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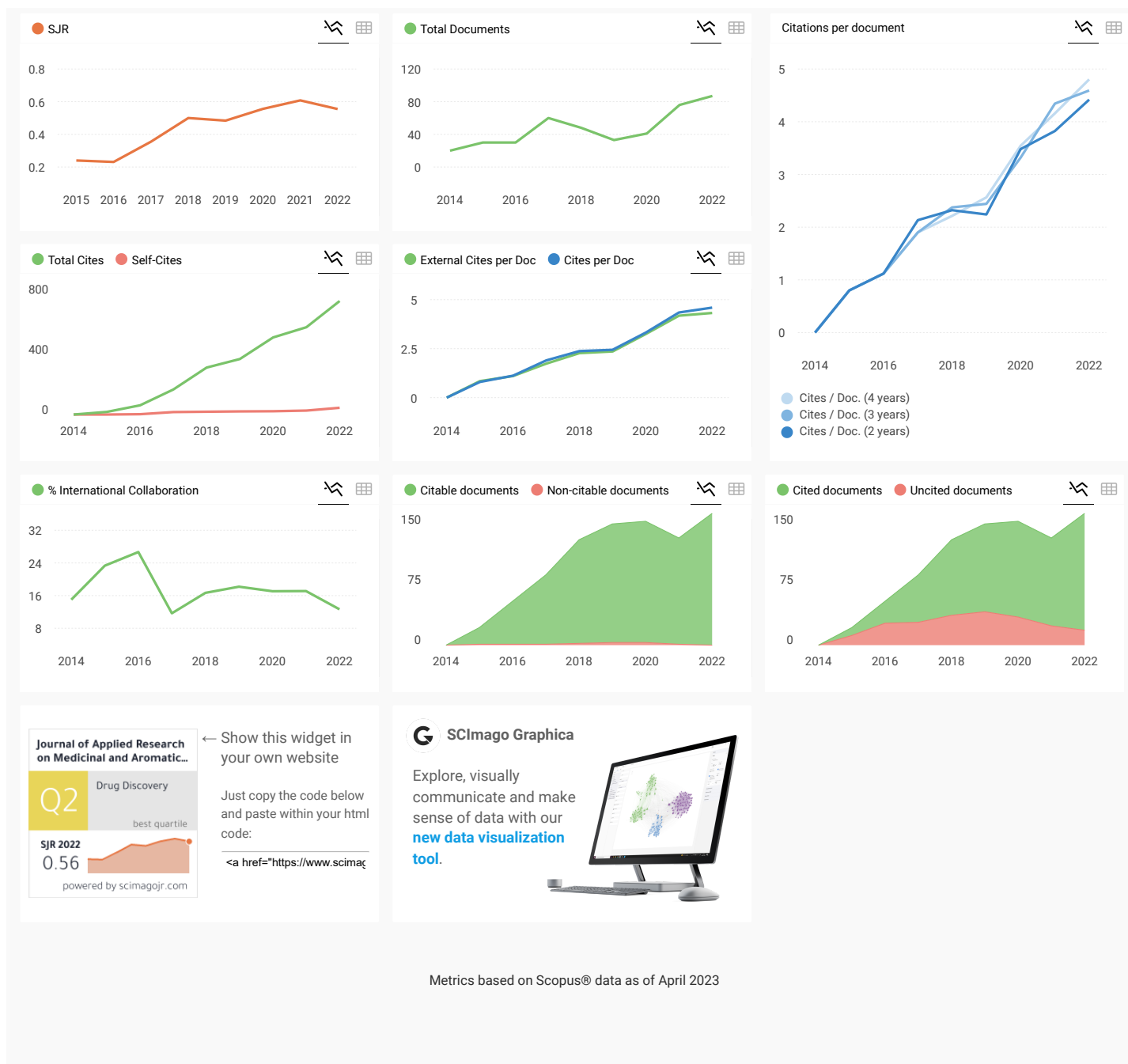
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Dear Rizal,
Thank you for contacting us.

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Short communication

Economic evaluation of the production of oil extracted from pressed sesame seed cake using supercritical CO₂ in ThailandKritika Buranachokpaisan^a, Yongyut Chalermchat^{b,d}, Rattana Muangrat^{b,c,d,*}^a Division of Food Science and Technology, Faculty of Agro-Industry, Chiang Mai University, Mae-Here, Muang, Chiang Mai 50100, Thailand^b Division of Food Process Engineering, Faculty of Agro-Industry, Chiang Mai University, Mae-Here, Muang, Chiang Mai 50100, Thailand^c Cluster of High Value Product from Thai rice and Plant for Health, Chiang Mai University, 239 Suthep, Muang, Chiang Mai 50200, Thailand^d Bioactive Compound Extraction Research Unit, Faculty of Agro-Industry, Chiang Mai University, Chiang Mai 50200, Thailand

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ABSTRACT

The optimal condition for extracting sesame oil from pressed sesame seed cake using supercritical CO₂, previously determined as an extraction temperature of 50 °C, extraction pressure of 220 bar and extraction time of 5 h to obtain the optimal extracted oil yield of 29.8% dry basis, was used to estimate the scale-up and cost of a supercritical CO₂ extraction plant. Economic evaluation of the process for extracting oil from pressed sesame seed cake using supercritical CO₂ was determined using two 360 L volume extraction vessels with an internal diameter of 0.43 m and height of 2.5 m, a CO₂ density of 806.61 kg/m³, a CO₂ flow rate to feed mass ratio of about 282.31 kg CO₂ per kg feed and a bed diameter (D) to bed height (L) ratio of 0.17. The result showed that the total estimated capital investment required to establish a supercritical CO₂ extraction plant with a capacity of 250 tons per year is 80.25 million Baht and the estimated manufacturing cost is 20.78 million Baht per year. The production cost is approximately 277.03 Baht per kg of oil and the selling price of extracted sesame oil is approximately 500 Baht per kg of oil. Thus, the net profit is 16.72 million Baht per year. As a result, the rate of return on investment and the payback period are 20.84 % and 3.56 years, respectively. The sensitivity analysis showed that the profitability of supercritical CO₂ extraction plant is highly dependent on selling price and annual production of the extracted sesame oil product. The results imply that the proposed up-scaled supercritical CO₂ plant is economically feasible.

1. Introduction

Pressed sesame seed cake, a by-product of sesame seed oil production, is mainly utilized as animal feed and fertilizer (Suja et al., 2005). Several studies have revealed that pressed sesame seed cake contains a high amount of residual oil containing several phytochemicals, especially sesamin and sesamol, which encourages their potential applications in the food, nutraceutical and cosmetic industries (Sahin and Elhussein, 2018). Moreover, the most efficient usage of the resource is of great interest due to the risk of exhaustion of natural resources. Recently, the global demand for sesame seed and its product, especially sesame oil, is growing in both fresh and processed form due to the rise of the healthy food trend (Ji et al., 2019). Since the current value of sesame oil is more than 350 Baht per kg of oil in Thailand, while the value of pressed sesame seed cake is only 10–15 Baht per kg, the extraction of oil from pressed sesame seed cake adds value to the by-product.

Generally, 98% of residual oil in pressed sesame seed cake can be recovered by conventional solvent extraction using hexane (Benítez-Benítez et al., 2016). However, the conventional method has many disadvantages; for example, the toxicity of organic solvents, environmental effects and process complexity should be considered before starting extraction (Bhattacharjee et al., 2007). Recently, supercritical CO₂ extraction has been widely used for food supplements and in the pharmaceutical industry because this method has a high extraction efficiency. Moreover, supercritical CO₂ is an excellent medium for extracting thermo-sensitive compounds, a safe, non-toxic and odourless solvent, and also can easily be removed from extracted products (Uwinea and Waskiewicz, 2020). In a previous study, the authors found that the yield of sesame oil extracted using supercritical CO₂ was comparable to that for conventional solvent extraction. It was found that the supercritical CO₂ extraction method can be utilized for extracting the residual oil from pressed sesame seed cake (Buranachokpaisan et al.,

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2021). Although the supercritical CO₂ extraction method has main disadvantages such as the risk and cost of high-pressure operation, the design method and operational procedures of the supercritical CO₂ extraction technique at high pressure and temperature are fully developed in several sections such as the extraction vessel, separator and liquid CO₂ accumulator. Therefore, both risks and costs can be minimized by optimization and large-scale production (Baldino and Reverchon, 2018; Perrut, 2000).

In our previous research, pressed sesame seed cake was collected from a sesame oil plant (Chaiseri Co., Ltd., Chiang Mai, Thailand) (Buranachokpaisan et al., 2021). The cake from the plant is considered as residue. The Chaiseri plant uses screw press extraction to produce sesame oil to be sold as a cooking oil. After the screw pressing, the pressed sesame seed cake is sold to animal feed plants and may contained residual oil ranging typically 21.70 – 36.05 % dry basis. But the cake samples we obtained in this present study contained approximately 36.05 % dry basis. This previous research therefore raised interest in recovering the residual oil from the pressed sesame seed cake to potentially increase its economic value using the supercritical CO₂ extraction method. There are several studies on the scale-up and economic analysis of supercritical CO₂ extraction of agricultural waste such as grape seeds, lemon verbena leaves, maize stover and waste date palm (Attard et al., 2015; Bulushi et al., 2018) but that of pressed sesame seed cake oil is insufficient. In our previous study, the optimal condition for extracting sesame oil from pressed sesame seed cake using supercritical CO₂ was obtained as follows: extraction temperature of 50 °C, extraction pressure of 220 bar and extraction time of 5 h (Buranachokpaisan et al., 2021). Thus, for an investment decision, this research aimed to estimate the scale-up and cost of a supercritical CO₂ extraction plant based on the optimal extraction condition.

2. Materials and methods

2.1. Supercritical CO₂ extraction

The optimal condition for extracting oil from pressed sesame seed cake was investigated using a pilot-scale supercritical CO₂ extractor (Guangzhou Heavensent Industrial Co., Ltd., China) at 175–250 bar and 40–60 °C for 1–5 h to obtain the highest oil yield and quality. The pressed sesame seed cake samples used in this study were obtained from roasted sesame seed oil plant in Thailand (Chaiseri Co., Ltd., Chiang Mai, Thailand). In each extraction, 2 kg of pressed sesame seed cake was placed into a 5 L extraction vessel. Liquid CO₂ in the storage tank was cooled to 2–6 °C by a refrigeration system then compressed to the required pressure by a high-pressure diaphragm pump and passed through a heat exchanger to obtain the supercritical phase. The supercritical CO₂ was delivered through a packed bed of pressed sesame seed cake in the extraction vessel. The average CO₂ flow rate was 140 L/h during extraction. The extracted oil sample and CO₂ were separated in the separator then the CO₂ was recycled back to the storage tank.

2.2. Scale-up criteria

In this research, the upscaling was investigated by maintaining constant scale-up criteria according to a review by de Melo et al. (2014) as follows:

- The ratio of solvent mass to feed mass is constant when the solute solubility limits the process
- The ratio of solvent flow rate to feed mass is constant when diffusion limits the process
- Both ratios from i and ii are constant when both solubility and diffusivity limit the process
- The ratio of bed diameter (D) to bed height (L) or D/L is constant for geometric similarity

2.2.1. Estimation of total capital investment

The total capital investment required to establish the full-scale supercritical CO₂ extraction plant was estimated using the method of Turton et al. (2009). The total capital investment consists of fixed capital investment (FCI) and the cost of manufacturing (COM).

2.2.2. Estimation of FCI

The FCI is the cost of purchasing and erecting equipment and facilities, consisting of direct expenses (e.g., purchase and installation of equipment) and indirect expenses (e.g., constructor's fee, engineering, supervision and contingency). The cost of the proposed equipment was estimated by considering the effect of capacity and time according to Eq. (1) (Rocha-Urbe et al., 2014).

$$C_2 \equiv C_1 \left(\frac{I_2}{I_1} \right) \left(\frac{V_2}{V_1} \right)^n \quad (1)$$

where C_2 is the purchase cost of equipment with the desired capacity at actual time, V_2 , C_1 is the purchase cost of equipment with known capacity at reference time, V_1 , n is a cost exponent (often around 0.6), I_1 is the cost index at the reference time and I_2 is the cost index at the actual time.

The remaining cost of FCI was calculated using the multiplication factors shown in Table 1, which were suggested by Duba and Fiori (2019).

2.2.3. Estimation of COM

The COM is the cost associated with the day-to-day operation and consists of three components: direct costs (e.g., raw material, utilities and operation labour), fixed costs (e.g., depreciation, taxes and insurance) and general expenses (e.g., administrator costs and research and development). The COM can be determined when FCI and the cost of raw material, waste treatment, utilities and operating labour can be estimated. The remaining components of the COM were estimated using the multiplication factors suggested by Turton et al. (2009) as shown in Table 2.

Depreciation was estimated using a straight-line depreciation method according to Eq. (2).

$$d = \frac{FCI_L - S}{n} \quad (2)$$

where d is depreciation, FCI_L is the depreciable capital investment, S is the salvage value which is often assumed to be zero and n is the life of the equipment in years, which is about 10 years as specified by the U.S. Internal Revenue Service.

As shown in Table 2, plant overhead costs comprised hospital and medical services, general engineering, safety services, cafeteria and recreation facilities, general plant maintenance and overheads, payroll overheads including employee benefits, control laboratories, packaging, plant protection, janitor and similar services, employment offices, distribution of utilities, shops, lighting, interplant communications and transportation, warehouses, and shipping and receiving facilities (Peters and Timmerhaus, 2003).

Table 1
Multiplication factors for estimating the fixed capital investment (FCI).

Items	Cost components	Multiplying factors
Direct expenses	- Purchase cost of equipment and accessories	0.85 FCI
Indirect expenses	- Engineering and supervision	0.05 FCI
	- Construction expenses and contractor's fee	0.05 FCI
	- Contingency	0.05 FCI
Total FCI		FCI

Table 2

Multiplication factors for estimating the cost of manufacturing (COM).

Items	Cost components	Multiplying factors
Direct manufacturing costs	- Raw materials	C_{RM}
	- Waste treatment	C_{WT}
	- Utilities	C_{UT}
	- Operating labour	$C_{DC} = 0.10 C_{OL}$
	- Direct supervisory and clerical labour	$C_{MR} = 0.02 FCI$
	- Maintenance and repair	$0.10 C_{MR}$
	- Operating supplies	$0.10 C_{OL}$
	- Laboratory charges	$C_{RM} + C_{WT} + C_{UT} + 1.20 C_{OL}$
	Total direct manufacturing costs	$+ 0.022 FCI$
Fixed manufacturing costs	- Depreciation	d
	- Local taxes and insurance	$0.05 FCI$
	- Plant overhead costs	$0.50 (C_{OL} + C_{MR} + C_{DC})$
	Total fixed manufacturing costs	$0.06 FCI + 0.55 C_{OL} + C_d$
General expenses	- Administration costs	$0.15 (C_{OL} + C_{MR} + C_{DC})$
	- Distribution and selling costs	$0.05 COM$
	- Research and development	$0.165 C_{OL} + 0.003 FCI + 0.10 COM$
	Total general expenses	
	Total COM	$0.09 FCI + 1.11 (C_{RM} + C_{WT} + C_{UT} + d) + 2.13 C_{OL}$

2.2.4. Profitability analysis

The profitability was evaluated from the rate of return on investment and the payback period, which was calculated according to Eqs. (3), (4) and (5), respectively, according to Turton et al. (2009) and Duba and Fiori (2019).

$$\text{Rate of return on investment} = \frac{\text{net profit}}{\text{total capital investment}} \quad (3)$$

$$\text{Payback period} = \frac{FCI}{\text{net profit}} \quad (4)$$

$$\text{net profit} = (\text{selling price} - \text{production cost}) \times \text{annual production} \quad (5)$$

2.2.5. Sensitivity analysis

A sensitivity analysis was elaborated to evaluate the relative importance of input parameters over the economic performance of the production of extracted sesame oil from pressed sesame seed cake using the supercritical CO₂ extraction plant. The input parameters selected to carry out the sensitivity analysis were C_{RM} , C_{UT} , C_{OL} , selling price and annual production of the extracted sesame oil, and FCI which affect the profitability of the supercritical CO₂ extraction plant. Net present value (NPV) and internal rate of return (IRR) were the profitability factors selected for the analysis. The NPV is the difference between the present value of cash inflows and outflows over a period of time, which it can be calculated by Eq. (6). The IRR is the discount rate that sets the NPV equal to zero. Additionally, the tornado diagram was performed for a better insight, with a change of $\pm 10\%$, $\pm 20\%$, and $\pm 30\%$ on each parameter once at a time.

$$\text{Net present value} = \sum_{t=1}^n \frac{FC_t}{(1+i)^t} - I_0 \quad (6)$$

where FC_t is the cash flow or net profit occurring in period time t , t is the period time in which the money will be invested ($t = 1, 2, 3, \dots, n$), n is the project lifetime, i is the discount rate and I_0 is the initial investment.

3. Results and discussion

3.1. Scale-up study

Typical experimental extraction data from previous work were available and illustrated in Fig. 1. From the Fig. 1, it suggests that there are two main mechanisms controlling the overall extraction for relatively comparable period, one with solubility limit where the rate of extraction was seemingly constant, suggesting enough oil was available at solid–fluid interface. The second was in diffusion – controlled regime where the internal diffusion rate dominated when less oil was available with the seed domain, as a result, the rate of extraction decreased at longer period.

The scale-up factors were applied by using the data for the optimal supercritical CO₂ extraction of pressed sesame seed cake obtained from our previous study (Buranachokpaisan et al., 2021). Under the range of those response values, the optimal operating condition for extraction using a 5 L extraction vessel was an extraction pressure of 220 bar and extraction temperature of 50 °C for 5 h, which provided the optimum yield and quality of extracted oil. The experimental yield of extracted oil was 29.80% on a dry basis (db); the oil contained 225.79 mg/100 g cake of sesamin, 75.57 mg/100 g cake of sesamolin and 7.03 mg/100 g cake of tocopherols and had Folin–Ciocalteu reducing capacity of 29.11 mg GAE/100 g cake (Buranachokpaisan et al., 2021).

For the supercritical CO₂ extraction process, the operating conditions, especially the pressure, have an important impact on fixed equipment's investment and operation cost. Although the increase of pressure can improve extraction efficiency, it will significantly increase the fixed equipment's investment and operation cost. Thus, the optimal extraction conditions for extraction efficiency might not be the most suitable for the economical selection. Sometimes, the optimal extraction efficiency and process cost conditions are significantly differences. However, this present study attended to select the optimal operating condition (at extraction temperature of 50 °C, pressure of 220 bar and time of 5 h) from previously study to obtain not only the high quantity but also the proper quality of extracted oil. Then, based on our

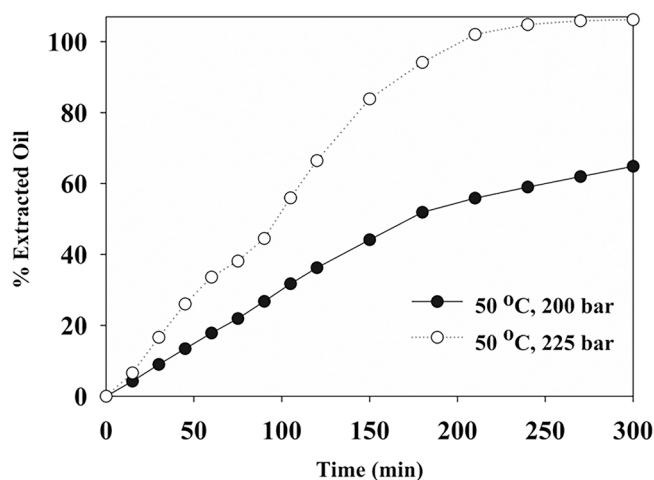


Fig. 1. Extraction curve for supercritical CO₂ extraction of residual oil from pressed sesame seed cake at temperature of 50 °C and pressures of 200 and 225 bar.

judgment, this study primarily selected substantial responses to find the optimum, such as clear oil yield, moisture content and volatile matter, acid value, free fatty acids (FFA, %), saponification value, iodine value, peroxide value, the content of sesamin, sesamol, and tocopherols and Folin–Ciocalteu reducing capacity. Therefore, this present study decided to estimate the scale-up and cost of a supercritical CO₂ extraction plant based on this optimal extraction condition for achieving an economic data. This economic data obtained will be applied to produce a good quality oil for commercializing and improving benefit of the sesame industries.

Under this optimal condition, the density of CO₂ is 806.61 kg/m³ (NIST, 2018) thus the ratio of CO₂ flow rate to feed mass was calculated to be 56.46 kg CO₂/h·kg feed. Consequently, the ratio of solvent mass to feed mass was determined to be 282.31 kg CO₂/kg feed. The last factor, D/L ratio, was determined to be 0.17. The size of the plant-scale supercritical CO₂ extractor was calculated based on the value of the scale-up factors to handle 250 tons of pressed sesame seed cake per year, which is the predicted availability in northern Thailand according to data from FAOSTAT (2018). Based on 300 working days with 24-hour operation, two 360 L extraction vessels with an internal diameter of 0.43 m and height of 2.5 m were calculated. The bulk density of pressed sesame seed cake is approximately 0.49 kg/L.

Fig. 2 shows the process flow diagram of the proposed plant-scale supercritical CO₂ extractor in our study. The extractor consists of a CO₂ cylinder, CO₂ storage vessel, heat exchanger, high-pressure CO₂ pump, two extraction vessels and a separator. Simulated semi-continuous operation was similar to that in the research of Duba and Fiori (2019) and Rocha-Urbe et al. (2014). Firstly, liquid CO₂ at 15 °C and 60 bar was cooled to 2–6 °C by a refrigeration system. After that, it was converted to the supercritical phase by compression using a high-pressure CO₂ pump to 220 bar and heating using a heat exchanger to 50 °C. The supercritical CO₂ was maintained at the required temperature and pressure in the extraction vessels by heating the jacket and backpressure regulator, respectively. While one extraction vessel was running, the other was depressurizing, unloading and preparing the next feed. When the extraction was complete, CO₂ and oil were depressurized and cooled to 75 bar and 30 °C, respectively, before separation to prevent the CO₂ freezing. Finally, the CO₂ was cooled to 15 °C before recycling back to the CO₂ storage vessel. CO₂ loss occurred during depressurization, unloading and oil collection so the system was continuously refilled with CO₂ from the CO₂ cylinder during the extraction process.

3.2. Estimation of total capital investment

From our previous study, the pilot-scale supercritical CO₂ extractor used as a reference consisted of 5 L and 24 L extraction vessels, a high-pressure pump, a heat exchanger system, a refrigeration system, a separator, an automatic backpressure regulator, and a process control and monitoring module. The operation pressure and temperature ranges were up to 350 bar and 85 °C, respectively. The price of the equipment including the accessories (e.g., piping and packing media) was 5,136,000 Baht (purchased by Chiang Mai University in 2015) before the scale-up study. In this scale-up research, the purchase cost of the plant-scale extractor with two 360 L extraction vessels in 2021 was estimated to be approximately 47.83 million Baht using Chemical Engineering Plant Cost Indices (CEPCI) of 556.8 and 754.7 at the reference (2015) and actual time (September 2021), respectively (Chemical Engineering, 2021). Additionally, the cost of the cold room for storing 250 tons of pressed sesame seed cake was estimated to be about 2.72 million Baht in 2021 based on the cost of a 43.24 m³ cold room (499,277 Baht) purchased in 2019 by the Department of Corrections in Thailand and using a CEPCI of 607.5 (Chemical Engineering, 2021). Table 3 shows the total estimated FCI of the scaled-up process for supercritical CO₂ extraction of oil from pressed sesame seed cake in this study.

The estimated manufacturing cost of the supercritical CO₂ plant for extracting oil from pressed sesame seed cake shown in Table 4 was based on the following assumptions. The raw materials of supercritical CO₂ extraction are the solid substrate (pressed sesame seed cake), the initial CO₂ and refilled CO₂. The refilled CO₂ was estimated based on the CO₂ loss, which is reported to be 2% of kg of feed in an industrial system

Table 3

Total estimated fixed capital investment (FCI) of scaled-up process for supercritical CO₂ extraction of oil from pressed sesame seed cake.

Item	Cost components	Cost in Million Baht
Direct expenses	Purchase cost of equipment and accessories	47.83
	- Supercritical CO ₂ extractor	2.72
	- Cold room (4 °C)	
Indirect expenses	- Engineering and supervision	2.97
	- Construction expenses and contractor's fee	2.97
	- Contingency	2.97
Total FCI		59.47

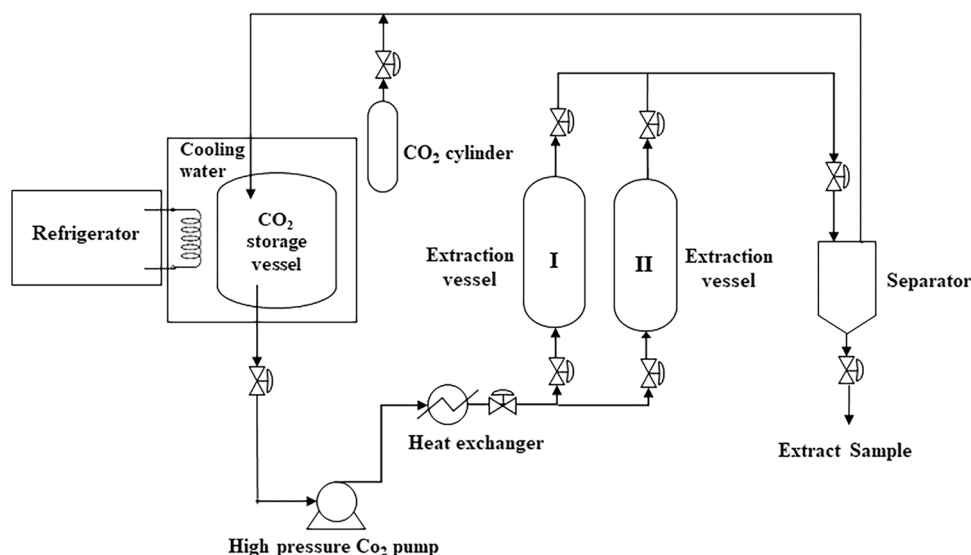


Fig. 2. Process flow diagram of plant-scale supercritical CO₂ extractor based on the optimal supercritical CO₂ extraction condition.

Table 4

Estimated cost of manufacturing (COM) of scaled-up process for supercritical CO₂ extraction of oil from pressed sesame seed cake.

Item	Cost components	Cost in Million Baht (per year)
Direct manufacturing costs	- Raw materials (C_{RM})	4.05
	- Waste treatment (C_{WT})	-
	- Utilities (C_{UT})	2.06
	- Operating labour (C_{OL})	1.30
	- Direct supervisory and clerical labour	0.13
	- Maintenance and repair	1.19
	- Operating supplies	0.12
	- Laboratory charges	0.13
	- Depreciation	5.05
	- Local taxes and insurance	2.97
Fixed manufacturing costs	- Plant overhead costs	1.31
	- Administration costs	0.39
	- Distribution and selling costs	1.04
General expenses	- Research and development	1.04
Total COM		20.78

(Duba and Fiori, 2019) at a cost of 60 Baht per kg of CO₂ (Lanna Industrial Gasses Co., Ltd., Thailand). In a supercritical fluid extraction process, the cost of waste treatment is assumed to be neglected due to the fact that leaked CO₂ is non-toxic and the residue is a dry solid without any residual toxic solvent, which may be incorporated into the soil. For operating labour, it was assumed that there will be two operators per shift and three shifts per day. The wage of the operators is approximately 18,000 Baht per month, based on the starting rate of junior engineers in Thailand. The cost of utilities mainly consists of the electric power required to compress, heat and cool CO₂, which was determined using enthalpy values of CO₂ at different locations in the closed loop. The enthalpy of CO₂ for cooling, heating and pumping was 169.34 kJ/kg CO₂ (NIST, 2018) and the ratio of CO₂ flow rate to feed mass was calculated to be 56.46 kg CO₂/h-kg feed. The cost of electric power was estimated to be 3.1 Baht per kWh based on the industrial rate in Thailand. Therefore, the utilities cost is approximately 2.06 million Baht per year. The remaining components of the COM were estimated and are shown in Table 4.

3.3. Profitability analysis

Depending on the efficiency of the screw press machine and pressing conditions, 5–20 % db of residual oil can be commonly found in pressed sesame seed cake (Martínez et al., 2017). Our previous research determined that the pressed sesame seed cake obtained from screw pressing at the sesame oil plant in Thailand (Chaiseri Co., Ltd., Chiang Mai, Thailand) contains 21.70–36.05 % db, higher than the commonly found in the pressed sesame seed cake. Under the optimal supercritical CO₂ extraction condition, 29.80 % db oil yield or approximately 0.30 kg of oil was recovered from 1 kg of pressed sesame seed cake. According to the COM from the scale-up study, it was found that about 277.03 Baht was needed to produce 1 kg of oil.

In Thailand, most commercialized sesame seed oil has been produced from roasted sesame seeds, not from raw seeds, and consumed as a food flavoring. Also, product under our investigation was from the roasted sesame seed cake residual, therefore the product that could be best referred to for selling price, should be roasted sesame seed oil already available on the market. Generally, the price of roasted sesame oil is higher than that of raw seed sesame oil due to its flavour and longer shelf life (Yin et al., 2020). The current selling price of roasted sesame oil produced in Thailand ranges from 260 to 740 Baht per kg of oil (Gluay Mai Brand, K.M. Sesame Co., Ltd.; Twin Elephants Brand and Butterfly Brand, Chaiseri Co., Ltd.). In this study, an average selling price of 500 Baht per kg of oil was selected to study the profitability. The cumulative cash flow diagram of the scaled-up process for supercritical CO₂ extraction is illustrated in Fig. 3. During the 2 years of plant

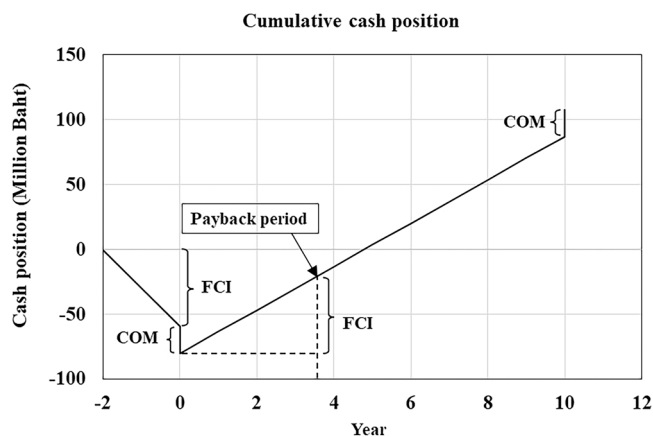


Fig. 3. Cumulative cash flow diagram of scaled-up process for supercritical CO₂ extraction of oil from pressed sesame seed cake.

construction, the FCI was used. When the plant was completely constructed, the production started in the first year then the COM was used. At the end of the 10 years of operation, it was assumed that the plant was closed down and the COM was recovered. The payback period, the duration needed to recover the FCI, is also shown in Fig. 3. Thus, the net profit of the scaled-up process for supercritical CO₂ extraction was calculated to be approximately 16.72 million Baht per year. As a result, the rate of return on investment and the payback period were 20.84 % and 3.56 years, respectively (as shown in Fig. 3). These results imply that the supercritical CO₂ plant for extracting oil from pressed sesame seed cake is economically possible.

Nevertheless, the selling price can affect the rate of return on investment and payback period of the project. Table 5 shows the effect of various selling prices on the net profit, rate of return on investment and payback period. When the selling price increases, the net profit and rate of return on investment increase, resulting in a reduction of the payback period. As shown in Table 5, the result implies that this project will be economically viable if the selling price of oil extracted from pressed sesame seed cakes is above 300 Baht per kg oil.

3.4. Sensitivity analysis

In order to highlight the most relevant parameters that significantly affect the profitability of the supercritical CO₂ extraction plant, the sensitivity analysis was performed. A 30 % increase or decrease in the cost of each parameter (C_{RM} , C_{UT} , C_{OL} , FCI, selling price and annual production of the extracted sesame oil) was implemented to observe the effect on the NPV and IRR. The results of the analysis of the impact of parameters changed on the NPV and IRR on extracted sesame oil obtained from supercritical CO₂ extraction plant as shown in Fig. 4. The

Table 5

Net profit, rate of return on investment and payback period at various selling prices.

Selling price (Baht/kg oil)	Net profit (Million Baht per year)	Rate of return on investment (%)	Payback period (years)
260	-1.28	-1.59	-46.57
300	1.72	2.15	34.51
350	5.47	6.82	10.87
400	9.22	11.49	6.45
450	12.97	16.17	4.58
500	16.72	20.84	3.56
550	20.47	25.51	2.90
600	24.22	30.19	2.46
650	27.97	34.86	2.13
700	31.72	39.53	1.87
740	34.72	43.27	1.71

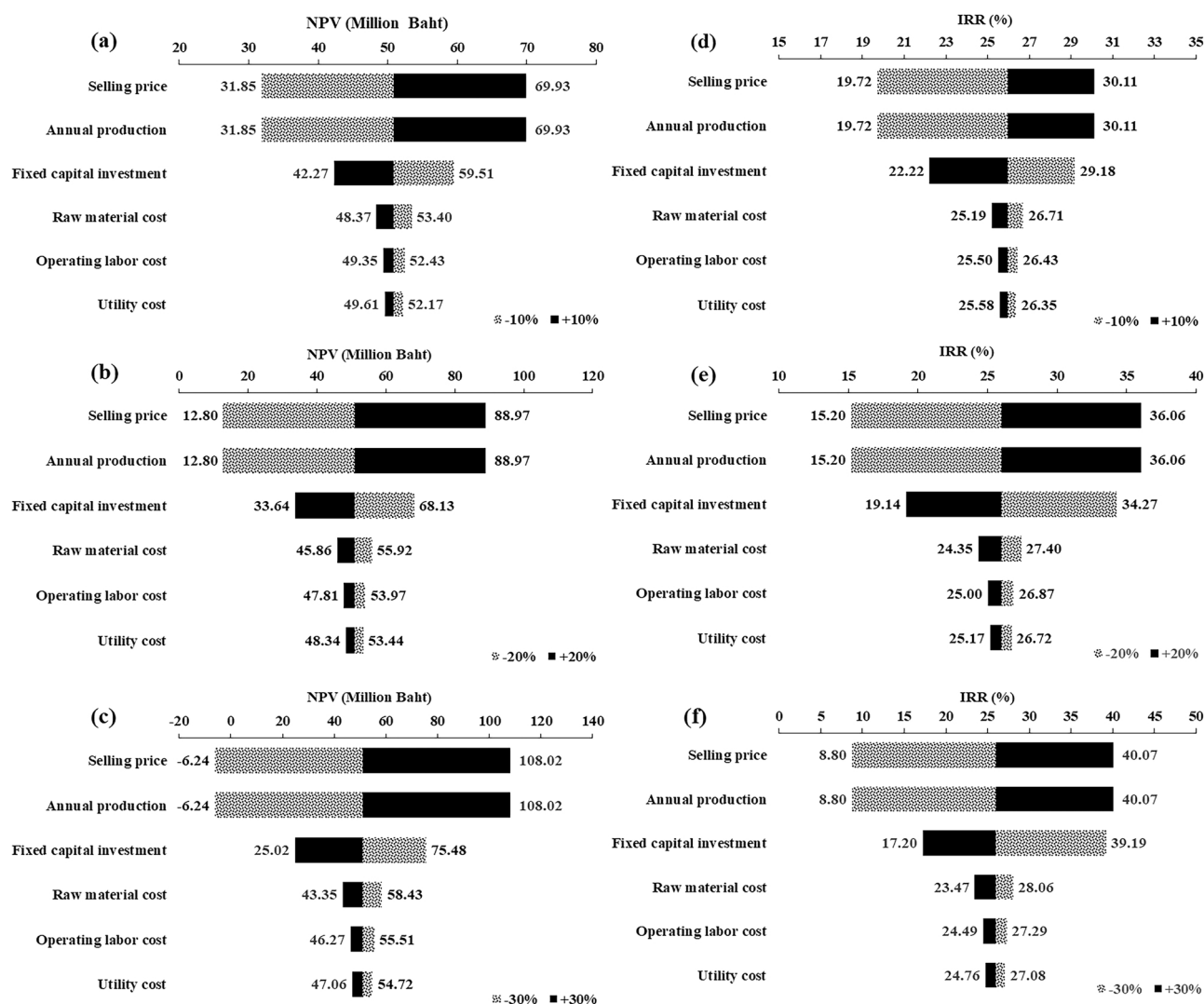


Fig. 4. Tornado chart for sensitivity analysis of net present value (NPV) and internal rate of return (IRR). Black solid bars and gray pattern bars represent the increase and the decrease of 10 % ((a) and (d)), 20 % ((b) and (e)) and 30 % ((c) and (f)) of economic parameters, respectively.

result showed a fluctuation in the NPV which could as well influence the profitability and feasibility of the extracted sesame oil production plant. The results from the study (Fig. 4) revealed the selling price and annual production of extracted oil product and also FCI had a greater effect on the NPV and IRR than did the CRM, COL and CUT costs, respectively. The change in the value of variables (C_{RM} , C_{UT} , C_{OL} , and FCI of the extracted sesame oil) within $\pm 30\%$ did not bring about negativity in the NPV. Meanwhile, the increase in the selling price and annual production of the oil product increased the NPV to 108.02 million Baht, and also the decrease in this parameter value resulted in negative NPV (as shown in Fig. 4(c)). This was because the selling price and the annual production of the extracted sesame oil product greatly affected the revenue incurred in the oil production plant. Consequently, the reduction in profitability of the plant due to negative changes in the sales price and the annual production of extracted sesame oil product will hypothetically pose the greatest risk to the economic sustainability of the plant, due to increases in electricity, fuel and labour cost in Thailand. A decrease in the selling price and annual production of the extracted sesame oil and FCI caused a decrease in the IRR. This would mean an improvement in the profitability since the IRR should be as higher as possible to undertake a project. However, the decrease in FCI seemed to be the most significant parameter influencing the IRR compared with the selling price and annual production of the extracted sesame oil.

Additionally, an increase or decrease in the cost of C_{RM} , C_{UT} , and C_{OL} could slightly decrease or increase the profitability of the supercritical CO_2 extraction plant, thus the profitability was hardly sensitive to direct manufacturing costs.

4. Conclusions

The economics of a supercritical CO_2 plant for extracting oil from pressed sesame seed cake were evaluated based on the optimal condition for lab-scale supercritical CO_2 extraction (extraction pressure of 220 bar, extraction temperature of $50^\circ C$ for 5 h). Under the optimum extraction conditions, the experimental yield of extracted oil was 29.80% db; it contained 225.79 mg/100 g cake of sesamin, 75.57 mg/100 g cake of sesamol and 7.03 mg/100 g cake of tocopherols and had Folin-Ciocalteu reducing capacity of 29.11 mg GAE/100 g cake. The high yield and suitable quality of oil were used to enhance the economic possibility. The scaled-up process for supercritical CO_2 extraction of oil from pressed sesame seed cake consisted of two 360 L extraction vessels with an internal diameter of 0.43 m and height of 2.5 m, using a CO_2 density of 806.61 kg/m^3 , a CO_2 flow rate to feed mass ratio of about 282.31 kg CO_2 per kg of feed and a D/L ratio of 0.17. After the scale-up study, the results showed that the estimated total capital investment required to establish a supercritical CO_2 extraction plant with a capacity

of 250 tons per year is about 80.25 million Baht (FCI + COM). With a COM of 20.78 million Baht per year, the production cost was determined to be 277.03 Baht per kg of oil. Based on the average selling price (500 Baht per kg oil) of pressed sesame seed cake oil, the net profit is approximately 16.72 million Baht per year. As a result, the rate of return on investment is 20.84 % and the payback period is 3.56 years. Of all economic parameters under sensitivity investigation, the selling price and the annual production of extracted oil product has a greater effect on the NPV and IRR than FCI, C_{RM} , C_{UT} , and C_{OL} . Moreover, the results also encourage the most efficient usage of the resource and may reduce the environmental impact. The authors believe that the results are attractive to any investors wishing to conduct a further detailed economic analysis for the establishment of supercritical CO₂ extraction plants to produce sesame oil from pressed sesame seed cake.

Declaration of Competing Interest

The authors have no conflict of interest to declare.

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