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Research article

Supply chain and environmental assessment of the essential oil production using Calendula (*Calendula Officinalis*) as raw material

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ABSTRACT

Biomass has been considered a potential source of value-added products and energy vectors. Most biomass studies have researched the best pathways or processes to upgrade this renewable raw material through stand-alone processes or biorefineries. The biomass supply chain is a crucial aspect in the economic analysis of biomass upgrading since most of the raw materials need to be transported. A supply chain analysis gives an idea about the availability, real costs, and storage conditions of the raw material to guarantee an accurate feasibility analysis and a standardized production process. Calendula *(Calendula Officinalis)* is an aromatic plant used to produce valuable extracts in the cosmetic and pharmaceutical industries. Nevertheless, high amounts of exhausted biomass (more than 95% w/w) are produced and wasted. Theseresidues represent an environmental issue to be solved through the implementation of valorizing options. This paper analyses the supply chain and environmental impact of essential oil production using Calendula *(Calendula Officinalis)* as a raw material in the Colombian context. The case study comprises a single-objective optimization of the calendula supply chain to produce essential oil and the life cycle assessment (LCA) of the process through a cradle-to-gate approach in the Colombian context. The results showed the best locations to upgrade Calendula in Colombia (i.e., Manizales and Bucaramanga), supplying 1.1 % of the total product demand. The optimal product flow to customers was 0.32 tons/year, and the required feedstock from suppliers was 162 tons/year. The agricultural stage of essential oil production represented the highest environmental impact of the supply chain. In particular, plastic sheets, organic fertilizers, and chemical fungicides were the main contributors to this impact.

1. Introduction

Biomass has been boosted as a platform to produce renewable energy and bio-based chemicals to mitigate the environmental impact of the excessive use of fossil fuels. Several biomass sources have been upgraded in energy-vectors and value-added products based on the chemical composition and best conversion pathways. Research efforts have been addressed towards developing efficient conversion technologies (Mo et al., 2011; Zhang et al., 2017). Biomass upgrading requires studying the costs of raw materials supply (e.g., transportation, storage, pre-conditioning). Thus, biomass supply chain systems (BSC) are analyzed to elucidate raw materials availability and the most convenient plant location. BSC systems are composed of 4 different stakeholders (i.e., suppliers, manufacturers, distribution centers, and customers). Stakeholders are linked by information, material, and capital flows, linking environmental and social burdens at different production stages (Seuring and Müller, 2008). Production processes are associated with all the steps before and after the raw material processing and manufacturing. Consequently, biomass upgrading processes should be analyzed as a whole system where all stakeholders are linked to produce high-quality products able to impact at local, national, and international levels. BSC systems must be appropriately managed to produce and distribute in the right quantity, at the right time, to the right site, a product/service, while the overall costs are minimized (Larson et al., 2001).

1.1. Supply chain modeling

The modeling of a supply chain consists of reproducing the stages involved using a mathematical model. However, all the aspects of a supply chain are difficult to model since many dynamic variables are present. The problem between model complexity and reality is overcome by defining the goal and scope of the supply chain. This statement can reflect real-world operations in a non-difficult way (Min and Zhou,

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2002). A supply chain analysis goal can be addressed to determine the best location to upgrade any feedstock. For this purpose, sustainability issues are considered based on the processing capacity and demand as constraints (Özdenkçi et al., 2017). Thus, the problem is how to represent all the aspects of reality in a controlled environment to determine the best configuration of the supply chain with a good grade of precision. The mathematical models can be identified and classified as deterministic, stochastic, hybrid, and information technology (IT)-driven models (Hillier et al., 2012; Silver, 1981).

1.2. Supply chain drivers

A BSC system can be analyzed considering different driving forces (e.g., economic, social, and environmental aspects). Thus, the first step to model a biomass supply chain is to summarize these driving forces or factors. Economic reasons usually are used to model a BSC system because the feasibility of a biomass upgrading process depends mainly on the raw material costs (Parra-Ramírez et al., 2020). The most common economic term used to model a supply chain is the monetary value. This term refers to the ratio between revenue and total cost (i.e., economic performance) (Min and Zhou, 2002). The monetary value measures the profit efficiency of supplying activities. The Monetary value can be categorized as asset utilization (Min and Zhou, 2002), return-on-investment (Min and Zhou, 2002), and cost behavior (Palmeros Parada et al., 2017). Customer service represents the ultimate objective of a supply chain. Product availability and response time are examples of these driving forces. Finally, the information/knowledge sharing is a driver that depends on synchronizing and "real-time" information supported in technical platforms (e.g., enterprise resource planning ERP).

1.3. Supply chain constraints

Supply chain constraints correspond to certain limitations or boundaries where a cluster of decision variables can be chosen. Most representative restrictions include (i) Capacity: refers to the financial, production, supply, and technical capability of each partner. These constraints create bottlenecks that must be considered in the modeling. (ii) Service compliance: refers to the excellent quality service offered by a company (e.g., manufacturing due dates and delivery time windows). (iii) The extent of demand: refers to the size of the market that must be included in the model.

1.4. Supply chain variables

Decision variables represent the outcomes of the supply chain model. These variables are related to supply chain drivers (objectives). Moreover, the supply chain objective is often expressed as a function of one or more decision variables. Some examples are network structuring, location, number of facilities, service sequence, allocation, volume, inventory level, the extent of sourcing, and number of stages. Location variables are addressed to determine the optimal site to implement processing facilities, warehouses, and supply sources. Allocation variables imply estimating which warehouses and plants should serve market segments, customers, or suppliers. Network structuring variables involve the distribution of the supply network. The number of facilities and equipment determines how many supply sources, plants, and warehouses are needed to meet market demand. The number of stages determines how many horizontal levels the supply chain should have. Service sequence determines the better routes for delivering and picking up the orders. Volume variables determine the optimal processing, purchasing, and shipping volume at each node. The inventory level involves the optimal quantity of raw material, work-in-process, finished product, and stock-keeping unit to be stored at each supply chain stage. The extent of sourcing determines which suppliers, outsourcing companies, third-party logistics firms, and IT service providers should be picked for long-term relation contracts.

1.5. Biomass supply chain (BSC)

All items mentioned above must be considered in the model formulation to design an optimum BSC system. In general, agricultural logistics is characterized by seasonal availability (Skoulou and Zabaniotou, 2007). There is a need for storing large amounts of biomass during an extended period to avoid rotting (Rentizelas et al., 2009). The BSC has to deal with low-density materials. Thus, special conditions for transportation, handling, and storage space are needed (Rentizelas et al., 2009). Finally, several biomass sources require customized handling and collection equipment. This fact increases the technological complexity of the supply chain (Rentizelas et al., 2009). Figure 1 presents some of the BSC characteristics, according to the company's three levels of decision-making.

Several authors have simulated and optimized agricultural supply chains of feedstocks used to produce biofuels or energy vectors considering different sustainability dimensions (i.e., economic, environmental, and social) and decision making characteristics (i.e., strategic, tactical, and operational) (Bowling et al., 2011; Santibañez-Aguilar et al., 2014; You et al., 2012). Similar approaches for optimization methodologies have been described in the open literature. Čuček et al. (2014) proposed a MILP supply chain model to be applied in first, second, and third-generation feedstocks (e.g., corn grains, corn stover, switchgrass, microalgae, and waste oil). These authors developed a four-layer structure involving agricultural, collection, processing, and usage stages. This model can account for optimal locations, different biomass types and processing technologies, seasonability, availability of resources, and losses. Taifouris and Martín (2018), proposed a MILP model for four different agricultural residues to produce biogas and digestate. The model can find the optimum type of residue, the number and size of digesters, and the facility location across 59 sites under a two-layer structure (agricultural and processing). Nevertheless, the supply chain of novel feedstocks (e.g., aromatic plants) has not been studied as a potential raw material to produce value-added products. This work states a novel optimization model to determine the best supply chain configuration of Calendula *(Calendula Officinalis)* to produce essential oil (EO) in Colombia. This analysis is done given the local government policies existing in this country to develop new agricultural projects reducing poverty in rural areas. The EO production as an active compound was calculated using the simulation package Aspen Plus v.9.0 (Aspen Technology, Inc, USA) to obtain the mass and energy balances of the process. The unit operations developed in Aspen Plus were mapped to the appropriate equipment costs models in Aspen Process Economic Analyzer (APEA) to perform the equipment sizing calculations and estimate the

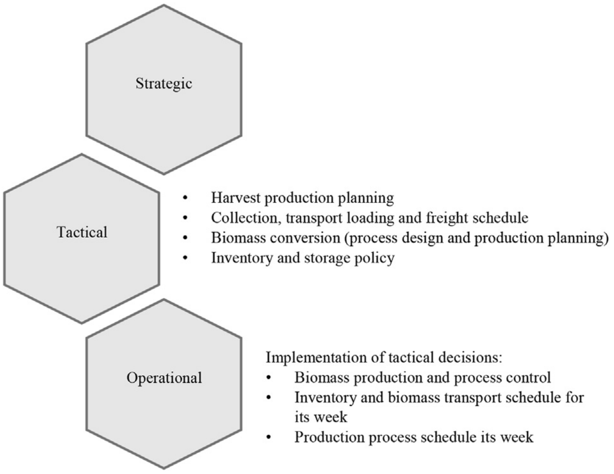

Figure 1. Decisions of BSC according to the three levels of decision making.

equipment costs. Three different plant capacities were assessed to determine the best scenario considering a particular demand. Finally, a life cycle assessment (LCA) was done to measure the environmental impacts of EO production using Calendula *(Calendula Officinalis)* in the Colombian context.

2. Materials and methods

The supply chain model of aromatic plants should be stated considering the number of horizontal links, actors, and interactions along the chain. Therefore, a characterization step is necessary.

2.1. Characterization of the supply chain

In Colombia, aromatic plants have an essential role in producing natural, cosmetics, and cleaning products. This chain is growing at a rate of 7 % per year. The increase of the aromatic plants market has ranked this country as the fifth most important producer in Latin-America (Gómez, 2017). Besides, the Colombian government has subscribed to an agreement with the Centre for the Promotion of Imports from developing countries CBI in The Netherlands to supports the Colombian small industries to provide natural ingredients (Global Biodiversity Information Facility, 2019).

The biobased products chain for cosmetic and pharmaceutical industries in Colombia can be divided into five horizontal links: 1) Raw material supply, 2) Natural ingredients production, 3) Industrialization, 4) Commercialization, and 5) Market. Figure 2 describes these links.

The first link of the chain corresponds to the raw material sourcing. In this link, primary activities related to agricultural production, harvest, and post-harvest are performed. The raw materials to produce natural components come from endemic species from Colombian biodiversity or foreign plants. The second link of the chain comprises the secondary transformation (i.e., extraction of active compounds) into the plant matrix to obtain common ingredients such as grasses, oils, EOs, hydrolats, and natural colorants. International companies involved in this link are related to distributors, importers, and contracted companies. Meanwhile, local companies are small and medium companies that take advantage of the country's extensive biodiversity. In 2016, 40.6 % of the total import of natural ingredients corresponded to hydrolats, 7 % to grasses, 28 % to EOs, and 24 % to natural colorants (Agencia de Noticias UN, 2012a). 90 % of the total natural ingredients used in Colombia are imported (Agencia de Noticias UN, 2012a).

The third link of the chain involves industrialization or tertiary transformation. Thus, all cosmetics, cleaning, and food companies are involved. The final customer consumes the outputs of this link. Three types of companies can be distinguished inside this link: Cosmetics Producers are a group of companies dedicated to producing cosmetic and cleaning-based products. The most relevant company in Colombia is Bel-Star (28 % of the market), Avon (21.4 % of the market), and Yanbal (18.4 % of the market) (Diaz Merchán, 2003). Multi-Segment Companies do not have an exclusive dedication to one product. This scheme allows these companies to produce cosmetics, cleaning, and food products through the same brand (i.e., using the same equipment). The major companies in this sector are Unilever (29 % of the market), Quala (22.56 % of the market), and Johnson & Johnson (22.5 %) (Diaz Merchán, 2003). Contracted Companies are a type of business that prioritizes production more than establish a self-brand. A third-party employs these companies to produce a specific good commercialized by the third-party brand (Diaz Merchán, 2003).

The fourth link of the chain corresponds to the commercialization of goods by distributors. These companies do not necessarily produce goods. Even so, these are committed to following market rules and sustainability. Marketers can be grouped into two segments: Distributors, international or national, wholesalers, and retailers. This group takes the merchandise from transformation companies and distributes them to an assigned area. The most relevant distribution companies in Colombia are FEDCO, La Riviera, Cutis Limitada, and Bella Piel. Brokers or commission agents work in the opening of new markets and earn commissions from management.

Based on the supply chain characterization described in Figure 2, the scope of this work focuses on the first three links of the chain. The first link comprises the calendula production and pretreatment (drying) in local sites (farms). The second link includes the EO production (this is adjusted on the second link as a local producer of natural ingredients for the cosmetic industry). The EO was extracted from calendula plants through steam distillation technology obtaining hydrolat as a by-product. The input investment data to model the EO production was obtained through a simulation process in Aspen Plus and Aspen Economic

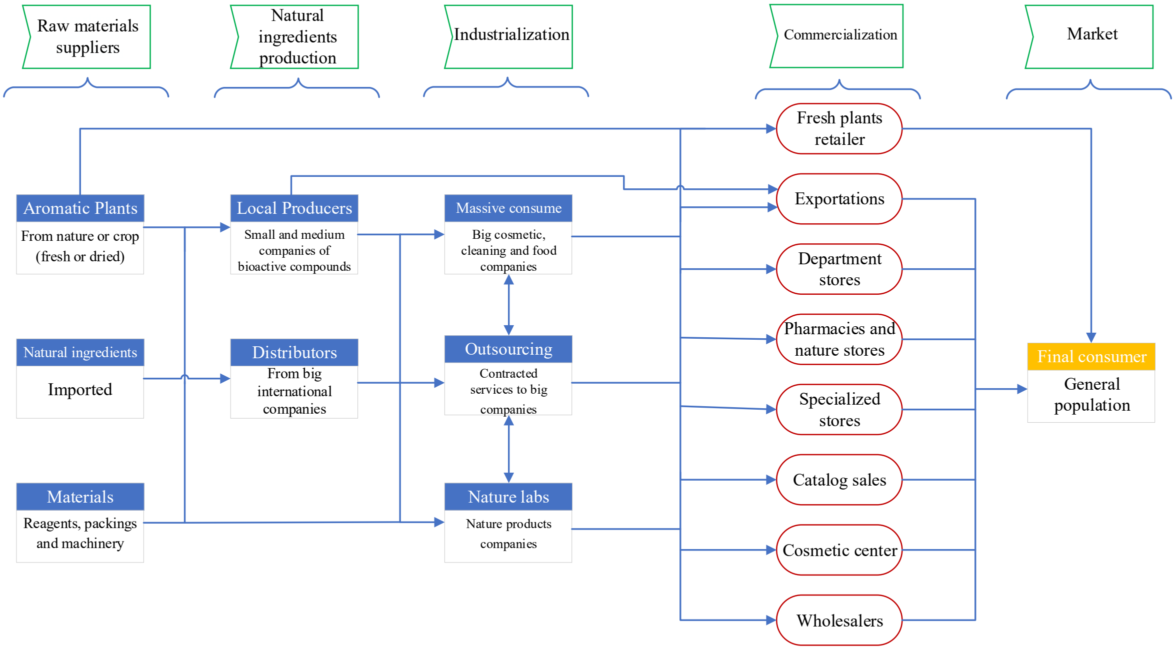

Figure 2. The supply chain of bioactive products in Colombia.

Analyzer (Aspen Technology, Inc, USA). Therefore, the supply chain network design is focused on optimizing the strategical decisions of localization and transport that surround EO production. These decisions are mainly the raw material (Calendula) supply from crops to the processing plant and EO distribution from processing plants to customers (cosmetic, cleaning, and food companies). An optimization model that determines the sourcing, transformation, and distribution sites were done. The optimal material flow to be sent among sites, based on capacity and demand, was chosen.

2.2. Model development

The proposed goal of the model implies the minimization of the supply chain costs (operational and fixed) along with the first three links of the chain. The proposed model is a general optimization framework under the following assumptions: 1) only essential oil was considered as a product, 2) three capacities were selected according to the raw material availability, 3) a particular share of demand was planned to be covered according to the supply of competitors. The approach of maximizing profit was not used due to by-product earnings were not considered in the model.

A representative scheme of the supply chain structure is presented in Figure 3. The acquisition and transportation of feedstock (dried Calendula) correspond to the upstream echelon. The capacity of the processing plant determines this acquisition. EO is obtained as a natural ingredient in the midstream echelon. Downstream comprises distribution operations for the essential oil to the national natural ingredients market.

Every entity in the chain, either sourcing, processing, or distribution site, can send and receive biomass and essential oil for fulfilling the site's demand. The design problem for the studied EO supply chain network involves the following inputs:

- ➢ Geographical location and source availability of feedstock suppliers.
- ➢ Biomass acquisition cost.
- ➢ Transport logistics (fleet capacity, cost, distances).
- ➢ Plant capacity and economic parameters (fixed and operational costs) according to the Colombian context.
- ➢ Essential oil demand in different regions inside the national context.
- ➢ Essential oil selling prices for the national market.

The proposed supply chain model provides the optimal sourcing crops, conversion facilities, and customer location sites, addressing the minimum total cost. In this way, the critical decision variables to be optimized are:

- ➢ Material flow rate (dried Calendula) from suppliers to conversion plants.
- ➢ Suppliers location.
- ➢ Processing plants location.
- ➢ Essential oil flow rate to different customers in the Colombian market.
- ➢ Customers' location according to demand.
- ➢ Economic performance is based on costs along the supply chain.

The regions considered as sourcing, processing and distribution sites involve capital cities. Besides, some municipalities were included in the mathematical modeling of the BSC considering the high potential to commercialize aromatic plants and derived products. The values of calendula availability in each region were obtained from Calendula production in 2012 (Agencia de Noticias UN, 2012b) and projected to 2020 according to the aromatic plant market growth in Colombia (Vega, 2018). The Calendula production per region was calculated based on a ponderation of the aromatic plant production multiplied by the total production of Calendula in 2020 (DANE, 2019). The Calendula EO demand per region was calculated based on the total EO importations in 2007 (Stashenko, 2009). The demand was projected to 2020 (PROCOLOMBIA, 2016), considering that only 10 % of the total natural ingredients for the massive consumer industry are produced in Colombia (Gómez, 2017). The share of Calendula EO in this percentage was supposed as the share of calendula production over the total aromatic plant production in the country. Therefore, the total demand for calendula EO was 71.5 tons per year, and this amount was multiplied by the share of the population per region. The produced amount of bioactive compounds per region by other producers was considered 0.7 % for calendula products, and 80 % was essential oil (Diaz Merchán, 2003). Only the regions where EO production plants are located were considered in the model (the share was calculated based on the number of EO production companies per region) (Empresite, 2019).

The EO extraction process data was obtained from a simulation in Aspen Plus v.9.0 (Aspen Technology, Inc, USA). The EO production is characterized by a low EO yield related to the fresh plant material at a high energy consumption rate. The approximate yield of fresh calendula flowers is 1.5 tons per hectare. The market value of dried Calendula is 9.66 USD per kg, representing 1450 USD per hectare. Finally, the EO yield from dried material is around 0.2 %. In terms of low-pressure steam

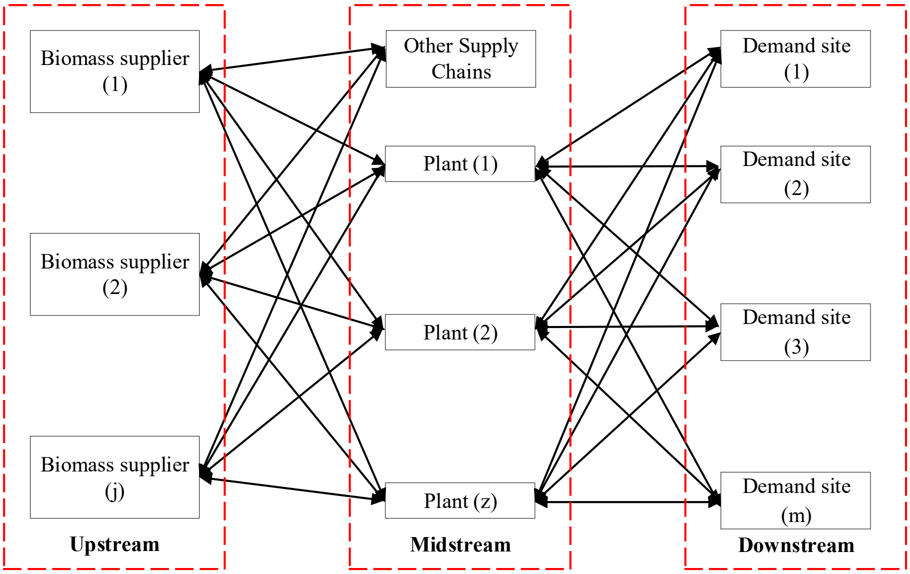

Figure 3. Supply chain model structure.

generation, to extract 1 kg of EO are needed 1310 kg of steam (i.e., 97.06 m^3 of natural gas). Natural gas is the most used fuel in Colombia. Thus, this fuel was considered as the energy source of the EO extraction process. Table 1 describes the main economic parameters of the analysis developed in the Aspen Process Economic Analyzer (Aspen Technology, Inc, USA). These economic parameters were based on the mass and energy balances of the EO extraction process at base case (87.6 ton per year). Moreover, Table 1 shows the three processing scales proposed and their respective investment costs (capital and operational).

The processing scales were defined according to the total calendula production in Colombia by 2020 (303 ton $year^{-1}$) as follows: small (5 % of the total production), medium (20 % of the total production), and large (50 % of the total production). These three scales presented a positive net present value. (NPV) The freight charge was calculated through the SICETAC platform (Colombian Transport Ministry) based on an average distance among the four main cities in Colombia. The freight cost for transporting dried flowers in a 5-ton pickup truck and essential oil in a TERMOKING van with refrigeration (Ministerio de Transporte, 2019) was estimated. The corresponding values of dried calendula flowers and essential oil were 0.11 USD ton^{-1} km^{-1} and 0.12 USD ton^{-1} km^{-1}, respectively.

2.3. Mathematical formulation

The modeling framework has been developed as a Mixed Integer Linear Programming (MILP) problem based on the chain structure presented in Figure 3. Table 2 describes the decision variables and parameters of the model. Moreover, according to the sets declared in the model, the variable domain is presented in Table 3.

2.3.1. Distances between regions

The distance among capital cities and important municipalities was calculated based on the Haversine formula. This equation is an approximate distance between two earth coordinates, approaching the perimeter of a sphere. The Haversine formula is given in Eq. (1).

$$Dist(j,\ z) = 2R\sin^{-1}\sqrt{\sin^2\left(\frac{Lati(j) - Lati(z)}{2}\right) + \cos(Lati(j))\cos(Lati(z))\sin^2\left(\frac{Longi(j) - Longi(z)}{2}\right)} \tag{1}$$

2.3.2. Real availability of feedstock

The real availability of Calendula in a region (j) is defined by Eq. (2), which considers the sent and received material.

$$Av(j,CA) = DispCA(j) - MSt(j,CA) + MRt(j,CA) \tag{2}$$

The calculation of the total sent and received material for and from a subregion (j) is performed using Eqs. (3) and (4), respectively.

$$MSt(j,CA) = \sum_z MS(j,z,CA) \tag{3}$$

$$MRt(j,CA) = \sum_z MR(j,z,CA) \tag{4}$$

2.3.3. Transportation costs

The cost of receiving material from a region (j) to a region (z) is considered to avoid double costs counting. Eq. (5) describes this variable. Eq. (6) determines the cost of the total received material.

$$Crec(j,z,CA) = MR(j,z,CA) * CT(CA) * Dist(j,z) \tag{5}$$

$$TCrec(j,CA) = \sum_z Crec(j,z,CA) \tag{6}$$

2.3.4. Capacity decision

In one region, only one processing plant of a determined scale can be settled. Eqs. (7), (8), (9), and (10) describe the constraints for choosing a processing plant scale according to the Availability of Calendula in a region (j). Eqs. (11), (12), (13), and (14) illustrate the constraints for the respective investment costs of each scale in a region (j). Eq. (15) describes the binary condition of choosing only one plant in a region (j). Eq. (16) describes a logical restriction that assures the total material flow of Calendula in a region j must be less or equal than the Availability of Calendula in the same region.

$$Mt(j,CA) = \sum_k MF(j,CA,k) \tag{7}$$

$$MF(j,CA,Small) = Cap(Small) * xEO(j,Small) \tag{8}$$

$$MF(j,CA,Medium) = Cap(Medium) * xEO(j,Medium) \tag{9}$$

$$MF(j,CA,Big) = Cap(Big) * xEO(j,Big) \tag{10}$$

$$CTinv(j) = \sum_k Cinv(j,k) \tag{11}$$

$$Cinv(j,Small) = COinv(Small) * xEO(j,Small) \tag{12}$$

$$Cinv(j,Medium) = COinv(Medium) * xEO(j,Medium) \tag{13}$$

$$Cinv(j,Big) = COinv(Big) * xEO(j,Big) \tag{14}$$

$$\sum_k xEO(j,k) \leq 1 \tag{15}$$

$$Mt(j,CA) \leq Av(j,CA) \tag{16}$$

2.3.5. Product flow

The product flow PF (j, i) is calculated by multiplicating the total feedstock material flow to produce EO with yield (*see* Table 2). Eq. (17) gives a way to estimate the product flow.

Table 1. Scales, yields, and economic indicators of EO processing plant.

Scale (a ton of CA $year^{-1}$)	Investment Costs (M.USD)	
Small: 16.6	0.37	
Medium: 61.1	0.95	
Large:137.4	1.94	
NPV base case (M.USD)[1]	**PP base case (years)**[2]	**MPS (ton $year^{-1}$)**[3]
2.4	1.17	16.13

[1] **NPV:** Net present value.
[2] **PP:** Payback period.
[3] **MPS:** Minimum processing scale.

Table 2. Input parameters and decision variables.

Parameters	Description	Unit
DispCA (j)	Calendula availability in region *j*	ton year^{-1}
CT (i)	Transport cost for material *i*	USD ton^{-1} km^{-1}
Cap (k)	The capacity of each plant *k*	ton year^{-1}
COinv (k)	Investment cost of each plant *k*	MUSD year^{-1}
Dist (j, z)	Distance between two regions *j* and *z*	km
DemEO (j)	EO demand in region *j*	kg h^{-1}
Produ (j)	EO produced in an existing plant in region *j*	kg h^{-1}
Lati (j)	Latitude of region *j*	Radians
Longi (j)	Longitude of region *j*	Radians
R	Earth's radius	km
P	Percentage of covered demand	%
yEO	EO yield	kg EO kg^{-1} dried Calendula
Variables		
Av (j,i)	Real availability of material *i* in region *j*	ton year^{-1}
Avt (i)	Total real availability of material *i*	ton year^{-1}
Crec (j, z, i)	Cost of received material *i* between two regions *z* and *j*	MUSD year^{-1}
Cinv (j, k)	Investment cost of a plant capacity *k* in a region *j*	MUSD
CTinv (j)	Total investment cost in region *j*	MUSD
Demt (i)	The total demand of material *i*	ton year^{-1}
DispCAt (i)	Total availability of material *i*	ton year^{-1}
MF (j, i, k)	Material flow at capacity *k* of material *i* in region *j* to produce EO	ton year^{-1}
MR (j, z, i)	Material flow *i* received from region *z* in region *j*	ton year^{-1}
MS (j, z, i)	Material flow *i* sent from region *j* to region *z*	ton year^{-1}
MRt (j, i)	Total material flow *i* received in region *j*	ton year^{-1}
MSt (j, i)	Total material flow *i* sent in region *j*	ton year^{-1}
MRtt (i)	Total received material flow *i*	ton year^{-1}
MStt (i)	Total sent material flow *i*	ton year^{-1}
Mt (j, i)	Total material flow *i* in region *j* to produce EO	ton year^{-1}
PF (j, i)	EO flow in a region *j*	ton year^{-1}
TCrec (j, i)	Cost of total received material *i* in a region *j*	MUSD year^{-1}
xEO (j, k)	Binary variable for capacity *k* in region *j*	[0, 1]

$$PF(j, EO) = Mt(j, CA)^{*}yEO \tag{17}$$

2.3.6. Product availability

Once the PF value is calculated, the real Availability of EO in a region can be determined using Eq. (2). This equation is slightly modified in terms of EO total flow. A new term is aggregated (*Produ*(*j*)). This term represents the EO production from existing local companies in the region. Eq. (18) follows:

$$Av(j, EO) = PF(j, EO) - MSt(j, EO) + MRt(j, EO) + Produ(j) \tag{18}$$

The total sent and received EO from a region (j) is determined in the same way as for Calendula through Eqs. (3) and (4). The transportation costs of the product are calculated using Eqs. (5) and (6). Parameters such as freight charges for EO were involved in the calculation of this cost. The total production of Calendula in Colombia is not enough to fulfill the total calendula EO demand. Thus, Eq. (19) represents that the Availability of EO supplies a certain percentage (*P*) of the demand (*DemEO*(*j*)).

$$Av(j, EO) \geq DemEO(j)^{*}P \tag{19}$$

Table 3. Subscript indices used in the model.

Set	Description
$i\varepsilon I$	Set of components
$j\varepsilon J$	Set of regions
$z\varepsilon Z$	Set of regions
$k\varepsilon K$	Set of sizes

2.3.7. Total variables

Eqs. (20), (21), (22), (23), and (24) are used to calculate the total values (the sum of all regions) of the main variables.

$$Avt(i) = \sum_{j} Av(j, i) \tag{20}$$

$$Demt(EO) = \sum_{j} DemEO(j) \tag{21}$$

$$DispCAt(CA) = \sum_{j} DispCA(j) \tag{22}$$

$$MStt(i) = \sum_{j} MSt(j, i) \tag{23}$$

$$MRtt(i) = \sum_{j} MRt(j, i) \tag{24}$$

The structured model to meet the optimal locations of calendula EO processing plants, sourcing, and distribution sites in Colombia, with the respective material flows at specific capacity, was defined as a mixed-integer linear programming (MILP) problem. The General Algebraic Modeling System GAMS has been widely used as specialized software for optimization. GAMS was used as a tool to model the BSC of Calendula in the Colombian context. The version GAMS Development Corporation. Release 24.7.4, Fairfax, VA, USA, 2016, was used to solve this optimization model through algorithm CPLEX. The objective function which minimizes the total cost is indicated in Eq. (25).

$$z=\sum_j TCrec(j,CA)+\sum_j TCrec(j,EO)+\sum_j CTinv(j) \tag{25}$$

The model statistics are comprised of 10650 equations, 15444 continuous variables, and 147 discrete variables.

2.4. Life cycle assessment methodology

SimaPro software (version 9.1.0.11) was used to perform the environmental assessment of the EO production. The Life cycle assessment (LCA) was developed considering the ISO 14001 and ISO 14040. The EcoInvent database was used. The goal and scope of the analysis, the functional unit, and the systems introduced in SimaPro software are described below:

2.4.1. Goal and scope

The main environmental impacts related to the cultivation of Calendula *(Calendula Officinalis)* and the production of EO (via steam distillation) were determined to detect hotspots along the supply chain. The agriculture activities for aromatic plants cultivation are not standardized in Colombia. Inventory data was collected from seed nurseries and farmers over the whole Colombian territory. The LCA was carried out based on a cradle-to-gate approach involving the Calendula crop activities (i.e., seedlings production, calendula sowing and harvesting, and transportation from the regional collection center to the processing plant, among others) and finishing in the EO production. The distribution of EO was not considered since this stage does not represent a significant environmental impact in comparison to the effects caused by the agricultural and processing steps. This product can be shipped in a single load with other materials since its regular package is in the milliliters level.

2.4.2. Functional unit

Considering the EO as a specialty chemical compound, a mass-based functional unit represents the system properly. According to Pérez-López et al. (2016), the mass is a standard functional unit for specialty chemicals production. In this way, 1 g of EO was chosen as a functional unit.

2.4.3. System boundary

The Calendula in Colombia is taken as an annual crop, cultivated in standard hectares with a rotation time of 7.5 months. Machinery (e.g., knapsack sprayer, chainsaw, tractor) and implements (e.g., tractor plow, roller packer) were used in the crop management practices and included in the system boundaries. Table 4 shows the fuel consumption of each machinery type on the respective subsystem. An illustrative representation of system boundaries is presented in Figure 4. Within the system, boundaries were considered the seedlings and agrochemicals (i.e., fungicides, herbicides, and fertilizers) production and transportation. Figure 4 presents the system boundaries of the LCA for EO production through steam distillation. This assessment includes two stages: the agricultural stage and the processing stage. Moreover, three central systems: seedlings production, calendula cultivation, and EO production, were considered.

- System 1: Seedlings production

The seedling production includes all the nursery activities, from sowing to delivery to the field plantation. It comprises three subsystems: substrate preparation, greenhouse building, and agrochemical application. In the first subsystem, suitable organic substrates were chosen: peat moss and soil and poured in plastic (PVC) seedbeds of 128 cavities. A high-density Polyethylene HDPE greenhouse with galvanized steel columns and concrete foundations is considered in the second subsystem. The area of the greenhouse is 132 m^2 per 1 ha of field crop. In the third subsystem, an iodine solution (5–10% w/w) is used to sterilize the seedbed, and Dithane (Mancozeb based) fungicide is used to prevent the formation of pathogen fungi. Besides, hen droppings are used as fertilizer. Water irrigation of 0.235 m^3 is needed per hectare. After 35–45 days the little calendula plants can be transplanted to the field crop.

- System 2: Calendula cultivation

Calendula cultivation involves four subsystems: 1) site preparation, 2) growing, 3) harvesting, and 4) stump removal. First, the site preparation subsystem aims to remove the weed and other invasive plants to prepare the soil for the new crop. A mowing machine is used to cut the wilder vegetation. A plow with a tractor is used to make the furrows. Dolomite and lime were used to increase the soil pH, agrogypsum for mineralizing and disinfecting (Agrodine and Diazinon). A PVC cover is used on every furrow to avoid weed growth. Finally, a water pipe dripping system is used; therefore, PVC piping material and a centrifugal pump were considered.

In the growing subsystem, the calendula seedlings from the greenhouse are sown and let grow in the field crop. This subsystem involves the implementation of hen droppings by hand (fertilizer), the fungicides application (Dithane and Bordelés broth), through a knapsack sprayer,

Table 4. Calendula crop operations based on Colombian practices (Castro et al., 2013; Correa Pezotti, 2014; Curioni and García, 2019; Gobernación de Antioquia, 2013; Hetz and Reina, 2013; More et al., 2010; Tomás Moore et al., 2014).

Phase	System	Time (month)	Activity	Machinery		Use rate (h ha^{-1})	Fuel Consumption (kg ha^{-1})	Input rates (kg ha^{-1})
				Equipment	Weight (kg)			
1	Site preparation	1–1.5	Cutover	Mowing machine	2500	1.7	4.62	-
			Ploughing	Plough + Tractor	6259	1.3	74	-
			Amendment	Handmade		20	-	Agri-gypsum: 500
								Hen droppings: 10
								Dolomite lime: 1000
			Disinfection	Knapsack sprayer	4	9	-	Agrodyne: 1.12
								Diazimon: 1.12
			Plastic covering	Handmade		9	-	PVC: 9936
			Water piping	Handmade		9	-	PVC: 3366
			Water pumping	Handmade		4	-	-
2	Growing	1.5–3.5	Fertilizing	Handmade	-	-	-	Hen droppings: 7000
			Fungiciding	Knapsack sprayer	4	60		Dithane: 300, Brodelés: 900
			Watering	-	-	-		Water: 1764
3	Harvesting	3.5–7.5	Fertilizing	Handmade	4	-	-	Hen droppings: 7000
			Fungiciding	Knapsack sprayer	4	120		Dithane: 1200, Brodelés: 3600
			Watering	-	-	-		Water: 3024

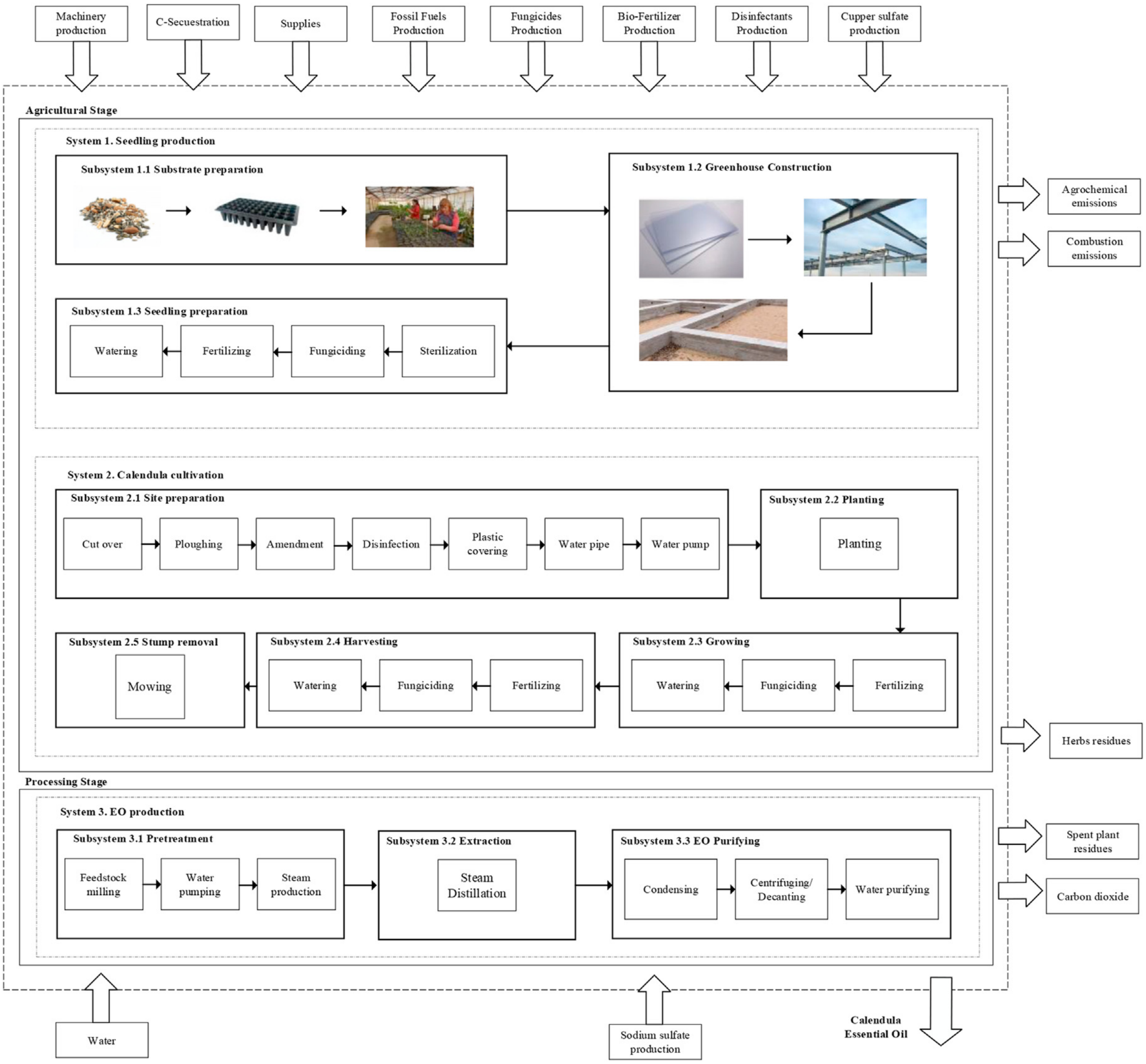

Figure 4. System boundaries of calendula EO production.

and the regular watering. The fertilizer application is only made once. The fungicide application is made each three weeks.

The harvesting subsystem starts after 3.5 months when calendula flowers can begin to be manually collected. At this time, fertilizing, fungicide, and watering activities keep operating. 583 kg of hen droppings, 100 kg of Dithane solution, and 300 kg of Bordelés broth solution are poured into the crop each week. Watering is maintained constant until harvesting ends. The harvest cycle is over after 12 weeks. At the end of the cycle, the calendula stump is removed by a mowing machine, and the fresh flowers are carried to a shelter, where the drying process takes place. After one week, the dried calendula flowers are transported in 5-ton pickup trucks to the processing plant.

- System 3: EO production

The steam distillation is a simple process where the dried calendula flowers are submitted to extraction to obtain EO. Here, the combustion of natural gas in the boiler to produce steam is considered. The electricity is provided by a hydroelectric plant (as the most used energy source in Colombia) to process the feedstock and separate the essential oil from hydrolat (centrifugation). Sodium sulfate is used in the refining process of EO to remove the remaining water. Finally, the final disposal of the extraction residues (spent flowers) is considered.

3. Results and analysis

3.1. Supply chain assessment

The optimal configuration for the supply chain of Calendula EO results in seven scenarios that comprise the optimal processing plant(s) locations, scale, and material flow. Tables 5 and 6, and Figure 5 describe the results comprehensively. Each scenario is based on the share of total EO demand in Colombia to be fulfilled by the project. The first scenario pretends to fulfill 0.7 % of the total demand. The number of processing facilities with the respective scales and locations for each scenario is described in Table 5. Percentages of less than 0.7 % give optimal solutions. Thus, no processing plants are needed (i.e., the existing processing plants in the country satisfy the demand). Percentages over 1.3 % turn the model unfeasible due to the total calendula availability in Colombia is exceeded.

Each scenario can involve different optimal locations. For instance, scenario 4 involves four optimal locations: two medium-scale plants in Cali and Bucaramanga, and two small-scale plants in Ibague and Cravo Norte (Arauca). The higher the demand, the bigger the scale of processing plants. Therefore, investment, and transportation costs increase along with these variables. The transportation costs are significantly lower than investment costs due to the natural ingredients industry processes small amounts of feedstocks to produce small quantities of high-value specialty extracts at high investment costs.

Table 5 exposes the optimal supply and distribution material flows for each scenario. Each processing plant sends EO to customers in other regions. The total EO flow increases along with capacity and demand. The model considers the presence of the imported EO and the production of EO by other local companies, making the optimal distribution channel focused on the regions where the EO demand is high. Scenario 1 addresses a medium-scale processing plant in Ibague. There is a high availability of calendula plantations in the surroundings (Venadillo, Lérida, Alvarado, etc.). Hence, the availability increases the offer of dry Calendula, and the transport cost is, consequently, reduced. The freight charge in a 5-ton pickup in Colombia is 0.11 US dollars ton-1 km-1 for calendula supply. The freight charge in a Thermoking truck with refrigeration is 0.12 US dollars ton-1 km-1, for essential oil distribution. The pickup is loaded each week with approximately 1 ton of dried Calendula (and 4 tons of other agricultural feedstocks). According to the SICE-TAC (Sistema de Información de Costos Eficientes para el Trapsnporte Automotor de Carga) platform (Mintrasporte, 2020), the economy of scale is often used by stakeholders to transport different types of agricultural feedstocks when they can be shipped in the same freight so that a discount in the transport cost must be considered. The logistic operation is managed under three-year contracts.

The mass flow of feedstock from the sourcing sites to the processing plants increases along the scale and demand. However, there are some exceptions, when the optimal processing site has enough Calendula availability to satisfy the EO demand (Cravo Norte and Ibagué in scenario 4). The percentages of the total production of Calendula in Colombia used by every processing plant and scenario are presented in the final two columns of Table 6. These percentages increase along with the feedstock mass flow, which in turn increases with the scale. Then, strategical decisions can be made to choose the most convenient Colombian economic and logistic context scenario.

Two economic aspects were considered to make the proper decision: profitability and calendula availability. The net present value of each scenario is determined by the scale and the demand to be fulfilled. Therefore, big-scale scenarios represent higher NPVs (higher profitability). Table 7 shows some economic indicators of the three selected scales.

Economic advantages are presented by big-scale scenarios, such as better profitability, lower payback periods, and jobs increasing in the rural areas due to the expansion of the market. However, the regional context presents some issues in Calendula supplying since its productivity is low, and it is harvested seasonally. Scenario 6 takes 86 % of the total Calendula produced in Colombia. Thus only 14 % is left for other uses. Therefore, the possibility to occupy a high percentage of calendula production lies in national trade policies. Logistic and political aspects were considered to choose scenario five as the most feasible solution, which uses 66 % of the total calendula production of the country with medium and high scale processing plants in Bucaramanga and Manizales, respectively. Nowadays, the agribusiness policies in Colombia foster the cultivation of aromatic plants to produce active compounds for cosmetic and pharmaceutical industries based on biodiverse species that can enhance the farmers' economy. The calendula market is permanently growing (approx. 20 % per year), and scenario 5 does not affect its stability. Table 8 exposes the material flow of feedstock from sources and products to customers of scenario 5.

In summary, the processing sites located at Bucaramanga and Manizales claim the minimum logistic cost along the supply chain for an EO demand of 0.8 ton per year (1.1 % of the total demand). Qualitative market studies about essential oils production projects in Colombia present the best locations for processing plants at industrial cities such as Bogotá, Medellín, and Cali (Escobar Fernández, 2018; Instituto de Investigación de Recursos Biológicos Alexander Von Humbolt, 2003). However, this study does not consider the logistical cost of transporting raw materials from the field production to processing sites. Middle industrial cities, such as Manizales and Bucaramanga, play an important role as potential sites to place essential oil processing plants optimally. These are close to farmers but close enough to big costumers to maintain the feasibility of the project.

Remarkably, the optimal sites to place the processing plants are always close to cultivation sites with high feedstock availability. The feedstock availability and distance to the processing plant are decision variables that determine whether a specific location is chosen or not, as the model always searches for the minimum cost. Then, the bulk density of the feedstock makes supplying a cost-demanding step. Similar results of processing plant locations have been found in the literature. The availability of raw materials, either algae, lignocellulosic, or municipal waste residues, is considered to determine the location of the processing plants (Čuček et al., 2014; Taifouris and Martín, 2018). There is a real scarcity of studies related to supply chain optimization for essential oils in academic literature.

3.2. Environmental assessment

Table 9 shows the potential environmental impacts of EO production from Calendula. More than 90 % of the total effect on every category is

Table 5. Optimal processing of plant locations, scales, and costs.

Scenario	Total satisfied demand for EO (%)	Optimal Location for PP*	Scale (ton year^{-1})	Investment Costs (MUSD year^{-1})	Transportation Costs (USD year^{-1})
1	0.7	Ibagué	61.1	0.95	271
2	0.8	Cravo Norte	16.6	0.37	0
		Venadillo	61.1	0.95	316
3	0.9	Ibagué	61.1	0.95	271
		Popayán	61.1	0.95	390
4	1	Cali	61.1	0.95	420
		Bucaramanga	61.1	0.95	465
		Ibagué	16.6	0.37	0
		Cravo Norte	16.6	0.37	0
5	1.1	Bucaramanga	61.1	0.95	468
		Manizales	137.4	1.94	1000
6	1.2	Manizales	137.4	1.94	3000
		Popayán	61.1	0.95	1000
		La Cumbre	61.1	0.95	625
7	1.3	Cali	137.4	1.94	3000
		Armenia	137.4	1.94	3000

* **PP**: Processing plant.

Table 6. Optimal material flows for each scenario.

Scenario	Optimal Location for PP	EO to customers (ton year^{-1})	Calendula from suppliers (ton year^{-1})	% of TPCC* per PP	% of TPCC* per scenario
1	Ibagué	0.071	43.64	20	20
2	Cravo Norte	0.029	0	5	26
	Venadillo	0.110	48.05	20	
3	Ibagué	0.092	43.64	20	40
	Popayán	0.086	31.41	20	
4	Cali	0.135	44.46	20	51
	Bucaramanga	0.100	27.58	20	
	Ibagué	0.010	0	5	
	Cravo Norte	0.029	0	5	
5	Bucaramanga	0.097	27.58	20	66
	Manizales	0.225	134.46	45	
6	Manizales	0.230	134.46	45	86
	Popayán	0.048	31.41	20	
	La Cumbre	0.108	51.09	20	
7	Cali	0.251	120.76	45	91
	Armenia	0.237	127.72	45	

[*] **TPCC:** Total production of Calendula in Colombia.

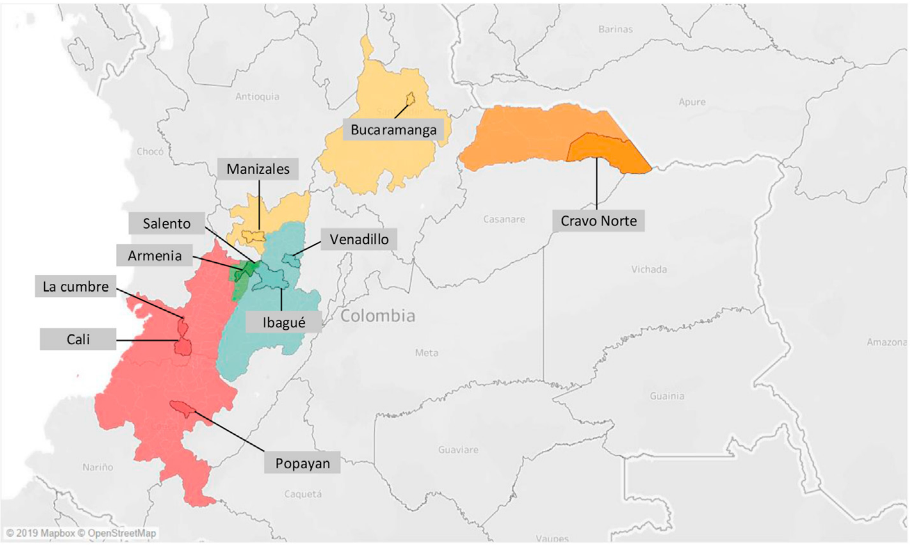

Figure 5. Optimal locations for processing plants (Tableau Software).

attributed to the agriculture stage. This is mainly due to the extensive use of fertilizers in the growing subsystem to assure the crop's maximum yield. Categories such as CC, OD, and FD, were impacted slightly by the processing stage (mainly the heat generation).

Within the agricultural stage, the systems with the highest contributions to the environmental impact were seedling production and calendula cultivation. Seedling production accounted for 25 % of the total effect, and calendula cultivation accounted for 74 %. The growing and harvesting subsystems represent more than 80% of the total impact in all the categories within the cultivation system. Figure 6 shows the contribution of each process (crop emissions, pesticides, amendment, disinfectant, fungicide, fertilizer, plastics, plowing, structures, substrates, machinery, and transport) to the environmental performance of the total agricultural stage.

Table 7. NPV and payback period for the three scales.

Scale (ton year^{-1})	NPV (MUSD)	Payback period (years)
16.6	0.001	9.92
61.1	1.9	1.25
137.4	5.3	0.79

Figure 6 presents the contribution to the environmental impact of agricultural stage practices. The extensive use of organic-based fertilizer, as hen droppings, in the cultivation system accounts for the highest environmental impact in the total agricultural stage. The most impacted categories by biofertilizer production were TE, WD, and ALO. Heavy metals and pathogenic microbes can affect water and terrestrial wildlife when added to the soil (United Poultry Concerns, 2009) (Blue, 2017). Moreover, all the processes involved in the poultry industry involve high water requirements and land occupation. Harvesting is the phase when the fertilizer application is highest (four months). Plastic production represents the second-highest impact in the agricultural stage. PVC pipes for watering and ground conditioning and HDPE sheets for seedlings planting effect mainly on the FD, CC, POF, and PMF categories. PVC production is related to carbon dioxide emissions, fossil fuels, and photochemical oxidants formation from reactive hydrocarbons. The fungicides production impacts mainly the HT, FET, and FE categories. Copper sulfate and Mancozeb (manganese-based fungicide) are potential water contaminators due to their water and organic matter fixation

Table 8. Material flows on the optimum scenario.

Manizales				Bucaramanga			
Calendula from suppliers (ton year^{-1})		EO to customers (kg year^{-1})		Calendula from suppliers (ton year^{-1})		EO to customers (kg year^{-1})	
Bogotá	0.31	Cali	14	Cúcuta	10.81	B/quilla	1
Zipaquirá	1.56	Pereira	30	Tunja	9.92	Cartagena	27
Medellín	1.94	Ibagué	24	Yopal	0.72	Cúcuta	9
Pereira	54.75	Neiva	19	Arauquita	6.13	St. Marta	7
Ibagué	17.46	Quibdó	8	-	-	V/dupar	17
V/cencio	11.84	Tunja	15	-	-	Arauca	4
Quibdó	6.42	Venadillo	0.3	-	-	Tunja	0.8
Tunja	0.88	Lérida	16	-	-	Riohacha	16
El Castillo	5.04	Aranzazu	97	-	-	Sincelejo	14
Venadillo	13.05	Certegui	0.1	-	-	Pivijay	0.7
Lérida	5.86	Carmen	0.2	-	-	Arauquita	0.6
Aranzazu	4.24	Salento	0.1	-	-	Cravo Norte	0.5
Certegui	3.68	-	-	-	-	-	-
Carmen	3.27	-	-	-	-	-	-
Salento	4.16	-	-	-	-	-	-

Table 9. Potential environmental impact of the production of 1 g of EO from Calendula.

Impact category	Total	Calendula cultivation and seedling production	Unit
Climate change (CC)	0.011	0.010	kg CO_2 eq
Ozone depletion (OD)	0	0	kg CFC-1 eq
Terrestrial acidification (TA)	$1.62 \cdot 10^{-4}$	$1.55 \cdot 10^{-4}$	kg SO_2 eq
Freshwater eutrophication (FE)	$9 \cdot 10^{-6}$	$9 \cdot 10^{-6}$	kg P eq
Marine eutrophication (ME)	$2.3 \cdot 10^{-4}$	$2.3 \cdot 10^{-4}$	kg N eq
Human toxicity (HT)	0.0142	0.014	kg 1,4-DB eq
Photochemical oxidant formation (POF)	$4.3 \cdot 10^{-5}$	$4 \cdot 10^{-5}$	kg NMVOC
Particulate matter formation (PMF)	$4.9 \cdot 10^{-5}$	$4.7 \cdot 10^{-5}$	kg PM10 eq
Terrestrial ecotoxicity (TE)	$2.2 \cdot 10^{-5}$	$2.2 \cdot 10^{-5}$	kg 1,4-DB eq
Freshwater ecotoxicity (FET)	$3.27 \cdot 10^{-4}$	$3.21 \cdot 10^{-4}$	kg 1,4-DB eq
Agricultural land occupation (ALO)	0.0038	0.0038	m^2
Water depletion (WD)	$5.87 \cdot 10^{-4}$	$4.41 \cdot 10^{-4}$	kg Fe eq
Fossil depletion (FD)	0.0027	0.0023	kg oil eq

solubility. It is essential to highlight the toxicity of Mancozeb for human health as a probable human carcinogen (Cornell Cooperative Extension, 2018). The impacts related to the crop itself affect mainly the ME and TA. Despite the calendula cultivation practices are based on organic agriculture policies, these generate effluents with moderate mineral content, which could increase terrestrial and marine eutrophication. The use of

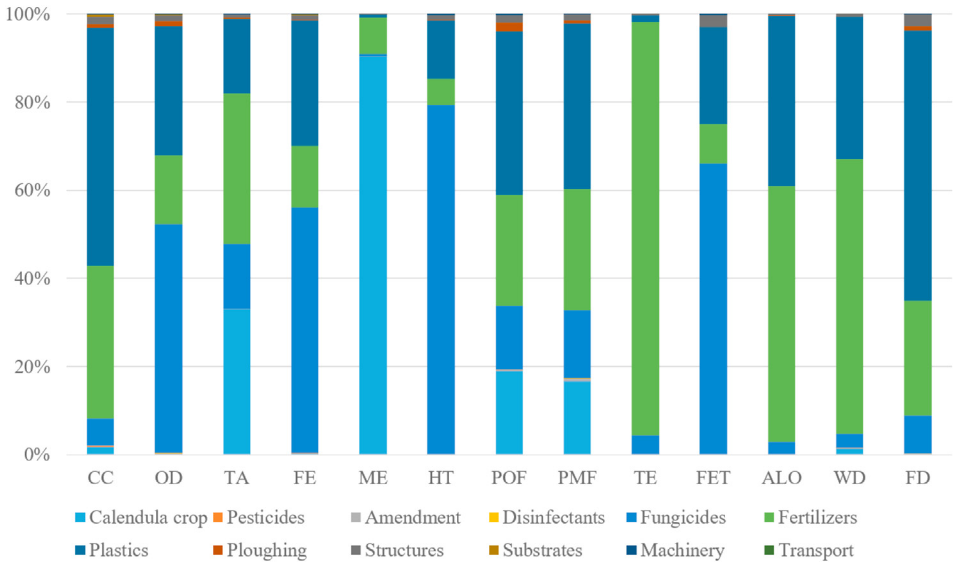

Figure 6. Contribution to the environmental impact of agricultural stage practices.

organic nitrogen-based fertilizers in the crop field affects mainly the TA category. The rest of the agriculture stage processes affect, to a lesser degree, the environmental impact category.

The contributions of the processing stage to the environmental impact are significantly lower than the agricultural stage. The pretreatment stage involves the generation of steam through a boiler and the milling of dried calendula flowers. The reaction stage comprises the extraction of the EO through steam. The downstream stage consists of separation and purification of the EO from hydrolat. The highest contribution to the environmental impact is presented by the pretreatment stage, where heat generation is needed to produce steam from tap water. It accounted the 99 % of the total effect on all the categories. According to the industrial heat generation in Colombia, the main fuel for boilers corresponds to natural gas, which is used for approximately 56 % of industries (Red de Investigación e Innovación en Combustión de USO Industrial- Unión Temporal Incombustion, 2014). The use of fossil fuel for producing steam has the strongest influence on the FD category (0.0004 kg oil eq). Moreover, carbon dioxide emissions from combustion contribute to CC (0.001 kg CO_2 eq).

The agricultural stage, specifically the cultivation system, was identified as the environmental hotspot in the life cycle of the EO production from Calendula. Some authors have developed similar environmental appraisals about cut flowers in Colombia regarding the literature data about the life cycle assessment of calendula cultivation and essential oil extraction. However, they only considered the agricultural stage as non-organic cultivation (Moreno Parrado et al., 2019). Although calendula flowers are used for ornamental purposes, the organic approach in calendula crops reduces the environmental impact compared to cut flowers. The CC impact category is reduced ten times, the FET and ME categories are reduced twenty and forty times, respectively. Saling et al. (2006) performed a complete LCA to determine the total environmental impact of the pigment application in poultry feeds from Calendula in China. In the agricultural stage, they consider similar operations to this study; nevertheless, the use of a cradle-to-grave approach and the geographical location of the study avoid a proper comparison.

4. Conclusions

This work has presented valuable contributions to the modeling of supply chains for natural-based products. The introduction summarizes the main aspects of how supply chain modeling works for biomass-based products. Important aspects were highlighted regarding the particularities of modeling a BSC, such as seasonality, controlled storage conditions, and low bulk densities. The optimization model gives a new approach to the traditional models that describe agroindustrial supply chains. The model structure outputs the optimal locations for processing, sourcing, and destination sites. Seven optimal scenarios were presented, which depend on the fulfilled demand. Bucaramanga and Manizales (scenario 5) were the most feasible locations to obtain the maximum total benefit. The agricultural stage (seedling production and field cultivation) was the most influential in the environmental impact matrix from the LCA study. This is explained by the extensive use of PVC beds, the organic fertilizer, and chemical fungicides application, as well as the fossil fuels identified as the highest contaminating activities or main hotspots. The processing stage presented a low environmental impact compared to the agricultural stage, in which the use of natural gas to generate low-pressure steam was the main hotspot.

The results of this study represent a helpful starting point to evaluate the feasibility and sustainability of a project to implement a calendula-based industry in Colombia. Stakeholders might consider this information valuable to invest in a more detailed engineering study since the optimal locations with the lowest logistic cost and the environmental hotspots of the chain (in a cradle-to-gate approach) are now clear. This study establishes the basis of an investment project that valorizes a non-conventional agroindustrial feedstock into a high-value product, contributing to the social development of farmers in Colombia. Future research work encourages authors to achieve a more detailed optimization model. The economic, environmental, and social aspects can be considered within the objective function, as developed in other supply chain works (Wang et al., 2011). The enhancement of some parameters in the model, such as a more accurate distance calculation between sites and the inclusion of the essential oil and hydrolat revenue (profit maximization), can be relevant for future studies. Finally, similar studies in the aromatic plant's supply chain field could be done for other bioactive ingredients.

Declarations

Author contribution statement

José-Andrés González-Aguirre, Juan Camilo Solarte-Toro & Carlos Ariel Cardona Alzate: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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References

Agencia de Noticias UN, 2012a. Colombia sería potencia en cosmética natural en 2032. Univ. Nac, Colomb [WWW Document].
Agencia de Noticias UN, 2012b. Aumentarán producción de caléndula en Colombia [WWW Document]. agenciadenoticias.unal.edu.co.
Blue, M.-L., 2017. Ecological Impact of Chicken Farming. Sciencing [WWW Document].
Bowling, I.M., Ponce-Ortega, J.M., El-Halwagi, M.M., 2011. Facility location and supply chain optimization for a biorefinery. Ind. Eng. Chem. Res. 50, 6276–6286.
Castro, D., Diaz, J., Serna, R., 2013. Cultivo y producción de plantas aromáticas y medicinales. Universidad Católica de Oriente, Rionegro, CO.
Cornell Cooperative Extension, 2018. Mancozeb. Pestic. Manag. Educ. Progr [WWW Document].
Correa Pezotti, G., 2014. Manual del cultivo de las plantas condimentarias de exportación bajo buenas prácticas agrícolas. Gobernación de Antioquia, Secretaría de Agricultura y Desarrollo Rural, Medellín, CO.
Čuček, L., Martín, M., Grossmann, I.E., Kravanja, Z., 2014. Multi-period synthesis of optimally integrated biomass and bioenergy supply network. Comput. Chem. Eng. 66, 57–70.
Curioni, A., García, M., 2019. Tecnología de producción de las aromáticas de hojas [WWW Document].
DANE, 2019. geoportal.dane.gov.co [WWW Document].
Diaz Merchán, J., 2003. Caracterización del mercado colombiano de plantas medicinales y aromaticas. Bogotá, CO.

Empresite, 2019. Aceites Esenciales [WWW Document].

Escobar Fernández, C.A., 2018. Proyecto de Emprendimiento - Viabilidad para la Creación de la Empresa "MILA". Univ. América. Fundación Universidad de América.

Global Biodiversity Information Facility, 2019. gbif.org [WWW Document].

Gobernación de Antioquia, 2013. Escuela de Campo: Cosecha y poscosecha de la caléndula.

Gómez, J.A., 2017. Caracterización Y Análisis De Competitividad De La Cadena De Ingredientes Naturales Para El Sector Cosmético Y Cosméticos Naturales. Bogotá, CO.

Hetz, E., Reina, L., 2013. Consumo y alternativas de ahorro de combustible en la utilización de tractores agrícolas. La Técnica Rev. las Agrociencias.

Hillier, F.S., Lieberman, G.J., Nag, B., Basu, P., 2012. Introduction to Operations Research. Tata McGraw-Hill Education Private Limited, New Delhi.

Instituto de Investigación de Recursos Biológicos Alexander Von Humbolt, 2003. Biocomercio Sostenible. Estudio del Mercado Nacional de Aceites Esenciales, Bogotá, CO.

Larson, P.D., Simchi-Levi, D., Kaminsky, P., Simchi-Levi, E., 2001. Designing and managing the supply chain: concepts, strategies, and case studies. J. Bus. Logist. 22, 259–261.

Min, H., Zhou, G., 2002. Supply chain modeling: past, present and future. Comput. Ind. Eng. 43, 231–249.

Ministerio de Transporte, 2019. SICETAC [WWW Document].

Mintrasporte, 2020. Sistema de Información de Costos Eficientes para el Transporte Automotor de Carga SICE-TAC [WWW Document]. https://www.mintransporte.gov.co/publicaciones/359/sistema_de_informacion_de_costos_eficientes_para_el_transporte_automotor_de_carga_sicetac/. (Accessed 16 November 2020).

Mo, L., Shao-Tong, J., Li-Jun, P., Zhi, Z., Shui-Zhong, L., 2011. Design and control of reactive distillation for hydrolysis of methyl lactate. Chem. Eng. Res. Des. 89, 2199–2206.

More, E., Fanlo, M., Melero, R., Cristobal, R., 2010. Guía para la producción sostenible de plantas aromáticas y medicinales. Gràfiques Muval, Barcelona, SP.

Moreno Parrado, C.A., Ricardo Hernández, R.E., Velásquez Arredondo, H.I., Lopera Castro, S.H., Hasenstab, C., 2019. An environmental evaluation of the cut-flower supply chain (Dendranthema grandiflora) through a life cycle assessment. Rev. EIA 16, 27–42.

Özdenkçi, K., De Blasio, C., Muddassar, H.R., Melin, K., Oinas, P., Koskinen, J., Sarwar, G., Järvinen, M., 2017. A novel biorefinery integration concept for lignocellulosic biomass. Energy Convers. Manag. 149, 974–987.

Palmeros Parada, M., Osseweijer, P., Posada Duque, J.A., 2017. Sustainable biorefineries, an analysis of practices for incorporating sustainability in biorefinery design. Ind. Crop. Prod. 106, 105–123.

Parra-Ramírez, D., Solarte-Toro, J.C., Cardona-Alzate, C.A., 2020. Techno-economic and environmental analysis of biogas production from plantain pseudostem waste in Colombia. Waste Biomas. Valoriz. 11.

Pérez-López, P., Jeffryes, C., Agathos, S.N., Feijoo, G., Rorrer, G., Moreira, M.T., 2016. Environmental life cycle optimization of essential terpene oils produced by the macroalga Ochtodes secundiramea. Sci. Total Environ. 542, 292–305.

PROCOLOMBIA, 2016. Ingredientes Naturales En El Sector Cosmético.

Red de Investigación e Innovación en Combustión de USO Industrial- Unión Temporal Incombustion, 2014. Determinación Del Potencial De Reducción Del Consumo Energético En Los Subsectores Manufactureros Códigos Ciiu 10 a 18 En Colombia. Medellín, CO.

Rentizelas, A.A., Tolis, A.J., Tatsiopoulos, I.P., 2009. Logistics issues of biomass: the storage problem and the multi-biomass supply chain. Renew. Sustain. Energy Rev. 13, 887–894.

Saling, P., Baker, R., Gensch, C.O., Quack, D., 2006. Differences in life-cycle assessment for the production of various carotenoid additives for use in poultry feeds. J. Sustain. Agric. 29, 15–41.

Santibañez-Aguilar, J.E., González-Campos, J.B., Ponce-Ortega, J.M., Serna-González, M., El-Halwagi, M.M., 2014. Optimal planning and site selection for distributed multiproduct biorefineries involving economic, environmental and social objectives. J. Clean. Prod. 65, 270–294.

Seuring, S., Müller, M., 2008. From a literature review to a conceptual framework for sustainable supply chain management. J. Clean. Prod. 16, 1699–1710.

Silver, E.A., 1981. Operations research in inventory management: a review and critique. Oper. Res. 29, 628–645.

Skoulou, V., Zabaniotou, A., 2007. Investigation of agricultural and animal wastes in Greece and their allocation to potential application for energy production. Renew. Sustain. Energy Rev. 11, 1698–1719.

Stashenko, E.E., 2009. Aceites Esenciales. División de Publicaciones UIS. Universidad Industrial de Santander UIS, Bucaramanga, CO.

Taifouris, M.R., Martín, M., 2018. Multiscale scheme for the optimal use of residues for the production of biogas across Castile and Leon. J. Clean. Prod. 185, 239–251.

Tomás Moore, L., Piedad, L., Villarreal, S., Desmarchelier, C., 2014. Manual de Cultivo y Manejo de Caléndula Proyecto de Atención Primaria de la Salud Con Plantas Medicinales Y Fitomedicamentos "Cultivando la Salud" Municipio de Malvinas Argentinas Provincia De Buenos Aires, ARGENTINA Asociación Argentina de Fitomedicina. (Asociación Argentina de Fitomedicina (AAF) Centro Orientamento Educacional-Italia (COE), Entre rios, AR.

United Poultry Concerns, 2009. Intensive Poultry Production: Fouling the Environment [WWW Document].

Vega, J.P., 2018. La producción de los cultivos de plantas aromáticas y especias crecieron 21% en 2017 [WWW Document]. www.larepublica.co.

Wang, F., Lai, X., Shi, N., 2011. A multi-objective optimization for green supply chain network design. Decis. Support Syst. 51, 262–269.

You, F., Tao, L., Graziano, D.J., Snyder, S.W., 2012. Optimal design of sustainable cellulosic biofuel supply chains: multiobjective optimization coupled with life cycle assessment and input-output analysis. AIChE J. 58, 1157–1180.

Zhang, S., Huang, X., Qu, C., Suo, Y., Liao, Z., Wang, J., 2017. Extractive fermentation for enhanced isopropanol and n-butanol production with mixtures of water insoluble aliphatic acids and oleyl alcohol. Biochem. Eng. J.