Oil Extraction from Spent Coffee Grounds: Experimental Studies and Exergoeconomic Analysis

Diana L. Tinoco-Caicedo[a,b,*], Medelyne Mero-Benavides[a], Katherine Córdova-Molina[a], Denisse Estrada-Ordoñez[a], Ana M. Blanco-Marigorta[c]

[a]ESPOL Polytechnic University, Escuela Superior Politécnica del Litoral, ESPOL, Facultad de Ciencias Naturales y Matemáticas (FCNM), Campus Gustavo Galindo Km. 30.5 Via Perimetral, P.O. Box 09-01-5863 Guayaquil, Ecuador
[b]ESPOL Polytechnic University, Escuela Superior Politécnica del Litoral, ESPOL, Centro de Energías Renovables y Alternativas (CERA), Campus Gustavo Galindo Km. 30.5 Via Perimetral, P.O. Box 09-01-5863 Guayaquil, Ecuador
[c]Department of Process Engineering, Universidad de Las Palmas de Gran Canaria, 35017, Las Palmas de Gran Canaria, Canary Islands, Spain.
dtinoco@espol.edu.ec

Currently, the spent coffee grounds (SCGs) are considered an agro-industrial waste with a high oil content that can be used as a feedstock in biorefineries. Therefore, the oil extraction from SCGs is considered a main stage, that should be sustainable and low-cost. The aim of this study is to determine and compare the exergetic and economic indicators of two SCGs oil extraction processes: soxhlet extraction (SE) and ultrasound-assisted extraction (UAE). The exergoeconomic balances were performed by using Engineering Equation Solver (ESS). In addition, the effects of the solvent to SCGs ratio on the extraction yield and on the exergoeconomic indicators were studied. The analysis aided by computational tools determined that the exergy destruction rate of the SE process (14.3 kJ/kg) is higher compared with the UAE process (4.50 kJ/kg). Therefore, the oil specific cost is reduced to 86% when using UAE process. Furthermore, in the UAE process, the increase in the hexane to SCGs ratio from 5 mL/g to 20 mL/g, reduces the oil specific cost by 68.5 % and increases the oil extraction yield from 10.5 % to 18.8 %. Future studies should focus on the ultrasound-assisted extraction process scale-up.

1. Introduction

Nowadays, the SCGs oil is considered a potential feedstock for the production of bioproducts used in health and energy applications (Atabani et al., 2019). Previous studies have found useful chemical compounds, such as fatty acids and caffeine, derived from the SCGs oil. Moreover, the SCGs oil has exhibited antioxidant and enzyme inhibitory properties (Zengin et al., 2020). Given that the oil extraction from SCGs is considered a main stage in a biorefinery for SCGs valorization (Atabani et al., 2019), different aspects of the process should be studied such as oil extraction yield, sustainability and profitability.

The oil extraction processes such as soxhlet, ultrasound-assisted, microwave assisted and maceration that have been experimentally studied at lab scale (Le et al., 2017) highlight the disadvantage of using the maceration process because it is time consuming and has the lowest yield (11 %). In contrast, the soxhlet and microwave assisted process are the highest (between 15 % and 16 %). However, the microwave assisted process has a potential for oxidative damage to valuable lipid products (Mercer and Armenta, 2011), while the UAE method had minimum effects on extractable compounds (Stratakos and Koidis, 2015). Also, UAE method has advantages over the other methods (Mwaurah et al., 2020), because it is had the lowest energy, water and solvent consumption. Therefore, the SE and the UAE processes are considered the most promising methods to extract oil on an industrial scale.

Furthermore, the experimental oil extraction yield from SCGs had been studied by using different solvents. (Somnuk et al., 2017) analyzed the effect of using different solvents such as hexane, anhydrous ethanol, hydrous ethanol, and methanol. They concluded the highest oil extraction yield is achieved when using hexane (14.7 %) and the lowest oil yield (7.5 %) was achieved when using methanol. Also, they demonstrated that the recirculation of hexane is technically possible.

Exergy is considered an important indicator of the sustainability of a process (Lucia and Grisolia, 2019). Furthermore, the exergoeconomic analysis have been used for designing, improving and optimizing industrial operations to increase efficiency and reduce operating costs (Bejan and Tsatsaronis, 2021). Although there are some experimental studies of oil extraction from SCGs, these studies do not analyze the exergy destruction rate and the operating cost of the process. Thus, there has been no exergoeconomic analysis of the solvent oil extraction from SCGs or other biomass.

There have only been found exergy analysis performed to mechanical oil extraction processes from other biomasses in different biorefineries. The palm oil extraction by expeller pressing was analyzed by exergy methods (Julio et al., 2021) and it was determined that this stage has a lower exergetic efficiency (49.3 %) compared to other stages of the biorefinery process such as transesterification (89 %), and hydroprocessing (70%). Another study (Khounani et al., 2021) determined that the safflower oil from straw by using a two large oil screw expeller, destroyed the 2.6 % of the overall exergy destruction rate from the biorefinery

In this context, this study aims to perform an exergoeconomic analysis of the SCGs oil ultrasound-assisted extraction (UAE) and the soxhlet extraction (SE) processes by using hexane as the solvent. In addition, the effect of the solvent to SCGs ratio on the oil UAE yield was studied experimentally. The exergetic, economic, and exergoeconomic balances were performed by using Engineering Equation Solver (ESS) software following the methodology from (Bejan and Tsatsaronis, 2021).

2. Materials and methods

2.1 Ultrasound-assisted oil extraction

Spent coffee grounds (SCGs) were obtained from an instant coffee factory located in Guayaquil, Ecuador. SCGs were dried in an oven drying (UNB 500, Memmert, Germany) at 105 °C according to the ASTM E871 method. Ultrasound-assisted extraction (UAE) was conducted using a 205 W Ultrasound homogenizer (Fisher Scientific) at room temperature (25 °C) according to a previous study (Le et al., 2017). The Hexane to SCGs ratios analyzed were 5:1, 10:1, 15:1 and 20:1. The oil extraction time was set at 30 minutes. At the end of the experimental run, the extract was filtered through 0.45 um membrane filter. The solvent recovery was carried out at 40 rpm, 40°C, and 300 mbar in a rotatory evaporator (BÜCHI 87 Rotavapor R-215). Extracted oil was weighed and oil yield was calculated using Eq. 1.

$$\text{Oil yield (\%)} = \frac{m_{oil}}{m_{SCGs}} \cdot 100 \tag{1}$$

2.2 Process description

2.2.1. Ultrasound-assisted oil extraction

The following UAE extraction process is based on the process conducted experimentally (described on section 2.1). Figure 1 a) shows the process flow diagram of the UAE process for the production of SCGs oil. SCGs (stream 1) and hexane (stream 2) enter the ultrasound-assisted extractor (EX-101) which consumes electricity from the national network. A solid-liquid mixture exits the EX-101 and enters the separator (F-101) to separate the defatted SCGs (stream 4) and the liquid mixture (stream 5). The liquid mixture of hexane and oil enters the evaporator (EV-101) which consumes electricity to evaporate hexane and to obtain the purified oil (stream 6). Finally, the solvent (stream 7) is condensed t by using chilled water (stream 8).

2.2.2. Soxhlet oil extraction

Figure 1 b) shows the process flow diagram of the soxhlet extraction (SE) process for the production of SCGs oil based on the operation conditions of a previous study (Al-Hamamre et al., 2012; Le et al., 2017). SCGs (stream 1) and hexane (stream 2) enter the soxhlet extractor (EX-201) which consume electricity from the national network to reach the operating temperature of 69 ºC (boiling point of the solvent). The retention time in the extractor is 3 hours (Al-Hamamre et al., 2012; Le et al., 2017). From the EX-201 exits a liquid mixture (stream 5) and the defatted SCGs (stream 4). The liquid mixture of hexane and oil enters the evaporator (EV-201) which consumes electricity to evaporate hexane and to obtain the purified oil (stream 6). Finally, the solvent (stream 7) is condensed by using chilled water (stream 8).
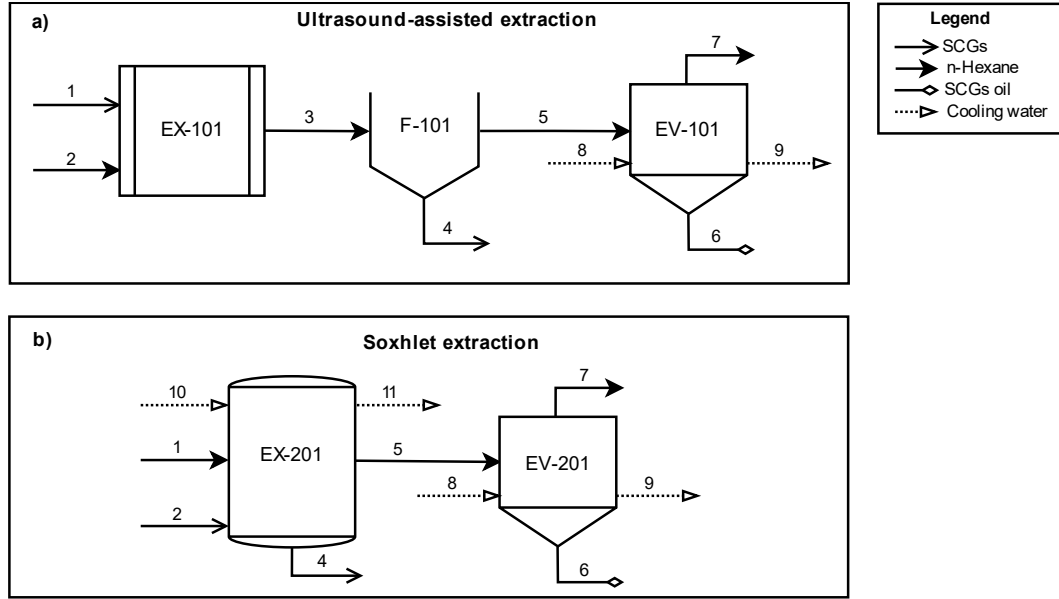
Figure 1: Process flow diagram of a) UAE and b) SE processes (Al-Hamamre et al., 2012; Le et al., 2017).

2.3 Exergoeconomic Analysis

The exergoeconomic analysis of the UAE and SE processes were developed by using equations Eq. (2) to Eq. (6)) (Bejan and Tsatsaronis, 2021). Engineering Equations Solver (EES) software was used to determine the thermophysical properties for the calculation of enthalpy and entropy of each state. The enthalpy (h) and entropy (s) of SCGs were determined using the heat capacity taken from literature (Afolabi et al., 2020).

$$e_i^{PH} = (h_i - h_o) - T_o(s_i - s_o) \tag{2}$$

$$e_i^{CH} = \sum_i x_i e_i^{ch} + RT_o \sum_i x_i \ln x_i \tag{3}$$

$$\dot{E}_{D,k} = \dot{E}_{F,k} - \dot{E}_{P,k} \tag{4}$$

$$\dot{C}_{F,\,k} + \dot{Z}_k = \dot{C}_{P,\,k} \tag{5}$$

$$\dot{C}_{D,k} = c_{F,k}\dot{E}_{D,k} \tag{6}$$

The economic analysis was carried out following the Total Revenue Requirement method (Bejan and Tsatsaronis, 2021). The purchase equipment cost (PEC) for each component of the process was obtained from vendors based on the required characteristics and they are presented in the results section. The cost of cooling water, n-hexane and electricity are 0.72 $/m³ (International Water Services Interagua C. Ltda., 2019), 0.03 $/kg, and 0.0765 $/kWh (Macías Centeno et al., 2018), respectively. The economic parameters used for the economic analysis and specific cost of biomass were taken from a previous study by authors (Tinoco-Caicedo et al., 2021). The total operating cost rate ($\dot{Z}_k$) was determined as is shown in Eq. (7).

$$\dot{Z}_k = \dot{Z}_k^{O\&M} + \dot{Z}_k^{CI} \tag{7}$$

where $\dot{Z}_k^{O\&M}$ and $\dot{Z}_k^{CI}$ are the cost rate associated with the capital investment and the cost rate for operation and maintenance, respectively.

Table 1 shows the fuel exergy ($\dot{E}_F$), product exergy ($\dot{E}_P$), fuel cost ($\dot{C}_F$), product cost ($\dot{C}_P$) and auxiliary equations at component level and for the overall system.

Table 1: Equations used for the exergoeconomic analysis.

Component	$\dot{E}_{F,k}$	$\dot{E}_{P,k}$	$\dot{C}_{F,k}$	$\dot{C}_{P,k}$	Auxiliary equation
EX-101/EX-201	$\dot{E}_1 - \dot{E}_4 + \dot{W}_{U-101}$	$\dot{E}_5 - \dot{E}_2$	$\dot{C}_1 - \dot{C}_4 + \dot{W}_{U-101} \cdot c_{EP}$	$\dot{C}_5 - \dot{C}_2$	$c_4 = c_5$
EV-101/EV-201	$\dot{E}_5 - \dot{E}_7 + \dot{E}_9 - \dot{E}_8 + \dot{W}_{EV-201}$	$\dot{E}_6$	$\dot{C}_5 - C_7 + C_9 - \dot{C}_8 + \dot{W}_{EV-101} \cdot c_{EP}$	$\dot{C}_6$	$c_7 = c_6$ $c_9 = c_8$
Overall system	$\dot{E}_F = \dot{W}_{U-101} + \dot{W}_{EV-101} + \dot{E}_1 - \dot{E}_4 + \dot{E}_2 - \dot{E}_7 + \dot{E}_9 - \dot{E}_8$				
	$\dot{E}_P = \dot{E}_6$				

3. Results and discussion

3.1 Experimental studies

Figure 2 a) shows the oil extraction yield for the UAE process at different Hexane to SCGs ratios. It is observed that the increase of the Hexane to SCGs ratio from 5 mL/g to 20 mL/g, increases the oil extraction yield from 10.5 % to 18.8 %. In addition, Figure b) shows the results from literature (Al-Hamamre et al., 2012; Le et al., 2017) for the SE process. It is observed that the highest yield is obtained at 15 mL/g (17 %) and at 20 mL/g the yield decreases, even less than the UAE process. It can be noted that the use of ultrasound waves is more efficient because they produce the destruction of cell membranes of the solid to extract the intracellular oil (Zhang and Wong, 2012). While the Soxhlet process used convection heating for the oil extraction.
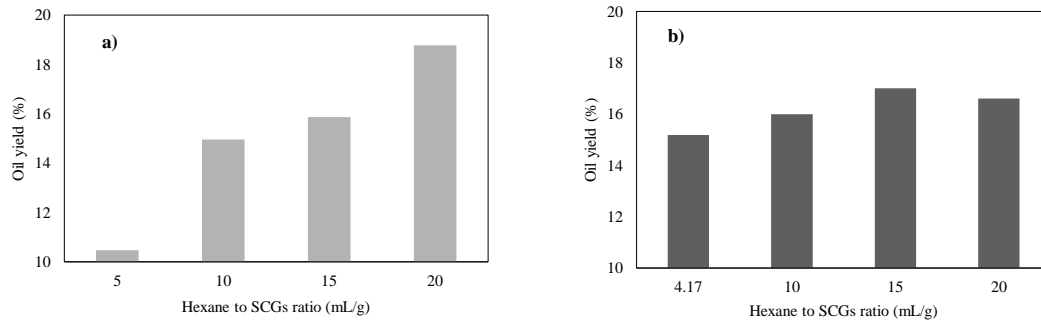

Figure 2: The effect of Hexane to SCGs ratio on the oil yield for a) UAE and b) SE processes (Al-Hamamre et al., 2012; Le et al., 2017)

3.2 Exergoeconomic analysis

The exergoeconomic indicators for the UAE and SE processes at different Hexane to SCGs ratios were determined. Figure 3 shows the exergy destruction rate at a component level and the overall exergetic efficiency for each process. SE process presents higher exergy destruction rates than UAE process. Also, it is observed that the EV-201 (in the SE process) is the component with the highest exergy destruction rate. This is mainly because the exergy rate of the hexane oil mixture stream in the SE process is higher than in the UAE process, due to the high energy consumption. A previous study (Atabani et al., 2019) observed that the SE process is a time-consuming process with low productivity that requires a higher amount of solvent and energy.

In addition, the exergetic efficiency tends to decrease when the solvent to SCGs ratio increases for both processes. It is evidenced that the UAE process has a higher exergetic efficiency and a lower exergy destruction rate than the SE process. This behavior could be attributed to the long period of time (2 to 3 hours) that is required for SE. In contrast, UAE process usually requires 30 minutes for the extraction, because longer periods of time could reduce the extraction yield (Mofijur et al., 2020).
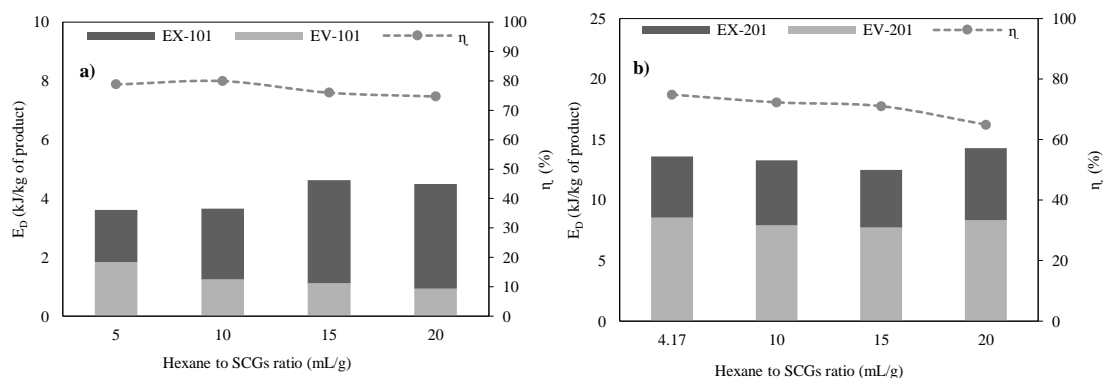

Figure 3: The effect of Hexane to SCGs ratio on the exergy destruction rate and the exergetic efficiency for a) UAE and b) SE processes (Al-Hamamre et al., 2012; Le et al., 2017).

Figure 4 shows the total investment cost for the UAE and SE processes. The total investment cost for the SE process is 28.4 % more expensive than the UAE process. This occurs mainly because the purchase equipment costs, and the energy consumption are higher in the SE process.
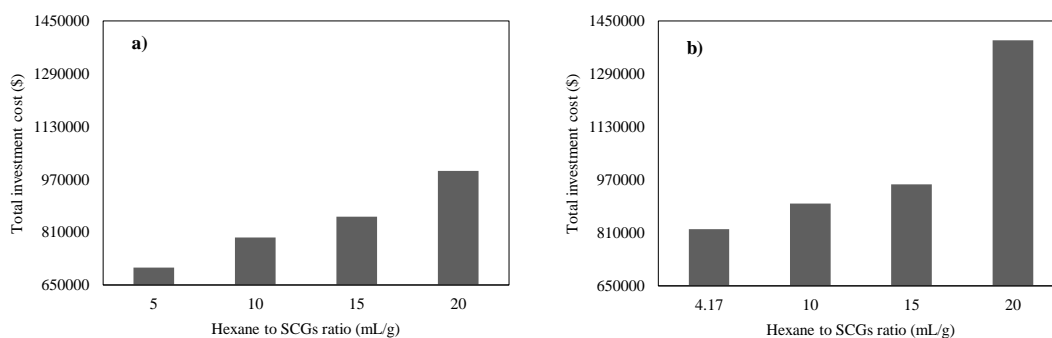
Figure 4: The effect of Hexane to SCGs ratio on the total investment cost for the a) UAE and b) SE processes (Al-Hamamre et al., 2012; Le et al., 2017).

Figure 5 shows that, in all cases, the exergy destruction cost rate represents more than 88.5 % of the operating cost rate, this means that the predominant cost in oil extraction processes is related to the exergy destruction rate. Consequently, an increase of the exergetic efficiency of the extraction process would significantly reduce the operating costs. Furthermore, it can be observed that the operating cost rate of the SE process is 78.2 % more expensive than the UAE process.
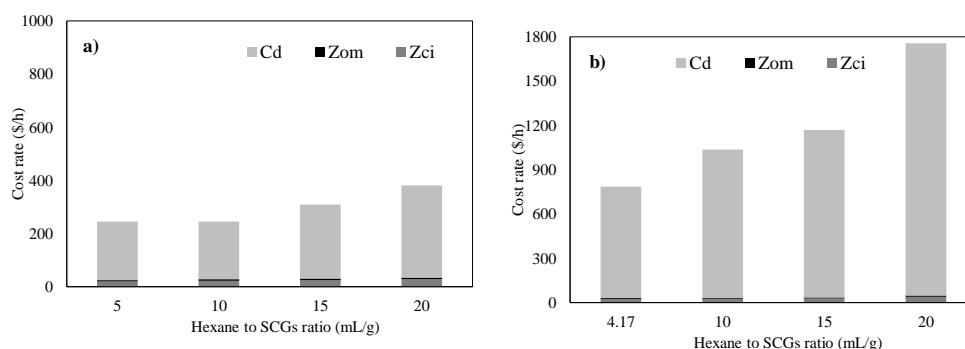

Figure 5: The effect of Hexane to SCGs ratio on the operational cost rate for the a) UAE and b) SE processes (Al-Hamamre et al., 2012; Le et al., 2017).

Although the operating costs are increased with the increment of the solvent to SCGs ratio, Table 2 shows that the oil specific cost is reduced up to 68.5% when using 20 mL/g. Furthermore, the oil specific cost is reduced up to 83.5% when UAE process is applied instead of SE process at 20 mL/g. The minimum oil specific cost obtained from SCGs was 0.12 $/kg.

Table 2: Results of the exergoeconomic analysis for UAE and SE processes

	UAE				SE			
Hexane to SCGs ratio (mL/g)	5	10	15	20	4.17	10	15	20
PEC ($)	26000	27500	28500	30000	29500	44500	59500	74500
$\dot{Z}^{CI}$ ($/h)	20.15	22.73	24.50	28.43	24.12	26.00	27.61	39.89
$\dot{Z}^{O\&M}$ ($/h)	5.04	5.47	5.90	6.32	7.17	7.60	8.03	8.45
Oil cost ($/kg)	0.38	0.21	0.15	0.12	2.72	1.28	0.91	0.73

4. Conclusions

This study aimed to perform an exergoeconomic analysis of two SCGs oil extraction processes: soxhlet extraction (SE) and ultrasound-assisted extraction (UAE) based on literature and experimental results, respectively. This research shows that the exergy destruction rate is reduced up to 79.7 % when UAE process is used instead of SE process. Also, the exergetic efficiency is increased by 5.5 % when the hexane to SCGs ratio increases from 5 mL/g to 20 mL/g in the UAE process. The operating cost can be reduced by 78.2 % when using UAE process. The specific oil cost is reduced from 0.38 $/kg to 0.12 $/kg when the solvent to SCGs ratio is increased and at 20 mL/g, the lowest specific oil cost is reached. Finally, the results suggest that UAE process

has more benefits from the exergy and economic viewpoints. Future studies should focus on ultrasound-assisted extraction process scale-up.

Nomenclature

c_i – unit exergy cost, \$/kJ

$\dot{C}_i$ – cost rate associated with exergy, \$/h

$\dot{E}$ – exergy rate, kJ/h

e^{PH} – physical exergy, kJ/kg

e^{CH} – chemical exergy, kJ/kg

EP – electric power

h – specific enthalpy, kJ/kg

m – mass, kg

PEC – purchased equipment cost, \$

R – ideal gas constant (kJ/kmol·K)

s – specific entropy, kJ/kg

T_o – dead state temperature

x_i – molar composition

$\dot{Z}_k$ – investment cost rate, \$/h

η – exergetic efficiency, %

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