

# Recent Advances in Sustainability Assessment of Medicinal Cannabis Cultivation and Production

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## Abstract

With the rapid growth of the medicinal cannabis sector, there is a growing concern regarding its environmental impact and sustainability. In recent years, life cycle assessment (LCA) studies on medicinal cannabis cultivation and processing have been conducted since 2021. However, there is a lack of comprehensive LCA studies that include all stages of medicinal cannabis cultivation and processing. In this systematic review, various LCA studies conducted from 2021 to 2025 using the ISO 14040/44 methodology are reviewed and discussed in terms of their goal and scope, life cycle inventory (LCI), life cycle impact assessment (LCIA), and results interpretation. Various environmental impact indicators are considered in this review, such as greenhouse gas emissions, energy demand, water usage, eutrophication, acidification, and resource depletion. All of these impact indicators point to a significant environmental impact of indoor cultivation in terms of greenhouse gas emissions, which vary from  $2.3 \times 10^3$  to  $5.2 \times 10^3$  kg CO<sub>2</sub> eq kg<sup>-1</sup> of dried cannabis product. Nevertheless, it is important to note that this is significantly influenced by regional electricity sources. Low carbon-based electricity sources, especially hydro-based sources, can reduce emissions to a significant level. Cultivation outdoors presents significantly lower emissions of (60–110 kg CO<sub>2</sub> eq kg<sup>-1</sup>), but fertilizers and substrates used in cultivation contribute significantly to emissions. Also, outdoor plants use 22.7 L plant<sup>-1</sup> d<sup>-1</sup> water at peak growth, while indoor plants use 9–11 L plant<sup>-1</sup> d<sup>-1</sup> water. Improvements in the life cycle of cannabis cultivation can be achieved through renewable energy use, water and fertilizers, substrate use and reuse, and inventories for post-harvesting activities like drying and extraction. Botanical parameters including genotype, planting density, and harvesting frequency are identified as significant but under-characterized determinants of LCA outcomes. Ethical and legal barriers are shown to be structural drivers of the LCA data gap. A SWOT analysis contextualizes the opportunities and constraints of the sector. Future research should focus on cradle-to-grave LCA and incorporate socio-economic factors for sustainability in the medicinal cannabis sector.

**Keywords:** Controlled Environment Agriculture (CEA); Carbon footprint; Energy consumption; Water management; Circular economy, SWOT analysis

## 1. Introduction

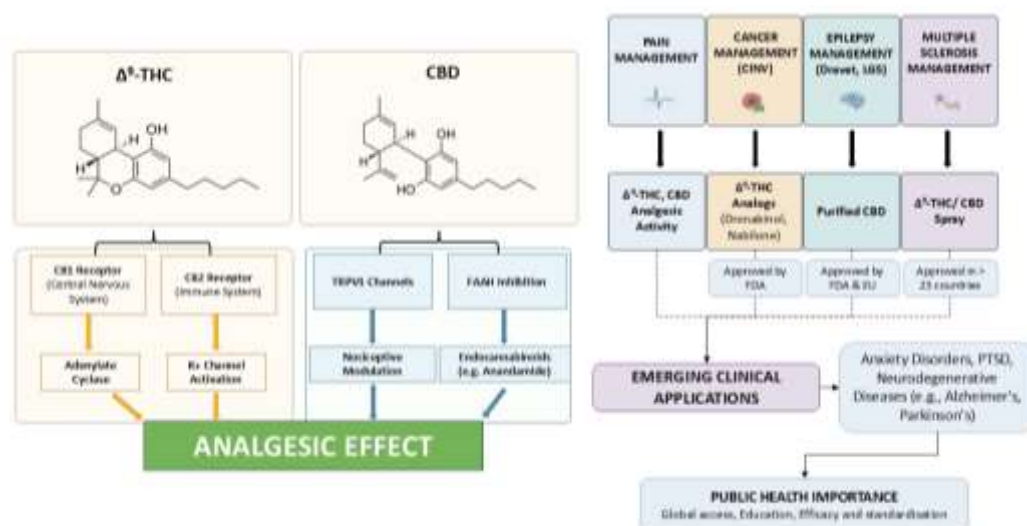
Medicinal cannabis (*Cannabis sativa* L.) has emerged as a significant pharmaceutical crop in the past decade [1]. Its legalization in many jurisdictions has expanded the production of high-value

flowers and extracts rich in  $\Delta^9$ -tetrahydrocannabinol ( $\Delta^9$ -THC) and cannabidiol (CBD) [2]. As with other intensive crops, the environmental footprint of cannabis is becoming a focus of public and scientific attention [3,4]. In past research, emphasis was placed primarily on pharmacology and potential use [5], resulting in knowledge gaps with respect to resource use, greenhouse gas (GHG) emissions [6], water demand and ecosystem impact associated with cultivation [7,8]. In more recent research, life cycle assessments (LCAs) have been used to quantify impact in various production systems: indoor, greenhouse, and outdoor [4,9,10]. There is limited data available for medicinal-grade production, which often involves stringent quality controls and energy-intensive indoor operations [11].

Medicinal cannabis is used in various therapeutic scenarios, thereby providing the rationale for conducting a thorough environmental assessment of its cultivation. In the management of pain,  $\Delta^9$ -THC and CBD have shown analgesic activity through different mechanisms.  $\Delta^9$ -THC exerts its effects by acting as a CB1 receptor agonist [12], thereby modulating pain signal transmission by inhibiting adenylate cyclase and activating inwardly rectifying potassium channels [2]. CBD, on the other hand, modulates pain signal transmission by acting on transient receptor potential vanilloid 1 channels and inhibiting fatty acid amide hydrolase [1].

In cancer management, cannabis-based medicine has shown efficacy as an antiemetic for chemotherapy-induced nausea and vomiting.  $\Delta^9$ -THC analogs, dronabinol, and nabilone have shown efficacy and have been approved by the FDA for this condition [13]. In epilepsy management, purified CBD has shown efficacy for Dravet syndrome and Lennox-Gastaut syndrome and has been approved by both the FDA and the European Union. In multiple sclerosis management [14], the  $\Delta^9$ -THC/CBD spray has shown efficacy in managing spasticity and neuropathic pain and has been approved in over 25 countries [15,16]. Other emerging trends include its application in anxiety disorders, post-traumatic stress disorder, and neurodegenerative diseases [2]. The entire process of cannabis cultivation and its application can be of direct public health importance.

The figure below summarizes and organizes all of this information. On the left side, it illustrates the chemical structures of the two main molecules,  $\Delta^9$ -THC and CBD, as well as their distinct mechanisms of action that lead to a shared analgesic effect. On the right-hand side, it organizes clinical applications into four main therapeutic areas (pain, cancer/CINV, epilepsy, multiple sclerosis) [2], detailing for each the analogs or pharmaceutical forms used and their specific regulatory approval status by the relevant authorities (FDA, EU). The figure also highlights the link to emerging trends and the overall impact on public health, encompassing issues of access, education, efficacy, and standardization, thereby providing a comprehensive overview of the medicinal cannabis value chain.



**Figure 1:** Mechanisms of action, approved and emerging therapeutic applications of the major cannabinoids.

During the cultivation stage, the most significant inputs are seeds, fertilizers, water, and energy for lighting. This stage has been consistently reported to be the most energy-intensive stage [7], with more than 80% of total energy consumption and greenhouse gas emissions [4,10]. In fact, indoor cultivation has been reported to have a carbon footprint ranging from  $2.3 \times 10^3$  and  $5.2 \times 10^3$  kg CO<sub>2</sub> eq kg<sup>-1</sup> of dried flower, and this is directly related to the local electricity supply's carbon intensity [3]. On the other hand, open-field cultivation drastically reduces the footprint by 60 - 110 kg CO<sub>2</sub> eq kg<sup>-1</sup>, replacing artificial lighting with solar irradiance, thereby emphasizing

96 the importance of LCA for land use assessment and hence its role in Global Assessment  
97 (GA) [4,17,18].

98 The second stage is harvesting and drying, which includes dehydrating the biomass using  
99 ventilation and dehumidification techniques. The processes require considerable amounts of  
100 thermal and electrical power, and maintaining a constant climate (20°C and 50% RH) can require  
101 up to 25% of the total electrical load after cultivation [19,20]. The LCA identifies this "hotspot" as  
102 being related to the quality of phytochemicals (terpenes and cannabinoids) and environmental  
103 impact.

104 The process of extraction and purification requires thermal, mechanical, and solvent  
105 treatment, to obtain the active compounds such as cannabinoids, decarboxylate, and concentrate,  
106 and filter, respectively [19]. All these processes generate emissions and waste streams that need to  
107 be accounted for in the LCA inventory [21]. Subsequently, the process of packaging and  
108 formulation requires the production of capsules, tinctures, and carrier oils, and packaging materials  
109 such as plastic containers, aluminum seals, and glass bottles, and secondary packaging materials  
110 such as paper boxes, etc. [22]. Lastly, the transport process requires the distribution of the product  
111 to hospitals, pharmacies, or stores for sale. This process is normally taken to be the system boundary  
112 in most of the present studies, such that the results are only "cradle to distribution" rather than  
113 "cradle to grave" assessments, implying that other important stages such as product use, packaging  
114 disposal, and product end-of-life management are still not well understood. Besides, other factors  
115 such as methodological differences, inadequate data for the LC inventory, and regional differences  
116 in the energy systems are limiting the results obtained so far [23]. Thus, crucial downstream  
117 activities like product use, packaging disposal, and end-of-life handling have not received sufficient  
118 research attention. In addition, methodological differences, limited LC data availability, and  
119 diversity in energy systems in various regions have limited the reliability of existing research  
120 outcomes [7,24].

121 Despite its established therapeutic benefits [8,25], medicinal cannabis has continued to  
122 experience socio-regulatory challenges, which have significant implications for the development  
123 of the cannabis market and the feasibility of environmental assessment research [1,26]. The  
124 perception of cannabis-derived products has continued to be affected by decades of stigmatization,  
125 during which industrial hemp and medicinal cannabis were equated with illicit narcotics [27]. The  
126 equation of medicinal cannabis with illicit narcotics has continued to limit consumer, prescriber,  
127 and retail acceptability, even for products with concentrations of  $\Delta^9$ -THC below the threshold for  
128 psychoactivity (<0.2% w/w for industrial hemp, as established by the EU Regulation) [28].

129 With respect to supply chain regulation, the risk of diversion, or the diversion of lawfully  
130 produced cannabis for human consumption into the illicit supply chain [29], necessitates  
131 traceability, seed-to-sale, destruction of non-conforming products, and chain of custody  
132 documentation. Such regulatory compliance activities add costs, which are not always reflected in  
133 the scope of the LCA, thus constituting a systematic underestimation of the overall production  
134 costs. International control, as established by the 1961 United Nations Single Convention on  
135 Narcotic Drugs [30], as amended by the 1971 and 1988 conventions, and the 2020 Commission on  
136 Narcotic Drugs decision, has continued to limit access to licensed production facilities for research  
137 purposes, thus constituting the main data scarcity, which has significant implications for the quality  
138 of the LCA.

139 The aim of this review is to critically evaluate and synthesize the literature regarding the  
140 environmental impacts of medicinal cannabis cultivation and production, identifying  
141 methodological limitations, quantifying the environmental burdens, and highlighting the major  
142 opportunities for improving sustainability within the medicinal cannabis supply chain. This has  
143 been achieved by conducting a systematic literature search of peer-reviewed literature published  
144 between 2021 and 2025. This aims to advance the state of knowledge in this emerging research  
145 area while highlighting gaps in the literature and avenues for future research to undertake  
146 comprehensive assessments of the medicinal cannabis supply chain.

## 147 2. Materials and Methods

### 148 2.1. Inclusion criteria and literature review

149 The literature was reviewed systematically from January 2021 to September 2025 to  
150 determine the appropriate literature available on the LCA of medical cannabis. The reason for  
151 considering 2021 as the starting year of this systematic literature review is that it is considered the  
152 year in which the first peer-reviewed LCA of medicinal cannabis was published. For this work, tree  
153 scientific literature databases were considered, and they are Scopus, PubMed and Web of science.  
154 The Boolean operators were applied to design an efficient query using words such as "cannabis,"  
155 "medicinal cannabis," "medicinal marijuana," "life cycle assessment," "LCA," "environmental

156 impact," "carbon footprint," "energy consumption," "water consumption," and "sustainability." The  
 157 literature search was carried out in English and French languages.

158 To ensure methodological rigor and objectivity, specific inclusion and exclusion criteria were  
 159 formulated. The inclusion criteria were based on peer-reviewed articles, academic theses, and  
 160 technical reports containing complete and/or partial LCAs, which had to contain at least one of the  
 161 essential components of LCI, LCIA, and interpretation. Excluded articles were those based only on  
 162 narrative reviews, conceptual and theoretical frameworks without underlying LCA data, and those  
 163 based on LCA assessments of industrial hemp intended for non-medicinal purposes, such as fiber,  
 164 seeds, and composite materials. The selection criteria ensured that the review remained pertinent  
 165 to environmental assessments related to medicinal cannabis cultivation and production systems. All  
 166 selection criteria are presented in Table 1.

168 Table 1. Inclusion and Exclusion Criteria

Category	Inclusion Criteria	Exclusion Criteria
Type of publication	Peer-reviewed journal articles, academic theses, and technical reports	Non-scientific publications, conference abstracts without data
Publication period	From 2021 to December 2025	Studies prior to 2021 without relevant reference data
Language	English or French	Other languages without accessible translation
Topic	Medicinal or high-THC cannabis production	Industrial hemp for fibre, seed, or composites
Methodology	Complete or partial LCA (inventory, impact, interpretation)	Narrative reviews or theoretical frameworks without practical application
Accessibility	Freely accessible or available through institutional subscriptions	Paywalled papers unavailable through institutional access

169 The selection process was carried out according to PRISMA methodology in three successive  
 170 stages of selection by title and abstract, then by conclusions, and finally by evaluation of the full  
 171 text to assess methodological validity. *Out of 342 documents initially selected, 57 were removed  
 172 after duplication, leaving 285 unique publications to be analyzed. Following this, 208 publications  
 173 were removed after evaluation by title and abstract, and another 64 after evaluation of the full text  
 174 for lack of LCA data and for not being relevant to a medicinal context, leaving 13 studies that  
 175 fulfilled all criteria for inclusion, as described in Figure 2.* The total of nine studies represents the  
 176 most comprehensive data set currently available regarding environmental performance of  
 177 medicinal cannabis systems, which is used to generate the comparative LCA production models  
 178 described in the following chapters.

180 Whereas there were nine studies found, an analysis of their spatial distribution indicates that there  
 181 is a focus on only seven unique geographical areas as depicted in Figure 3. This difference may  
 182 be accounted for by the fact that there were two studies from America that covered multiple states.  
 183 Such a distinction is crucial to ensure that there is a match between the document flow as depicted  
 184 on the PRISMA diagram and the actual geographic reality of the production areas.

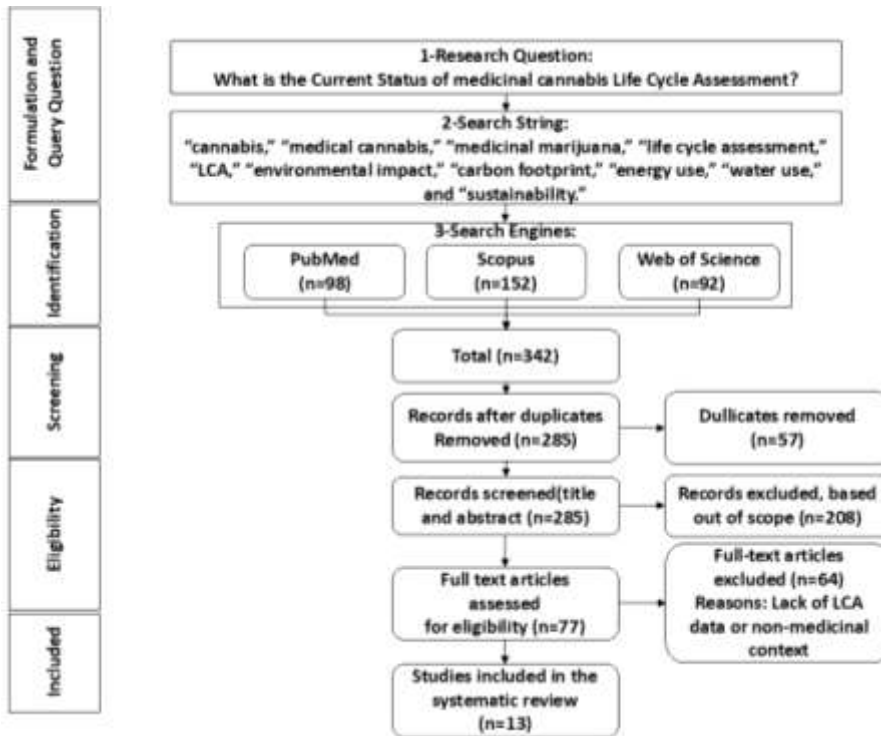


Figure 2: PRISMA flowchart of the selection process.

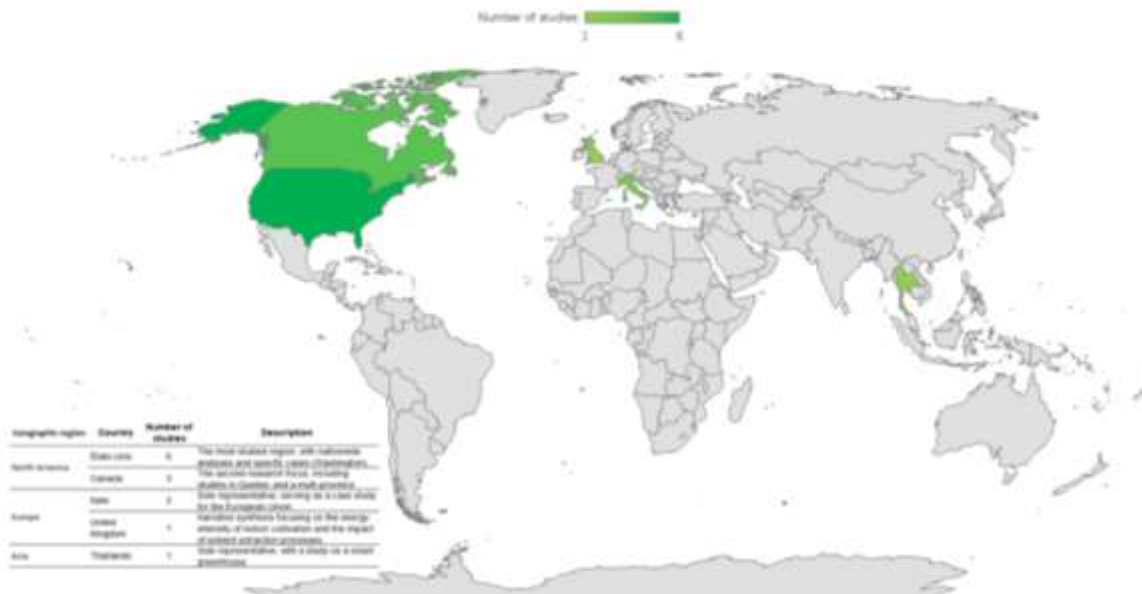


Figure 3: Geographical distribution of the nine studies included in the systematic review, showing the spatial concentration of LCA research on medicinal cannabis production systems.

## 2.2. LCA framework for cannabis systems

ISO 14040/44:2006 guidelines were followed as a basis to develop this review's methodology. According to these guidelines, LCA is an iterative process consisting of four interconnected phases: goal and scope definition, LCI, LCIA, and interpretation [31,32].

In the goal and scope definition phase, the purpose of the study, the functional unit (FU), and boundaries of the LCAs are established. In medicinal cannabis LCAs, it is established that 1 kg of dried cannabis flowers is the most frequently applied FU to date [4]. Nevertheless, alternative FUs such as 100 g of THC are proposed to establish a higher correlation to therapeutic value [9]. Boundaries of medicinal cannabis LCAs are generally established to cradle-to-gate, i.e., up to the gate of the farm or facility, although cradle-to-grave LCAs are limited in number to date [11].

LCI aims to quantify all relevant inputs and outputs of a medicinal cannabis LCA established in step 2. Inputs to medicinal cannabis include electricity, fuels, irrigation water, fertilizers, growing medium, and infrastructures, whereas outputs include emissions such as CO<sub>2</sub>, NO, VOCs,

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204 and wastewater effluents. Data are generally collected in foreground studies conducted in  
205 cultivation facilities or experimental trials and supplemented with background data from  
206 established databases such as ecoinvent [33].

207 During this phase, the flow of inventories is converted into environmental impact indicators  
208 using characterization factors [34]. The impact categories reported in LCAs of cannabis  
209 cultivation are GWP, eutrophication, acidification, human toxicity, photochemical ozone  
210 formation, and resource depletion [9]. ReCiPe and TRACI are often used as methods [35].

211 Lastly, interpretation is carried out to determine hotspots, compare scenarios, and develop  
212 mitigation strategies [31]. In this phase, sensitivity analysis is performed to evaluate the impact of  
213 assumptions related to factors such as yield, electricity mix, efficiency of HVAC, and functional  
214 unit selection [4]. The environmental impact of medicinal cannabis is compared with other  
215 systems, including agriculture [7]:

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### 3. Results and Discussion

#### 3.1. synthesis of LCA studies

Table 2 provides a synthesis of key LCA studies on medicinal cannabis cultivation and processing, identified through the systematic review using the keywords and inclusion criteria.

**Table 2.** Summary of published LCA studies on medicinal cannabis.

System & Location	FU	System Boundaries	GWP (kg CO <sub>2</sub> eq FU <sup>-1</sup> )	Energy Use (kWh FU <sup>-1</sup> )	LCA Software / LCI Database	LCIA Method	Key Hotspots / Main Drivers	Reference
Indoor (warehouse), USA (50 states, geographically resolved)	1 kg dried flower	Cradle-to-gate	2283 - 5184 (median ≈ 3658)	1817 - 4576	Custom engineering model + ecoinvent v3.4 + US LCI Database (NREL)	TRACI v2.1 (IPCC AR4, GWP100)	Electricity grid, HVAC, lighting (> 80 % of total)	[4]
Outdoor (farm), Washington, USA	1 kg dried biomass	Seed-to-sale	27.5	102	SimaPro + ecoinvent v3.11 + US LCI Database	IPCC 2021 GWP 100 v1.03	Electricity (pumps); propane; gasoline	[10]
Mixed-light greenhouse, Washington, USA	1 kg dried biomass	Seed-to-sale	140	NM			Supplemental lighting + HVAC	
Indoor (efficient facility), Washington, USA	1 kg dried biomass	Seed-to-sale	12.4	NM			Optimized electricity use	
Indoor / Greenhouse / Outdoor, USA (national scale)	1 kg dried flower	Cradle-to-grave	Indoor ~4500 Greenhouse ~2500 Outdoor ~700	NM	Custom electricity energy model + EPA eGRID (no LCA software)	IPCC GWP100 (simplified carbon footprint model)	Sectoral energy use approximately 595 PJ yr <sup>-1</sup> ; ~44 Mt CO <sub>2</sub> -eq yr <sup>-1</sup>	[24]
Italy (EU) scenarios: outdoor/organic, outdoor/conventional, indoor (incl. therapeutic flowers)	1 kg product (flowers or edibles)	Cradlcollectin g/estimatinge-to-gate	Scenario-specific LCA values reported (comparative Italy)	Reported per scenario	SimaPro v9.0.0.49 + ecoinvent v3.6 + EU background data	CML-IA method	Fertilizers; energy use for indoor systems	[20]

System & Location	FU	System Boundaries	GWP (kg CO <sub>2</sub> eq FU <sup>-1</sup> )	Energy Use (kWh FU <sup>-1</sup> )	LCA Software / LCI Database	LCIA Method	Key Hotspots / Main Drivers	Reference
Smart greenhouse, Thailand	NM	NM	~622 (“smart greenhouse” case, estimated)	Reported	no particular LCI database (collecting/estimating)	ReCiPe (Midpoint)	Cooling/heating; climate control	[36]
Indoor (synthesis air/indoor), Global	1 kg dried flower (reference synthesis)	NM	2200 - 6600 (reported LCA range)	NM	No LCA software (narrative review - not a primary LCA)	Multiple LCIA methods (synthesis of primary studies)	HVAC; lighting; supplemental CO <sub>2</sub>	[37]
Outdoor (pots), Québec, Canada	1 kg flower	Cradle-to-gate	61.8 - 110.7 / kg	Negligible	OpenLCA 2.0.1+ ecoinvent v3.8 + Custom model	ReCiPe 2016 Midpoint (H)	Peat substrate (65-75 %); fertilizers	[9]
Indoor vs Outdoor, Canada (multi-province)	1 kg dried flower	Cradle-to-gate	Indoor ≈ 3260-5400; Outdoor ≈ 10 % of indoor (e.g. ~326 in BC)	High (indoor)			HVAC/heating (gas) in cold climates; electricity mix	
Global Synthesis	1 kg dried flower (reference)	NM	2300 - 5200	up to 5000 kWh kg <sup>-1</sup> (indoor)	No LCA software (literature synthesis)	Multiple LCIA methods (synthesis)	Supplemental CO <sub>2</sub> = 11-25 % of indoor emissions	[38]
Hemp biomethane recovery, USA	1 MJ biomethane	Cradle-to-gate	Variable (net negative)	NR	OpenLCA	TRACI	Anaerobic digestion; biomass transport	[39]
Indoor, UK narrative synthesis	1 kg dried flower	Cradle-to-distribution	2300-5000	1800–4500	Literature synthesis	Multiple	Lighting; HVAC; solvent extraction	[7]
Outdoor (field), Italy (Mediterranean)	1 kg hemp seed	Cradle-to-farm-gate	18.72 kg CO <sub>2</sub> eq (highest scenario) (varies by genotype)	NR	SimaPro 9.0 + ecoinvent (European datasets)	ReCiPe 2016 Midpoint (H) + Carbon Footprint	N fertilization and planting density main drivers; genotype effect	[40]
Outdoor cannabis, Québec, Canada	1 kg dried flower or 100 g THC	Cradle-to-farm-gate	Varies by fertilizer treatment (L+ vs H-) (GWP reduced with optimized N/K)	NR	OpenLCA software v2.0 + Custom model + ecoinvent v3.8	ReCiPe 2016 Midpoint (H) (GWP, MFEP, TA, FD, MD)	N fertilization (GWP); eutrophication (K/P); FU choice alters ranking	[41]
Cannabis sector review, Global	Various FU (literature synthesis)	Rapid literature review scope	2300-5200 kg CO <sub>2</sub> (indoor, from Summers) ~1.8 kg CO <sub>2</sub> per gram (home cultivation)	NR	No LCA software (rapid lit. review)	Multiple LCIA methods (synthesis of primary studies)	Fossil fuel heating dominant in cold climates; illicit cultivation unquantified	[11]

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NM = Not Mentioned; CEA = Controlled Environment Agriculture; FU = Functional Unit; HVAC = Heating, Ventilation and Air Conditioning; GWP = Global Warming Potential; TRACI = Tool for the Reduction and Assessment of Chemical and other Environmental Impacts; ReCiPe = Life Cycle Impact Assessment method; CED = Cumulative Energy Demand; EF = Environmental Footprint (EU method).

As numerous literature reviews demonstrate, energy consumption is the key factor determining the environmental footprint associated with cannabis cultivation. Available empirical analyses consistently show that indoor cultivation generates the highest environmental impacts per kilogram of dried flower produced. This result is primarily due to the energy intensity of artificial lighting systems, heating, ventilation, and air conditioning (HVAC), as well as dehumidification systems required to maintain stable environmental conditions for plant growth.

The electricity consumption of indoor facilities typically ranges from 2000 to over 5000 kWh per kilogram of dried flowers [4,24]. Lighting and climate control systems alone account for over 80% of total greenhouse gas emissions. The global warming potential (GWP) values reported in the literature generally range from 2283 to 5184 kg CO<sub>2</sub> eq kg<sup>-1</sup> of dried flower, with a national median estimated at approximately 3658 kg CO<sub>2</sub> eq kg<sup>-1</sup> [24].

This significant variability is primarily explained by the carbon intensity of the regional electricity mix and by heating requirements linked to local climate conditions. Facilities located in regions heavily dependent on coal or subject to harsh winters logically have the highest values.

At the sectoral level, it has been estimated that indoor cannabis cultivation could consume approximately 595 PJ per year and generate nearly 44 Mt CO<sub>2</sub> eq annually [4], a magnitude comparable to that of certain national agricultural sectors.

Although general trends emerge for indoor facilities, atypical cases have been documented, Bottem and Ryan report that an optimized indoor facility in Washington State has a carbon footprint of only 12.4 kg CO<sub>2</sub> eq kg<sup>-1</sup>, a value significantly lower than that of outdoor cultivation (27.5 kg CO<sub>2</sub> eq kg<sup>-1</sup>) and hybrid greenhouse cultivation (140 kg CO<sub>2</sub> eq kg<sup>-1</sup>) assessed in the same geographic context. This result, which may seem counterintuitive at first glance, is explained by the facility's access to a highly decarbonized electricity mix, dominated by hydropower. This example illustrates the mitigation potential that can be achieved when the primary energy hotspot is effectively managed. It should nevertheless be emphasized that such performance cannot be generalized to facilities operating in more typical contexts, characterized by less favorable electricity grids.

Greenhouse systems are based on a hybrid model that combines natural solar radiation, supplemental lighting, and partial climate control. They generally reduce energy consumption by 40 to 60 percent compared to fully controlled indoor systems [10]. Published GWP values for greenhouses cover a wide range, from a few hundred to approximately 2,500 kg CO<sub>2</sub> eq kg<sup>-1</sup> for the most energy-intensive configurations [4], while modern greenhouses optimized for mixed lighting can fall below 150 kg CO<sub>2</sub> eq kg<sup>-1</sup> [10]. A study of a smart greenhouse reports an intermediate value of approximately 622 kg CO<sub>2</sub> eq kg<sup>-1</sup> [36]. The environmental performance of greenhouse systems, however, remains strongly influenced by geographic location, seasonal heating needs in cold regions, and cooling requirements in hot areas [4].

Open-field cultivation is generally recognized as the most energy-efficient and lowest-emission system per unit of product. The reported values typically range from 60 to 110 kg CO<sub>2</sub> eq kg<sup>-1</sup> of dried flower in Quebec [41], which is up to two orders of magnitude lower than indoor systems. This reduction in emissions is primarily due to the exclusive use of solar radiation and natural ventilation. However, some open-field systems nationwide can reach 700 kg CO<sub>2</sub> eq kg<sup>-1</sup> depending on the agronomic practices employed [4].

Aside from the cultivation system, which may be classified into indoor, greenhouse, and outdoor cultivation, the botanical characteristics of cannabis varieties have been identified as important [42,43] yet less reported determinants of LCA results [44]. Three parameters have been identified as important determinants of LCA results:

1-Genotype: The chemotype or chemical phenotype of cannabis varieties is a key determinant of the functional unit denominator in potency-based LCAs. High-CBD cannabis varieties such as Charlotte's Web and Cannatonic, have been characterized to contain 10-20% CBD per weight, while balanced THC-CBD chemotypes may contain 5-10% each [45,46]. The difference in cannabinoid density among cannabis varieties may range from 10-40% [47], and per plant yield may vary, thereby affecting the environmental impact per milligram of active ingredient administered the most clinically relevant functional unit. Genotype may also influence crop morphology and canopy architecture, thereby affecting energy demand per unit of biomass in controlled environments.

2-Planting density: Increased planting density, such as 16-25 plants m<sup>-2</sup> for sea-of-green cultivation systems and 1-4 plants m<sup>-2</sup> for single plant cultivation systems [48,49], may decrease per plant yield and fertilizer demand per kilogram of yield [50]. In LCAs, planting density may

influence allocation calculations per individual unit, thereby affecting LCI completeness and accuracy of system expansion calculations.

3-Harvesting frequency: In sea-of-green cultivation systems, 4-6 harvests per year may result in a greater yield per unit area, thereby increasing substrate turnover and waste generation per unit area [51]. Conversely, single harvest systems may result in less substrate consumption per crop, thereby increasing infrastructure depreciation per crop. However, this aspect has not been addressed in previous LCA studies and is identified as a key area for further primary data collection.

The process of converting plant biomass into purified extracts relies on an integrated value chain. Figure 4 presents a model of this chain, highlighting the key stages of biological maturation (phases 1 through 4), followed by the mechanical and chemical separation methods used to obtain THC and CBD isolates.

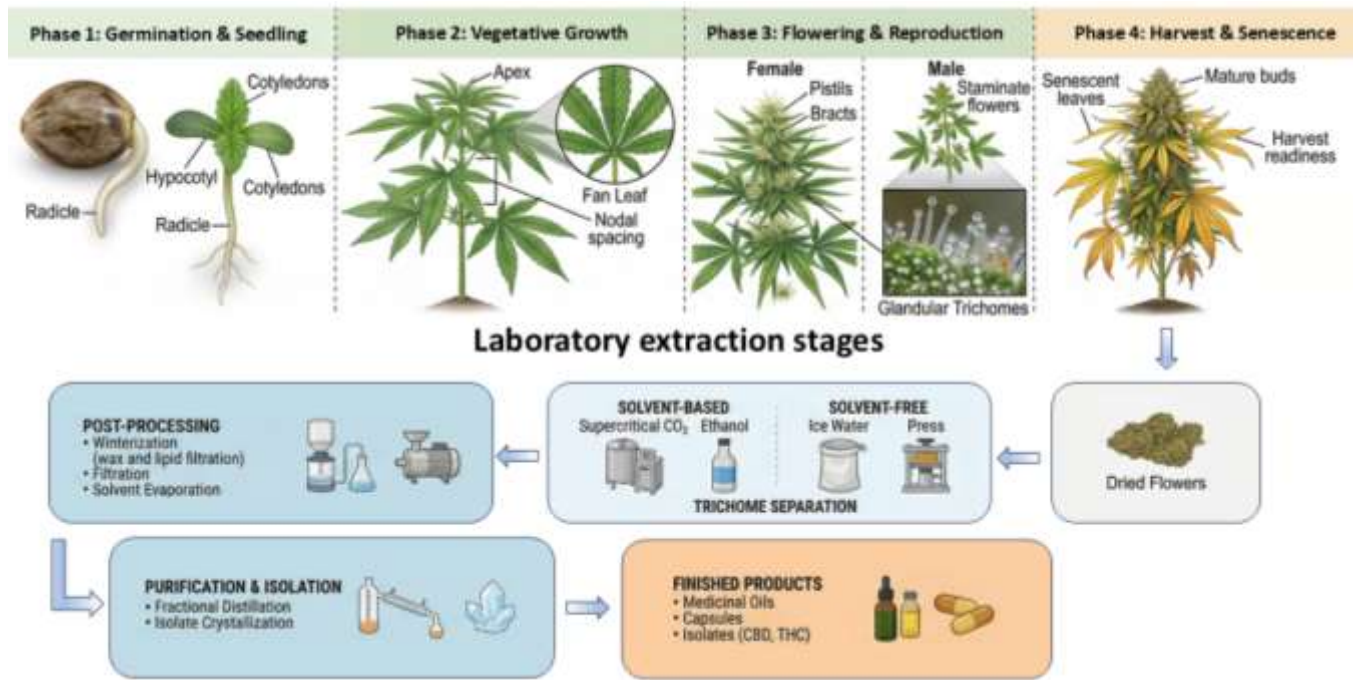


Figure 4: The Life Cycle of Cannabis and the Processing Flow of Extracts in the Laboratory

A comparative summary of the GWP values reported in the literature for the three growing systems is presented in Figure 5. This representation highlights the structural gap between indoor, greenhouse, and open-field systems, primarily determined by the carbon intensity of energy inputs.

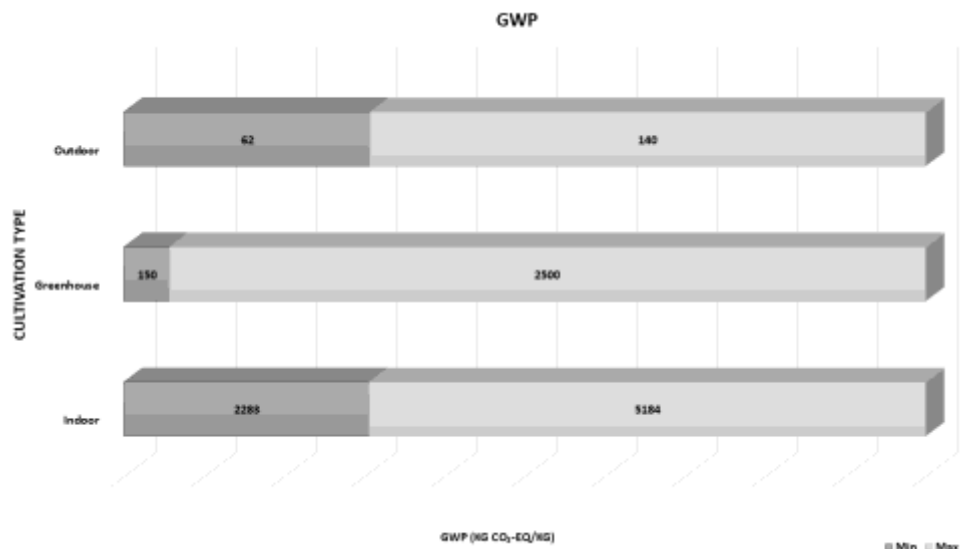


Figure 5: Comparison of cradle-to-gate GWP for indoor, greenhouse, and outdoor medicinal cannabis systems with regard to CO<sub>2</sub> emissions. [4,9,20,24,36–38].

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307 Outdoor systems may face other environmental problems despite their low carbon footprint.  
308 For example, substrates containing peat may account for 65 - 75% of total GWP in some  
309 cases [9], owing to associated emissions from peat extraction. Fertilizer production and  
310 application may also be a concern and may potentially impact eutrophication and acidification  
311 categories [52]. Another concern is water management, water consumption may be as high as  
312 22.7 L plant<sup>-1</sup> day<sup>-1</sup> during peak growth [53,54]. Although it is technically challenging to irrigate  
313 in controlled environments, it is believed that the increased water usage observed under outdoor  
314 conditions (22.7 L/plant/day during peak growth stages compared to 9-11 L/plant/day in  
315 controlled environments) can be ascribed to increased evapotranspiration under full sunlight and  
316 possibly larger biomass production under outdoor cropping conditions.

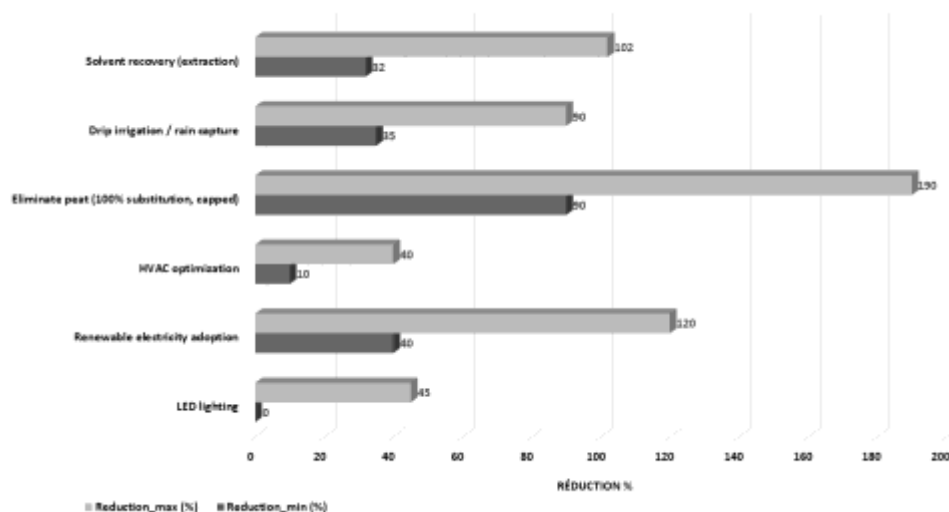
317 In addition, the type of functional unit (FU) used in LCA is fundamental in interpreting  
318 results. An FU of 1 kg of dry flowers might give preference to those crops that are cultivated in  
319 a way that maximizes biomass, regardless of  $\Delta^9$ -THC content.  $\Delta^9$ -THC or CBD concentrations  
320 are normally in the range of 5-25%, depending on cultivar and growing practices [55]. Typical  
321 therapeutic doses administered vary between 5 and 30 mg per dose [56]. Consequently, a UF  
322 based on pharmacological function, for example, per milligram of active ingredient delivered,  
323 could alter the comparative hierarchy of systems by expressing impacts per effective therapeutic  
324 dose [45]. It should also be noted that most published LCAs stop at the cradle-to-gate stage and  
325 exclude post-harvest stages such as drying, extraction, purification, and formulation. However,  
326 these operations can be particularly energy-intensive drying alone can contribute several  
327 kilograms of CO<sub>2</sub> eq per kilogram of product [24].

328 With regard to oil extraction, some estimates indicate emissions of between 3600 and 5900  
329 kg CO<sub>2</sub> eq per kilogram of oil produced [10]. This correspond to approximately 4 kg of CO<sub>2</sub>-eq  
330 per gram of concentrated oil. These findings collectively indicate that it is likely that the overall  
331 environmental impact of post-harvest processing may be comparable to that of the cultivation  
332 phase and in some cases may even surpass it.

333 The omission of post-harvest processing in the overall analysis presents a considerable  
334 potential for underestimation of the overall cannabis-based medicines' footprint. Therefore, it is  
335 essential to extend the analysis to include cradle-to-grave assessments in order to achieve a more  
336 accurate and comprehensive representation of cannabis-based medicines' life cycle.  
337

### 3.2. Recommendations for improving sustainability

An analysis of the hotspots identified in the LCA literature on controlled-environment cannabis production underscores the predominance of energy consumption, the production and management of extraction solvents, and the use of peat-based substrates as principal contributors to environmental impacts. Recent research published in Nature Sustainability reports that the carbon footprint of indoor cultivation can range from 2283 to 5184 kg CO<sub>2</sub> eq kg<sup>-1</sup> of dried flower, with the majority of emissions attributable to the high electrical intensity of lighting and climate control systems [4]. Therefore, decarbonizing electricity and optimizing energy use are key priorities. The relative mitigation potential of key interventions is summarized in **Figure 6**.



**Figure 6.** Potential reduction ranges (%) for key mitigation strategies (LED, renewable electricity, HVAC optimization, peat substitution, drip irrigation/rainwater harvesting, solvent recovery) [4,19,57–60].

More specifically, **Figure 6** indicates substantial variability in the mitigation potential across intervention categories. The adoption of renewable electricity exhibits one of the highest reduction ranges approximately 40 to 120%, reflecting the dominant contribution of grid electricity to overall impacts, the maximum reduction of 120% observed for the adoption of renewable energies suggests not only the elimination of the carbon burden associated with electricity consumption, but also the accounting of impacts avoided through the expansion of the system or the reinjection of decarbonized surpluses into high-carbon regional energy mixes. In contexts characterized by carbon-intensive electricity mixes, this factor alone can yield transformative reductions. At the agronomic stage, peat use constitutes a significant source of emissions due to peatland oxidation and the energy required for extraction. Recent LCAs on growing media indicate that partial substitution of peat with bio-based alternatives (compost, plant fibers, hydrochar or biochar) can reduce the substrate's global warming potential by 10 to 35% for intermediate substitution rates, with higher reductions when substitution is greater and alternative processes are optimized [58].

Moreover, water efficiency enhancement via localized irrigation, also known as drip irrigation, and alternative resource usage such as rainwater harvesting are cited as strategies that can lead to significant reductions in water resources and their consequences, provided that it is done in a properly sized and pump-efficient manner [50,54]. In addition, a switch to high-efficiency LED lighting technologies from high-pressure sodium (HPS) lighting is a known strategy to reduce electricity usage in controlled horticulture environments [61]. Again, however, this is contingent on light output, photoperiodicity, and HVAC usage.

As far as the extraction step is concerned, it has been identified in LCA literature as one of the major mitigation options regarding the recovery of solvents through distillation/closed loop systems, which can reduce the impacts related to the production and disposal of new solvents [62]. By reducing the amount of new solvents to be produced, it is possible to significantly reduce emissions related to raw materials extraction, chemicals production, and transport.

Residual biomass valorization is another area that presents an enormous but underutilized potential in the circular economy. In the post-flower harvest stage, the residual biomass in the fields comprises considerable quantities of plant material such as stems, leaves, roots, and seed cakes that make up about 60-80% of the total above-ground dry weight [63]. The valorization options that can be implemented in the circular economy context comprise biocomposites (production of hempcrete from the residual biomass) [23], animal feed production (seed cakes and leaves) [64], biochar production (thermal degradation of woody biomass) [65], and anaerobic digestion with biomethane production [39]. The implementation of these valorization options in the life cycle assessment approach can decrease the environmental impact per functional unit by 15-40%, depending on the replacement factor of the substituted product.

However, the amount of these environmental benefits is highly dependent on the recovery rate and the carbon intensity of the energy mix powering the regeneration unit [66]. High recovery efficiencies combined with a low-carbon electricity mix can significantly enhance net GHG emission reductions, whereas energy-intensive regeneration supplied by carbon-intensive grids may partially offset the expected gains. Consequently, solvent recovery should be assessed within a systemic LCA framework that integrates both material circularity and the energy profile of the recovery infrastructure.

### 3.3. SWOT Analysis of LCA Application to Medicinal Cannabis

Table 3 synthesizes the principal strengths, weaknesses, opportunities, and threats associated with LCA methodology as applied to medicinal cannabis production systems, based on the 15 reviewed studies.

**Table 3.** SWOT analysis of LCA methodology applied to medicinal cannabis production systems.

STRENGTHS	WEAKNESSES
<p>Robust ISO 14040/44 framework provides standardized and replicable methodology</p> <p>Growing evidence base across indoor, greenhouse, and outdoor systems</p> <p>Demonstrated mitigation pathways: renewable electricity, LED, drip irrigation, peat substitution, solvent recovery</p> <p>High cannabinoid value per unit product justifies environmental investment</p> <p>Emerging policy frameworks (EU Green Deal, national carbon pricing) create compliance incentives</p>	<p>System boundaries rarely extend beyond cradle-to-gate post-harvest stages systematically omitted</p> <p>Functional unit inconsistency (mass vs potency-based) limits cross-study comparability</p> <p>Primary data access severely restricted by commercial confidentiality of licensed producers</p> <p>Geographic concentration: &gt;80% of studies from North America limited global transferability</p> <p>No standardized allocation method for multi-product cannabis systems</p>
OPPORTUNITIES	THREATS
<p>Integration of cradle-to-grave system boundaries including product use and end-of-life</p> <p>Harmonization of functional units (e.g., per therapeutic dose) to improve clinical LCA relevance</p> <p>Carbon pricing mechanisms incentivize low-impact production innovations</p> <p>Residual biomass valorization (stems, leaves, roots) via biochar, biocomposites, or anaerobic digestion</p> <p>Prospective LCA benchmarking of vertical farming, aeroponics, and in vitro cannabinoid biosynthesis</p>	<p>Ethical and legal barriers restrict primary data collection from licensed production facilities</p> <p>International scheduling (UN Single Convention) limits research access and data sharing globally</p> <p>Grid carbon intensity variability undermines geographic generalizability of published GWP values</p> <p>Illicit cultivation (significant global market share) remains entirely uncharacterized in LCA literature</p> <p>Rebound effects from emerging production technologies not yet quantified</p>

The SWOT analysis shows that, despite the establishment of a strong methodological basis, with its roots in the ISO 14040/44 framework [31,32], and the development of a growing body of evidence based on 13 different studies in various countries with different production structures, there are significant structural weaknesses in the published results. The critical weaknesses are the limited cradle-to-gate scope, the variability in functional unit definitions, and the lack of transparency in primary data sets. The opportunities are significant, including policy relevance to sustainability, the integration with the growing field of the circular economy through biomass

valorization, and advances in cultivation technologies, all providing opportunities for environmental improvements or refinements in the methodology. The threats are largely structural or legal in nature, with scheduling constraints on access due to international scheduling, variability in grid carbon intensity limiting the generalizability across different regions, and the existence of an uncharacterized illicit production sector creating bias in global-level sustainability estimates.

#### 4. Future Research and Knowledge Gaps

However, it is to be noted that despite the robustness of all reviewed literature, there are a number of methodological limitations to be considered. Firstly, there is a large variability of FUs considered in all reviewed literature, ranging from mass-based FUs such as 1 kg of dried flowers to potency-based FUs such as 100 g of THC or CBD. Such variability limits direct comparability of results across different production systems and may lead to a level of bias in interpreting results.

Second, uncertainty in data still remains a significant concern due to limited access to primary data from licensed operations. As a result, a number of LCAs are conducted using modeled or secondary data, which may lead to a level of deviations in results in terms of energy, water, and material flows. Third, there is a significant level of geographical limitations in reviewed literature, with a large number of studies conducted in North America and a lack of representation of results from other climates (e.g., Europe, Africa, and Latin America). Such results should be extrapolated with caution to these regions, as differences in electricity mix, agronomic practices, and policy drivers may significantly impact LCA results.

In addition, the emphasis of system boundaries up to the gate does not include downstream activities such as formulation, distribution, and EoL management, thus creating the possibility of incomplete assessments of total environmental burdens of medicinal cannabis. It is also important to highlight the fact that most of the literature published has relied on secondary data, general modeling, and assumptions, especially for energy and water consumption, and agronomic inputs [10,20]. To develop high-quality databases for certain production facilities, there is a need for structured collaborations with licensed producers to gather representative primary data. This would greatly improve the accuracy and credibility of the results. In the future, research conducted using cradle-to-grave system boundaries and FUs would improve the results' comparability and robustness.

Ethical and legal constraints are systemic factors in the life cycle assessment data gap in medicinal cannabis studies but are not sufficiently appreciated in the scientific community. Access challenges are significant in jurisdictions where cannabis is defined as a Schedule I/IV controlled substance under national and/or international laws. These include requirements from Institutional Review Board approvals for controlled substance studies, licensing of investigators who handle plant materials, and confidentiality agreements that restrict licensed producers from disclosing information regarding production processes. These challenges make it necessary for life cycle assessors to rely on modeled data and/or industry averages, which introduce uncertainty in the inventory data at different stages of the life cycle assessment process. The self-censoring effect of authors who withhold disclosures in their publications to protect their business partners is also likely to affect the quality of the available evidence base. The United Nations Commission on Narcotic Drugs' decision in 2020 [67] to reschedule cannabis from Schedule IV (the most restrictive category of controlled substances) to Schedule I of the 1961 Single Convention may be an initial step in the long process of relaxing access restrictions to cannabis in different jurisdictions and could potentially ease access in the future; however, its effect on the life cycle assessment data gap remains unrealized to date.

Moreover, there is limited literature on illicit or small-scale artisanal production. Current literature is almost entirely focused on legal and commercial crops, while unregulated production still makes up a significant percentage of the global market [68]. The development of proxy estimates or scenarios would also contribute to the completion of the overall picture of the environmental impacts of the sector. Finally, the integration of the social and economic dimensions still appears to be insufficient. Indeed, few studies combine environmental LCA with social LC analysis, such as working conditions, impacts on local communities, and governance, and life cycle cost analysis. Such an LCA-S-LCA-LCC approach would allow for

466 a more holistic analysis of the sustainability of medicinal cannabis supply chains, in line with  
467 the principles of LC Management [69].

468 The opportunity to recover residual biomass is also an area that is largely untapped with  
469 regard to reducing environmental burdens. For instance, after harvesting flowers from cannabis  
470 plants, there is still a large quantity of biomass that is not utilized or valorized, such as stems,  
471 leaves, and roots. Such biomass has the opportunity to be utilized as biocomposites, health-  
472 oriented cannabis-based edible products, animal feed, renewable energy production materials,  
473 or even as materials to be utilized to produce biochar. Such an opportunity to valorize cannabis  
474 biomass has the potential to not only improve resource productivity but also minimize waste  
475 generation and its subsequent environmental burdens. If such an opportunity is included in LCA  
476 models, such as through system expansion or allocation methods, it is possible to obtain a more  
477 accurate assessment of the environmental burdens avoided with regard to biomass valorization  
478 pathways.

479 Lastly, alternative cultivation methods are still in their infancy. Techniques such as  
480 vertical farming, aeroponics, and in vitro cannabinoids are promising and may significantly  
481 impact medicinal cannabis value chains. LCAs are required to forecast their environmental  
482 impact and prevent any rebound effects that may occur due to increased energy demand.  
483 Moreover, the interface of LCA, policy-making, and markets is still in its infancy. If policy  
484 scenarios are considered, such as carbon pricing or renewable portfolio standards, it would help  
485 public policy-making to favor low environmental impact and high therapeutic value cannabis  
486 productions

## 487 5. Conclusions

488 LCA provides a structured framework for quantifying the life cycle environmental impacts  
489 of medicinal cannabis production. The literature consistently shows that indoor cultivation  
490 systems are highly energy-intensive, particularly when supplied by fossil fuel dominated  
491 electricity mixes, resulting in emissions of several thousand kg CO<sub>2</sub> eq kg<sup>-1</sup> of dried flower. On  
492 the other hand, outdoor systems tend to have lower carbon footprint scores, although this is  
493 largely influenced by upstream inputs such as peat-based substrates and agricultural inputs.  
494 From the comparative assessment of the carbon footprint of indoor and outdoor cultivation  
495 systems, it is evident that no system is better than the other but rather that the major hotspots  
496 vary. For indoor systems, electricity consumption and climate control are major contributors to  
497 carbon footprint scores. For outdoor systems, substrate production and input management are  
498 major contributors to carbon footprint scores. Water use is a major contributor to carbon  
499 footprint scores in both indoor and outdoor systems, although it is more pronounced outdoors.  
500 Nutrient and substrate management lead to eutrophication and acidification potentials.  
501 Extraction and post-harvest processing are also significant sources of GHG emissions, thus  
502 emphasizing the need to include these in the system boundaries beyond cultivation. The  
503 mitigation measures proposed in the LCA literature include electricity generation, efficient  
504 HVAC and LED solutions, replacement of peat-based substrates, precise fertilization, irrigation,  
505 and solvent recovery. Implementation of these measures can lead to a significant reduction in  
506 the environmental impact of medicinal cannabis cultivation. Future research should prioritize  
507 cradle-to-grave LCAs, harmonized FUs, integration of socio-economic indicators, and  
508 assessment of emerging technologies.

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## 518 Abbreviations

LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment

ISO	International Organization for Standardization
GHG	Greenhouse Gas
GWP	Global Warming Potential
FU	Functional Unit
HVAC	Heating, Ventilation and Air Conditioning
CEA	Controlled Environment Agriculture
NO <sub>x</sub>	Oxides of Nitrogen
VOCs	Volatile Organic Compounds
TRACI	Tool for the Reduction and Assessment of Chemical and other Environmental Impacts
ReCiPe	Life Cycle Impact Assessment Method
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
LED	Light Emitting Diode
HPS	High Pressure Sodium
PV	Photovoltaic
PJ yr <sup>-1</sup>	Petajoules per year
Mt CO <sub>2</sub> yr <sup>-1</sup>	Megatonnes of CO <sub>2</sub> per year
NR	Not Reported
S-LCA	Social Life Cycle Assessment
LCC	Life Cycle Costing
RH	Relative Humidity
Kg CO <sub>2</sub> eq	kilogram CO <sub>2</sub> equivalent
kWh	Kilowatt hour
L plant <sup>-1</sup> d <sup>-1</sup>	Litres per plant per day

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