Preliminary Design of a Pressurized Liquid Extraction Unit for Phytochemicals Extraction

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Abstract

In the present research, a Pressurized Liquid Extraction (PLE) unit has been preliminarily designed to extract bioactive compounds from medicinal plants. The design steps included 1) Developing design bases with general information about the process; 2) Preparing a concept process flow sheet in which the unit operation type, the required equipment, the main input, output flows, and the flows related to the utilities are shown; 3) Determining the operational mode of the process; 4) Determining the type of equipment, and 5) Doing calculations and balancing energy and process materials. In this design, 500 kg of dried chopped plant and a combination of ethanol and water as solvent were used as input materials to the extractor. A batch mode is considered for the extraction operation and a continuous mode is considered for concentration operation. Unit operations were designed based on a fixed-bed extractor, and the required subsidiary equipment was determined according to the desired conditions for the process also, a falling film evaporator was used to concentrate the extract. By determining the flows, balancing the materials and energy, and doing the process-related calculations, the Process Flow Diagram (PFD) was finally obtained.

Keywords: Bioactive Compounds, Pressurized Liquid Extraction (PLE), Preliminary Design, Medicinal Plants.

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Introduction

A large amount of valuable compounds in medicinal plants, known as bioactive compounds, has led to the development of several techniques for extracting these types of compounds. Researchers have always been trying to find a more cost-effective and environment-friendly technique for their extraction. In the past, conventional techniques were used to extract bioactive compounds. However, more advanced techniques have entered the market, which are more environment-friendly and have a higher extraction yield compared to the conventional techniques. Pressurized Liquid Extraction (PLE) is one of the modern extraction techniques known as green and environment-friendly technology due to less consumption of organic solvents compared to the conventional techniques. In addition, it is a fast technique for extracting the compounds from plants in a short time.

Due to the limitations of the conventional extraction techniques (long extraction time, essential expensive and high-purity solvents, evaporation of large amounts of solvent, low selectivity of the extraction, and degradation of temperature-sensitive compounds through high heat, etc.), modern techniques are preferred. The modern techniques have several advantages over the traditional ones, including their reduced process time, low energy consumption, reduced use of harmful and costly solvents, and increased extraction yield [1-4]. PLE is one of the modern extraction techniques known as a green technique, which is also known as pressurized solvent extraction, accelerated solvent extraction, and enhanced solvent extraction. In this type of extraction, solvents with temperature and pressure higher than the boiling point are used. Numerous studies have been conducted on the PLE technique, some of which are listed in Table 1.

Table 1. Operational parameters of the extraction of bioactive compounds through PLE technique.

Sample	Solvent	Operational pressure (MPa)	Operational temperature (°C)	Solid to solvent ratio (g/ml)	Compounds	Amount of compounds	Reference
Black bamboo leaves	Ethanol: water 50%	10.34	200	0.08	Antioxidants	2.49	[5]
Red grape skin	Methanol: water 60:40	10.1	50	na	Phenolic compounds Anthocyanins	na	[6]
Blackberry	Ethanol: water 50%	7.5	100	na	Total phenol Anthocyanin Antioxidant	na	[7]
Spinach	Ethanol: water 70:30	13.8	100	na	Flavonoid	na	[8]
Anatolia	Ethanol: water 70:30	10.34	40	0.04	Gastrodin Vanillyl alcohol	na	[9]
Cortex dictamni	Methanol	10.34	150	0.035	Bioactive compounds	na	[10]
Momordica charantia	Ethanol: water 80:20	10	160	0.083	Total phenol antioxidant	na	[11]

Mosses	n-hexane	15	80	0.05	Aromatic hydrocarbons	na	[12]
Phyllanthus amarus	Deionized water	11	192	0.041	Phenolic compounds	na	[13]
Soya bean	Ethanol: water 70:30	10.1	100	0.0045	Isoflavons	na	[14]
Ginger	Ethanol: water 70:30	10.1	100	0.024	Gingerol	14.1	[15]
Green coffee	Hot water	10.3	150	0.013	Antioxidants	na	[16]
Trifolium	Methanol:water 70:30	10	125	na	Isoflavons	na	[17]
Potato peel	Methanol:water 90:10	6.9	160	0.01	Phenolic acids	na	[18]

na= not accounted

Moreover, the characteristics of the solvent used for extraction in different studies are also presented in Table 2.

Table 2. Solvents in studies related to PLE technique.

Sample	Type of solvent	Amount of solid(g)	Amount of solvent(ml)	Reference
Ginger	Ethanol:water 70:30	1	41	**[15]**
Green coffee	Water	0.2	15	**[16]**
Parsley flakes	Ethanol:water 50%	0.25	20	**[19]**
Black currant	Deionized water	1	25	**[20]**
Momordica charantia	Ethanol	1	60	**[11]**
Black cohosh	Methanol:water	0.08	1	**[21]**
Chinese herbal medicine	1-alkyl 3-methylmidazolium chloride	1.5	40	**[22]**
Jabuticaba	Ethanol:water 99:1	4.5	20	**[23]**
Onion	Methanol: water 65:35	0.1	20	**[24]**
Turmeric leaves	n-hexane	2	33	**[25]**
Apple	Methanol:water	0.5	30	**[26]**
Potato peel	Ethanol: water 70:30	0.4	20	**[18]**

It has been shown in the literature that a mixture of water and simple alcohols such as methanol and ethanol increases the extraction yield compared to pure alcohol, due to the improved solubility and increased contact between the analyte and the extraction solvent. Another reason for the increase of the extraction yield by using a combination of solvents is that, for example, if we use a mixture of two solvents: the first solvent increases the solubility between the analyte and the solvent and the second solvent increases the adsorption of the analyte. For extracts in the food industry and other applications, water and ethanol are usually used as the extraction solvents [4, 5, 27].

Preliminary Design Procedure

For the preliminary design of a process, the following steps are usually taken [28]: The first step is to obtain basic information about the process. After obtaining the basic information required for the

design, the general flow sheet of the process should be found, which determines the main unit operations in the process and the main flows for the process. The flowsheet is an important and key document in the process design and should be the accurate, comprehensive, and complete presentation of the process prepared at the time of creating the process. At this stage, a decision is made on the selection of the necessary operational units. Next, the operation mode of the desired process must be identified. At this stage, it is necessary to determine the continuity or batch of the process and continue the process according to the calculations related to the mode of operation. According to the flowsheet, it is necessary to determine the appropriate equipment for the unit operation and the subsidiary equipment used in the process. Through balancing mass and energy, much of the information required for the preliminary design is obtained.

Results and discussion

Basic Information and Design

Raw Material

The amount of input plant for the process was considered 500 kg of the dried chopped plant. According to the literature, the smaller the size of these particles, the greater the mass transfer and heat transfer applied to these particles.

Solvent

The type of solvent according to the previous studies presented in Table 1 was a combination of 70% ethanol and 30% volumetric water (v/v). This solvent was chosen as a suitable solvent because it was safer and more stable, while less toxic and harmful compared to other solvents. As shown in Table 2, the amount of solvent required for extraction was 15 m^3, and according to the literature, 8 m^3 of solvent is required for washing after extraction (50% to 100% of the solvent required for extraction) [6, 8, 11, 14, 21, 29, 30, 31, 32, 33]. Hence, 23 m^3 (19603 kg) of solvent was required for the extraction process.

Operational temperature

According to Table 1, the suitable operation temperature for extraction was considered as 100 °C. The required temperature for this process is between 50 to 200 °C and according to the results of the related studies, a temperature of 100 °C is a suitable temperature for the design of this process. In this process, the temperature is one of the main factors as by its increase, the surface tension of the solvent decreases, and the surface of the matrix get wet. As a result, the analytes dissolve much faster in the solvent. Moreover, increasing the temperature reduces the viscosity of the solvent and

increases the penetration of the solvent in the matrix. It also increases the penetration rate and thus the mass transfer of the molecule in the solvent. In other words, high temperature increases the solvent capacity to dissolve the analytes and the solubility of water in organic solvents. The increase in solubility is due to the increase in temperature, which contributes to the accessibility of closed pores and the analytes in them. Because of this temperature increase, a faster penetration rate occurs. Higher temperatures may also cause the degradation of some plant compounds sensitive to high temperatures [27].

Operational Pressure

According to the studies presented in Table 1, the appropriate pressure for the selected temperature is 100 bar. Pressure, like temperature, is one of the main factors in the process. The main function of high pressure in this technique is to keep the solvent phase in liquid at temperatures above its boiling point. Another function of pressure is that by applying force to the solvent, it causes the solvent to enter the pores of the matrix and absorb the analytes [27].

Utilities

The utilities required in this process included the following:

- Electricity required for the pump;
- Nitrogen required for deoxygenation, leak testing and pressure application;

Thermal medium for heating and cooling the tank and its contents; according to the existing rules of thumb for design, water vapor with a temperature of 120 °C is used for heating and water with a temperature of 20 °C is used for cooling [34].

Fluid for Leak Testing, Deoxygenation and Pressure Source

Some inert gases are used to neutralize the environment. Nitrogen is a dry, non-combustible substance, and by replacing combustible gases with nitrogen, we can prevent the ignition of materials. Replacing oxygen with nitrogen along with moisture result in higher safety of the instruments. In order to start a system, an inert gas such as nitrogen must be used in the system. Sometimes the amount of nitrogen used is very high, but this gas is cheaper than the other non-flammable gases [35].

Block Flow Diagram

In this process, two main unit operations (extraction and concentration) are performed. The main input and output currents to each of these operations are shown in Figure 1.
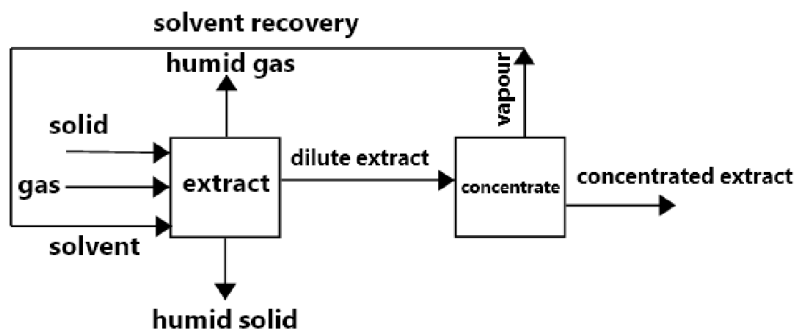
Figure 1. Block flow diagram of the bioactive extraction process.

Operational Mode

With a general comparison between the continuous and batch operational modes and according to the process conditions under study, we selected the batch operational mode for the extraction stage of this process. Because the access to the feedstock was limited, the retention time in this process was long. Only one common equipment was used to produce different products. Due to the presence of solid particles in the input materials, the system needed to be washed regularly. In each batch, the quality of each product was confirmed. It has been mentioned in the literature that due to the difficulties and problems of designing a suitable device for loading solids, the pressurized liquid extractors are usually made in the form of batch systems, in which the extraction is done in a fixed-bed vessel. This equipment are the most suitable options for products with large quantity and small volume, such as pharmaceutical and food products [36]. The design equations related to this process are unsteady. In this type of process, timing is very important. Batch calculations include unsteady balances that are very different from the steady-state design calculations. Batch sequencing, i.e., categorizing and timing the stages in the batch process is one of the most important issues to be considered. For this reason, it is necessary to obtain the time interval of each part of the process in order to present its timing through the Gantt chart, which is explained in the following[37]. In addition, in the concentration stage, a continuous operation mode is considered for the falling film evaporator.

Equipment

For this process, a solvent storage tank as well as an extract storage tank, a pump, a nitrogen source, a suitable extractor, a suitable heating and cooling system, a proper solvent circulation system, a pump to transfer the extract to an evaporator, and a falling film evaporator were used.

The amount of solvent was one batch and some solvent was stored in the tank for washing (usually 50-100% of the solvent was used). In total, the volume of the tank was about 23 m^3 [38]. As this tank had oval top and bottom and since its height to diameter ratio was 1.5 (H/D = 1.5) (in the

literature, the height to diameter ratio is usually changing between 0.7-2) [39, 40]. A centrifugal pump was used to load the solvent to the extractor. The recommended velocity for pumping water or similar solvents is suggested to be 0.3-1.5 m/s (with an average of 0.9)[38]. Assuming that the loading time of the solvent was 15 minutes, and considering that, the volume of the solvent entering the extractor was 15 m^3, the cross-sectional area of the desired pipe was estimated to be 6 inches. We selected SCH 10, with a thickness equal to 3.4 mm and an inner diameter equal to 0.164 m; then, the actual velocity was obtained to be 0.8 m/s. By calculating the equivalent length for the elbows and valves in the discharge and suction heads [38], the equivalent length was estimated to be 4.92 m for the elbows and 0.492 m for the valves. The total head due to friction loss was equal to 21.648 m. Finally, the total head was equal to 27.448 m (equivalent to 0.228 MPa).

The extractor required for this type of process is a fixed-bed, in which the dried plants are placed in a basket in a fixed and immobile manner, and to estimate the volume of the extractor, the amount of the input material must be used. According to the initial assumptions, 500 kg of dry solid was the solid input to the extractor and 15 m^3 of solvent (Table 2) was the solvent input to the extractor. 30% of the total volume is considered for vapors and gases, then, estimated volume for the extractor was approximately equal to 20 m^3. As the extractor was a cylinder, the diameter of the extractor was obtained to be 2.32 m and its height was obtained to be 4.67 m.

Thermal mediums were considered for heating and cooling the extractor and heating the evaporator. Heating and cooling for the extraction system were wrapped as half pipes around the extractor and used for both cooling and heating of the extractor. Heating fluid (water vapor with a temperature of 120 °C) and cooling fluid (water with a temperature of 20 °C) were used for heating and cooling in the half pipes. Moreover, for heating the evaporator, hot water with a temperature of 70 °C is used.

The extract tank is selected as a cylinder with a flattop and bottom. Considering that the volume of the extract extracted from the extractor is 23.0138 m^3, we consider the volume of this reservoir to be equal to 23.5 m^3. Therefore, as the calculations related to the volume of the tank indicate, the diameter of the desired tank is 1.38 m and its height is 4.14 m.

The extract was loaded continuously to the evaporator for 2 hours. Since the extract volume was 23.0138 m^3, the solvent flow rate was obtained to be equal to 0.191 m^3 per minute. According to the calculations related to the pump and considering that the material of the tube was stainless steel, its inner diameter was 0.164 m and its inner cross section 0.0211 m^3, it could be estimated that the actual velocity of the fluid inside the tube was 0.15 m/s. According to the elevations and the calculations related to the pump, the total head of the pump was estimated to be 25.208 m, which was equivalent to 0.213 MPa.

For concentrating the extract, a falling film evaporator is a suitable option because it is used for temperature-sensitive materials, such as food and medicine, or for materials with short liquid retention time. It is also suitable for liquids that contain small amounts of solids. The temperature difference between the thermal medium and the liquid inside the evaporator is small. In this type of evaporator, due to gravity, the film created is thinner. These types of evaporators have a compact location and occupy less space [41-44].

In this type of evaporator, the feed is pumped to the top of the evaporator and a distributor is installed inside the tubes. The fluid moves downwards along the tube in the form of a liquid film with the help of gravity. When the condensed liquid reaches the bottom of the chamber, a liquid-vapor separator directs the vapor to the condenser [41-44]. It should be noted that the falling film evaporator is a combination of shell and tube heat exchanger and a vapor-liquid separator [45].

Process Description

Overall, the total time for extraction and concentration operations from the beginning to the end is 8 hours (1 working shift). To perform the extraction operation, several steps were taken consecutively, including preparation and loading, extraction, washing after extraction and discharging. These steps are described in the following. As mentioned, one of the most important parameters in the batch process is the operation time of the process, which is estimated below for each operation separately.

For each batch, 500 kg of chopped dried plant with a density of 900 kg/m^3 was loaded in the extractor. Since the operation was done at high pressure, to prevent the leakage of material from the extractor during the operation, a leak test was performed. The purging scheme was based on reducing the amount of oxygen in the extracting atmosphere from 21% to 1%. For purging calculations, dilution purging method was used since the ratio of height to diameter of the extractor was not significant (H/D=2) [38]. The volume of nitrogen required for the purging operation was equal to 60.88 m^3.

After loading the solvent and during the extraction operation, the circulation pump was turned on. For the present process, half pipes were used around the extractor for heating and cooling, as mentioned, for heating, the fluid water vapor with a temperature of 120 °C was used, and for cooling, the fluid water with a temperature of 20 °C was used. The required time for heating the system from the ambient temperature to the operation temperature was 15 minutes. By applying 20% of safety factor, the extractor-heating rate reached 251044.5 kJ/min. Moreover, the heating rate to compensate for the loss was calculated to be 31.34 kJ/min considering the extraction time of 40 minutes and the safety coefficient of 20%. To apply pressure to the extractor, nitrogen gas under

pressure was used. The choice of nitrogen gas was appropriate because it is a cheap, non-flammable inert gas. The volume of the injected gas to apply pressure was equal to 4.45 m^3 (fluid volume change was assumed to be insignificant).

The extraction operation time, which involved removing bioactive compounds from the plant at a temperature of 100 °C and a pressure of 100 bar, was 40 minutes. During this period, the external circulation of the solvent took place. After extraction period, for cooling, cold water with a temperature of 20 °C was used. Accordingly, to cool the temperature of the extractor contents to 30 °C, -2925448.4 kJ energy was required. The cooling rate was -234308.172 kJ/min with a cooling time of 15 minutes and a safety coefficient of 20%. To break the pressure of the extraction tank after the extraction operation, the pressure was reduced to atmospheric pressure. To discharge liquid from the extractor, the discharge time was considered 3.5 minutes [38]. Solid washing done in order to remove the extracted compounds stuck in the solid matrix took 30 minutes. At the end of the batch, solid discharge takes place. Extraction yield is usually defined as follows:

Extraction yield (mg/g) = Average of analytes in the extracted extract (mg) / average mass of the plant sample (g). In fact, the compounds in the extract in mg are divided by the dry weight of the plant sample in g, some of which are presented in Table 3.

Table 3. Extraction yields in the studies related to PLE.

Sample	Extraction yield(mg/g)	reference
Ginger	Compounds=20.8	[15]
Salvia miltiorrhiza	Tanshinons=13.1	[46]
Soya bean	Compound=1.13	[14]
Phyllanthus	Phenolic compounds=57	[13]
Scutellaria	Baicalin=20.81	[47]
Medicinal plants	Compounds=23.8	[48]
Rhizome and tuberous root	Compounds=51	[49]
Schisandra chinensis	Compounds=17	[27]
Green coffee	Antioxidant=26.5	[16]
Brazilian ginseng	Compounds=33.1	[50]
Peel of cider apple	Sample 1=12.014	[51]
Horse chestnut herb	Deacyl saponin=37	[52]
Milk thistle fruit	Silybin=11.6	
Turmeric rhizome	Curcumin=10.6	
Thyme herb	Thymol=11.7	
Coptidis	Berberine=7.1	[53]

According to the literature and the results presented in Table 3, we considered the obtained extraction yield to be 2.5% (w/w). The amount of input material to the evaporator according to the amount of extraction yield obtained is 19615.4 kg. In this process, the evaporation time is considered 2 hours. Therefore, an evaporator with an evaporation rate of 9807.7 kg/h should be used. More than 95% of the ethanol in the extract is removed [54-56]. In this process, it is assumed

that the ethanol is completely removed and the resulting bioactive compounds exit the evaporator along with the remaining water without any loss. According to the sources studied, if we consider the operating temperature of the evaporator to be 50 °C, we see that some water also evaporates at any temperature that the materials evaporate. According to the studies in various articles (where the extract enters the next stage, i.e., the drying stage), and according to the available sources regarding the output bioactive compounds obtained from the evaporator which enter the dryer [57-62], the mass balance is as shown in Figure 2:


Figure 2. Evaporator mass balance.

For the falling film heat exchangers and evaporators, the outer diameter of the tubes is generally considered to be in the range of 1.5 to 2 inches (0.038 to 0.051 m). In this process, its maximum value (0.051 m) is considered [63]. According to the tables related to the steel tubes, the appropriate diameter for the desired tube can be found. Given that sch=10 is equal to 2.77 mm, the internal diameter of the falling film evaporator tubes is estimated to be equal to 0.042 m. The value of the total heat transfer coefficient of the input extract is $1450 \frac{W}{m^2 k}$ [63].

The temperature difference between the operating temperature of the evaporator and the input extract to the evaporator tubes and the amount of heat required for heating the evaporator is equal to $20180796.18 \frac{KJ}{h}$ according to the calculations and given the safety coefficient of 20%. Considering all of these values, the amount of heat transfer surface can be calculated, which is equivalent to 695.9 m^2 [64]. According to the studies in this regard [64], the number of tubes required can be calculated given the amount of heat transfer surface, the number of tubes and the outer diameter of the tubes. As mentioned, the outer diameter of each tube is considered 0.051 m and according to the sources, the length of the tube can be considered to be between 4-10 m. We consider the average value for the length of the tubes. As a result, L = 7 is considered [42]. Therefore, the number of the tubes in the evaporator is estimated to be 621. Considering the triangular arrangement and the single-pass current for the tubes, the CTP value for the single-pass currents in the tube is equal to 0.93 and the CL value for the triangular arrangement of the tubes is equal to 0.866 [65]. The approximate value of the tube pitch is considered 0.07 m [28]. The resulting shell diameter is also obtained to be 1.9 m.

The value of Reynolds number in the evaporator tubes is calculated to be 71.22 [64]. Given that the Reynolds number is in the slow flow range, the value of the relevant heat transfer coefficient is calculated to be 2750.5 $\frac{W}{m^2 k}$ [64]. The retention time and the thickness of the falling film are obtained to be 23 s and 0.00011 m [64]. In this process, the vertical separator is selected as the vapor-liquid separator in the falling film evaporator. To calculate the diameter of the tank required for the design of the vapor-liquid separator, the sedimentation rate of the liquid droplets of 1.8 $\frac{m}{s}$ is obtained [66]. As a result, the diameter of the tank is obtained to be equal to 1.34 m.

Gantt chart and Flow Sheet

Eight working hours is considered for this process. The Gantt chart for this process is shown in Figure 3:
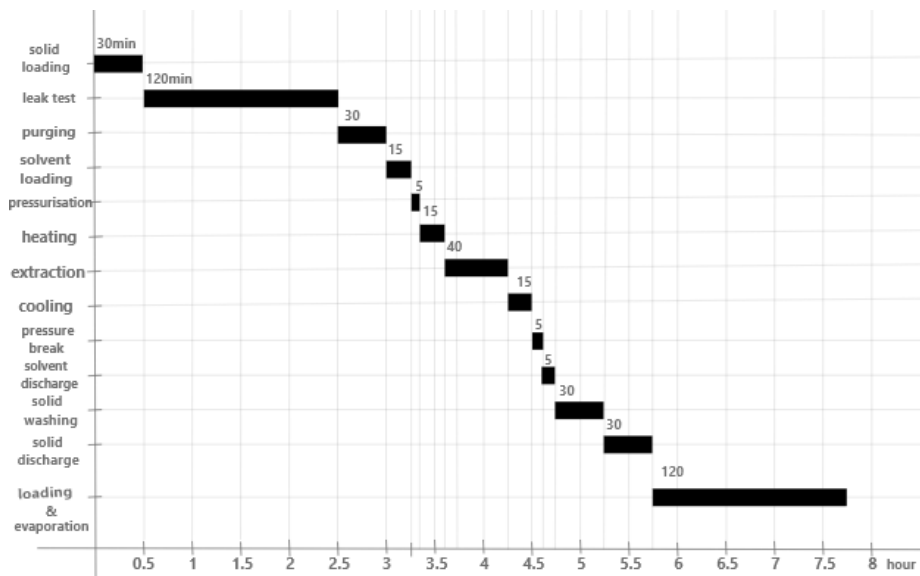
Figure 3. Gantt chart of the batch operation.

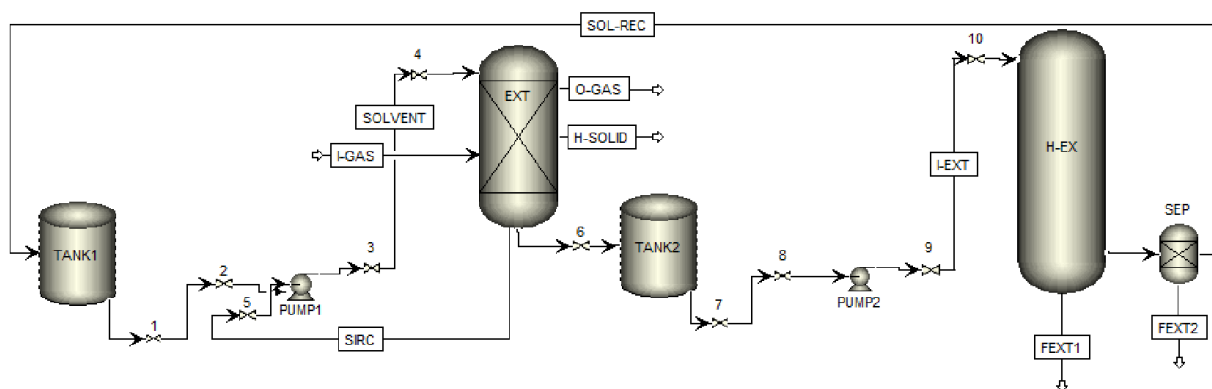The process flow sheet of the process is shown in Figure 4.

Figure 4. Flowsheet of the process.

Conclusion

The industrial sustainability of the phytochemicals extraction will benefit from the implementation of intensified processes such as PLE [67]. To implement this technique, a commercial unit must be designed. The first step in designing a factory is the development of a preliminary design. The basic conditions [68] for this design were as follows: 70/30 (v/v) ethanol/water as a solvent, operation temperature of 100 °C, operation pressure of 100 bar, nitrogen gas for pressure application, and extraction time of 40 minutes. The amount of solvent for extraction was 15 m^3, which extracted the compounds form 500 kg of dried plants. According to the results, 12.5 kg of bioactive compound was finally extracted. The diluted extract is continuously transferred to the falling film evaporator and is converted into a concentrated extract then enters the drying stage. The operational mode of the process is batch in the extraction stage and continuous in the evaporation stage. Finally, Gantt and PFD diagrams related to the process are presented according to the calculations and relationships related to the batch process.

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