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Process integration for turmeric products extraction using supercritical fluids and pressurized liquids: Economic evaluation

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ABSTRACT

An economic evaluation of an integrated process to produce products derived from turmeric was performed. Process integration of supercritical fluid extraction (SFE), pressurized liquid extraction (PLE), and supercritical antisolvent process (SAS) has been investigated in order to obtain turmeric essential oil (TEO) and powdered curcuminoid-rich extract (PCE). Scale-up led to a decrease in the cost of manufacture (COM) for both the products. Volatile oil and powdered curcuminoid-rich extract COMs decreased from US$ 112.70 kg^{-1} to US$ 85.58 kg^{-1} and from US$ 174.80 kg^{-1} to US$ 141.63 kg^{-1}, respectively, when a raw material costing US$ 7.27 kg^{-1} was used, and the capacity of the system increased from 2× 50 L to 2× 500 L. The raw material cost had a significant effect on the process expenses. When the capacity of the system was 2× 50 L, and the raw material cost decreased from US$ 7.27 kg^{-1} to US$ 1.59 kg^{-1}, the COM of volatile oil and powdered curcuminoid-rich extract decreased from US$ 112.70 kg^{-1} to US$ 64.97 kg^{-1} and from US$ 174.80 kg^{-1} to US$ 140.96 kg^{-1}, respectively. The economic evaluation results of this study clearly demonstrate that the integrated process is a feasible alternative and an attractive option to produce derivatives from turmeric.

1. Introduction

Turmeric (*Curcuma longa* L.) is a plant widely cultivated in countries and regions with tropical and subtropical climates, such as India, China, and Indonesia, as well as in certain Latin American countries, such as Brazil and Peru (Jayaprakasha et al., 2005). Annual worldwide production of turmeric is estimated to be 1100,000 t/year. India is the largest producer, exporter, and consumer of turmeric, being responsible for 82% of the world's production and 45% of the overall exports (Nair, 2013). Turmeric is known for its characteristic rhizomes. Turmeric has been used since ancient times as a condiment, preservative, flavoring agent, and in folk medicine. Currently, turmeric and its derivatives have aroused great interest due to their pharmacological properties (Araujo and Leon, 2001). Due to turmeric's properties and the general interest in replacing synthetic additives by natural compounds, turmeric and derivative products, such as turmeric powder, extracts and oleoresins, have great potential for insertion into the food industry and in the markets of natural additives. According to Sloan and Adams (2014), in 2012, whole-food supplement sales topped US$ 1.2 billion. Turmeric and its derivative products were projected to be among the top 10 best-selling supplements through 2016 by the Nutrition Business Journal (NBJ), representing a market of approximately US$ 235 million. Functional and pharmacological properties

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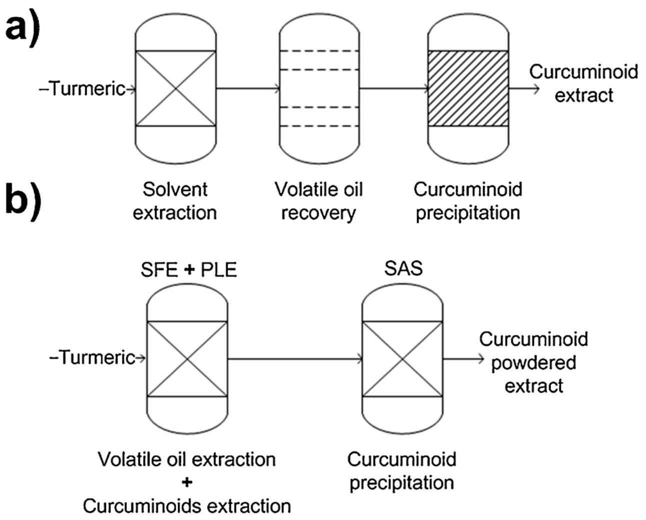

Fig. 1 – (a) Process flow diagram for traditional volatile oil recovery and curcuminoids extraction process; (b) Process flow diagram for the SFE+PLE–SAS process.

of turmeric derivative products are mainly due the presence of two secondary metabolites in the rhizomes: volatile oil and curcuminoids (Gounder and Lingamallu, 2012). Turmeric owes its characteristic aroma to an essential oil present in the rhizomes. Due to its antioxidant, antimutagenic, anticarcinogenic, anti-fungal, anti-bacterial and insect repellent properties, turmeric volatile oil is widely used in pharmaceutical applications (Ling et al., 2012). In the food industry, volatile oil is mainly used in the production of some confectionary products and soft drinks (Ravindran et al., 2007). Curcuminoids are a group of phenolic compounds responsible for the yellow color of the rhizomes. These compounds have been recognized for their biological activities, such as anti-inflammatory, anti-bacterial, anti-carcinogenic, and antioxidant agents (Osorio-Tobón and Meireles, 2013). Additionally, being a colorant, curcuminoids have great potential in the food and pharmaceutical industries. Today, curcuminoids are used primarily as natural coloring agents to replace synthetic dyes in chutneys, pickles, mustard, butter, and cheese, among other products (Stankovic, 2004).

In the conventional process to obtain volatile oil and curcuminoids (Fig. 1a), turmeric is ground to a predetermined particle size and loaded in the extractors. Turmeric should be dried to optimum moisture level because excessive moisture affects the percolation rate and product quality. Next, the solvent is admitted from the top and sprayed on to the charge to exhaust the raw material. Such solvents as methanol, ethanol, and acetone are commonly used in industrial production, due to the high solubility of curcuminoids in these solvents (Garcia et al., 2010). Afterward, volatile oil is recovered from the mother liquor left over after solvent extraction. The above extract is re-extracted with hexane to recover a composite of fixed and volatile oils, and this composite can be subjected to fractional distillation to obtain the volatile fraction. However, steam distillation, which only removes the volatile oil, is a tedious and expensive process (Verghese, 1993). After removing the volatile oil and the solvent, the concentrated extract is dissolved in alkali, filtered, and acidified with acid to precipitate the curcuminoids (Ravindran et al., 2007).

Such factors as contact with light, oxygen, high temperatures and use of toxic solvents highlight the need to develop novel processes that overcome these drawbacks. Alternative techniques that involve the use of supercritical fluids and pressurized liquids have great potential to overcome the limitations of the conventional process. These processes are environmentally friendly, and they protect the integrity of the compounds. Meanwhile, extracting volatile compounds using supercritical carbon dioxide ($scCO_2$) is one of the most interesting applications of supercritical technology because of the high solubility of these substances in CO_2 and the easy removal of the solvent through pressure reduction (Reverchon and De Marco, 2006).

For example, according to Carvalho et al. (2015), the supercritical fluid extraction (SFE) of turmeric volatile oil allows us to obtain a high extraction yield in a fast process with a relatively low solvent consumption. Conversely, pressurized liquid extraction (PLE) involves extraction using liquid solvents at temperatures above their atmospheric boiling point, enhancing solubility and mass transfer properties (Mustafa and Turner, 2011). For instance, Osorio-Tobón et al. (2014) demonstrated the feasibility of use of PLE to obtain curcuminoid-rich extracts using ethanol as an extraction solvent. Additionally, $scCO_2$ is a supercritical fluid that is most widely used due to its favorable characteristics, such as its low toxicity, low cost, easy removal, and non-flammability (Silva and Meireles, 2014). Supercritical antisolvent (SAS) process takes advantage of these characteristics. SAS uses the slight solubility of curcuminoids in CO_2 and a moderate solubility of ethanol in CO_2 to eliminate the solvent and to precipitate the curcuminoids, thereby obtaining a powdered extract.

Process integration and intensification is an attractive approach to produce valuable products of higher quality with reduced energy consumption and consequently reduced costs (Boyadzhiev et al., 2006). According to Moraes et al. (2015), integrating processes is different from intensifying processes. In the first case, the best process for each product is searched, while in the second case, the same equipment is used for different, though similar, unit operations. Process integration has been successfully applied to supercritical fluids: for example, SFE integrated with low-pressure solvent extraction for bixin production from annatto seeds (Moraes et al., 2015). Fujii (2012) developed process integration of SFE and acid treatment for astaxanthin extraction from a vegetative microalga. Process intensification using supercritical fluids also has been successfully applied: for example, biodiesel production (Lim and Lee, 2013), as well in the production of pharmacological compounds, such as levodopa (Damen et al., 2009).

In this context, an integrated process known as SFE+PLE–SAS is proposed in order to produce turmeric volatile oil (TEO) and powdered curcuminoid-rich extract (PCE). As shown in Fig. 1b, the first stage is characterized by intensification of the SFE and PLE processes. Initially, volatile oil is obtained using $scCO_2$ through SFE. Next, the same equipment is used to extracted curcuminoids by PLE using ethanol as a solvent. Finally, the solvent is eliminated, and curcuminoids are precipitated using $scCO_2$ through the SAS process. It is important to highlight that contrary to the conventional process, the integrated process proposed in this work uses solvents recognized as safe (GRAS) and process conditions that contribute to preserve the characteristics of the bioactive compounds. Additionally, due to the lower number of unit operations and processes used, this integrated process represents a more efficient, economical, and environmentally friendly alternative to obtain TEO and PCE.

The objective of this study was to provide an economical evaluation of an integrated process for the production