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Published in:
Journal of CO2 Utilization

DOI:
10.1016/j.jcou.2023.102547

Published: 01/08/2023

Document Version
Publisher's PDF, also known as Version of record

Please cite the original version:
Khalati, E., Oinas, P., & Favén, L. (2023). Techno-economic and safety assessment of supercritical CO_2 extraction of essential oils and extracts. *Journal of CO2 Utilization*, *74*, Article 102547.
https://doi.org/10.1016/j.jcou.2023.102547

Journal of CO2 Utilization 74 (2023) 102547

Contents lists available at ScienceDirect

Journal of CO2 Utilization

journal homepage: www.elsevier.com/locate/jcou

Techno-economic and safety assessment of supercritical CO_2 extraction of essential oils and extracts

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ARTICLE INFO

Keywords:
Supercritical CO_2 extraction
Herbaceous extracts
Multiproduct process plant
Closed-cycle production
Techno-economic analysis

ABSTRACT

Currently, products based on herbaceous plants are receiving global attention due to the significant rise in human awareness of environmental protection and well-being. These products contain compounds with valuable medicinal and nutritional effects. However, extracting these substances via conventional methods can be challenging concerning economic and environmental effects. Compared to conventional techniques, supercritical CO_2 extraction is a clean technology that mitigates environmental issues and enhances extraction yields. This work focuses on developing a commercial-scale closed-cycle process using supercritical CO_2 as a solvent with the possibility of varying feedstock material. The full process encompasses the raw material pre-treatment, the $scCO_2$ extraction of compounds, and solvent recovery. This multiproduct processing unit includes three products: essential oil from garden angelica and extracts from roseroot and maral root. The process model was established using Aspen Plus®. Parallel to process design, safety was assessed by a hazard and operability study (HAZOP) to evaluate possible deviations during the operation. For assessing the feasibility of the process, a comprehensive techno-economic assessment was conducted. With this analysis, it can be seen that the designed production process is not only feasible but also economically profitable. For an annual production capacity of 13,240 kg, considering the three products, capital expenditure of 5.4 M€ was estimated. As to profitability, an internal rate of return of 40% and a payback time of 2.5 years resulted. In addition to economic benefits of the designed process, waste production was reduced by recycling used solvents and employing different approaches for mitigating greenhouse gas emissions.

1. Introduction

Currently, herbal products have attracted the interest of industries, such as pharmaceuticals, food, and cosmetics, due to growing awareness of nature conservation and its effects on well-being. This new trend has led to the possibility of developing value-added products from cultivated herbs. One avenue for exploiting herbs is to refine valuable natural extracts for sale to food and healthcare companies. However, despite these positive initiatives, local people have derived less benefit from this program than do wholesalers and retailers, who substantially profit from trading the same product in larger volumes [24,54]. This disparity hinders local economic growth, thereby decreasing novel employment opportunities in rural areas. Consequently, developing new local business opportunities based on herbal products near agricultural areas would play an important role in maintaining the agrarian economy. Establishing production plants with the aim of extracting valuable herbal compounds is one of the promising solutions due to the growing market of natural extracts.

Conventional extraction methods such as soxhlet extraction, steam distillation and solvent extraction have been extensively used commercially. However, some of these techniques, including solvent extraction, require the use of organic or aqueous solvents which can frequently conflict with environmental protection regulations. The disadvantages associated with the application of organic solvents are their hazardous effects on the operator's health, remaining traces of solvents in the final extract, and disposal of organic waste issues [13,34]. Moreover, high-temperature extraction methods with long operating times are not appropriate for extracting volatile compounds from plants. Techniques such as steam distillation can thus thermally degrade bioactive volatiles of essential oils [10]. Due to environmental challenges and concerns about the quality of extracts, more eco-friendly and selective solvent extraction methods have been proposed. Recently, the supercritical CO_2 ($scCO_2$) extraction method has emerged as a new and

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https://doi.org/10.1016/j.jcou.2023.102547
Received 13 March 2023; Received in revised form 18 June 2023; Accepted 11 July 2023
Available online 19 July 2023

Nomenclature

Aspen EDR	Aspen Exchanger Design and Rating.
PEA	Aspen Process Economic Analyzer.
BLEVE	Boiling liquid expanding vapour explosion.
CAGR	Compound annual growth rates.
CW	Cooling water.
CWR	Returned cooling water.
CWS	Supplied cooling water.
CO_2-eq	CO_2 equivalent.
GB	Compressor.
KB	Cutter.
HD	separator.
r	Discount rate.
AA	Dryer.
DB	Extractor.
FCI	Fixed capital cost.
FIC	Flow indicator controller.
FT	Flow transmitter.
GHG	Greenhouse gas.
KA	Grinder.
HAZOP	Hazard and operability study.
EA	Heat exchanger.
ISBL	Inside battery limit.
IRR	Internal rate of return.
MSP	Minimum selling price.
LIC	Level indicator controller.
NFW	Net future worth.
NPV	Net present value.
n	n_{th} year of operation.
OSBL	Outside battery limit.
OPEX	Operational cost.
PIC	Pressure indicator controller.
PI	Pressure indicator.
PT	Pressure transmitter.
GA	Pump.
S	Stream.
ROI	Return on investment.
FB	Silo.
t_{pp}	Payback period.
t	Project lifetime.
RK-ASPEN	Redlich-Kwong-Aspen.
SV	Safety valve.
GD	Static mixer.
$scCO_2$	Supercritical CO_2.
SW	Switch.
TIC	Temperature indicator controller.
TCI	Total capital cost.
TT	Temperature transmitter.
UNIQ-RK	UNIQUAC-Redlich-Kwong.
VOCs	Volatile organic compounds.
WSH	Washing machine.

green technology that eliminates or minimizes the need for using traditional solvents and reduces volatile organic compounds (VOCs) emissions [3,37,50,53]. For supercritical extraction, CO_2 is a chemically non-flammable and non-toxic inert gas that has a critical point of 31 °C and 73.8 bar which is accessible compared to critical points of other solvents such as water. Besides, $scCO_2$ has other useful properties including high selectivity, short operating time, and desirable fractionation possibility for enhancing the extraction yield [32]. According to Doneanu and Anitescu [6], $scCO_2$ extraction not only maintained the quality of the garden angelica essential oil but also reduced the concentration of undesired compounds, coumarins, in the final product. However, solvent extraction negatively affected the pungent and aromatic compounds of garden angelica essential oil due to thermal degradation. Loss of aromatic compounds reduces the value of the essential oil used in medical, cosmetic, and fragrance products. Further, in the case of roseroot extraction, Iheozor-Ejiofor and Dey [11] reported that using $scCO_2$ with water (10%) as a co-solvent could extract a higher concentration of favorable compounds, including rosavin, from roseroot compared to conventional solvents such as ethanol. Although their experiments indicated that the application of methanol as a solvent could also lead to higher yields, it is not a desirable solvent in food and cosmetic-based applications compared to water and ethanol [11]. Sovová et al. [42] also examined the selective extraction of 20 hydroxyecdysone hormone using ethanol-modified $scCO_2$. Their lab-scale experimental results showed that modified $scCO_2$ enhanced the level of the desired compound in the extract by 67% compared to the solvent extraction using ethanol.

In recent years, various studies have been conducted to assess the feasibility of using $scCO_2$ extraction commercially [21,46,49]. Gwee et al. [9] presented that for a yearly manufacturing capacity of 5280 kg volatile oils from *Aquilaria sinensis* in Malaysia, net profits were 17.4 M$ and 7.4 M$ for resin and lignified ring, respectively, over the 15 years of plant life [9]. The techno-economic analysis performed by Soh et al. [41] indicated that $scCO_2$ extraction of patchouli oil with an annual 400, 000 kg processing capacity in Singapore had a return on investment (ROI) of 27.4% with a total profit of 5.27 M$ after 10 years [41]. Recently, Santos et al. [33] also reported that $scCO_2$ extraction provides an overall efficiency of 97% in separating terpenes from orange bark oil. The developed process had the potential to be used as a clean technology in cosmetics and food-producing companies [33]. Therefore, according to the results of several case studies, $scCO_2$ extraction is a promising method to selectively isolate and produce valuable extracts from plants and other agricultural products. However, it can be difficult to operate continuously throughout the year in rural areas if the production is confined to the extraction of a single product. As a result, having a mobile production plant that uses different raw materials is advantageous to have a profitable business. The mobility of the production system also facilitates its placement close to farmland and its relocation in the event of changes in production plans. According to the literature review, there are limited techno-economic studies and feasibility evaluations of a $scCO_2$ extraction plant with a variety of products. This work aims to evaluate the viability of developing a multiproduct $scCO_2$ extraction plant commercialized in Finland. To this end, a feasibility evaluation of $scCO_2$ extraction was carried out to extract valuable compounds from roseroot, maral root and garden angelica on a commercial scale. The experimental results of research on garden angelica, roseroot, and maral root conducted by Doneanu and Anitescu [6], Iheozor-Ejiofor and Dey [11], and Sovová et al. [42] were used as a basis for designing the scaled-up process.

Roseroot (*Rhodiola rosea*), maral root (*Rhaponticum carthamoides*), and garden angelica (*Angelica archangelica*) originate from cool climates, and they easily germinate and grow in the Nordic countries [14,31,8]. The natural extracts from these three herbs have been employed for diverse applications. The essential oil from garden angelica and extracts of maral root and roseroot have been applied by medical experts globally due to their valuable properties. In addition to pharmaceutical applications, they can be applied in cosmetics and skincare products, food supplements, functional food, and beverages.

For the feasibility study, it was assumed that the production plant was located near farmland, thus making it possible to directly transfer the harvested materials from fields to the extraction plant. This process was simulated in the Aspen Plus® environment. To determine the

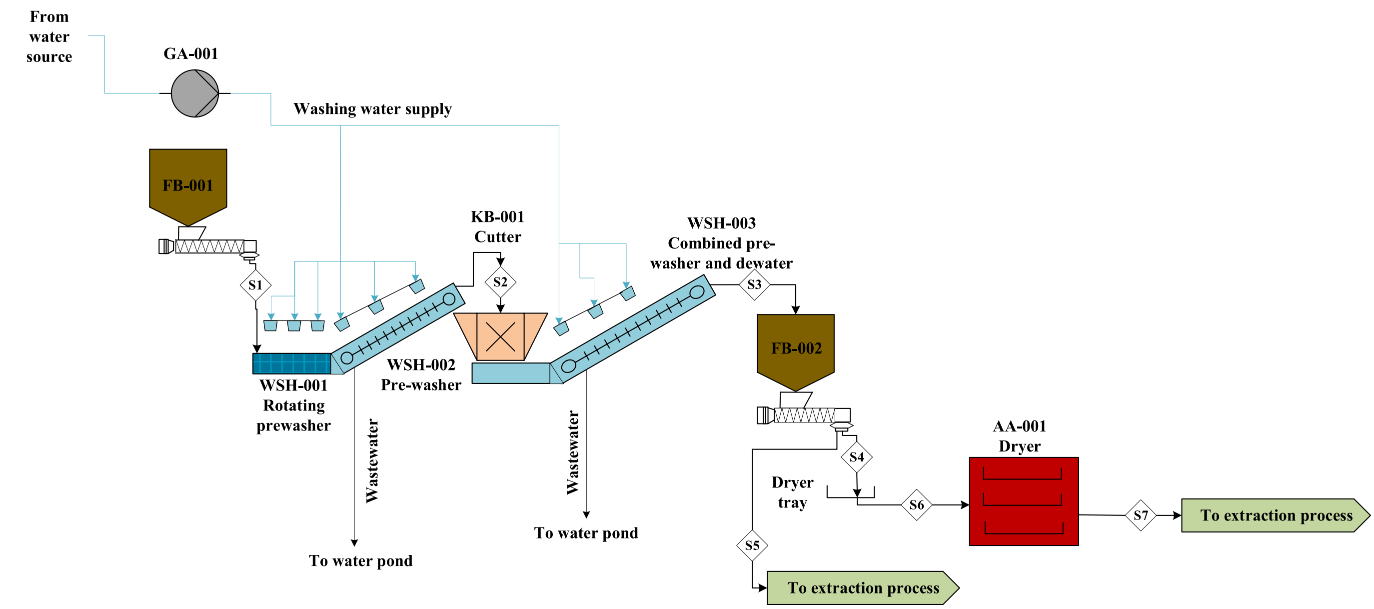

Fig. 1. Process flow diagram for the pre-treatment section.

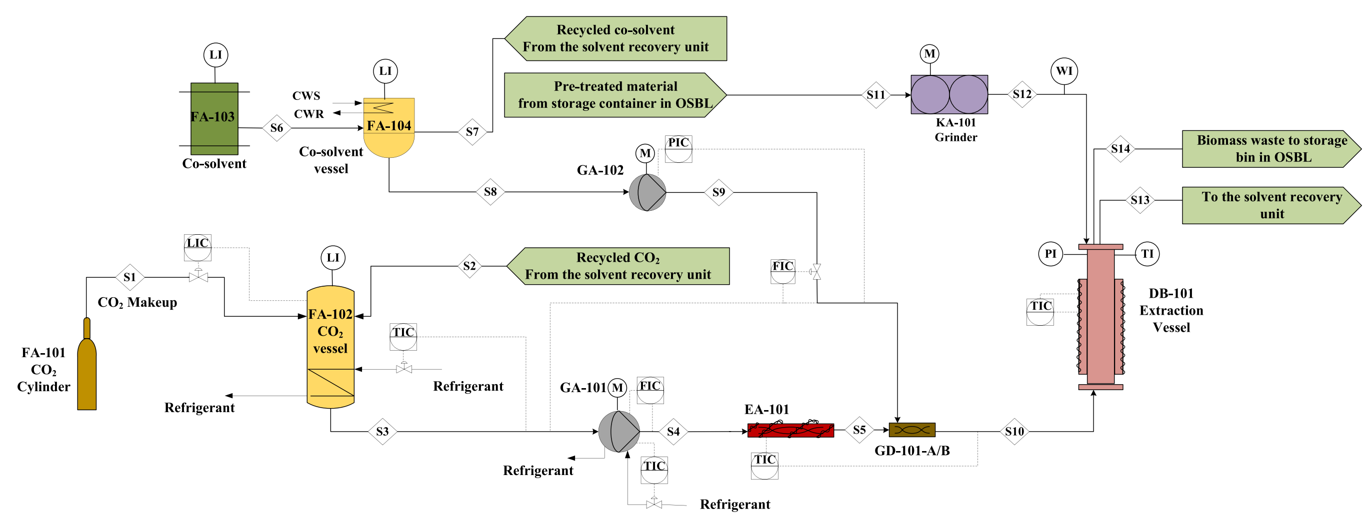

Fig. 2. Process flow diagram of the extraction stage in $scCO_2$ extraction process.

viability of the design, economic calculations were performed based on the capital cost and annual operating expenses. Profitability analysis of the process was also carried out based on estimating the net present value, payback period, and internal rate of return for the designed process plant. The safety analysis of the process was carried out to determine safety requirements and develop policies and industrial strategies, early in the conceptual design phase. As the final step, the greenhouse gas emissions of the main process were estimated to improve the process design in the next phase of the process development.

2. Methodology

This section presents the main stages of the $scCO_2$ extraction process as well as details of technical diagrams and economic calculations. The process modeling was conducted using a combination of experimental data retrieved from the literature and process simulation software [11,42,6]. The operation of the process plant was based on using three different dried and fresh roots: roseroot, maral root and garden angelica. While roseroot and maral root must be dried before storing, in the case of the garden angelica root, the drying step was not considered. Each of the raw materials was planned to be used in different time periods without any overlap. The extraction unit was considered to be a semi-batch process with a 3-hour operating time. The pre-treated solid material was first placed into an extraction basket and later located in the extraction vessel. The basket was considered to be cylindrical with a special design to avoid the transfer of the solid material to the CO_2 line. In this work, three different basket sizes were planned to be used to supply the bulk density required for each case. Following extraction, the residual biomass from the roots was to be sold as feedstock to bio-refineries for the production of bioenergy products such as biogas. To improve the efficiency of energy products, it is necessary to apply an appropriate method of compacting, granulating and briquetting, as well as pre-treatment techniques [12,5]. These methods enhance the density and thermal characteristics of biomass pellets. Optimization of biomass residue properties for bioenergy production was not part of this research and was to be carried out in the later stages of the study. The designed processing plant was planned to operate throughout the year while considering a two-week overhaul time. Annual application periods of roseroot, maral root and garden angelica were 5.5, 3 and 3 months, respectively.

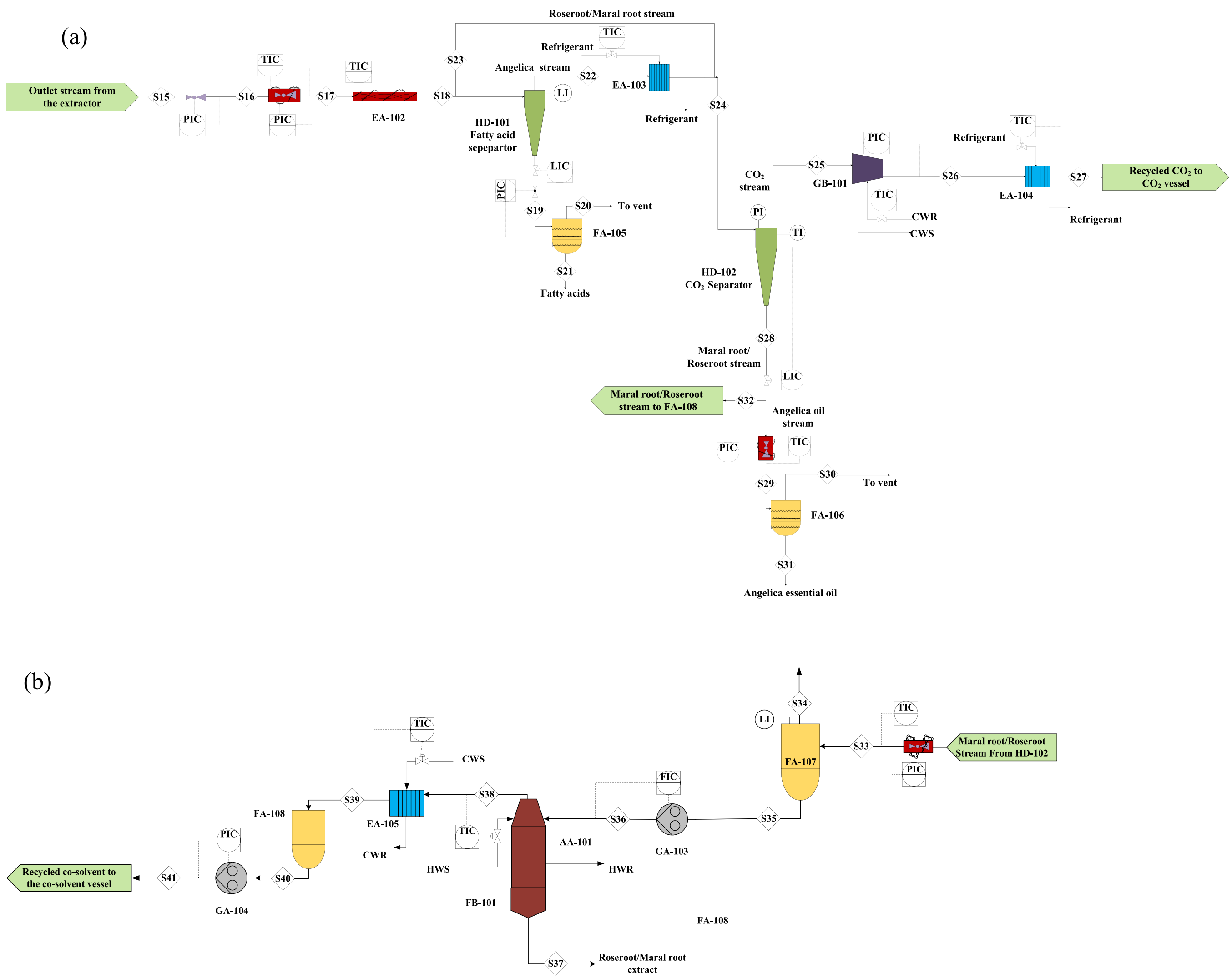

Fig. 3. Process flow diagram of the (a) solvent and (b) co-solvent recovery stages in $scCO_2$ extraction process.

Table 1
Economic assumptions.

General	
Year basis	2022
Project lifetime	20 years
Recovery period	10 years
Discount rate	10%
Taxation rate	20%
Number of daily shifts	2 (8 operating hour/shift)
Weekly operating days	5 days
Total number of employees	8
Total capital cost	
Outside battery limit (OSBL)	4% of FCI
Indirect costs	16% of FCI
Contingency	25% of FCI
Working capital	15% of OPEX
Depreciation	Straight-line over 10 years
Manufacturing cost	
Average operating labor costs with overheads	60 k€/year per operator
Operating supplies	0.3% of FCI
Maintenance (materials including equipment spares)	10% of equipment cost
Laboratory charges	7% of operating labor costs
Insurance and taxes	3% of FCI
General expenses	
Administrative costs	20% of operating labor costs
Distribution and additional marketing service	2% of OPEX
Research and development	5% of OPEX

Table 2
Raw material and utility prices.

Component	price	Source
CO_2	18 €/standard cylinder	Linde ($year$)[15]
Ethanol	0.915 €/kg	(“[18])
Roseroot	1.485 €/kg	Vendor quote
Maral root	2.97 €/kg	Vendor quote
Garden angelica	0.75 €/kg	Vendor quote
Process water	3 €/m^3	(“[48])
Electricity	28 €/GJ	Statistics: Energy prices e-publication ($year$)[43]
Refrigerant	7.2 €/ GJ	Turton et al., ($year$)[45]
Hot water	1 €/m^3	(Helen[26])
Cooling water	0.26 €/m^3	(“[47])

2.1. Process description

The process plant is divided into three sections: pre-treatment, extraction, and solvent recovery units. The flowsheet of the pre-treatment area is shown in Fig. 1. In this section, cultivated herbs are collected in silo FB-001 before entering rotating pre-washer WSH-001. After washing fresh herbs in machines WHS-001 and WHS-002, they are cut into smaller pieces using cutter KB-001. The root cuts are transferred

Table 3
Emission factors for different sources.

Source	Emission factor	Reference
Electricity	$0\ g_{CO_2}/kWh$	Toivio, Lettenmeier ($year$)[44]
Heating	$0\ g_{CO_2}/kWh$	(Helen[25])
Bioethanol	$0.8\ kg_{CO_2}/l_{bioethanol}$	Pacheco, Silva ($year$)[28]
Treated water	$0.6\ kg_{CO_2}/l_{water}$	Awaitey ($year$)[4]
Biofuel	$0\ kg_{CO_2}/l_{biofuel}$	(Neste[27,23])

Table 4
Calculated values for different items of the fixed capital cost (FCI).

Items	Cost (M€)	% of C_{FCI}
ISBL		
Equipment	1.1	21%
Delivery	0.1	2%
Installation	0.5	10%
Piping	0.4	8%
Instrumentation, automation & control	0.4	8%
Electricity	0.3	6%
Total ISBL cost	*2.8*	55%
OSBL		
Buildings (including services)	0.1	2%
Service facilities	0.1	2%
Total OSBL cost	*0.2*	4%
Indirect costs		
Engineering & supervision	0.4	8%
Contractor's fee	0.2	4%
Construction and start-up	0.2	4%
Total indirect costs	0.8	16%
ISBL+OSBL+ indirect costs	3.8	75%
Contingency	1.3	25%
Total fixed capital investment (FCI)	5.1	100%

Table 5
Operational cost (OPEX).

Item	Cost (M€/year)
Direct operating cost	
Raw materials	0.9
Utilities	0.15
Operating supplies	0.02
Operating labor with overheads	0.5
Laboratory charges	0.03
Maintenance (materials)	0.11
Fixed operating cost	
Insurance and taxes	0.15
Rent	0.03
General expenses	
Administrative costs	0.12
Distribution and marketing costs	0.05
Research and development	0.11
Total operating cost (OPEX)	**2.2**

to silo FB-002 before drying. Roseroot and maral root pieces are loaded onto trays (stream S4) and dried in dryer AA-001, to increase their storage time before the extraction process. The compounds of garden angelica roots are heat sensitive. Thus, they are directly transferred from silo FB-002 to the supercritical extraction plant without drying (stream S5).

Before starting the extraction, the pre-treated feedstock is loaded into the extractor. The $scCO_2$ extraction process operates in different conditions depending on the type of root loaded into the extractor. Figs. 2 and 3 show the simplified process flow diagrams of the extraction unit and solvent as well as co-solvent recovery stages, respectively. The specifications of these units for each of the raw materials are mentioned in Sections 2.1.1, 2.1.2, and 2.1.3. The operating conditions and properties of the main streams are presented in Appendix A.

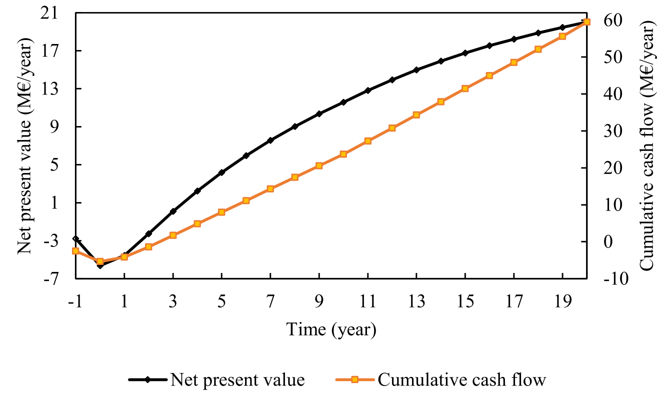

Fig. 4. The cumulative cash flow and net present value of the $scCO_2$ unit over the lifetime of the plant.

2.1.1. *Case 1: roseroot extract*

Before beginning the extraction, the dried roots of roseroot are packed into the extractor DB-101, considering a density of 100 kg/m^3. The ratio of CO_2 flow rate to the feed mass is 3 h^{-1}. CO_2 is precooled to 5 °C in vessel FA-102 with an internal cooling coil before pressurizing in the high-pressure pump GA-101. After pressurizing pre-cooled CO_2 up to 200 bar in pump GA-101 and heating it to the temperature 81 °C in heat exchanger EA-101, it is mixed with water, co-solvent, using static mixer GD-101. Next, the stream of $scCO_2$ and the co-solvent goes through extractor DB-101 and contacts the loaded feedstock. The operating conditions of the extraction column are set at 80 °C and 200 bar. Based on the literature review of the extraction quality, the crude extract yield is 18.4 wt% of the packed dried material [11]. For the separation of the extract from CO_2, the outlet stream of the extractor is depressurized to 35 bar using pressure regulating valves and then heated to 35 °C in heat exchanger EA-102. In the case of roseroot, the first cyclone separator (HD-101) is not in use as it is only applied for isolating fatty acids from the essential oil of garden angelica. Thus, the pressurized stream (stream S24) passes through the second cyclone separator (HD-102) where more than 99% of used CO_2 is separated from the co-solvent and extracts. Recovered CO_2 is reused for extraction, after compression to 50 bar in compressor GB-101 and condensation in heat exchanger EA-104. After the separation of CO_2, the bottom product of separator HD-102 (stream S28) mainly contains the co-solvent and the dissolved extracts in the liquid phase. The liquid product is depressurized to 1 bar and flows into thin film dryer AA-101, to isolate the roseroot extract and recover the co-solvent. The dryer operates at vacuum conditions, 0.17 bar, to reduce the operating temperature and energy consumption. The bottom product of dryer AA-101 is the roseroot extract collected in the collector attached to the bottom of the dryer. During the drying process, ~98% of the co-solvent is recovered, and it is condensed to be reused in the extraction process.

2.1.2. *Case 2: maral root extract*

The extraction and separation stages for maral root are similar to the roseroot extraction, while the operating conditions are different. The dried roots are charged into extractor DB-101 taking into account a volumetric density of 80 kg/m^3. The ratio of CO_2 flow rate in the extractor to the feed mass is 0.5 h^{-1}. The operating pressure and temperature of extractor DB-101 are kept constant at 280 bar and 60 °C, and thin film dryer AA-101 operates at 0.35 bar. In this case, ethanol is utilized as a co-solvent, and approximately 96% of CO_2 and 94% of co-solvent are recovered. The extraction yield is 1.1 wt% of the dried packed material at the mentioned operating conditions [42].

2.1.3. *Case 3: garden angelica essential oil*

In the case of garden angelica, the fresh roots are loaded into extractor DB-101 with an apparent density of 500 kg/m^3. For the

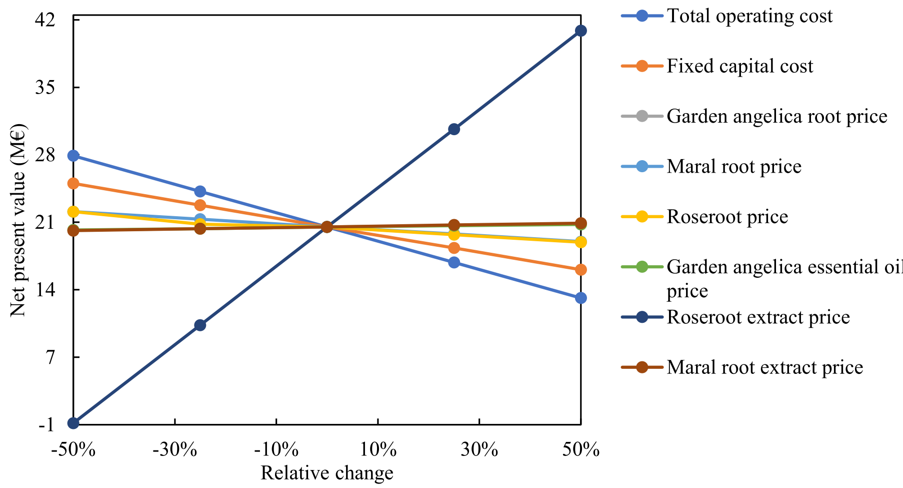

Fig. 5. The impact of proportional changes in operating and capital costs, raw material expenses, and product prices on the net present value.

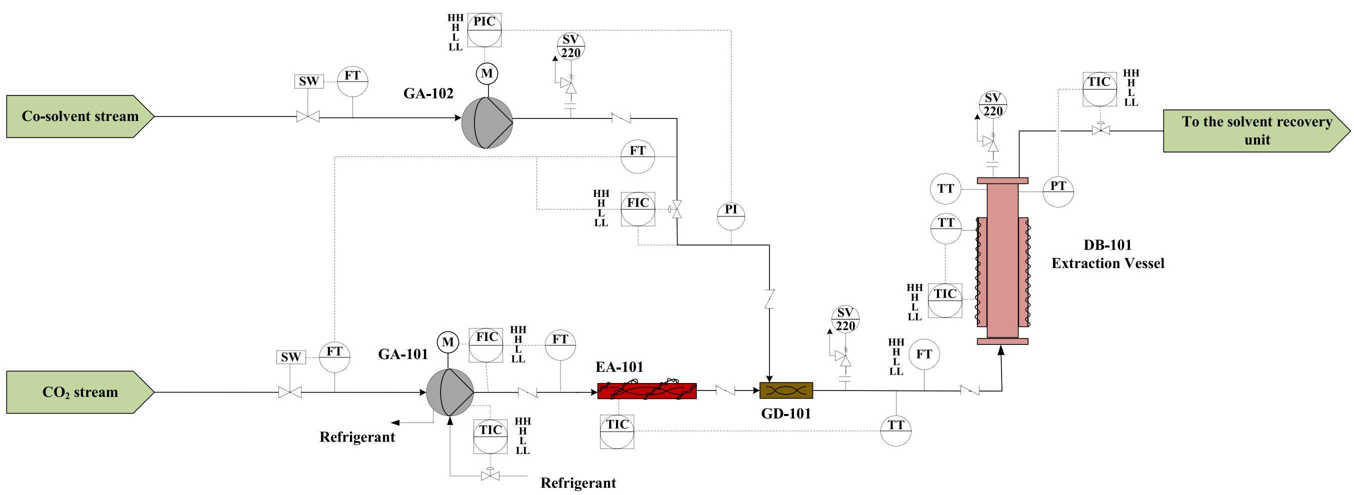

Fig. 6. The revised process diagram of the $scCO_2$ extractor.

extraction, no co-solvent is employed, and $scCO_2$ is only used to extract the essential oil, During the extraction, the CO_2 flow rate to feed mass ratio was 0.5 h^{-1}. For the extraction process, liquid CO_2 is precooled to 5 °C and compressed to 120 bar. Pressurized CO_2 is heated in heat exchanger EA-101 to reach the desired extraction conditions of 120 bar and 40 °C. During the extraction stage, fatty acids are simultaneously extracted along with the essential oil in extractor DB-101. Hence for obtaining a high-quality essential oil, separator HD-101 is considered for removing fatty acids. The extractor outlet stream, containing the essential oil and fatty acids (stream S15), is depressurized and then heated in heat exchanger EA-102. The heated stream passes through separator HD-101. In this separator, fatty acids are collected as the bottom product at 10 bar and 60 °C. The top product of separator HD-101 (stream S22) is precooled in heat exchanger EA-103, and it enters separator HD-102 where the concentrated essential oil is obtained at 10 bar and 5 °C. The essential oil yield is 0.18 wt% based on the loaded fresh material [6]. After the second separation step, more than 99% of used CO_2 is recovered and recycled back to the main process after compression and condensation.

2.2. Process modeling basis

The extraction process for each case was modeled in Aspen Plus® V11. The process plants were simulated based on using 200 kg of raw material per batch. Since the compositions of the feedstocks were complex, their properties were characterized by considering their main components [40,6,8]. The properties of the user-defined components were also estimated using Aspen Property Estimation System.

For process modeling, a wide range of pressure was used. Therefore, for high-pressure units, such as the extractor and high-pressure pumps, above 10 bar, the Redlich-Kwong-Aspen (RK-ASPEN) equation of the state model was employed to calculate the thermodynamic properties of the process [1,30,52,51]. This method can handle non-polar and polar components, mixtures of hydrocarbons, and light gases such as CO_2 at high pressures [19]. For low-pressure equipment (<10 bar) including the thin film dryer, UNIQUAC-Redlich-Kwong (UNIQ-RK) thermodynamic model was applied [1]. During the process modeling, the intensity of energy consumption and required utility usage were estimated based on mass and energy balance results obtained from the simulation results.

2.3. Equipment sizing

Based on the capacity of the scaled-up process, the required volume for the extraction vessel was calculated from the lab-scale data by keeping the velocity of CO_2 constant in the extractor [16]. The sizes of the main equipment are shown in Appendix A. The selection and sizing of the main equipment in the pre-treatment and main extraction sections were conducted based on the relevant guidelines and using technical tools. For sizing the heat exchangers, Aspen EDR was employed as the main tool.

Table 6
The operating conditions and properties of the streams for the pre-treatment section based on a 3-hour extraction time per semibatch process.

Parameters	Streams						
	S1	S2	S3	S4	S5	S6	S7
	Roseroot						
Total mass (kg)	864	864	864	864	-	864	200
Biomass (kg)	148	148	148	148	-	148	148
Extract (kg)	42	42	42	42	-	42	42
Water (kg)	674	674	674	674	-	674	10
Density (kg/m^3)	830	830	830	830	-	830	626
Pressure	1	1	1	1	-	1	1
Temperature (℃)	20	20	20	20	-	20	24
	Maral root						
Total mass (kg)	760	760	760	760	-	760	200
Biomass (kg)	179	179	179	179	179	179	179
Extract (kg)	11	11	11	11	11	11	11
Water (kg)	570	570	570	570	-	570	10
Density (kg/m^3)	800	800	800	800	-	800	600
Pressure	1	1	1	1	-	1	1
Temperature (℃)	20	20	20	20	-	20	24
	Angelica root						
Total mass (kg)	200	200	200	200	200	-	-
Biomass (kg)	49.1	49.1	49.1	49.1	49.1	-	-
Extract (kg)	0.7	0.7	0.7	0.7	0.7	-	-
Water (kg)	150	150	150	150	150	-	-
Fatty acid (kg)	0.2	0.2	0.2	0.2	0.2	-	-
Density (kg/m^3)	800	800	800	800	800	-	-
Pressure (bar)	1	1	1	1	1	-	-
Temperature (℃)	20	20	20	20	20	-	-

2.4. Economic analysis

In this work, cost assessments were conducted by estimating the capital cost assessment and the total operating cost. In addition, for profitability analysis, net present value (NPV) was also calculated over a 1-year construction period and a 20-year operating time.

2.4.1. Cost assessment

The equipment and utility costs were estimated using Aspen Plus® simulation results, Aspen Process Economic Analyzer (APEA), Aspen Exchanger Design and Rating (Aspen EDR), and vendor data were the main resources and tools. The utility supply systems and fire protection equipment costs were part of service facility expenses. Table 1 shows the summary of the assumptions considered for economic assessment. Indirect costs are not directly related to the expenses of the actual facility installation. Therefore, engineering and supervision costs, contractor's fees, and construction expenses are in the scope of indirect costs. In this work, operating labor costs included personnel and overhead costs.

Expenses directly related to the production operation were included in the manufacturing costs. Manufacturing costs were divided into three categories: variable production costs, fixed charges and plant overhead costs. In addition to the manufacturing costs, total operating costs also contained general expenses including administrative costs, distribution and marketing costs, and research and development.

The main raw materials for the process included CO_2, ethanol, water, roseroot, maral root, and garden angelica. Fresh CO_2 was stored as a liquefied gas in 38 standard cylinders with a capacity of 34 kg CO_2 in each one. Cylinders were placed into two sets of storage racks which provided a reliable method of transporting cylinders. The utilities included electricity for heaters, pumps, and the thin film dryer, and cooling water (CW) as well as a refrigerant that were used for coolers and condensers. The raw material and utility costs were estimated based on literature and current market prices which are summarized in Table 2.

2.4.2. Profitability analysis

Net present value (NPV) is a proper tool to accurately investigate the profitability of the process. As shown in Eq. (1), NPV is the total of the present value of all cash flows that include all cash inflows and outflows occurring over the project lifetime (20 years).

Table 7
The operating conditions and properties of the streams for the extraction stage in scCO_2 extraction process based on a 3-hour extraction time per semibatch process.

Parameters	Stream number													
	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14
	Roseroot													
Total mass (kg)	1	1895	1896	1896	1896	4	186	190	190	2086	200	200	2124	163
CO_2 (kg)	1	1895	1896	1896	1896	-	-	-		1896	-	-	1896	
Biomass (kg)	-	-	-	-	-	-	-	-	-	-	148	148	-	148
Extract (kg)	-	-	-	-	-	-	-	-	-	-	42	42	38	5
Water (kg)						4	186	190	190	190	10	10	190	10
Density (kg/m^3)	864	743	789	744	516	994	980	980	722	555	626	626	561	626
Pressure	50	50	50	200	200	1	1	1	200	200	200	200	200	200
Temperature (℃)	10	10	5	41	81	25	40	40	88	80	80	80	80	80
	Maral Root													
Total mass (kg)	14	309	323	323	323	1	20	21	21	344	200	200	346	198
CO_2 (kg)	14	307	321	321	321					321	-	-	321	-
Ethanol (kg)		2	2	2	2	1	20	21	21	23	-	-	23	-
Biomass (kg)	-	-	-	-	-	-	-	-	-	-	179	179	-	179
Extract (kg)	-	-	-	-	-	-	-	-	-	-	11	11	2	9
Water (kg)	-	-	-	-	-	-	-	-	-	-	10	10	-	10
Density (kg/m^3)	864	752	795.1	782.6	752.4	799	794	795	631	771	600	600	792	600
Pressure	50	50	50	280	280	1	1	1	280	280	280	280	280	280
Temperature (℃)	10	10	5.0	50	57	25	29	29	78	60	60	60	60	60
	Angelica root													
Total mass (kg)	0.2	321	321	321	321	-	-	-	-	321	200	200	322	199.4
CO_2 (kg)	0.2	321	321	321	321	-	-	-	-	321	-	-	321	-
Biomass (kg)	-	-	-	-	-	-	-	-	-	-	49.1	49.1	-	49.1
Extract (kg)	-	-	-	-	-	-	-	-	-	-	0.7	0.7	0.4	0.3
Water (kg)	-	-	-	-	-	-	-	-	-	-	150	150	-	150
Fatty acid (kg)	-	-	-	-	-	-	-	-	-	-	0.2	0.2	0.1	0
Density (kg/m^3)	864	864	897	734	607	-	-	-	-	607	800	800	607	800
Pressure (bar)	50	50	50	120	120	-	-	-	-	120	120	120	120	120
Temperature (℃)	10	10	5	25	40	-	-	-	-	40	40	40	40	40

Table 8
The operating conditions and properties of the streams for the solvent recovery stage in $scCO_2$ extraction process based on a 3-hour extraction time per semibatch process.

Parameter	S15	S16	S17	S18	S19	S20	S21	S22	S23	S24	S25	S26	S27	S28	S29	S30	S31	S32
Roseroot																		
Total mass (kg)	2124	2124	2124	2124	-	-	-	-	2124	2124	1897	1895	1895	227	-	-	-	227
CO_2 (kg)	1896	1896	1896	1896	-	-	-	-	1896	1896	1895	1895	1895	1	-	-	-	1
Extract (kg)	38	38	38	38	-	-	-	-	38	38	-	-	-	38	-	-	-	38
Water (kg)	190	190	190	190	-	-	-	-	190	190	2	-	-	188	-	-	-	188
Density (kg/m^3)	561	359	89	81	-	-	-	-	81	81	73	112	743	812	-	-	-	812
Pressure	200	100	35	35	-	-	-	-	35	35	35	50	50	35	-	-	-	35
Temperature (°C)	80	53	20	35	-	-	-	-	35	35	35	40	10	35	-	-	-	35
Maral root																		
Total mass (kg)	346	346	346	346	-	-	-	-	346	346	-	309	309	37	-	-	-	37
CO_2 (kg)	321	321	321	321	-	-	-	-	321	321	-	307	307	14	-	-	-	14
Ethanol (kg)	23	23	23	23	-	-	-	-	23	23	-	2	2	21	-	-	-	21
Extract (kg)	2	2	2	2	-	-	-	-	2	2	-	-	-	2	-	-	-	2
Density (kg/m^3)	792	712	93	81	-	-	-	-	81	81	-	113	752	762	-	-	-	762
Pressure	280	150	35	35	-	-	-	-	35	35	-	50	50	35	-	-	-	35
Temperature (°C)	60	48	20	35	-	-	-	-	35	35	-	40	10	35	-	-	-	35
Angelica root																		
Total mass (kg)	322	322	322	322	0.2	0.03	0.2	321.4	-	321.4	-	320.9	320.9	0.5	0.5	0.1	0.4	-
CO_2 (kg)	321	321	321	321	0	0.03	-	321	-	321	-	320.9	320.9	0.1	0.1	0.1	-	-
Extract (kg)	0.4	0.4	0.4	0.4	0	-	0	0.4	-	0.4	-	-	-	0.4	0.4	-	0.4	-
Fatty acid (kg)	0.2	0.2	0.2	0.2	0.2	-	0.2	-	-	-	-	-	-	-	-	-	-	-
Density (kg/m^3)	607	435	19	17	11	2	836	17	-	20	-	123	739	891	8	2	846	-
Pressure (bar)	120	60	10	10	1	1	1	10	-	10	-	50	50	10	1	1	1	-
Temperature (°C)	40	22	20	60	44	44	44	60	-	5	-	30	10	5	25	25	25	-

$$NPV = \sum_{n=1}^{n=t} \frac{NFW_n}{(1+r)^n} \quad (1)$$

where NFW_n is the net future worth in year n, t is the project lifetime, and r stands for the discount rate. As shown in Table 1, the discount rate was 10%. Other criteria including internal rate of return (IRR) and payback period (t_{pp}) were also estimated to assess the profitability of the process. In this work, t_{pp} was estimated based on interpolation between the cumulative cash flow in different years during the life of the project, and it was the time that the cumulative cash flow equaled the investment cost. In addition, a sensitivity analysis was carried out on important variables such as raw material costs, capital and operating costs, and product selling prices to determine the impact of their variation on the NPV.

2.5. *Safety analysis*

Deviations from the design intent can not only negatively impact the economy and the environment but can also have disastrous impacts on human health. In the early stages of project development, a rigorous analysis of the plant design is necessary to detect hazardous scenarios. Determining and resolving a risky situation is associated with taking into account process design adjustments and adding passive and active safety systems to reduce potential risks. Different methods of safety analysis have been introduced and used by companies in industrial development processes. Among these techniques, the Hazard and Operability Study (HAZOP) is a well-known potential hazard identification method in the process industry [38]. In the case of a HAZOP study, the process plant or designated section for safety analysis must first be subdivided into nodes for detailed examination. Within each node, a specific section of piping, valves and equipment is incorporated. In this work, the most critical identified node was the extractor section which had supercritical operating conditions. This node was analyzed using HAZOP and identifying possible variations in the operating parameters. By identifying potential hazards and operational risks, further process changes and improvements to reduce or eliminate risks were considered.

2.6. *Greenhouse gas emissions*

In this study, annual greenhouse gas (GHG) emissions were measured in terms of CO_2 equivalent (CO_2-eq) emissions [7]. In this method, the rate of GHGs emitted was computed by estimating the amount of CO_2 equaling the total emissions of the gases released. Sources of GHGs have commonly been divided into 3 categories. Scope 1 refers to direct CO_2-eq emissions from the production process, such as emissions related to solvent loss and biomass residues. Scope 2 covers emissions associated with the generation of purchased energy, namely electricity and heating. Scope 3, known as value chain emissions, represents the indirect GHGs emitted by upstream and downstream activities outside of production plant operations.

For evaluating GHG emissions, it was assumed that purchased electricity and heating, applied co-solvents and used transportation fuels were generated using renewable resources. Table 3 shows the emission factor of each item. At this stage of the project, value chain emissions resulting from agricultural activities and land use were assessed qualitatively.

3. Results and discussion

3.1. *Economic assessment*

The estimated fixed capital investment (FCI) was 5.1 M€. The factors contributing to the FCI are presented in Table 4. The cost of the equipment comprises the cost of pre-treatment, extraction and solvent recovery units. Outside battery limit (OSBL) costs were about 7% of the

Table 9
The operating conditions and properties of the streams for the co-solvent recovery stage in $scCO_2$ extraction process based on a 3-hour extraction time per semibatch process.

Parameters	Streams								
	S33	S34	S35	S36	S37	S38	S39	S40	S41
	Roseroot								
Total mass (kg)	227	1	226	226	40	186	186	186	186
CO_2 (kg)	1	1	-	-	-	-	-	-	-
Extract (kg)	38	-	38	38	38	-	-	-	-
Water (kg)	188	-	188	188	2	186	186	186	186
Density (kg/m^3)	1040	2	1040	1040	1321	0.1	979	979	980
Pressure	1	1	1	1	0.2	0.2	0.2	0.2	1
Temperature (°C)	25	25	25	25	57	57	40	40	40
	Maral root								
Total mass (kg)	37	15	22	22	2	20	20	20	20
CO_2 (kg)	14	14	-	-	-	-	-	-	-
Ethanol (kg)	21	1	20	20	-	20	20	20	20
Extract (kg)	2	-	2	2	2	-	-	-	-
Density (kg/m^3)	4	2	832	832	1258	1	794	794	794
Pressure	1	1	1	1	0.4	0.4	0.4	0.4	1
Temperature (°C)	25	25	25	25	53	53	29	29	29

Table 10
Sizes of the main equipment.

Tag no.	Equipment	Quantity	W/D (m)	L (m)	H (m)
Pre-treatment section					
FB-001	Silo	1	1.5		1.7
WSH-001	Washing machine	1	1	1.5	1.1
WSH-002	Washing machine	1	1.2	5	1.3
KB-001	Cutter	1	0.9	1.9	1.3
WSH-003	Combined washing machine and dewatering machine	1	1.2	2.5	0.6
FB-002	Silo	1	1.5		1.7
AA-001	Dryer	6	0.8	1.6	2.3
Extraction, solvent recovery, and co-solvent recovery sections					
FA-101	CO_2 cylinder	38	0.25		1.5
FA-102	Vertical vessel	1	0.4		2
FA-103	Vertical vessel	1	0.6		1
FA-104	Vertical vessel	1	0.25		0.5
KA-101	Grinder	1	0.6	0.75	1.5
DB-101	Extractor (volume: 2.3 m^3)	1	0.9		3.6
HD-101	Separator	1	0.1		0.4
FA-105	Storage vessel	1	0.12		0.24
HD-102	Separator	1	0.2		0.8
FA-106	Vertical vessel	1	0.15		0.3
FA-107	Vertical vessel	1	0.15		0.5
AA-101	Thin film dryer	2	0.3		1.5
FA-108	Vertical vessel	1	0.25		0.5

inside battery limit (ISBL) investment. ISBL costs are associated with procurement and process plant construction and installation costs, while OSBL expenses are related to off-site developments required for a process plant start-up and running. The reported value is reasonable considering the scope of the project and related impacts on the plant infrastructure [39]. The ratio of indirect costs to FCI was 16% which is in the acceptable range of 15–35%. In this ratio, FCI included the non-manufacturing expenses of the completely installed facility [29].

Currently, the application of mobile $scCO_2$ extraction technology which can process various raw materials with flexible extraction capacity is not common commercially. As a result, there are still possibilities of unforeseen expenses that can inevitably increase total costs in the future. Besides, changes in raw material and product prices would also impact operating cost estimates. Thus, a high contingency of 25% was considered in calculating the FCI. In this project, working capital was estimated to be 15% of the total operating cost. Therefore, the total capital cost (TCI) was 5.4 M€.

The operating costs were estimated based on annual production capacities of 12,750 kg roseroot extract, 415 kg maral root extract, and 75 kg garden angelica essential oil. The summary of total operating costs is presented in Table 5. Based on the calculations, the minimum selling prices (MSPs) were estimated by adjusting the prices of the products to reach NPV of 0 € at the end of the project lifetime. Consequently, MSPs of roseroot and maral root extracts and garden angelica essential oil were respectively 260 €/kg, 160 €/kg, and 650 €/kg. According to the prices offered by vendors, the calculated MSPs were in the acceptable ranges of market prices. Moreover, Health, wellness and cosmetics companies are more interested in higher purity and quality of $scCO_2$ extracts in order to produce premium quality products. Therefore, their sale prices were comparable to similar high-quality extracts available in the market.

3.1.1. *Profitability analysis*

Fig. 4 shows the values of the cumulative cash flow and NPV throughout the project lifetime based on the 10% discount rate. The estimated construction period was 1 year. The zero point on the time axis depicts the point at which the construction of the process plant is completed, and it is ready for start-up. The fixed capital investment, working capital, and start-up costs were considered during the installation and start-up time when there was no income from the production. At the end of the project lifetime, the NPV was 20 M€ which indicated the profitability of the project. Based on the annual cash flow forecast, t_{pp} was 2.5 years which is the time that the cumulative cash flow equals the total capital investment. For the investment, the minimum acceptable profit was assumed to be 10%. The internal rate of return (IRR) of 40% was reached which surpasses the generally accepted profitability criteria. Hence, the production of the selected oils and extracts with the developed process can be considered economically very feasible.

3.1.2. *Sensitivity analysis*

The viability of the project can be affected by uncertainties regarding factors like future economic and market conditions, availability and prices of raw materials and intermediate supplies, as well as the readiness of the applied technologies. Therefore, it is an important step to analyze the sensitivity of cash flows and economic criteria to the variation of the forecast figures. The results of the evaluation provide insight into the level of risk associated with assessing the project's expected performance [29]. In this work, sensitivity analysis was conducted by

Table 11
The HAZOP study for the extraction section.

Streamline/ Equipment	Process parameter	Guide word	Deviation	Consequences	Causes	Actions
From pump (GA-102) to static mixer (GD-101) streamline	Flow	No/less	No/less co-solvent flow	1. Inadequate delivery of co-solvent to the 2. process 3. No or less yield in the extractor (DB-101) 4. Backflow of CO_2 from mixer (GD-101) 5. Potential damage to pump (GA-102)	1. Low liquid level or no co-solvent in the collecting tank 2. Pump (GA-102) is not working properly 3. Flow control valve measurement is wrong 4. Pipeline plugging 5. Pipeline rupture 6. Block valves are closed	1. Proper maintenance of the pump (GA-102) 2. Proper maintenance of the valves 3. Proper maintenance of pipelines 4. Considering flow switch on the inlet line of pump (GA-102) to prevent the dry running 5. Installing a check valve to prevent backflow of CO_2 6. Flow alarm and indicators for no and less flow
		More	More flow of co-solvent	1. Affecting the extraction yield negatively 2. Out-of-spec co-solvent to CO_2 ratio	1. Flow control valve measurement is wrong 2. Motor inverter of the pump (GA-102) is not working properly 3. Stroke of pump is wrong	1. Proper maintenance of the pump 2. Proper maintenance of the valves 3. Flow alarms and indicators for high and very high flow
	Pressure	Less	Less pressure	1. Backflow of CO_2 from mixer (GD-101) 2. Inadequate delivery of co-solvent to the 3. process 4. No or less yield in the extractor 5. Potential damage to pump (GA-102)	1. Pipeline plug 2. Pressure measurement is wrong 3. Pump (GA-102) is not working properly 4. Block valves are closed 5. Low liquid level or no co-solvent in the collecting tank	1. Proper maintenance of the pump, installing alarms 2. Proper maintenance of the valves 3. Proper maintenance of pipelines 4. Considering flow switch on the inlet line of pump (GA-102) to prevent the dry running 5. Installing a check valve to prevent backflow of CO_2 6. Pressure alarms for low and very low pressure
From pump (GA-101) to mixer (GD-101) streamline	Flow	No/less	No/less CO_2 flow	1. Inadequate delivery of CO_2 to 2. process 3. No or less yield in the extractor 4. Backflow of co-solvent from mixer (GD-101) 5. Potential damage to pump (GA-101) 6. Out-of-spec CO_2 to feed ratio	1. Low CO_2 level or no CO_2 in the collecting vessel 2. Pump (GA-101) is not working properly 3. Mass flow control measurement is wrong 4. Check valve is closed 5. Pipeline plug 6. Pipeline rupture	1. Proper maintenance of the pump (GA-101) 2. Proper maintenance of the valves 3. Proper maintenance of pipelines 4. Considering flow switch on the inlet line of pump (GA-101) to prevent the dry running 5. Installing a check valve to prevent backflow of co-solvent 6. Flow alarms for low and very low flow
		More	More flow of CO_2	1. Affecting the extraction yield 2. Out-of-spec CO_2 to feed ratio	1. Flow measurement is wrong 2. Pump (GA-101) is not working properly	1. Proper maintenance of the pump 2. Proper maintenance of valves 3. Flow alarms for high and very high flow
	Temperature	Lower	Lower CO_2 temperature	1. Affecting the extraction yield 2. More required electrical heating duty in heat exchanger (EA-101)	1. More CO_2 flowrate 2. Temperature control of pump (GA-101) is not working properly 3. Setpoint for outlet temperature of CO_2 after heater (EA-101) in the controlling system of the electrical heater is out-of-spec 4. Wrong measurement of the temperature control of the electrical heater (EA-101)	1. Installing low and very low temperature alarms 2. Regular inspection of the controlling systems 3. Regular inspection and maintenance of the electrical heating system
		Higher	Higher CO_2 temperature	1. Affecting the extraction yield 2. Potential damage to pump (GA-101)	1. Setpoint temperature of CO_2 is out-of-spec in temperature controlling system of pump (GA-101) or heater (EA-101) 2. Electrical heat duty in heater (EA-101) is more than required	1. Installing high and very high temperature alarms 2. Regular inspection of the temperature controlling systems 3. Proper maintenance and inspection of the cooling

(*continued on next page*)

Table 11 (*continued*)

Streamline/ Equipment	Process parameter	Guide word	Deviation	Consequences	Causes	Actions
					3. Temperature controlling system is not working properly for electrical heating 4. Cooling system of pump (GA-101) is not working properly due to the wrong temperature measurement 5. Blockage of cooling system temperature control valve 6. Cooling utility is not available or enough	system and availability of the cooling utility
	Pressure	Less	Less pressure	1. Backflow of co-solvent from mixer (GD-101) 2. Inadequate delivery of CO_2 to 3. process 4. No or less yield in the extractor 5. Potential damage to pump (GA-101)	1. Line plug 2. The control valve measurement is wrong 3. Pump (GA-101) is not working properly	1. Proper maintenance of the pump 2. Proper maintenance of the valves 3. Proper maintenance of pipes 4. Considering flow switch on the inlet line of pump (GA-101) to prevent the dry running 5. Installing a check valve to prevent backflow of co-solvent 6. Installing pressure alarms for low and very low pressure
		More	More pressure	1. Potential damage to pump (GA-101) if the outlet pressure is more than the pump spec 2. Affecting the extraction yield	1. Failure of pump (GA-101) 2. Mass flow control is not working properly	3. Considering flow switch on the inlet line of pump (GA-101) to prevent the dry running 4. Proper maintenance of the pump 5. Installing pressure safety relief valve 6. Installing pressure alarms for high pressure
From GD-101 to DC-101 streamline	Flow	No/low	No/less flow	No extraction or less extraction yield	1. The block valve is closed or blocked 2. Static mixer (GD-101) internals are not working well	1. Regular maintenance of valves 2. Installing flow indicator and alarms 3. Regular maintenance and inspection of the static mixer
	Temperature	Lower	Lower CO_2 temperature	1-Affecting the extraction yield 2-More required electrical heating duty in EA-101	1-More CO_2 flowrate 2-Temperature control of pump (GA-101) is not working properly 2- Setpoint for outlet temperature of CO_2 after heater (EA-101) in the controlling system of the electrical heater is out-of-spec 3-Wrong measurement of the temperature control of the electrical heater (EA-101)	1-Installing low and very low temperature alarms 2-Regular inspection of the controlling systems 3-Regular inspection and maintenance of the electrical heating system
		Higher	Higher CO_2 temperature	1. Affecting the extraction yield 2. Potential damage to pump (GA-101)	1. Setpoint temperature of CO_2 is out-of-spec in temperature controlling system of pump (GA-101) or heater (EA-101) 2. Electrical heat duty in heater (EA-101) is more than required 3. Temperature controlling system is not working properly for electrical heating 4. Cooling system of pump (GA-101) is not working properly due to wrong temperature measurement 5. Blockage of the cooling system temperature control valve 6. Cooling utility is not available or enough	1. Installing high and very high temperature alarms 2. Regular inspection of the temperature controlling systems 3. Proper maintenance and inspection of the cooling system and availability of the cooling utility
	Pressure	No/ Low	No/Lower pressure	Affecting the extraction yield or no extraction	1. Block valve is closed or blocked 2. Static mixer (GD-101) internals are not working well	1. Regular maintenance of valves 2. Installing flow indicator and alarms 3. Regular maintenance of the static mixer
		High	High pressure	1. Affecting the extraction yield	Block valve is closed or blocked	1. Regular maintenance of valves

(*continued on next page*)

Table 11 (*continued*)

Streamline/ Equipment	Process parameter	Guide word	Deviation	Consequences	Causes	Actions
				2. Rupture of the static mixer		2. Installing pressure indicator and alarms 3. Regular maintenance of the static mixer 4. Installing pressure safety relief valve
	Pressure	No	No pressure	1. No extraction 2. Backflow of the outlet stream	1. CO_2 inlet feed is blocked or closed 2. Extractor is not closed well 3. Extractor can leak	1. Regular inspection and maintenance of installed instrument 2. Proper startup of the column 3. Installing pressure indicators and alarms
DC-101		Lower	Lower pressure	1. Affecting the extraction yield 2. Backflow of the outlet stream	1. CO_2 inlet feed is blocked or closed 2. Extractor is not closed well 3. Extractor can leak 4. The pressure control valve is not working properly in the outlet stream	1. Regular inspection and maintenance of installed instrument 2. Proper startup of the column 3. Installing pressure indicators and alarms 4. Proper maintenance and inspection of the controlling systems
		Higher	Higher pressure	1. Affecting the extraction yield 2. Potential damage to extractor and its connections	1. CO_2 outlet is closed or blocked 2. Temperature controlling system is not working 3. The pressure control valve is not working properly in the outlet stream and pressure rises with temperature increase 4. Temperature setpoint is out-of-spec	1. Regular inspection and maintenance of extractor and stream connections 2. Proper startup of the column 3. Installing pressure indicators and alarms 4. Installation of pressure safety relief valve 5. Proper maintenance and inspection of the controlling systems
	Temperature	Higher	Higher temperature	1. Affecting the extraction yield 2. Pressure increases in the extractor 3. Potential damage to extractor and connections	1. CO_2 outlet is blocked or closed 2. Temperature controlling system is not working properly 3. Temperature setpoint is out-of-spec	1. Regular inspection and maintenance of extractor and stream connections 2. Proper startup of the column 3. Installing temperature indicators and alarms 4. Proper maintenance and inspection of the controlling system

variation of FCI and operating costs, raw material prices, and sale prices of products to assess their impact on the NPV. Fig. 5 shows the NPV subjected to proportional changes in the mentioned economic parameters. Based on the results, the sale price of the roseroot extract had the most significant impact on NPV changes, and around 50% decrease in the selling price of this product could lead to an unprofitable project.

3.2. Safety analysis

During $scCO_2$ extraction, the major hazards are mainly associated with high-pressure operating conditions. The identified hazardous scenarios consist of overpressure, boiling liquid expanding vapour explosion (BLEVE), and dust explosion [2,17]. To minimize the risks of handling solid materials, the designed plant was considered to be located in an ATEX-certified container, with a capacity of 85 m^3. The container was intended to be equipped with proper ventilation systems and explosion-proof equipment.

Moreover, the HAZOP study led to the classification of the deviated process parameters of the high-pressure equipment and pipelines in the selected node. The deviations were related to temperature, pressure, and mass flow rates. A summary of the HAZOP results is provided in Appendix A. The results show that a higher temperature or pressure in extractor DB-101 could damage its structure and connections. As a result, the recommended actions to reduce the risks involved not only the installation of process indicators and alarms but also the development of regular inspection and maintenance plans. In addition, the installation of safety valves and control systems would restore the process to normal conditions. Outlet streams of safety valves were planned to be connected to a common venting system that directed the expelled gas streams to the atmospheric vent. The recommended safety actions were taken into account when revising the process diagram developed for the selected node, as illustrated in Fig. 6.

3.3. Greenhouse gas emissions

In this work, direct emissions were primarily due to solvent loss during the refining of extracts, leading to an annual release of 100,000 kg_{CO_2}. With regard to waste streams, the post-extraction biomass residues were to be used as a CO_2-neutral raw material in biorefineries for the production of bioenergy products. Accordingly, under Commission Implementing Regulation (EU) 2018/2066 (2018), it was considered to be zero-emission feedstock. For Scope 2 emissions, purchased utilities were green electricity and eco-friendly heating with emissions of 0 ton_{CO_2}. Upstream emissions from the production of renewable co-solvent were negligible relative to direct GHG emissions. To minimize GHG emissions from agricultural activities, the herb growing process was planned to be based on regenerative agriculture. This technique has acquired popularity, particularly in Finland, with the intention of reaching zero agricultural carbon footprint. This emerging approach emphasizes improvements in soil health, biodiversity, water management and production performance, as well as emissions mitigation [22]. Additionally, the mobility feature of the process provided an opportunity to locate the extraction plant close to the agricultural lands where the herbs are grown, thereby reducing transport emissions. In the case of relocating the mobile unit, transportation emissions were almost nil due to the use of renewable fuels.

Therefore, taking into account Scopes 1–3 emissions, the annual carbon footprint of the final products was 100,000 kg_{CO_2}. Based on the results, the optimization of the separation steps played an important role in drastically reducing the level of GHG emissions. The optimization of separation units is thus one of the principal objectives which will be carried out within the framework of the detailed technical design of the subsequent phase of the research.

4. Economic potential of $scCO_2$ extraction products

Currently, the application of natural products to different businesses is increasing as a result of increased awareness of environmental and health protection. These products are widely used in health and well-being foods, pharmaceuticals, and cosmetics. Based on the statistical data, the global value of the health and wellness food industry was $840 billion in 2022 and is projected to increase with a compound annual growth rate (CAGR) of 4.5% by 2026 [35]. As for the global revenue of natural and bio-based cosmetics, it reached $12 billion in 2021 and is expected to rise with 7% CAGR by 2027 [36]. The rising demand for natural products also directly influences CAGRs of herbal extracts. Currently, garden angelica essential oil is extensively used in functional food, cosmetic, and medical industries. Statistics indicate that 16% of health supplements used in North America and Asia-Pacific contain garden angelica extract. As a result, a market growth of $11.7 billion is expected to occur by 2029 for the garden angelica extract, with a CAGR of 4.8% [20]. The worldwide demand for the roseroot extract is also booming due to the increasing consumption of plant extracts in various industries. The market for this extracted product is projected to reach $2.6 billion with 6.3% CAGR by 2028 [20]. Moreover, owing to growing demand from the cosmetics and healthcare industry, the global application of ecdysterone has improved in recent years. Ecdysterone is a plant-based compound extracted from maral root. The market potential of this natural product is expected to increase with a CAGR of 12.5% over the forecast period, 2017–2030 [20]. Consequently, growing market demand is expected for $scCO_2$ extraction products which can directly improve the rural economies in Finland.

5. Conclusion

In recent years, techno-economic assessment studies have shown promising results for the application of commercialized $scCO_2$ extraction technology to extract valuable compounds from herbaceous plants. Designing a multiproduct and mobile $scCO_2$ extraction plant is a new concept which was assessed in this work with the aim of establishing a $scCO_2$ extraction plant near farmland in rural areas. The use of different raw materials facilitates the continuous operation of the production plant in agricultural areas throughout the year. This work not only addressed the feasibility of the developed design but also analyzed safety and environmental aspects of the project. The designed system was closed-loop since in supercritical CO_2 extraction, carbon dioxide was recycled almost completely (99% in most cases), thus having a negligible solvent loss. The profitability analysis showed that the industrial application of the process developed in Finland would be viable considering 40% internal rate of return, payback period of 2.5 years, and 20 M€ net present value over 20 years. According to the cost assessments, minimum sales prices for garden angelica essential oil and extracts of roseroot and maral root were 650 €/kg, 260 €/kg, and 160 €/kg, respectively. Given the reported quality of $scCO_2$ extraction products, they have the potential to compete with traditionally produced extracts available on the market. The current study also showed that the primary source of emissions was solvent loss during solvent recovery. Consequently, the carbon footprint can be reduced by optimizing the separation steps. Besides, as this new multiproduct extraction plant is in the early stages of technology readiness level, the expected contingency expenses were higher than the available $scCO_2$ extraction plants. As a result, further studies will be carried out to gather the data needed to optimize the design and operation of processes, thereby reducing the capital investment.

CRediT authorship contribution statement

Elham Khalati: Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Visualization. **Pekka Oinas:** Conceptualization, Writing – review & editing, Supervision. **Leena Favén:** Project administration, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

Acknowledgements

This research is part of the NovelBaltic Project (project number: 605102) which was supported by Interreg Baltic Sea Region (EU).

Appendix A

See appendix Tables 6–11.

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