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Life cycle assessment of *Salvia officinalis* L. under mediterranean conditions: An integrated agronomic and process-based approach

Eljo Daci[1*], Ilirjan Malollari[1], Dhurata Premti[1], Glejdis Hajdini[1]

[1] Department of Industrial Chemistry, University of Tirana, Zogu I Boulevard, 1001, Tirana, Albania
* Corresponding author's e-mail: eljodaci@hotmail.it

ABSTRACT

This study presented a comprehensive life cycle assessment (LCA) of *Salvia officinalis* L., integrating agronomic data, irrigation modeling, and industrial extraction simulation into a unified analytical framework. The primary objective was to quantify environmental impacts, energy consumption, and process efficiency across the entire life cycle – from cultivation and harvesting to processing, utilization, and final disposal under representative Mediterranean conditions. To achieve this, experimental data obtained from field cultivation were combined with advanced irrigation scheduling, enabling precise estimation of crop water requirements and optimization of irrigation intervals. In parallel, extraction processes were performed, allowing evaluation of mass and energy balances, solvent consumption, and process performance. This integrated methodology ensures a robust and realistic assessment of the environmental footprint associated with sage production. The results clearly indicate that the cultivation phase is the dominant contributor to overall environmental impact, with the highest energy demand (12.95 MJ/kg) and the extraction phase with the largest share of greenhouse gas emissions (8.63 kg CO_2 eq/kg). These impacts are primarily associated with irrigation, fertilization, and field operations. In contrast, processing and downstream stages contribute comparatively lower but still significant environmental burdens. Importantly, the study identified key optimization strategies that enhance both environmental and process performance. An optimized irrigation interval of 10 days significantly improves water-use efficiency while maintaining biomass productivity. Additionally, the use of a mixed solvent system (hexane: methanol in a 1:3 ratio) increases extraction yield to 1.6%, representing the highest efficiency among tested conditions, while also reducing overall solvent consumption and associated impacts. Overall, the findings highlight critical environmental hotspots within the life cycle of *Salvia officinalis* L. and provide actionable recommendations for improving sustainability. The integration of agronomic optimization and LCA offers a powerful approach for developing efficient and environmentally responsible production systems for sage-derived bioactive compounds.

Keywords: *Salvia officinalis* L., life cycle assessment, sustainability, Mediterranean agriculture.

INTRODUCTION

Salvia officinalis L. is a widely cultivated medicinal and aromatic plant belonging to the Lamiaceae family, recognized globally for its rich content of essential oils and phenolic compounds, which confer a wide range of biological activities and industrial applications. Native to the Mediterranean basin, this perennial shrub has adapted well to semi-arid climates characterized by hot, dry summers and mild, wet winters, making it particularly suitable for cultivation in regions such as Southern Europe, North Africa, and parts of Western Asia. Its ecological adaptability, combined with its high economic value, has contributed to its widespread cultivation and commercialization (Hamidpour et al., 2014).

The increasing global demand for natural products, driven by consumer awareness of health, sustainability, and environmental protection, has led to a significant expansion in the cultivation and industrial processing of *Salvia officinalis*. However, this intensification of production has raised important concerns regarding environmental sustainability. Large-scale cultivation requires significant inputs of water, fertilizers, pesticides, and energy, all of which contribute to environmental pressures such as soil degradation, water scarcity, biodiversity loss, and greenhouse gas emissions (El Bilali and Allahyari, 2018).

Water use is one of the most critical factors in sage cultivation, especially in Mediterranean regions where water resources are limited, and climate change is exacerbating drought. Inefficient irrigation practices can lead to excessive water consumption, increased energy use for pumping, and soil salinization. Therefore, optimizing irrigation scheduling is essential for improving both productivity and sustainability. Tools and data developed by the FAO allow for precise estimation of crop water requirements based on climatic data and crop characteristics, enabling more efficient water management (Allen et al., 1998).

Fertilization practices also play a significant role in determining the environmental impact of *Salvia Officinalis* L. cultivation. The use of synthetic fertilizers contributes to greenhouse gas emissions, particularly nitrous oxide (N_2O), which has a global warming potential significantly higher than carbon dioxide. Moreover, nutrient leaching can lead to eutrophication of water bodies, negatively affecting aquatic ecosystems. Sustainable fertilization strategies, including the use of organic fertilizers and precision agriculture techniques, can help mitigate these impacts.

Beyond cultivation, the processing and extraction stages are also associated with considerable environmental burdens. The extraction of essential oils and bioactive compounds typically involves the use of organic solvents such as hexane, ethanol, and methanol, as well as significant amounts of thermal energy. These processes contribute to energy consumption, solvent emissions, and waste generation. The selection of appropriate extraction methods and solvents is therefore crucial for minimizing environmental impacts while maximizing extraction efficiency (Chemat et al., 2012).

In this context, the application of life cycle assessment (LCA) has become increasingly important as a tool for evaluating the environmental performance of agricultural and industrial systems. LCA is a standardized methodology, defined by ISO 14040 and ISO 14044, that enables the comprehensive assessment of environmental impacts associated with all stages of a product's life cycle from raw material extraction ("cradle") to disposal ("grave") (ISO, 2006a; ISO, 2006b). This holistic approach ensures that environmental burdens are not shifted from one stage of the life cycle to another, providing a more accurate and complete picture of sustainability.

The LCA framework consists of four main phases: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation (Guinée et al., 2011). In the first phase, the objectives of the study, system boundaries, and functional unit are defined. The LCI phase involves the collection and quantification of input and output data, including energy use, raw materials, emissions, and waste. The LCIA phase translates these data into environmental impact categories, such as global warming potential, acidification, eutrophication, and resource depletion. Finally, the interpretation phase involves the analysis of results to identify key environmental hotspots and recommend improvement strategies.

In the context of medicinal and aromatic plants, LCA provides valuable insights into the environmental performance of different cultivation and processing systems. It allows researchers and decision-makers to identify the most resource-intensive and polluting stages of the life cycle, thereby supporting the development of more sustainable practices. For example, several studies have shown that the cultivation phase is often the dominant contributor to environmental impacts due to irrigation, fertilization, and mechanization (Nemecek et al., 2016; Notarnicola et al., 2017).

Recent advancements in green extraction technologies offer promising alternatives to conventional methods. Techniques such as supercritical fluid extraction, ultrasound-assisted extraction, and microwave-assisted extraction have been shown to reduce solvent use, energy consumption, and processing time, while maintaining or even improving extraction efficiency (Chemat et al., 2019). The adoption of these technologies can significantly enhance the sustainability of sage processing.

Another important aspect of sustainable production is the implementation of circular economy principles. In the case of *Salvia officinalis*, the residual biomass generated after extraction still contains valuable compounds and can be repurposed for other applications, such as bioenergy production, composting, or secondary extraction. This not only reduces waste but also improves resource efficiency and economic viability.

Environmental impact indicators commonly used in LCA studies of medicinal plants include cumulative energy demand, global warming potential (expressed as CO_2 equivalents), water footprint, acidification potential, and eutrophication potential (Rebitzer et al., 2004). Among these, global warming potential is particularly important due to the contribution of agriculture and industry to climate change. Reducing greenhouse gas emissions through improved management practices and technological innovations is, therefore, a key objective of sustainable production systems.

In Mediterranean countries such as Albania, the cultivation of *Salvia officinalis* L. represents an important economic activity, contributing to rural development and export revenues. The country's favorable climate and long tradition of medicinal plant production provide a strong foundation for the development of a sustainable and competitive industry. However, achieving this goal requires the adoption of modern agricultural practices, efficient resource management, and comprehensive environmental assessment tools such as LCA.

In conclusion, *Salvia officinalis* L. is a highly valuable medicinal and aromatic plant with diverse applications and significant economic potential. However, the environmental impacts of its cultivation and processing necessitate the adoption of sustainable practices. Life Cycle Assessment provides a robust framework for evaluating these impacts and identifying opportunities for improvement. By integrating agronomic data, process simulation, and environmental analysis, it is possible to develop optimized production systems that balance economic efficiency with environmental sustainability, thereby ensuring the long-term viability of sage-based industries.

This study applied a comprehensive LCA methodology to evaluate the environmental performance of *Salvia officinalis* L. across its entire production chain under Mediterranean conditions. The LCA framework follows the standardized guidelines defined by ISO 14040 and ISO 14044, ensuring methodological consistency, transparency, and reproducibility.

MATERIALS AND METHODS

Goal and scope definition

The primary goal of this study was to quantify environmental impacts, energy consumption, and process efficiency associated with the production of *Salvia officinalis* L., while identifying critical hotspots and opportunities for optimization. The study adopted a cradle-to-grave approach, encompassing all relevant stages from raw material production (cultivation) to end use. The assessment was structured into four interconnected phases: (i) Goal and scope definition, (ii) Life cycle inventory, (iii) Life cycle impact assessment, and (iv) interpretation.

Specific objectives included:

- Quantification of cumulative energy demand (MJ/kg biomass),
- Evaluation of greenhouse gas emissions (kg CO_2 eq/kg),
- Assessment of water use and irrigation efficiency,
- Optimization of extraction processes using solvent systems,
- Integration of experimental and simulation data.

The scope was defined geographically within Mediterranean climatic conditions, in Elbasan county region, Albania, characterized by seasonal rainfall patterns, high evapotranspiration rates, and water scarcity challenges (Figure 1).

System boundaries

The system boundaries included all major stages of the life cycle, as illustrated below:

1. Cultivation phase

This phase includes:

- Soil preparation (plowing, harrowing),
- Planting and establishment,
- Irrigation management,
- Fertilization (organic and/or synthetic),
- Pest and weed control,
- Field maintenance operations.

The energy inputs in this phase included fuel for machinery, electricity for irrigation, and embodied energy in fertilizers.

2. Harvesting and drying

This phase involved:

- Mechanical or manual harvesting,
- Transportation to drying facilities,
- Natural or controlled drying processes.

Drying is a critical step affecting both biomass quality and energy consumption. Controlled drying may require thermal energy inputs.

3. Extraction process

The extraction phase includes:

- Grinding and pre-treatment of biomass,

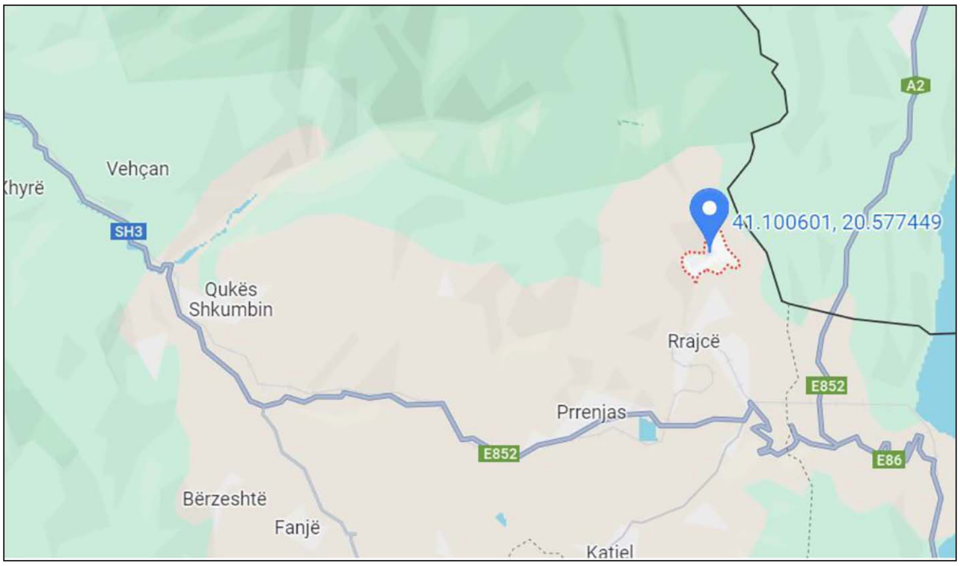

Figure 1. Cultivation field location 41.60 °N 20.35 °E

- Solvent extraction and solvent recovery (hexane: methanol),
- Separation and purification.

4. End use and disposal

This phase includes:

- Use of extracted compounds (pharmaceutical, cosmetic, food),
- Disposal or reuse of residual biomass,
- Waste management.

The functional unit of the study was defined as 1 kg of dry Salvia officinalis biomass at the processing gate. Although field measurements were initially recorded on a fresh biomass basis, all inventory flows were converted to dry biomass equivalents before life cycle impact assessment. Fresh-to-dry conversion was performed using measured moisture content according to the biomass conversion equation:

$$M_{dry} = M_{fresh} \times (1 - MC) \quad (1)$$

where: M_{dry} – dry biomass (kg), M_{fresh} – fresh biomass (kg), MC – moisture content (fraction).

For the average harvest moisture content of 65%, 2.86 kg of fresh biomass corresponded to 1 kg of dry biomass after the full drying procedure. Consequently, all inputs, including irrigation water, fertilizer application, diesel consumption, electricity use, extraction solvents, and emissions, were normalized to the declared functional unit of 1 kg dry biomass.

The broad scope of the system for analyzing the life cycle of *Salvia officinalis* L. is described below in Table 1.

Field data collection protocol

Irrigation modeling and reproducibility

The irrigation requirements of *Salvia officinalis* were determined using the FAO model

Table 1. *Salvia officinalis* L. system scope

System phase	Main activities	Key inputs	Outputs / Environmental Impacts
Soil preparation	Plowing, tillage, land preparation	Fuel, mechanical energy	CO_2 emissions from machinery, soil degradation
Cultivation	Planting, growth, irrigation, fertilization	Water, fertilizers (NPK), energy	N_2O emissions from soil, nutrient runoff, water use
Crop management	Agronomic care and plant protection	Pesticides (if applied), water	Chemical emissions, soil and water contamination
Harvesting	Collection of leaves/ biomass	Fuel, manual labor	Plant residues, CO_2 emissions from machinery
Drying and Pre-processing	Dehydration of plant material	Thermal/electrical energy	CO_2 emissions, biological mass loss

based on the FAO Penman–Monteith approach (Allen et al., 1998; Smith, 1992). The model was employed to compare two irrigation management scenarios: (i) daily irrigation and (ii) irrigation applied every 10 days.

Climatic data

The climatic inputs were derived from representative Mediterranean environmental conditions corresponding to the cultivation region. The simulation parameters are presented in Table 2.

Reference evapotranspiration was calculated according to the FAO Penman–Monteith equation (Allen et al., 1998), (Equation 2)

$$ET_0 = [0.408\Delta(Rn - G) + \gamma(900/(T+273))\, u_2(es - ea)] \,/\, [\Delta + \gamma(1 + 0.34u_2)] \quad (2)$$

where: ET_0 is reference evapotranspiration (mm day^{-1}), Δ is the slope of the saturation vapor pressure curve (kPa °C^{-1}), Rn is net radiation (MJ m^{-2} day^{-1}), G is soil heat flux density (MJ m^{-2} day^{-1}), γ is the psychrometric constant (kPa °C^{-1}), T is mean daily air temperature (°C), u_2 is wind speed at 2 m height (m s^{-1}), and $es - ea$ is vapor pressure deficit (kPa).

Crop parameters

Crop evapotranspiration (ETc) was calculated as the known formula for evapotranspiration (Equation 3):

$$ETc = Kc \times ET_0 \quad (3)$$

The crop coefficients used for *Salvia officinalis* were adapted from the literature values reported for Mediterranean aromatic and medicinal plants and FAO guidelines for herbaceous crops (Allen et al., 1998; Kiziloglu et al., 2008; Singh et al., 2019) (Table 3).

Table 2. Abiotic parameters collected from field measurements

Parameter	Value
Mean temperature	22.5 °C
Maximum temperature	30.2 °C
Minimum temperature	14.8 °C
Relative humidity	65%
Wind speed (2 m)	2.1 m s^{-1}
Sunshine duration	8.2 h day^{-1}
Reference evapotranspiration (ET_0)	4.5 mm day^{-1}

Soil hydraulic properties

The soil for cultivation consisted of approximately 80% clay and 20% silt. The hydraulic properties assumed in the model are listed below and are consistent with values reported for clay-rich agricultural soils under Mediterranean conditions (Saxton and Rawls, 2006; Allen et al., 1998) (Table 4)

The effective root depth was set to 25 cm according to field measurements of mature *Salvia officinalis* plants and values reported for medicinal and aromatic crops (Kiziloglu et al., 2008).

Irrigation scenarios

Two irrigation scheduling strategies were evaluated:

1. Daily irrigation (1-day interval)
2. Irrigation every 10 days

For each scenario, energy consumption is calculated after checking that the oil yield after the extraction is preserved

Energy and emission calculations

The irrigation water requirement obtained was converted into energy consumption using the following formula (Equation 4):

$$Energy\ (MJ) = Water\ Applied\ (\text{m}^3) \times Energy\ Factor \quad (4)$$

Table 3. Kc values during different cultivation seasons

Growth stage	Duration (days)	Kc
Initial	30	0.60
Development	40	0.85
Mid-season	60	1.05
Late season	90	0.80

Note: The average seasonal Kc value applied in the simulation was 0.90.

Table 4. Hidraulic properties values according to soil nature

Parameter	Value
Field capacity	36%
Permanent wilting point	18%
Total available water	180 mm m^{-1}
Rooting depth	0.25 m
Maximum root zone depletion	45%
Soil water holding capacity	45 mm

An energy factor of 2.76 MJ m^{-3} was assumed for groundwater extraction and field distribution, consistent with values reported for pressurized irrigation systems (Jackson et al., 2010; Lal, 2004).

Greenhouse gas emissions were estimated following the formula below (Equation 5):

$$CO_2eq\ (kg) = \mathit{Energy\ Consumption}\ (MJ) \times 0.0434\ kg\ CO_2eq\ MJ^{-1} \quad (5)$$

where: 0.0434 kg CO_2eq MJ^{-1} corresponds to the emission factor for electricity and pumping operations used in the life cycle inventory (IPCC, 2019; Nemecek and Kägi, 2007).

Salvia Officinalis L. extraction process

Solid–liquid extraction experiments were performed using the UESLC Computer Controlled Solid–Liquid Extraction Unit (EDIBON, Spain). The system is based on a continuous multistage countercurrent Rotocel-type extractor, which reproduces the extraction mechanism employed in industrial solid–liquid extraction processes. The integrated SCADA monitoring system enabled continuous measurement and control of process variables, ensuring experimental reproducibility and data reliability (Figure 2).

During the extraction of sage (*Salvia officinalis*) using different solvents, a significant quantitative variation was observed in the content of the oil phase (Table 5).

RESULTS

Life cycle inventory data, calculation procedures, and uncertainty assessment

LCI was developed using the primary data collected during the cultivation of *Salvia officinalis* under field conditions in Albania. Additional secondary data, including energy coefficients and emission factors, were obtained from internationally recognized literature and databases. All inventory flows were normalized to the functional unit of 1 kg of dried *Salvia Officinalis* biomass. The inventory includes all major agricultural operations, including soil preparation, fertilization, irrigation, harvesting, drying, and transportation (Table 6).

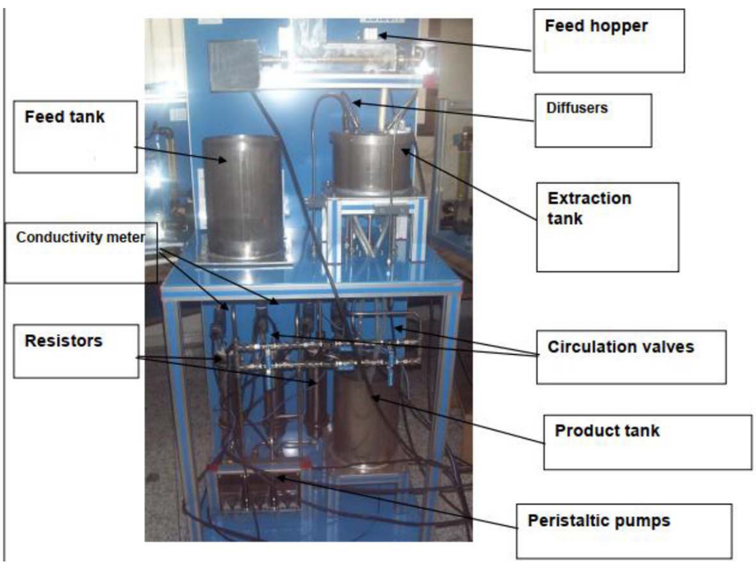

Figure 2. UESLC equipment description

Table 5. Extraction procedure using different solvents

Solvent	Biomass quantity	Extraction time	Biomass–solvent ratio
Ethanol	100 g dried biomass	30 min	1:5
Methanol	100 g dried biomass	30 min	1:5
Hexane	100 g dried biomass	30 min	1:5
Hexane–Methanol mixture (1:3)	100 g dried biomass	30 min	1:5

The energy consumption analysis highlights that irrigation is the most intensive activity during the cultivation phase and should be managed within the applied 10-day irrigation interval. Given the Mediterranean climate, characterized by high evapotranspiration rates, irrigation becomes essential for maintaining biomass yield (Figure 3)

The results show that the Hexane–Methanol mixture at a 1:3 ratio yielded the highest oil phase extraction, with 25 mL of extract obtained. This outcome suggests a synergistic effect between the polar solvent (methanol) and the non-polar solvent (hexane). Methanol facilitates the dissolution of polar and semi-polar compounds such as phenols, flavonoids, and certain oxygenated terpenes, whereas hexane is more effective in extracting lipophilic compounds and non-polar terpenes. The combination of the two solvents broadens the range of soluble compounds and enhances mass transfer of active substances from the plant matrix into the solvent phase (Table 7).

This distribution indicates that improving irrigation efficiency can significantly reduce overall energy consumption. The total greenhouse gas

Table 6. Life cycle inventory for the *Salvia Officinalis* L. treatment process

Process stage	Input/Output	Quantity	Unit	Data source
Soil preparation	Diesel fuel	0.06	L kg^{-1} biomass	Field measurements
Soil preparation	Machinery operation	2.32	MJ kg^{-1} biomass	Calculated from diesel use
Irrigation	Water	500	L kg^{-1} biomass	Experimental data
Irrigation	Electricity for pumping	0.30	kWh kg^{-1} biomass	Pump specifications
Fertilization	Nitrogen fertilizer (N)	0.080	kg kg^{-1} biomass	Field records
Fertilization	Phosphorus fertilizer (P_2O_5)	0.040	kg kg^{-1} biomass	Field records
Fertilization	Potassium fertilizer (K_2O)	0.050	kg kg^{-1} biomass	Field records
Crop management	Labor energy equivalent	0.40	MJ kg^{-1} biomass	Literature conversion
Harvesting	Diesel fuel	0.02	L kg^{-1} biomass	Field measurements
Drying	Thermal energy	5.82	MJ kg^{-1} biomass	Experimental calculation
Extraction	Hexane consumption	1.25	L kg^{-1} biomass	Experimental ratio
Extraction	Methanol consumption	3.75	L kg^{-1} biomass	Experimental ratio
Extraction	Electricity/thermal recovery energy	2.50	kWh kg^{-1} biomass	Process calculation
Extraction	Crude extract yield	0.016	kg kg^{-1} biomass	Experimental result (1.6%)
Solvent recovery	Recovered solvent	85	%	Assumption/Literature
Transportation	Diesel fuel	0.04	L kg^{-1} biomass	Estimated transport distance
Final product	Extract obtained	0.016	kg kg^{-1} biomass	Experimental data

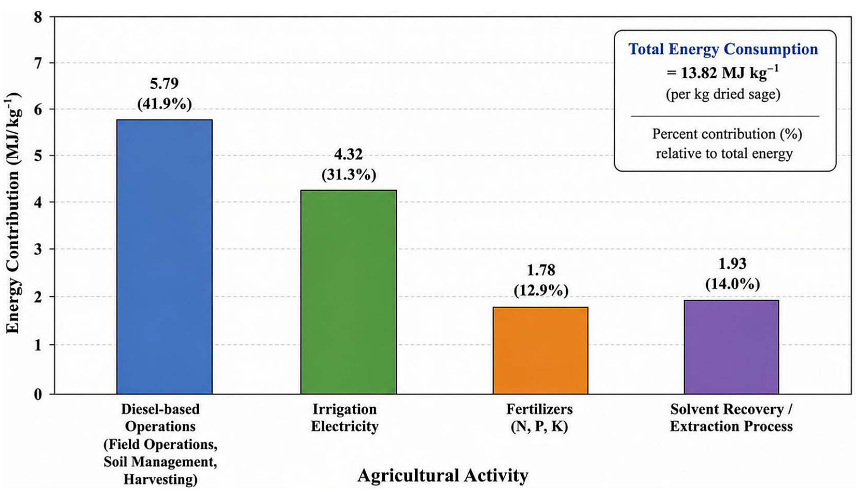

Figure 3. Related energy consumption values for the *Salvia officinalis* L. cultivation process

emissions were calculated at 9.41 kg CO_2 eq/kg, with the majority originating from the extraction process, methanol, and hexane production (Figure 4). Emission sources include fuel combustion (machinery), electricity use (irrigation systems), and fertilizer-related emissions (N_2O).

The hotspot analysis reveals that solvent production is the dominant contributor to the climate change impact of the extraction process, accounting for approximately 86.9% of the total greenhouse gas emissions. Among the solvents, methanol production contributes 5.62 kg CO_2-eq kg^{-1} biomass (59.7%), making it the largest environmental hotspot, followed by hexane production (2.56 kg CO_2-eq kg^{-1} biomass; 27.2%). The remaining impacts are comparatively minor. Extraction energy contributes 4.8%, while fertilization contributes 3.8%. Agricultural operations – including machinery and harvesting (1.7%), transport (1.1%), irrigation (0.9%), and drying (0.9%) – together account for less than 5% of the total impact. The environmental performance of the extraction system is governed primarily by solvent manufacture, indicating that strategies such as solvent recovery and recycling, reducing solvent-to-biomass ratios, or substituting conventional solvents with lower-impact alternatives would yield the greatest reductions in greenhouse gas emissions.

Irrigation modeling demonstrated that irrigation scheduling plays a critical role in both productivity and environmental performance. Figure 5 presents a comparative analysis of irrigation frequency on key environmental performance indicators in the cultivation of *Salvia officinalis* L. Two irrigation regimes are evaluated: daily irrigation and a 10-day irrigation interval.

The results demonstrate that daily irrigation leads to higher resource consumption and environmental impact, with irrigation water use reaching approximately 500 L/kg product, energy consumption 5.79 MJ/kg, and CO_2 emissions 0.61 kg CO_2-eq/kg. In contrast, the 10-day irrigation interval significantly reduces all three indicators, with water use decreasing to 274 L/kg, energy consumption to 2.37 MJ/kg, and emissions to 0.33 kg CO_2-eq/kg.

This substantial reduction highlights the strong influence of irrigation scheduling on system sustainability. The findings indicate that less frequent irrigation improves water-use efficiency as well as lowers energy demand and greenhouse gas emissions, without compromising overall production assumptions. Therefore, irrigation interval optimization represents a critical strategy for enhancing the environmental performance of *Salvia officinalis* L. cultivation systems. This finding highlights the importance of precision agriculture techniques in improving sustainability.

Table 7. Extraction results using different solvents

Solvent	Solvent + biomass quantity	Obtained volume (solvent + oil phase)	Extracted oil phase	Extraction yield (%)
Ethanol	500 mL ethanol + 100 g plant material	497 mL	12 mL	1.2%
Methanol	500 mL methanol + 100 g biomass	502 mL	22 mL	1.3%
Hexane	500 mL hexane + 100 g biomass	498 mL	18 mL	1.5%
Hexane–Methanol (1:3)	125 mL hexane + 375 mL methanol + 100 g biomass	510 mL	25 mL	1.6%

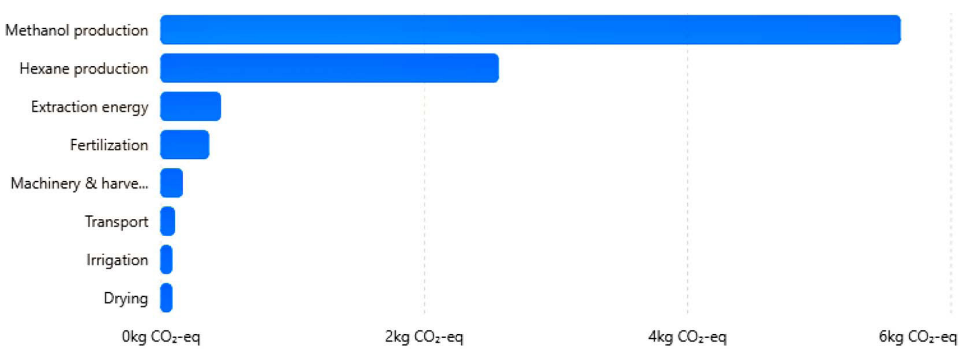

Figure 4. Total CO_2 emission production for the *Salvia officinalis* L. process

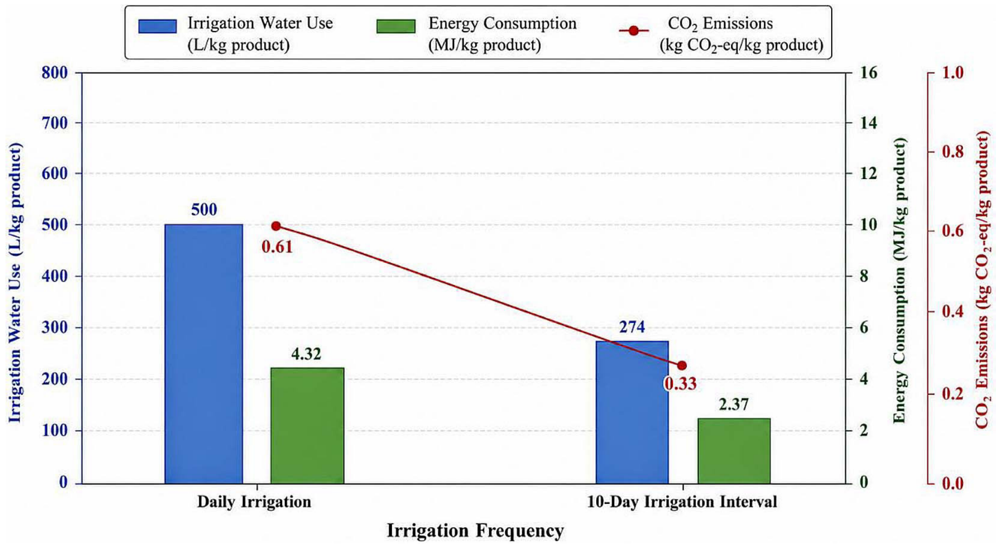

Figure 5. Energy impact on irrigation frequency

The similarity in extraction yield between the daily and 10-day irrigation regimes suggests that secondary metabolite concentration remained relatively stable despite reduced irrigation frequency. This is consistent with the reports that *Salvia officinalis* tolerates moderate water deficits without significant losses in essential oil content or extractable phytochemicals, provided that water stress does not become severe. Under these conditions, the reduction in irrigation primarily affects resource consumption rather than extraction performance, allowing improvements in water-use efficiency and environmental sustainability without compromising process productivity (Table 8).

A sensitivity analysis was conducted to evaluate how variations in key parameters affect overall environmental performance, such as irrigation frequency, energy consumption, and solvent ratio, as assembled in Figure 6.

Figure 4 illustrates the influence of ±20% variations in key inventory parameters on the overall life-cycle energy demand and greenhouse gas emissions. The baseline scenario corresponds to a total energy consumption of 13.82 MJ kg^{-1} product and total GHG emissions of 9.41 kg CO_2-eq kg^{-1} product. Increasing irrigation energy by 20% increased total energy demand to 15.16 MJ kg^{-1} and GHG emissions to 10.41 kg CO_2-eq kg^{-1}, highlighting the significant contribution of irrigation electricity to the environmental profile. A 20% increase in fertilizer use produced a more moderate effect, increasing energy consumption to 14.42 MJ kg^{-1} and emissions to 9.98 kg CO_2-eq kg^{-1}.

The extraction process exhibited a considerable influence on the environmental performance. Increasing extraction energy by 20% raised the total energy demand to 15.10 MJ kg^{-1} and GHG emissions to 10.73 kg CO_2-eq kg^{-1}, demonstrating that solvent extraction and solvent recovery are important contributors to the overall life-cycle impacts. Similarly, reducing solvent recovery efficiency by 20% produced one of the largest individual effects, increasing energy consumption to 15.95 MJ kg^{-1}

Table 8. Comparison of the extraction yield under different irrigation regimes

Parameter	Daily irrigation	10-day irrigation interval	Change (%)
Irrigation water (L kg^{-1} dry biomass)	500	274	−50.0
Irrigation energy (MJ kg^{-1} dry biomass)	4.32	2.37	−45.1
Extraction yield (%)	1.60	1.60	0.0
Oil phase obtained (mL per 100 g dry biomass)	25	25	0.0
Biomass–solvent ratio	1:5	1:5	No change
Extraction time (min)	30	30	No change
Solvent system	Hexane–Methanol (1:3)	Hexane–Methanol (1:3)	No change

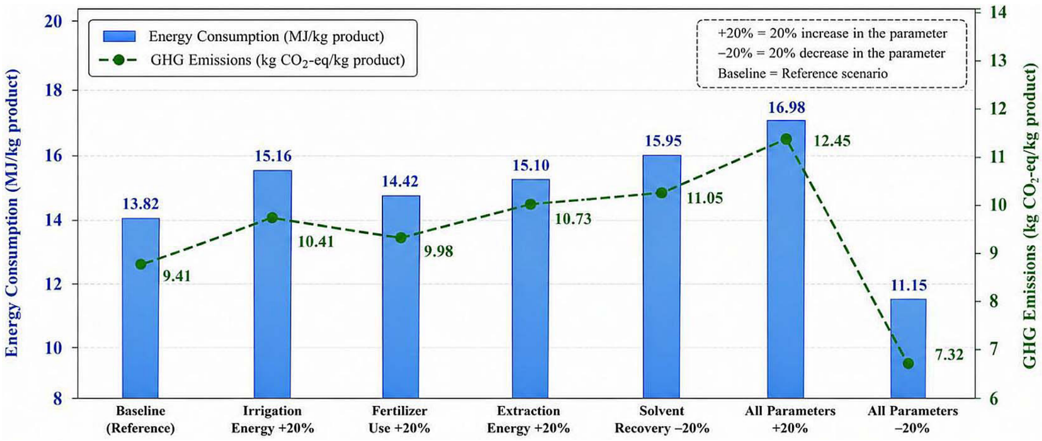

Figure 6. Factor combined sensitivity analysis of *Salvia officinalis* L. LCA

and GHG emissions to 11.05 kg CO_2-eq kg^{-1}, reflecting the additional burden associated with solvent replacement and recovery operations.

The combined +20% scenario, where all major parameters were simultaneously increased, produced the highest environmental impacts, reaching 16.98 MJ kg^{-1} and 12.45 kg CO_2-eq kg^{-1}, corresponding to increases of approximately 22.9% and 32.3%, respectively, compared with the baseline. Conversely, simultaneously decreasing all parameters by 20% reduced energy demand to 11.15 MJ kg^{-1} and GHG emissions to 7.32 kg CO_2-eq kg^{-1}, representing reductions of approximately 19.3% and 22.2%, respectively.

Overall, the sensitivity analysis identifies irrigation energy, extraction operations, and solvent recovery efficiency as the most influential parameters affecting the environmental performance of *Salvia officinalis* essential oil production (Table 9). These results indicate that improvements in irrigation management, process energy efficiency, and solvent recycling offer the greatest potential for reducing both energy consumption and greenhouse gas emissions across the production system.

The uncertainty analysis indicates that solvent production is the primary source of uncertainty, accounting for nearly 87% of the total climate change impact. Variability in agricultural inputs (fertilizer, irrigation, machinery operation, drying, and transport) has a comparatively minor influence on overall results, because these processes contribute less than 10% of the total emissions. Consequently, although the absolute climate impact may vary by approximately ±25–30%, the identification of solvent production, particularly methanol as the dominant environmental hotspot, remains robust. This finding suggests that improving solvent recovery, increasing recycling efficiency, or adopting lower-carbon solvents would substantially reduce both the overall environmental burden and the uncertainty associated with the life cycle assessment.

Table 9. Overall uncertainty evaluation

Parameter	Data source	Typical uncertainty	Effect on results	Confidence
Fertilizer application	Literature/IPCC	±20–30%	Low	Medium
Irrigation electricity	Literature	±15–25%	Low	Medium
Agricultural machinery fuel use	Literature	±15–20%	Low	Medium–High
Drying energy	Engineering estimate	±20–30%	Low	Medium
Transport distance	Estimated distance	±10–20%	Very low	High
Hexane production emission factor	Ecoinvent/GaBi databases	±20–30%	High	High
Methanol production emission factor	Ecoinvent/GaBi databases	±20–35%	Very high	High
Extraction electricity	Laboratory estimate	±15–25%	Medium	Medium
System assumptions (allocation, boundaries)	Methodological	±10–20%	Medium	Medium

CONCLUSIONS

The results obtained in this study are consistent with the findings reported in previous LCA studies on agricultural and agro-industrial systems, which consistently identify the cultivation phase as the most environmentally intensive stage (Nemecek et al., 2016; Notarnicola et al., 2017). This agreement reinforces the reliability of the applied methodology and confirms that the environmental profile observed for *Salvia officinalis* L. is not an isolated case, but rather reflects a broader pattern inherent to plant-based production systems, particularly under Mediterranean conditions. In comparison with similar medicinal and aromatic plants, the energy consumption observed in this study falls within the expected range reported in the literature. However, a notable outcome is that the greenhouse gas emissions are slightly lower than those reported in comparable studies. This improvement can primarily be attributed to the optimized irrigation strategy adopted, specifically the 10-day irrigation interval. By reducing unnecessary water application and minimizing the energy required for pumping and distribution, this approach demonstrates how targeted agronomic interventions can lead to measurable environmental benefits without compromising biomass yield. The integration of experimental field data with advanced modeling tools, such as irrigation simulations and process modeling, significantly strengthens the robustness of the analysis. This combined approach enables a more accurate representation of real-world conditions while also allowing the exploration of alternative scenarios and optimization strategies. A key conclusion emerging from the results is that the cultivation phase overwhelmingly dominates the environmental impact of the entire life cycle. This dominance is largely driven by irrigation requirements, which constitute the primary source of energy consumption. In Mediterranean climates, where water scarcity is a defining characteristic, irrigation is both essential for crop productivity and a major contributor to environmental burden. The findings clearly indicate that irrigation is the single most critical factor influencing both energy use and associated emissions. The dominance of the cultivation phase, the critical role of irrigation, and the effectiveness of optimization strategies collectively demonstrate that informed management decisions can lead to substantial environmental benefits. These insights contribute to the development of more sustainable agricultural systems and support the growing demand for environmentally responsible production of bioactive compounds derived from *Salvia officinalis* L.

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