressure	26 MPa
S/F	100 kg CO_2/kg feed
Phenolic-rich extract (PREa) [b] – 4th step	
Extraction yield	33.5 g/100 g bagasse[b]
Extraction time	2 h
Temperature	70 °C
Pressure	10 MPa
S/F	300 kg solvent/kg feed
Phenolic-rich extract (PREb) [c] – Single stage	
Extraction yield	35.0 g/100 g rind[c]
Extraction time	0.5 h
Temperature	60 °C
Pressure	10 MPa
S/F	45 kg solvent/kg feed

[a]Values were obtained from [a]Viganó et al. [9], [b]Viganó et al. [10] and [c]Viganó et al. [11]; [b]Initial mass of bagasse; [c]Initial mass of rind; S/F: solvent mass to feed mass ratio.

ated with scaling-up the processes. Economic evaluations of single or sequential processes to obtain extracts from passion fruit by-products have not been found up to now. Therefore, the aim of this work was to provide economic evaluations of two extraction processes: a sequential multi-stage process to produce four extract fractions from passion fruit bagasse that were obtained by Viganó et al. [9] and Viganó et al. [10]; and a single-stage process to produce extract rich in phenolic compounds from passion fruit rind that was obtained by Viganó et al. [11].

2. Material and methods

2.1. Process simulation model

Simulations of extraction processes were performed using the SuperPro Designer 9.0® software (Intelligen Inc., Scotch Plains,NJ, USA). The flowsheets of the extraction processes developed for the simulation are presented in Figs. 1 and 2 for the sequential multistage and single-stage processes, respectively. The input parameters and process conditions were obtained from previous works performed by Viganó et al. [9], Viganó et al. [10] and Viganó et al. [11]. Yield data and operation conditions, such as temperature, pressure, and solvent mass (S) to dry feed mass (F) ratio were used as input data for the model (Table 1).

2.1.1. Sequential multi-Stage process (SFE + PLE) to obtain four extract fractions from passion fruit bagasse

Viganó et al. [9] and Viganó et al. [10] developed a sequential extraction process consisting of the application of SFE followed by PLE (Fig. 1). The SFE stage consists of three steps, while PLE stage comprises of one step. The process was simulated as follows. Initially, dried and ground passion fruit bagasse is loaded in the extraction vessel (P-4/E-101 or P-5/E-102). Then, CO_2 is cooled (−4 °C) using P-7/HX-101 and then pressurized (17 MPa) using P-8/PM-101. CO_2 reaches the supercritical condition after to be heated (60 °C) by P-9/HX-102 and then enters in P-4/E-101 or P-5/E-102. After the temperature and pressure conditions are achieved in the extraction vessel, a 15 min static time is counted. Afterward, SFE is performed and the CO_2 and tocols-rich extract (TRE) are recovered after the separation process (P-12/S-101 and P-13/S-102). In order to simulate the process, the CO_2 recycle was added to what was described by Viganó et al. [9]. CO_2 is recovered from P-12/S-101 (20 °C, 3 MPa) and P-13/S-102 (15 °C, 0.1 MPa) and it is recycled using a gas compressor P-15/C-101 (32 °C, 6 MPa). The complete process described above is performed for the second and third extraction steps, but under 17 MPa and 50 °C and 26 MPa and 60 °C in order to obtain a fatty-acids-rich extract (FARE) and carotenoids-rich extract (CRE), respectively.

Once the SFE process has finished, the raw material is retained inside P-4/E-101 or P-5/E-102 and the PLE process is started. The mixture of ethanol and water is pressurized (10 MPa) using P-1/PP-101 and heated (70 °C) using P-2/HX-101. After reaching the desired temperature and pressure inside P-4/E-101 or P-5/E-102, a 15 min static time is counted. Once the extraction is started, the phenolic-rich extract (PREa) flows to the P-17/EV-101, where the ethanol fraction is separated (40 °C, 0.02 MPa) and recycled. The remaining aqueous extract is dried using P-18/FDR-101 and the dried PREa (15 °C, 0.02 MPa) is obtained. The last two steps (evaporation and drying) were added to what was described by Viganó et al. [10] in order to simulate the process. Then, the cleaning and maintenance of the system are performed, and the SFE + PLE process is repeated.

2.1.2. Single-stage process (PLE) to obtain phenolic compounds from passion fruit rind

A single-stage pressurized liquid extraction (PLE) was reported by Viganó et al. [11] to obtain a phenolic-rich extract (PREb) from passion fruit rind (Fig. 2). The process was simulated as follows. Initially, dried and ground passion fruit rind is loaded in the extraction vessel (P-4/E-101 or P-5/E-102). Then, the mixture of ethanol and water is pressurized (10 MPa) using P-1/PP-101 and heated (60 °C) using P-2/HX-101. After reaching the desired temperature and pressure inside the extraction vessel, a 15 min static time is counted. Once the extraction is started, the PREb flows to the P-7/EV-101, where the solvent is separated (60 °C, 0.05 MPa). The remaining aqueous extract is dried using P-18/FDR-101 and the dried PREb (12 °C, 0.05 MPa) is obtained. The last two steps (evaporation and drying) were added to what was described by Viganó et al. [11] in order to simulate the process. Then, the cleaning and maintenance of the system are performed, and the PLE process is repeated.

2.2. Economic evaluations

2.2.1. Economic evaluation parameters

Values based on past vendor quotations and literature are a good alternative to deal with the difficulty of obtaining equipment quotations and detailed specifications in the first stages of a project [14]. Although current vendor quotations are the most accurate information to obtain the values of the equipment, these costs are generally for equipment with capacities other than required [15]. Scaling the equipment cost to the required capacity is possible through Eq. (1) [15,16], where C_1 is the equipment cost with capacity Q_1, C_2 is the known base cost for equipment with capacity Q_2 and n is a constant depending on the equipment type. Values of n were collected from literature [14,17–19]. The base costs used in