

Article

Rethinking Efficiency: How Increased Electricity Use Can Reduce Environmental Impacts in Controlled Hemp Cultivation—A Life Cycle Assessment (LCA) Study

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Abstract

This study aims to assess the environmental profile and identify environmental hotspots of indoor hemp (*Cannabis sativa* L.) cultivation through environmental impact analysis under four scenarios combining two nutrient solutions and two lighting intensities (540 W and 900 W). Indoor cultivation of industrial hemp is becoming increasingly relevant as plant production shifts to controlled environments, raising the need to evaluate its environmental implications. The assessment was conducted using the Life Cycle Assessment (LCA) methodology in accordance with the ISO 14040 and ISO 14044 standards, applying a cradle-to-gate system boundary and a functional unit of 1 kg of dried hemp inflorescence. Primary data were obtained from a controlled cultivation experiment, while secondary data were drawn from validated databases. The carbon footprint ranged from 1050 to 1610 kg CO₂ eq per kilogram of dried inflorescence. Scenarios with 900 W lighting showed 30–35% lower impacts per kilogram compared to 540 W variants. Electricity production and consumption were identified as major environmental hotspots, dominating most impact categories. The study concludes that improving input–output efficiency is essential for sustainable indoor cultivation and that integrating renewable energy sources, such as photovoltaics or biomass, could further reduce environmental impacts.

Keywords: climate change; hemp inflorescence; hydroponics; indoor agriculture; LCA



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1. Introduction

Hemp (*Cannabis sativa* L.) is a versatile plant whose applications are rapidly expanding across various industrial sectors, from construction [1] and textiles to food production, medicine, and biotechnology [2–4]. Thanks to its unique properties, the area designated for hemp fiber cultivation in the EU increased by 60% between 2015 and 2022 [5]. Several countries, including Germany, Canada, Malta, and Thailand, have moved to legalize non-medical cannabis use [6]. As more countries adopt similar policies, global cannabis production is likely to increase in the coming years. Hemp is gaining increasing attention not only as a traditional raw material but also as a key component of sustainable innovations, such as bioplastics [7], soil remediation [8], and renewable energy sources [9]. Industrial hemp is capable of absorbing heavy metals (e.g., Cd, Cr, Cu, Ni, Pb, and Zn) and radionuclides, while also reducing the content of polycyclic aromatic hydrocarbons

and cesium in contaminated soils [8]. These elements are absorbed by the plant's roots, which is beneficial for environmental remediation but can lead to their accumulation within the plant itself [10,11]. Therefore, hemp intended for medical purposes, such as the production of cannabidiol oils, tinctures, and food products, is typically grown using indoor systems [12].

Although industrial hemp is traditionally grown in Europe as a field crop primarily for fiber production [13], there are other production possibilities and alternative cultivation methods, particularly in controlled environments. Controlled environment cultivation provides stable and reproducible growth conditions. Indoor systems offer distinct advantages, including strict control of environmental variables, which minimizes the risk of contamination by undesirable substances and ensures consistent, high-quality production outputs [14]. Controlled environments in indoor plant-production systems, e.g., greenhouses, high tunnels, buildings, or container units with artificial lighting [15], allow precise manipulation of growth parameters, thereby facilitating optimization and improvements in productivity [16,17]. Vertical indoor farming systems have demonstrated potential to improve nutritional value and significantly reduce water consumption in agricultural production [18]. High light intensities with a high photosynthetic photon flux density in indoor settings can significantly increase cannabis yield. For instance, higher PPFD levels can result in 1.6 times increase in inflorescence dried weight, which is economically beneficial [19]. Indoor cultivation ensures a consistent quality of hemp products by maintaining stable growing conditions. This consistency is crucial for industries that rely on specific hemp qualities, such as the pharmaceutical and nutraceutical sectors [19,20]. However, these technological advantages come at the cost of substantially higher energy and material inputs, raising critical questions about the environmental sustainability of indoor cultivation systems.

While hemp is frequently presented as an environmentally friendly crop [21], the extent of its sustainability depends strongly on management practices. Irrigation and fertilization are essential for growth but can lead to environmental impacts when applied intensively or inefficiently [22,23]. Given the rapidly increasing scale of hemp production, it is essential to thoroughly analyze the environmental aspects of hemp cultivation to optimize indoor methods, ensure their long-term sustainability, and identify the most environmentally impactful stages of the cultivation cycle.

Indoor plant production facilities require considerable energy inputs. Some of the major inputs are high-intensity lighting for plant growth, dehumidification processes to prevent mold, and heating and cooling of the facility [24,25]. Light levels reach 500 times higher than those suitable for reading, ventilation rates are 6 times higher than in advanced laboratories, and power density can climb to 2000 W/m², comparable to contemporary data centers [26]. Additional energy is used for CO₂ generation [27], typically elevated to 4 times natural levels to boost growth efficiency, as well as for ventilation and waste heat removal. In the context of climate change mitigation and energy transition policies, such high energy intensity poses a significant challenge to the environmental viability of indoor agriculture. While these measures shorten growth cycles, they may also reduce overall energy intensity [26]. The primary challenges in achieving sustainability in indoor cultivation systems primarily involve high energy demands, significant capital costs, and the limited variety of crops suitable for cultivation [28].

Only two studies have investigated the carbon footprint of indoor cannabis production [26,27]. Some studies indicate that growing cannabis in controlled environments can have a higher carbon footprint than certain industrial sectors. Other studies have examined water consumption, particularly in regions where cannabis is cultivated outdoors or in

greenhouse systems, identifying high irrigation demands that may lead to local water scarcity issues [29].

However, this study is unique in that it evaluates four different cultivation systems based on variations in fertilizer concentration and light intensity in relation to yield across defined groups.

2. Materials and Methods

2.1. Goal and Scope Definition

This study evaluates the environmental impacts of different cultivation practices associated with the production of industrial hemp in indoor systems. The primary objective was to quantify environmental profiles using the Life Cycle Assessment (LCA) method and to assess them across selected impact categories, as well as through the analysis of material and energy flows throughout the entire life cycle of the defined indoor system.

Furthermore, the study aims to determine specific combinations of light intensity and nutrient input under which the environmental impacts per kilogram of dried hemp inflorescence are minimized and to quantify the extent of these reductions. The analysis examines whether increasing lighting power within the studied range raises yield enough to reduce the per kilogram environmental impact. The study also focuses on identifying the main environmental hotspots within the cultivation cycle and on assessing how input–output relationships influence the overall performance of the system.

It is hypothesized that higher (900 W) lighting intensity, when accompanied by a proportionally increased biomass yield, enhances input-use efficiency and consequently reduces environmental impacts per functional unit. Conversely, excessive nutrient application without adequate light supplementation may lead to an overall increase in environmental impacts. LCA is a standardized analytical tool used for evaluating the environmental aspects of a product, process, or service across its entire life cycle. It is structured in accordance with the international standards ISO 14040 and ISO 14044 [30,31], which provide the framework and requirements for conducting consistent and transparent analyses. The impact assessment was conducted using the ReCiPe 2016 Midpoint (H) method, V1.09, implemented in SimaPro Craft Analyst 10.2.0.0 (PRé Sustainability B.V., Amersfoort, The Netherlands) software. The Cut-off System Model was applied, in which the full environmental impact is attributed to the primary process entering the system, while secondary materials and by-products leave the system without carrying any additional environmental impacts [32]. The functional unit (FU) was defined as 1 kg of dried hemp inflorescence, representing the target output of the cultivation system.

Since primary data were available, the system boundaries were defined to include only the cultivation phase and post-harvest handling of the biomass, excluding any other post-harvest processes such as emissions from processing, recycling, packaging, and waste management. The environmental assessment considered impacts associated with water use, energy production and consumption, fertilizer production and application, material production and use, transportation of inputs to the cultivation facility, and hemp plant growth management.

All relevant inputs, ranging from the preparation of the cultivation setup to harvest and post-harvest handling of the biomass, were inventoried in detail. The system boundaries included unit processes, which are the smallest components of the production system for which specific data were collected. Economy allocation principles were applied in this study. The scope was limited to the defined experimental setup and did not consider the market value of co-products, because, in the case of the plant's green biomass (excluding inflorescence), composting was assumed without economic valorization. Therefore, accord-

ing to the economy allocation principles, the full environmental impact is connected with production of inflorescence only.

Propagation by cuttings was not included in the assessment, as all treatments were based on clones cultivated under identical conditions. This approach allowed for a consistent and reliable comparison of different cultivation scenarios, eliminating variability from the early growth phase.

The findings of this study contribute to the development of more environmentally responsible cultivation systems and offer practical insights for stakeholders engaged in indoor growing technologies. By promoting resource efficiency and reducing emissions, the study supports the transition toward more sustainable agricultural practices in indoor hemp production. The results also offer a clear perspective on the environmental profile of indoor cultivation, which is expected to become increasingly relevant due to factors such as population growth, climate change, and resource scarcity. New and existing indoor growers may use these results as guidance when evaluating sustainable cultivation investments. The system boundaries are illustrated in Figure 1.

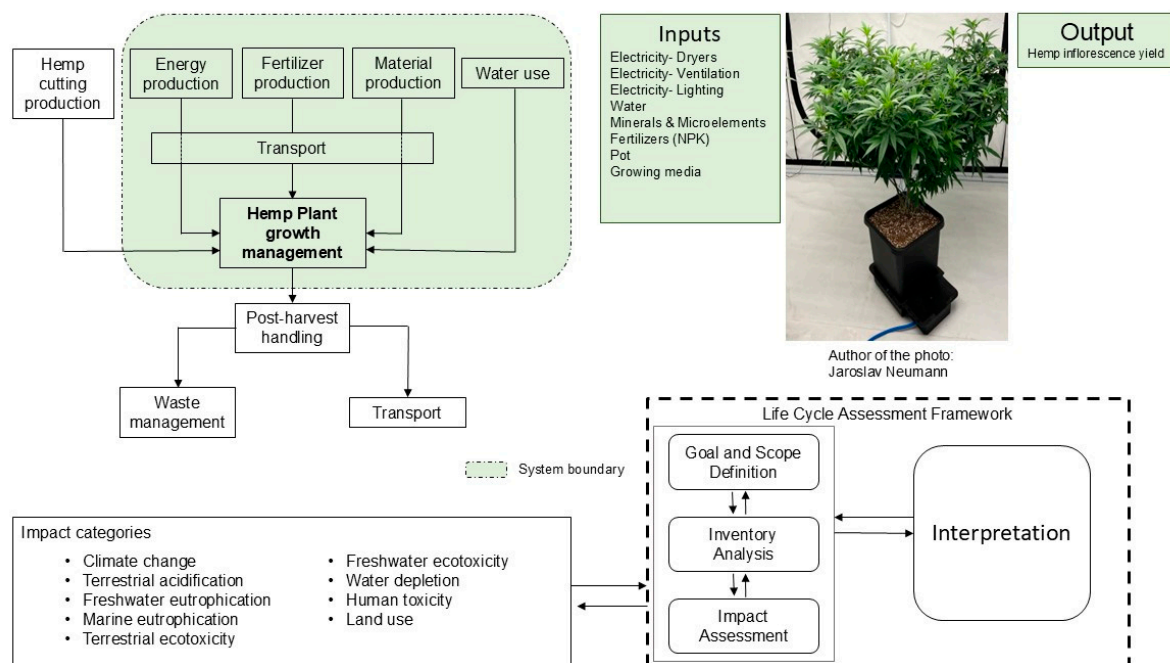


Figure 1. System boundaries.

2.2. Primary Data Collection (Hemp Cultivation)

This study assesses the environmental impacts associated with the indoor cultivation of industrial hemp using life cycle assessment (LCA), based on empirical data and the cultivation methodology described in [33]. Rather than cultivating hemp specifically for this research, data were obtained from controlled experimental setups designed to ensure methodological consistency and adherence to scientific standards. The cultivation process, including fertilization, lighting, and nutrient management, was thoroughly described in the previous study. This allowed the current LCA study to build on a validated and standardized cultivation framework.

The experiment was conducted in 2022 and lasted a total of 12 weeks. Plants were grown individually in 11-L plastic pots filled with a coconut fiber and perlite mix (60:40). The cultivation experiment was conducted in two independent runs on separate dates under identical controlled environmental conditions. Four treatment groups were established, combining two light intensities and two nutrient solutions, each consisting of eight plants per run. The experimental unit for yield was defined as the treatment group per run (batch

of eight plants). To address how between-run variability enters uncertainty, we quantified relative yield differences between the two runs and verified that these variations did not alter the relative ranking of scenarios. Therefore, averaged yield values were used for all subsequent LCA calculations. The recorded yield parameters serve as a fundamental basis for further analysis and discussion, particularly in the context of assessing the environmental footprint of indoor hemp cultivation under controlled conditions. An overview of all input data and average yields per treatment group is provided in Table 1.

Table 1. Inventory table: inputs and outputs of life cycle (for 1 kg of dried hemp inflorescence).

	Unit	S1-L1	S1-L2	S2-L1	S2-L2
Output					
Yield (ø)	g	365	609	344	590
Input from Technosphere					
Tap water	l	156	156	156	156
Stone wool	g	20	20	20	20
Coconut fiber	kg	19	19	19	19
Perlite	kg	3.53	3.53	3.53	3.53
Flowerpot–1 year amortization	p	1	1	1	1
Inorganic nitrogen fertilizer as NO ₃	g	16.1	16.1	16.1	16.1
Inorganic nitrogen fertilizer as NH ₄	g	0.86	0.86	0.86	0.86
Inorganic phosphorus fertilizer as P ₂ O ₅	g	4.36	4.36	34.7	34.7
Inorganic potassium fertilizer as K ₂ O	g	16.5	16.5	36	36
Calcium carbonate (CaCO ₃)	g	39.4	39.4	37	37
Magnesium oxide (MgO)	g	6.5	6.5	12.6	12.6
Sulphite	g	5.01	5.01	27.2	27.2
Microelements (Fe, B, Cu, Zn, Mn, Mo)	g	0.58	0.58	0.51	0.51
Electricity production (Regional mix)–Lighting	kWh	272	419	272	419
Electricity production (Regional mix)–Fan, ventilation	kWh	158	158	158	158
Electricity production (Regional mix)–Dryers	kWh	515	515	515	515

S1-L1: solution 1, lighting 1, S1-L2: solution 1, lighting 2, S2-L1: solution 2, lighting 1, S2-L2: solution 2, lighting 2, between-run yield differences ranged from 3% to 54%.

The processes incorporated into the model system included tap water consumption for irrigation systems and dilution of plant protection products, as well as processes involving the production, use, and consumption of plastic containers/seed trays. Additionally, the model accounted for the production and use of the growing medium (coconut fiber and perlite), nutrient inputs including their production, distribution, and application, and electricity consumption for lighting, climate control, and drying.

After harvest, inflorescences were manually separated from stems and leaves. The separated flowers were then dried for ten days at a constant temperature of 20 °C and relative humidity of 50%. Waste biomass was considered composting material with negligible economic value. Therefore, no allocation was applied, as environmental impacts were attributed solely to the economically valuable product, the dried inflorescences. This assumption corresponds to the operational reality of the cultivation system, where inflorescence represents the only marketable output.

The nutrient solutions used in this study were divided into S1 (solution 1) and S2 (solution 2) formulations, with S2 further separated for the vegetative and flowering phases. The S1 solution contained moderate concentrations of nutrients, while S2 was designed with a higher phosphorus concentration and a specific potassium-to-calcium-to-magnesium ratio (1:2:4) to optimize plant growth. During the vegetative phase, S2 contained increased levels of nitrate nitrogen (NO₃), phosphorus (P₂O₅), and potassium (K₂O) to promote early plant development. In contrast, the flowering phase formulation of S2 had a significantly

higher phosphorus and sulphate (SO_4) concentration, supporting flower production and overall biomass yield. These adjustments ensured that nutrient availability was tailored to the specific needs of the plants at different growth stages.

The plants were exposed to two different lighting intensities (L1 = lighting 1, L2 = lighting 2) throughout their growth cycle, with separate settings for the vegetative phase, which lasted four weeks, and the flowering phase, which lasted eight weeks. For the vegetative phase, the photoperiod was set to 18 h for both lighting intensities; for the flowering phase, it was set to 12 h for both. The lighting configuration was specified to deliver an appropriate energy input for each developmental stage.

During the vegetative phase, the lighting system operated at:

- 360 W ($\approx 300 \mu\text{mol m}^{-2} \text{s}^{-1}$ PPFD) under the first intensity setting (L1)
- 540 W ($\approx 500 \mu\text{mol m}^{-2} \text{s}^{-1}$ PPFD) under the second, higher intensity setting (L2)

As the plants transitioned into the flowering phase, light intensity was significantly increased to support inflorescence development:

- 540 W ($\approx 900 \mu\text{mol m}^{-2} \text{s}^{-1}$ PPFD) under the lower intensity setting (L1)
- 900 W ($\approx 1300 \mu\text{mol m}^{-2} \text{s}^{-1}$ PPFD) under the higher intensity setting (L2)

The efficacy of the LED grow light used in this study is $2.8 \mu\text{mol} \cdot \text{J}^{-1}$. The four cultivation groups were defined based on combinations of two lighting intensities and two nutrient solution regimes:

- S1-L1
- S1-L2
- S2-L1
- S2-L2

These data were used to determine the material, energy, and system requirements of each group. The collected information included input and output data related to individual cultivation treatments, as well as technosphere inputs (Table 1).

The quality of primary data used in the inventory phase was assessed in terms of temporal, geographical, and technological representativeness, as well as completeness and reliability, following ILCD guidelines [34]. The collected data were based on direct measurements from experimental cultivation (2022), corresponding to the Czech context and the specific crop system studied.

2.3. Secondary Data

Data were sourced from the following life-cycle inventory (LCI) databases: AGRIBALYSE® [35], the French national LCI database providing harmonized inventories and impacts for agricultural and food products; Agri-footprint 6.0 [36], a process-based LCI database covering global agri-food supply chains (crops, fertilizers, feed, processing); Ecoinvent 3.9 [37], a comprehensive multi-sector LCI database with geographically explicit datasets for energy, materials, transport, and waste; and WFLDB [38] (World Food LCA Database), a curated set of food- and agriculture-focused LCI datasets aligned with best-practice modeling for comparability. All inventoried data are part of the Life Cycle Inventory.

To ensure more precise and representative results, a specific energy mix for the Czech Republic in 2022 was modelled, incorporating all relevant energy sources available during the year in which the experiment was conducted. This energy mix was based on data from [39,40], ensuring alignment with the actual energy composition and providing a more accurate assessment of the environmental impacts associated with electricity consumption in the study.

2.4. Impact Categories and Impact Assessment Method

The selection of impact categories is based on the recommendations by Dijkman et al. [41], who identified suitable categories for the assessment of agricultural systems. Impact categories were chosen to reflect dominant pressure pathways in indoor hemp cultivation and to enable comparability with agricultural LCA practice. Following their approach, the following midpoint impact categories were included climate change, terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, water depletion and human toxicity. In addition to the suggested categories, land use was also included due to its relevance for crop-based systems.

To enhance the interpretability of the results, the impact categories human carcinogenic toxicity and human non-carcinogenic toxicity, both quantified using the same reference unit (kg 1.4-DCB), were consolidated into a single category of human toxicity. This methodological decision is supported not only by the shared reference substance but also by the partially overlapping exposure routes and associated health effects.

3. Results

3.1. Environmental Impact per Cultivation Scenario

The environmental impact per 1 kg of dried hemp inflorescence was quantified. Table 2 (Table A1) presents the results of the total environmental impact per impact category, calculated based on the defined FU. The average yields of dried hemp inflorescence varied considerably across the cultivation scenarios: S1-L1 yielded 365 g, S1-L2 only 609 g, S2-L1 reached 344 g, and S2-L2 produced 590 g. Since the environmental impacts were calculated per kilogram of output, these yield differences are critical, as they directly influence the amount of input materials required to reach the defined FU. For example, under identical operating conditions and holding all other inputs constant, doubling the yield results in an approximately 50% reduction in per kilogram environmental impact across all scenarios.

Table 2. Environmental impact per functional unit (1 kg of dried hemp inflorescence).

Impact Category	Unit	S1-L1	S1-L2	S2-L1	S2-L2
CCH	kg CO ₂ eq	1.52×10^3	1.05×10^3	1.61×10^3	1.08×10^3
TA	kg SO ₂ eq	4.31×10^0	2.97×10^0	4.58×10^0	3.07×10^0
FE	kg P eq	2.40×10^0	1.66×10^0	2.54×10^0	1.71×10^0
ME	kg N eq	1.59×10^{-1}	1.10×10^{-1}	1.68×10^{-1}	1.13×10^{-1}
TE	kg 1.4-DCB	2.70×10^3	1.86×10^3	2.87×10^3	1.92×10^3
FX	kg 1.4-DCB	6.58×10^1	4.55×10^1	6.98×10^1	4.70×10^1
WD	m ³	6.78×10^0	4.64×10^0	7.21×10^0	4.79×10^0
HT	kg 1.4-DCB	2.72×10^3	1.88×10^3	2.89×10^3	1.94×10^3
LD	m ² a crop eq	3.97×10^1	2.74×10^1	4.22×10^1	2.83×10^1

S1-L1: solution 1, lighting 1, S1-L2: solution 1, lighting 2, S2-L1: solution 2, lighting 1, S2-L2: solution 2, lighting 2, CCH: Climate change, TA: Terrestrial acidification, FE: Freshwater eutrophication, ME: Marine eutrophication, TE: Terrestrial ecotoxicity, FX: Freshwater ecotoxicity, WD: Water depletion, HT: Human toxicity, LD: Land use. SimaPro Craft Analyst 10.2.0.0 software; ReCiPe 2016 Midpoint (H) V1.09/World (2010) H; Cut-off System Model approach; Characterization model.

Among all scenarios, S2-L1, which combines a higher nutrient input (S2) with standard lighting intensity (L1), consistently showed the highest environmental impact in most assessed impact categories. For instance, the climate change (CCH) impact reached 1610 kg CO₂ eq, which is 7% higher than in S1-L1 and more than 53% higher than in the lowest-emitting scenario, S1-L2. Similarly, human toxicity (HT) in S2-L1 was the highest at 2890 kg 1.4-DCB, which represents a 54% increase compared to S1-L2. The same trend was observed

in terrestrial ecotoxicity (TE–2870 kg 1.4-DCB) and land use (LD–42.18 m² crop eq), where S2-L1 also showed the highest values.

In contrast, S1-L2, which combines a lower nutrient input (S1) with higher lighting intensity (L2), showed the lowest values across nearly all categories. Compared to S2-L1, freshwater ecotoxicity (FX) was reduced by 35%, climate change impact by 35%, and water depletion (WD) by 36%. Its impact on marine eutrophication (ME) reached only 0.11 kg N eq, the lowest value among all tested setups.

The remaining two scenarios, S1-L1 and S2-L2, showed intermediate results, falling between the two extremes. S1-L1 exhibited lower environmental impacts than any scenario with higher nutrient input but had still higher impacts than S1-L2. For example, its water depletion was 6.78 m³, which is 46% more than in the most efficient scenario, S1-L2. On the other hand, S2-L2, despite the higher lighting intensity, still showed significantly higher values. For instance, human toxicity reached 1940 kg 1.4-DCB, over 40% more than in S1-L2. This suggests that nutrient input has a more substantial influence on overall environmental impact than lighting intensity alone.

In general, the data highlighted the importance of input management in minimizing environmental impacts in hemp production systems. The values should be interpreted as indicative trends rather than absolute numerical constants [42]. Therefore, a stronger focus should be placed on the relative comparison between scenarios rather than on the absolute values. In this context, the results serve as a tool to identify cultivation strategies with higher or lower environmental impacts.

3.2. Contribution Analysis

3.2.1. Full System Aggregated Input Analysis

A contribution analysis was conducted for four indoor hemp cultivation treatments using the characterization model (Figure 2; Table A2). To improve comprehensibility and simplify interpretation of system inputs in the figure, detailed background flows were aggregated into broader, functionally relevant categories for graphical representation.

Electricity consumption, particularly from fossil-based sources, was identified as the dominant contributor across nearly all impact categories. Emissions from lignite mining and combustion played a critical role in the overall environmental impact, contributing significantly to greenhouse gases, sulphur oxides (SO_x), nitrogen oxides (NO_x), particulate matter, and heavy metals [35]. These emissions influenced multiple categories, including climate change, terrestrial acidification, both freshwater and marine eutrophication, and mainly human toxicity.

The highest climate change impacts were observed in scenario S2-L1, where electricity use constituted a major share of the carbon footprint. Specifically, lighting accounted for 460 kg CO₂ eq, ventilation for 270 kg CO₂ eq, and drying systems for as much as 870 kg CO₂ eq per kilogram of dried hemp inflorescence. Altogether, electricity-related emissions in S2-L1 were approximately 54% higher than in the lowest impact scenario, S1-L2, as high-lighting intensity scenarios (L2) showed lower environmental impacts per FU due to their substantially higher yields of hemp inflorescence.

In the categories of terrestrial acidification and eutrophication, emissions from lignite combustion and energy production residues (e.g., overburden, ash) played a key role. These by-products often contain nitrogen and phosphorus compounds that may leach into the environment, with pronounced effects in high-fertilization scenarios (S2).

Terrestrial and freshwater ecotoxicity were heavily influenced by the infrastructure of regional electricity mix, including the use of enriched uranium, natural gas, and photovoltaic components, as well as residues from coal extraction and combustion. The highest

impact within these categories was observed in treatment S2-L1, where electricity consumption by dryers emerged as the primary contributor.

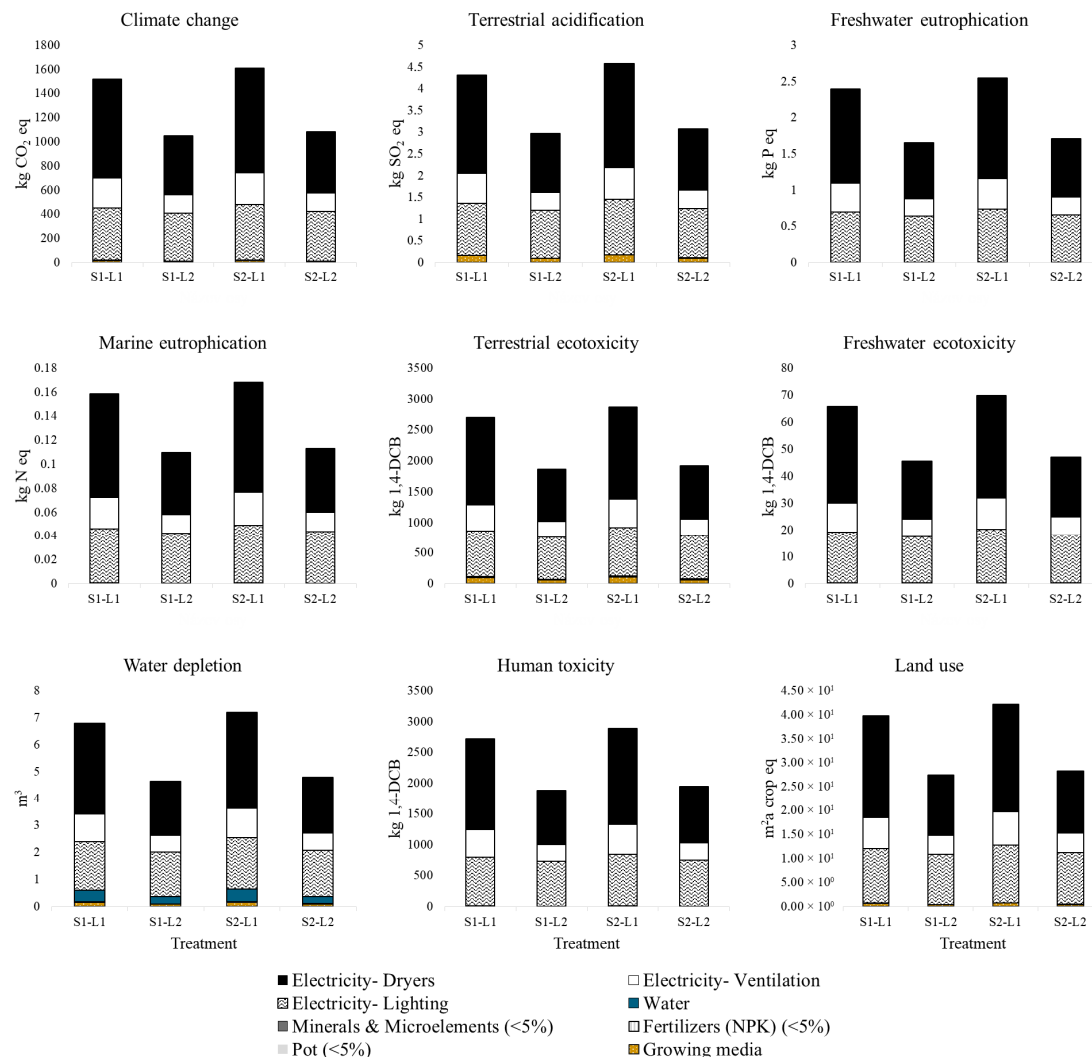


Figure 2. Contribution analyses: Environmental load per 1 kg of dried inflorescence, S1-L1: solution 1, lighting 1, S1-L2: solution 1, lighting 2, S2-L1: solution 2, lighting 1, S2-L2: solution 2, lighting 2, Climate change (kg CO₂ eq), Terrestrial acidification (kg SO₂ eq), Freshwater eutrophication (kg P eq), Marine eutrophication (kg N eq), Terrestrial ecotoxicity (kg 1,4-DCB), Freshwater ecotoxicity (kg 1,4-DCB), Water depletion (m³), Human toxicity (kg 1,4-DCB), Land use (m²a crop eq), Fertilizers (NPK): including NO₃[−], NH₄⁺, P₂O₅, and K₂O fertilizers, Minerals & Microelements: including calcium carbonate, magnesium oxide, sulphite, and microelements (Fe, B, Cu, Zn, Mn, Mo), Growing media: including stone wool, coconut fiber, and perlite. Inputs contributing less than 5% in all categories are marked as '<5%'. SimaPro Craft Analyst 10.2.0.0 software; ReCiPe 2016 Midpoint (H) V1.09/World (2010) H; Cut-off System Model approach; Characterization model.

The highest levels of environmental impact in the category human toxicity were also recorded in scenario S2-L1, largely due to emissions associated with fossil-based electricity, steel production, and related industrial processes.

Likewise, scenario S2-L1 showed the highest water consumption, 7.24 m³ per kilogram of dried biomass, with 50% of which was used for drying. Compared to S1-L2 (4.58 m³), this represents an increase of more than 58%.

Land use was primarily driven by electricity generation from biomass, lignite, and wood residues. Across all impact categories, electricity consistently emerged as the main contributor, accounting for over 98% of the total impact in both S1-L1 and S2-L1 scenarios.

Fertilizer inputs had a secondary effect through indirect eutrophication and acidification. In scenarios with lower light intensity (L1), the influence of growing media also became more pronounced, particularly due to their relatively higher share in the total impact.

3.2.2. Fertilizer-Focused Contribution Analysis

To enhance the clarity and visibility of the results, environmental impacts were displayed as the contributions of individual mineral fertilizers (Figure 3; Table A3). Although the broader system analysis must account for the influence of electricity consumption, this section focuses exclusively on the environmental impact associated with fertilizer application. Given the varying biomass yields across scenarios, these differences were considered, enabling a realistic evaluation of the efficiency and environmental impact of different fertilization strategies.

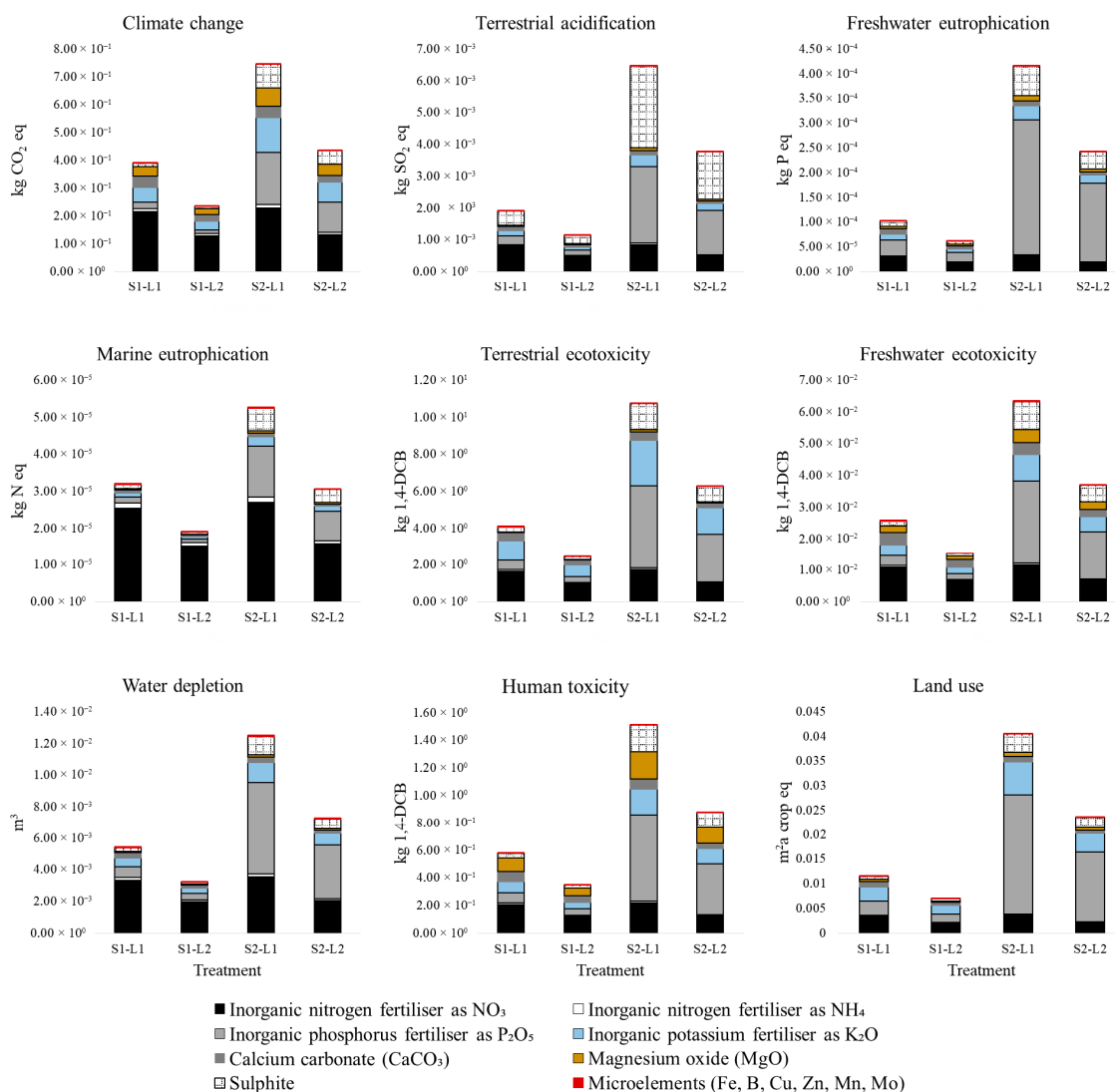


Figure 3. Contribution analyses: Environmental load of nutrients per 1 kg of dried inflorescence, S1-L1: solution 1, lighting 1, S1-L2: solution 1, lighting 2, S2-L1: solution 2, lighting 1, S2-L2: solution 2, lighting 2, Climate change ($\text{kg CO}_2 \text{ eq}$), Terrestrial acidification ($\text{kg SO}_2 \text{ eq}$), Freshwater eutrophication (kg P eq), Marine eutrophication (kg N eq), Terrestrial ecotoxicity (kg 1,4-DCB), Freshwater ecotoxicity (kg 1,4-DCB), Water depletion (m^3), Human toxicity (kg 1,4-DCB), Land use ($\text{m}^2 \text{a crop eq}$), SimaPro Craft Analyst 10.2.0.0 software; ReCiPe 2016 Midpoint (H) V1.09/World (2010) H; Cut-off System Model approach; Characterization model.

The results showed that scenarios with higher fertilization intensity (S2) exhibited substantially higher environmental impacts on average by 88% in most categories compared to lower-dose variants (S1). Across scenarios, the fertilizer-only climate change impact per FU lies in the range 0.235–0.746 kg CO₂ eq. The S2-L1 variant with high fertilization under low lighting intensity, consistently showed the highest environmental impact among the tested scenarios. This suggests that simply increasing fertilizer input, without optimizing other parameters, amplifies environmental pressure per unit of product.

In the climate change category, ammonium nitrate (NH₄NO₃) was identified as the dominant emission source, due to the energy-intensive production processes of nitric acid (HNO₃) and anhydrous ammonia NH₃. This input significantly contributed to climate change category across all scenarios, particularly in S2-L1. Each additional 1 g of mineral N, applied as NO₃[−] or NH₄⁺, increases the climate change impact by 4.8 g CO₂ eq, whereas 1 g of P, applied as P₂O₅, adds 1.84 g CO₂ eq.

Terrestrial acidification was mainly influenced by nitric acid production, which is part of ammonium nitrate synthesis. In addition, sulphite production associated with sulphur dioxide emissions from industrial processes also contributed to acidification potential. The highest overall impact was observed in the S2-L1 treatment, where sulphite accounted for up to 39.6% of the total acidification impact, highlighting its considerable contribution under high-fertilization scenarios.

In both freshwater and marine eutrophication, the highest impacts were again observed in high-fertilization scenarios. For freshwater eutrophication, the combined effects of nitrogen and phosphorus inputs were evident, particularly from ammonium nitrate and single superphosphate. In marine systems, nitrogen-based fertilization, especially ammonium nitrate, was the key contributor. The S2-L1 treatment consistently showed the highest environmental impacts in both eutrophication categories. Each gram of mineral nitrogen applied to the system, as NO₃[−] or NH₄⁺, contributes 0.22 mg N eq to marine eutrophication and each gram of phosphorus applied, as P₂O₅, contributes 2.76 mg P eq to freshwater eutrophication.

Terrestrial ecotoxicity was primarily driven by nitrogen and potassium-based mineral fertilizers. Potassium chloride production, which involves potash mining, transport, steam use, and salt tailings, played a significant role in increasing environmental pressure. In freshwater ecotoxicity, the impact of calcium carbonate and phosphorus fertilizers was reflected in the results, due to emissions from their respective industrial production processes. The highest environmental impact in both categories was observed in the S2-L1 treatment, while the lowest values were recorded in the S1-L2 scenario, highlighting the importance of input optimization.

Human toxicity followed similar patterns to ecotoxicity. Nitrogen fertilizers, especially ammonium nitrate, were dominant contributors, with additional contributions from micronutrients and by-products from other fertilizer manufacturing processes. Notably, magnesium oxide also contributed to this category, accounting for up to 16.3% of the total impact in treatment S1-L1.

A particularly specific result was observed in the land use category, assessed under S1 and S2 scenarios. The highest land occupation was found in S2-L1, with the main contribution stemming from organic nitrogen fertilizer. Once again, this is due to the complex and resource-intensive production of ammonium nitrate including nitric acid, chemical facilities, and electricity use. Significant contributions also came from phosphate fertilizers through phosphate rock beneficiation and chemical conversion, potassium chloride due to energy and transport demands associated with potash mining, and magnesium oxide production due to reliance on industrial heat.

3.3. Normalization

The normalized environmental impact model calculated per FU (Figure 4; Table A4) revealed that the most affected categories were human toxicity (HT), freshwater eutrophication (FE), and freshwater ecotoxicity (FX). These categories showed the highest impact values across all scenarios, with the highest impacts found in S2-L1 and S2-L2, indicating a strong influence of fertilizer application and related field emissions. These results highlighted that nutrient inputs remain a critical factor shaping the environmental profile of indoor cultivation systems.

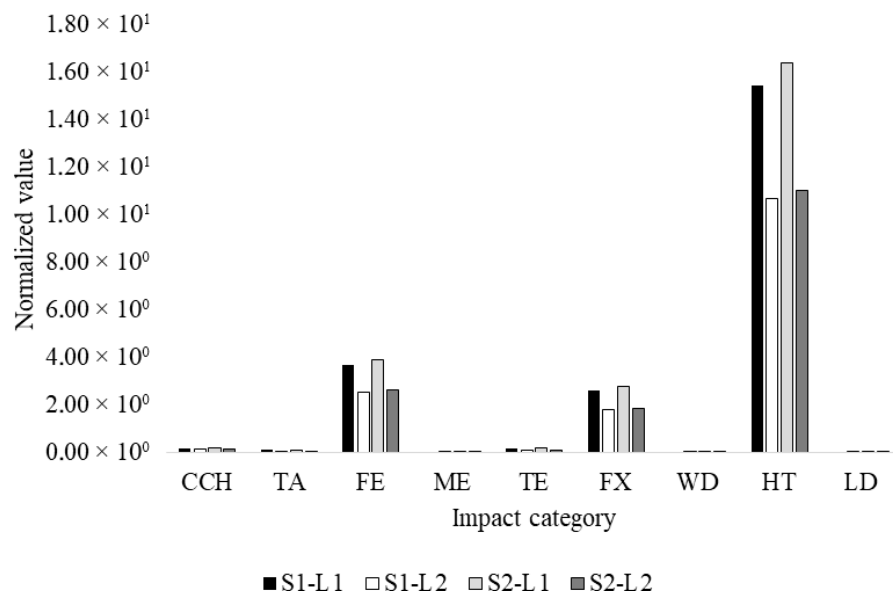


Figure 4. Normalization, S1-L1: solution 1, lighting 1, S1-L2: solution 1, lighting 2, S2-L1: solution 2, lighting 1, S2-L2: solution 2, lighting 2, CCH: Climate change, TA: Terrestrial acidification, FE: Freshwater eutrophication, ME: Marine eutrophication, TE: Terrestrial ecotoxicity, FX: Freshwater ecotoxicity, WD: Water depletion, HT: Human toxicity, LD: Land use, results are expressed as normalized values, SimaPro Craft Analyst 10.2.0.0 software; ReCiPe 2016 Midpoint (H) V1.09/World (2010) method; Normalization model.

In contrast, the least affected impact categories included water depletion, land use, and marine eutrophication. The impact values in these categories were consistently low compared to others, suggesting that indoor growing systems have relatively minor effects in these areas, likely due to closed-loop water use, spatial efficiency, and the limited interaction with marine ecosystems.

3.4. Sensitivity Analysis

The sensitivity analysis was conducted (Table A5) in accordance with the requirements of ISO 14044 [31], to verify the robustness of the results with respect to variations in the electricity mix. For all four cultivation scenarios, three alternative compositions of the Czech electricity mix were modeled. The first variant assumed a 25% increase in lignite share at the expense of nuclear energy, to evaluate the effect of a more fossil-intensive system. The second variant, reflecting a 25% increase in nuclear energy, corresponds to the current Czech energy mix [40], where the contribution of nuclear power has significantly increased. The third variant incorporated a 25% increase in renewable energy sources (hydropower, pumped storage, biomass, biogas, wind, solar, and geothermal), offset by a reduction in lignite, reflecting the decarbonization trend.

The results showed that increasing the share of lignite led to an average rise in total environmental impact by more than 100%, whereas scenarios with a higher share of nuclear

or renewable energy reduced impacts by approximately 20–30%. However, the results clearly demonstrate that the overall environmental performance of indoor cultivation systems is highly sensitive to the composition of the electricity mix. Shifting toward a more carbon-intensive mix substantially amplifies total impacts, whereas increasing the share of low-carbon or renewable sources markedly improves the sustainability profile of all scenarios.

4. Discussion

An LCA approach was adopted to evaluate the environmental impacts of indoor hemp cultivation under varying light and fertilization conditions. As a well-established and widely used environmental management tool, LCA enables a comprehensive evaluation of inputs and outputs across the entire production system [43].

4.1. Selection of the Functional Unit and Allocation Approach

In this study, the FU was defined as 1 kg of dried hemp inflorescence, in line with common practice in agricultural LCA [44]. This value was selected based on experimentally observed yields ranging from 344 g to 609 g per plant, with 1 kg representing a realistic and comparable amount of production. The choice of the FU has a significant impact on the interpretation of LCA results, especially when comparing agricultural systems. Using different FUs (e.g., mass-based, area-based, or nutritional) can lead to different rankings of environmental performance [45].

Economy allocation was applied in this study. The FU included only the market value of dried inflorescence, and no market value of co-products (e.g., seeds or stalks) were considered within the system boundaries. Some other studies focused on hemp cultivation applied, for example, mass allocation to divide the impacts between hemp seed oil (20%) and flour (80%) [46], but those co-products can be characterized by market value. In this study, an economy allocation was applied, as the dried inflorescence represented the only economically valuable output of the system, while the remaining biomass was treated as residual material without market value. The approach of allocation is based on the ISO 14044 [31]. Further, the weight ratio of the stems versus inflorescence was not carried out as this was not relevant for the experiment reproducibility, since the reproducibility of yield-related parameters in *Cannabis sativa* experiments is limited due to a wider range of cultivation practices in the industry. For example, the research of Reichel et al. [47] showed that stem diameter is strain (cultivar) dependent.

4.2. Comparison with Previous Studies on the Environmental Impacts of Indoor Hemp Cultivation

Direct comparisons are limited due to methodological inconsistencies across agricultural LCA studies, including differences in data quality, regional context, and interpretation. Presenting results as trends remains a valid and communicative approach [22]. A consistent finding, also observed in our study, is the dominant impact of electricity use.

A previous study found that greenhouse gas (GHG) emissions from indoor cannabis cultivation, accounting for modeled natural gas use, electricity use with geographically resolved grid emissions, and upstream/downstream processes, range from 2283 to 5184 kg CO₂ eq per kg of dried cannabis flower [27]. By contrast, this study restricts the system boundary to electricity-only (lighting, ventilation, drying) and applies the 2022 Czech grid emission factor. Under these conditions, GHG emissions range from 1040 to 1600 kg CO₂ eq per kg of dried cannabis flower, with electricity contributing 98.8–99.0% of the total climate change impact across all treatments.

Another study reports an approximate 4600 kg CO₂ per kg of dried indoor cannabis based on a model that converts operational energy for cultivation (light-

ing/HVAC/dehumidification, ventilation, pumps) and transportation into CO₂ emissions using building end-use modeling and market/manufacturer data [26]. Because prior work reports CO₂ and uses non-comparable system boundaries, we avoid a like-for-like quantitative comparison. Even so, it is reasonable to assume that electricity consumption and, where relevant, natural gas use are among the dominant contributors to total environmental impacts.

4.3. Strategies for Sustainable Indoor Cultivation of Hemp

Accurately quantifying energy use across all operational stages is crucial for reliable estimations of environmental impacts [48]. Methods such as Life Cycle Energy Assessment and Life Cycle Carbon Emissions Assessment enable a more precise identification of emission reduction opportunities. A key factor in this regard is the source of electricity consumed, which significantly influences the outcomes of carbon accounting and impact assessment in LCA [49].

The carbon intensity of electricity in the Czech Republic is substantially higher compared to countries with a higher share of renewable energy sources, because lignite constitutes a large part of the Czech electricity mix. Emissions from lignite-based electricity generation can reach up to 0.901 kg CO₂ eq/kWh [50], which is several times higher than that of wind (0.019 kg CO₂ eq/kWh) or solar energy (0.011 kg CO₂ eq/kWh). National energy mixes play a crucial role in LCA outcomes, with renewable-based systems achieving substantially lower greenhouse gas emissions [51].

Results of the sensitivity analysis indicated that an increased share of lignite in the electricity mix significantly amplified total environmental impacts across all cultivation scenarios, confirming the strong dependency of the overall results on the national energy structure. For these reasons, this study adopted a location-based approach based on data for the relevant period [39,40]. This method ensures a more realistic estimate of emissions [49].

However, while these constraints are central to indoor cultivation, shifting production outdoors is not a guaranteed remedy. Poorly managed field systems can introduce new trade-offs, nutrient and pesticide runoff, higher water use and land occupation, and weather-driven yield volatility, potentially raising inputs per kilogram of product [26,52,53]. One promising approach is the integration of renewable energy sources. For instance, the use of small-scale biomass gasifiers can enable partial energy self-sufficiency in indoor cultivation facilities. These systems can generate electricity, heat, and biochar, the last being a byproduct with potential soil-enhancing properties, thus reducing operational costs and increasing the overall sustainability of hemp production [20].

Another option with significant potential to reduce environmental impacts is the use of solar energy [54]. Carbon footprint calculations have shown a substantial difference between electricity supplied from the public grid and electricity generated through photovoltaic panels. In one analyzed system, the carbon footprint of electricity from the conventional grid reached 134.8 kg CO₂ eq per square meter, compared to only 4.1 kg CO₂ eq per square meter for photovoltaic energy [55]. This difference highlights the considerable environmental benefits of renewable energy sources in meeting the energy demands of indoor cultivation facilities. Our results also indicate a reduction in overall environmental impacts when 25% of electricity from lignite was substituted by renewable energy sources, although the effect was less pronounced than in studies assessing full photovoltaic replacement. This difference may be partly attributed to the model boundary assumptions, as in case of this study, the photovoltaic systems were not considered to be integrated directly at the cultivation site, where on-site generation could further reduce energy-related impacts.

Although increasing light intensity in indoor cultivation systems may initially appear to raise environmental impacts, recalculations per unit of production often reveal the

opposite. While higher light input increases energy use, it also significantly improves yields, thereby reducing the impact per kilogram of dried biomass. For indoor cultivation of hemp, the combination of 360 W during the vegetative stage and 900 W during the flowering stage, together with the S1 nutrient solution, reduced the environmental impacts per kilogram of dried inflorescence by approximately 30–32% compared to lower light treatments. This highlights that higher input does not necessarily result in higher impact, efficiency is the key.

This principle is supported by LCA case studies on microgreen production, where yield gains from intensified cultivation outweighed the associated environmental impact [56]. Similarly, our findings confirm that while fertilizers can contribute substantially to the overall impact, optimizing light conditions improves biomass production and resource efficiency. Light intensity is no longer just a biological parameter, but an economic and environmental one. Lower-concentration nutrient solutions can maintain yield and cannabinoid quality while reducing both costs and environmental impact. [33]. This confirms that thoughtful input management, whether related to lighting or fertilization, can offer both economic and ecological benefits, which aligns with the focus on resource-use efficiency in our assessment.

4.4. Environmental Implications of Fertilization Intensity and Nutrient Management

This study confirmed a significant environmental impact associated with the use of nitrogen-based fertilizers. Fertilizers containing nitrogen (N) and phosphorus (P) are responsible for approximately 78% of global freshwater and marine eutrophication [57]. Excessive nitrogen and phosphorus input is a major driver of eutrophication and biodiversity loss in global agricultural systems [58]. The environmental impact, however, is not limited to fertilizer application alone. The production phases of mineral fertilizers and agricultural operations each account for roughly 12% of the total cumulative energy demand [59]. This is primarily due to emissions generated during the extraction and industrial processing of raw materials such as ammonium nitrate, potassium chloride, and single superphosphate.

5. Conclusions

This study evaluated the environmental performance of indoor hemp cultivation under four controlled scenarios combining different lighting intensities and nutrient regimes. Optimizing input–output efficiency is essential. Higher lighting intensity can be justified when the yield scales proportionally. For indoor hemp cultivation, within the bounds of this study, four scenarios, a 12-week cycle, the 2022 Czech grid, and a cultivation-only scope with cradle-to-gate approach, priority should be given to the combination of S1 nutrient solution, and 900 W light intensity during the flowering stage, as this configuration achieved the most favorable balance between productivity and environmental performance. In this setting, the electricity intensity is $7000 \text{ kWh} \cdot \text{kg}^{-1}$, with drying accounting for 47% of electricity use. If the share of renewable electricity in the national energy mix increases by approximately 25% at the expense of lignite-based generation, total environmental impacts decrease by about 17% and if, instead, nuclear increases by 25% at the expense of lignite, impacts decrease by 29%; conversely, a lignite-heavy shift leads to an increase of 113%

The conclusions are explicitly bounded to the tested four cultivation scenarios and the 2022 Czech electricity mix. Therefore, generalization to other regional contexts should be made with caution.

Further research should focus on identifying the optimal light design, specifically, determining the threshold where increased light intensity continues to enhance yield without proportionally raising. Future studies could also focus on the relationship between yield changes and corresponding variations in environmental impact.

Although the present study provides valuable insights, it has several limitations. The limited number of repetitions restricts statistical evaluation, and the system boundary did not include post-harvest waste management or potential material reuse. Future studies should incorporate additional replicates to strengthen data robustness and extend the system boundary to include waste valorization.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

LCA	Life Cycle Assessment
FU	Functional unit
GHG	Greenhouse gas
NPK	Nitrogen (N), Phosphorus (P), and Potassium (K) fertilizers

Appendix A

Table A1. Uncertainty analysis of environmental impact categories (ReCiPe 2016 Midpoint).

	Treatment	Mean	Median	SD	CV	2.5%	97.5%	SEM
CCH	S1-L1	1.51×10^3	1.51×10^3	1.12×10^2	7.44×10^0	1.30×10^3	1.74×10^3	3.55×10^0
	S1-L2	1.05×10^3	1.05×10^3	8.20×10^1	7.80×10^0	9.06×10^2	1.23×10^3	2.59×10^0
	S2-L1	1.61×10^3	1.60×10^3	1.17×10^2	7.32×10^0	1.39×10^3	1.86×10^3	3.71×10^0
	S2-L2	1.09×10^3	1.09×10^3	8.18×10^1	7.53×10^0	9.27×10^2	1.25×10^3	2.59×10^0
TA	S1-L1	4.31×10^0	4.30×10^0	2.77×10^{-1}	6.42×10^0	3.80×10^0	4.92×10^0	8.75×10^{-3}
	S1-L2	2.97×10^0	2.96×10^0	1.93×10^{-1}	6.48×10^0	2.63×10^0	3.38×10^0	6.09×10^{-3}
	S2-L1	4.58×10^0	4.57×10^0	2.95×10^{-1}	6.44×10^0	4.02×10^0	5.19×10^0	9.33×10^{-3}
	S2-L2	3.07×10^0	3.06×10^0	1.98×10^{-1}	6.45×10^0	2.70×10^0	3.47×10^0	6.26×10^{-3}
FE	S1-L1	2.43×10^0	1.89×10^0	1.90×10^0	7.84×10^1	5.78×10^{-1}	7.33×10^0	6.01×10^{-2}
	S1-L2	1.70×10^0	1.32×10^0	1.48×10^0	8.70×10^1	4.14×10^{-1}	5.43×10^0	4.67×10^{-2}
	S2-L1	2.52×10^0	1.92×10^0	2.17×10^0	8.62×10^1	6.07×10^{-1}	8.49×10^0	6.86×10^{-2}
	S2-L2	1.72×10^0	1.33×10^0	1.51×10^0	8.76×10^1	4.08×10^{-1}	5.49×10^0	4.76×10^{-2}
ME	S1-L1	1.57×10^{-1}	1.53×10^{-1}	3.43×10^{-2}	2.18×10^1	1.01×10^{-1}	2.34×10^{-1}	1.08×10^{-3}
	S1-L2	1.10×10^{-1}	1.07×10^{-1}	2.46×10^{-2}	2.23×10^1	7.19×10^{-2}	1.66×10^{-1}	7.78×10^{-4}
	S2-L1	1.69×10^{-1}	1.64×10^{-1}	3.77×10^{-2}	2.23×10^1	1.10×10^{-1}	2.62×10^{-1}	1.19×10^{-3}
	S2-L2	1.13×10^{-1}	1.11×10^{-1}	2.40×10^{-2}	2.13×10^1	7.17×10^{-2}	1.62×10^{-1}	7.58×10^{-4}
TE	S1-L1	2.80×10^3	2.43×10^3	1.45×10^3	5.17×10^1	1.29×10^3	6.34×10^3	4.58×10^1
	S1-L2	1.85×10^3	1.62×10^3	8.78×10^2	4.74×10^1	8.77×10^2	4.09×10^3	2.78×10^1
	S2-L1	2.97×10^3	2.63×10^3	1.48×10^3	5.00×10^1	1.37×10^3	6.84×10^3	4.69×10^1
	S2-L2	1.90×10^3	1.69×10^3	8.52×10^2	4.49×10^1	9.18×10^2	4.44×10^3	2.69×10^1

Table A1. Cont.

	Treatment	Mean	Median	SD	CV	2.5%	97.5%	SEM
FX	S1-L1	6.74×10^1	4.83×10^1	7.28×10^1	1.08×10^2	2.30×10^1	2.30×10^2	2.30×10^0
	S1-L2	4.77×10^1	3.51×10^1	5.25×10^1	1.10×10^2	1.55×10^1	1.60×10^2	1.66×10^0
	S2-L1	7.24×10^1	5.27×10^1	7.71×10^1	1.07×10^2	2.49×10^1	2.57×10^2	2.44×10^0
	S2-L2	4.80×10^1	3.53×10^1	4.12×10^1	8.57×10^1	1.73×10^1	1.65×10^2	1.30×10^0
WD	S1-L1	4.12×10^1	1.50×10^2	1.31×10^3	3.18×10^3	-2.91×10^3	2.33×10^3	4.14×10^1
	S1-L2	-1.21×10^1	7.65×10^1	9.44×10^2	-7.81×10^3	-2.02×10^3	1.58×10^3	2.98×10^1
	S2-L1	7.67×10^1	1.72×10^2	1.30×10^3	1.70×10^3	-2.81×10^3	2.42×10^3	4.11×10^1
	S2-L2	-2.83×10^0	1.70×10^2	9.88×10^2	-3.49×10^4	-2.51×10^3	1.62×10^3	3.12×10^1
HT	S1-L1	1.39×10^3	9.94×10^2	2.60×10^3	1.86×10^2	1.28×10^3	1.51×10^3	5.81×10^1
	S1-L2	9.78×10^2	7.11×10^2	1.83×10^3	1.88×10^2	8.98×10^2	1.06×10^3	4.10×10^1
	S2-L1	1.52×10^3	1.09×10^3	2.91×10^3	1.91×10^2	1.39×10^3	1.65×10^3	6.50×10^1
	S2-L2	9.80×10^2	7.14×10^2	1.64×10^3	1.67×10^2	9.08×10^2	1.05×10^3	3.66×10^1
LD	S1-L1	3.86×10^1	3.88×10^1	2.04×10^1	5.29×10^1	-5.51×10^0	7.97×10^1	6.46×10^{-1}
	S1-L2	2.68×10^1	2.67×10^1	1.43×10^1	5.35×10^1	-3.08×10^0	5.55×10^1	4.53×10^{-1}
	S2-L1	4.20×10^1	4.25×10^1	2.07×10^1	4.94×10^1	-2.63×10^0	8.26×10^1	6.56×10^{-1}
	S2-L2	2.75×10^1	2.73×10^1	1.50×10^1	5.45×10^1	-2.49×10^0	5.57×10^1	4.75×10^{-1}

S1-L1: solution 1, lighting 1, S1-L2: solution 1, lighting 2, S2-L1: solution 2, lighting 1, S2-L2: solution 2, lighting 2, CCH: Climate change (kg CO₂ eq), TA: Terrestrial acidification (kg SO₂ eq), FE: Freshwater eutrophication (kg P eq), ME: Marine eutrophication (kg N eq), TE: Terrestrial ecotoxicity (kg 1.4-DCB), FX: Freshwater ecotoxicity (kg 1.4-DCB), WD: Water depletion (m³), HT: Human toxicity (kg 1.4-DCB), LD: Land use (m²a crop eq), SimaPro 9.3.0.2 software; ReCiPe 2016 Midpoint (H) V1.09/World (2010) H; Cut-off System Model approach; Characterization model, Confidence interval: 95%.

Table A2. Contribution analyses: Environmental load of full system per functional unit (1 kg of dried hemp inflorescence).

Impact Category	Treatment	Growing Media	Flowerpot-1 Year Amortization	Fertilizers (NPK)	Minerals & Microelements	Tap Water	Electricity-Lighting	Electricity-Ventilation	Electricity-Dryers
CCH	S1-L1	1.6×10^1	1.1×10^0	3.0×10^{-1}	8.9×10^{-2}	1.3×10^{-1}	4.3×10^2	2.5×10^2	8.2×10^2
	S1-L2	9.9×10^0	6.3×10^{-1}	1.8×10^{-1}	5.3×10^{-2}	7.9×10^{-2}	4.0×10^2	1.5×10^2	4.9×10^2
	S2-L1	1.8×10^1	1.1×10^0	5.5×10^{-1}	1.9×10^{-1}	1.4×10^{-1}	4.6×10^2	2.7×10^2	8.7×10^2
	S2-L2	1.0×10^1	6.5×10^{-1}	3.2×10^{-1}	1.1×10^{-1}	8.2×10^{-2}	4.1×10^2	1.5×10^2	5.1×10^2
TA	S1-L1	1.6×10^{-1}	3.2×10^{-3}	1.3×10^{-3}	6.3×10^{-4}	4.7×10^{-4}	1.2×10^0	6.9×10^{-1}	2.3×10^0
	S1-L2	9.6×10^{-2}	1.9×10^{-3}	7.7×10^{-4}	3.8×10^{-4}	2.8×10^{-4}	1.1×10^0	4.2×10^{-1}	1.4×10^0
	S2-L1	1.7×10^{-1}	3.3×10^{-3}	3.7×10^{-3}	2.8×10^{-3}	5.0×10^{-4}	1.3×10^0	7.4×10^{-1}	2.4×10^0
	S2-L2	9.9×10^{-2}	2.0×10^{-3}	2.1×10^{-3}	1.6×10^{-3}	2.9×10^{-4}	1.1×10^0	4.3×10^{-1}	1.4×10^0
FE	S1-L1	2.7×10^{-3}	2.7×10^{-4}	7.6×10^{-5}	2.6×10^{-5}	8.8×10^{-5}	6.9×10^{-1}	4.0×10^{-1}	1.3×10^0
	S1-L2	2.1×10^{-4}	1.6×10^{-4}	4.6×10^{-5}	1.6×10^{-5}	5.3×10^{-5}	6.4×10^{-1}	2.4×10^{-1}	7.8×10^{-1}
	S2-L1	2.8×10^{-3}	2.9×10^{-4}	3.3×10^{-4}	8.1×10^{-5}	9.3×10^{-5}	7.3×10^{-1}	4.2×10^{-1}	1.4×10^0
	S2-L2	1.7×10^{-3}	1.7×10^{-4}	2.0×10^{-4}	4.7×10^{-5}	5.4×10^{-5}	6.6×10^{-1}	2.5×10^{-1}	8.1×10^{-1}
ME	S1-L1	3.5×10^{-4}	2.3×10^{-5}	3.0×10^{-5}	2.5×10^{-6}	8.6×10^{-6}	4.6×10^{-2}	2.6×10^{-2}	8.6×10^{-2}
	S1-L2	2.1×10^{-4}	1.4×10^{-5}	1.8×10^{-5}	1.5×10^{-6}	5.2×10^{-6}	4.2×10^{-2}	1.6×10^{-2}	5.2×10^{-2}
	S2-L1	3.7×10^{-4}	2.4×10^{-5}	4.5×10^{-5}	7.9×10^{-6}	9.1×10^{-6}	4.8×10^{-2}	2.8×10^{-2}	9.1×10^{-2}
	S2-L2	2.2×10^{-4}	1.4×10^{-5}	2.6×10^{-5}	4.6×10^{-6}	5.3×10^{-6}	4.3×10^{-2}	1.6×10^{-2}	5.3×10^{-2}
TE	S1-L1	9.7×10^1	7.7×10^{-1}	3.3×10^0	8.0×10^{-1}	9.4×10^0	7.5×10^2	4.3×10^2	1.4×10^3
	S1-L2	5.8×10^1	4.6×10^{-1}	2.0×10^0	4.8×10^{-1}	5.6×10^0	6.9×10^2	2.6×10^2	8.5×10^2
	S2-L1	1.0×10^2	8.2×10^{-1}	8.8×10^0	2.0×10^0	9.9×10^0	7.9×10^2	4.6×10^2	1.5×10^3
	S2-L2	6.0×10^1	4.8×10^{-1}	5.1×10^0	1.2×10^0	5.8×10^0	7.1×10^2	2.7×10^2	8.7×10^2
FX	S1-L1	2.6×10^{-1}	1.2×10^{-2}	1.8×10^{-2}	7.7×10^{-3}	1.1×10^{-2}	1.9×10^1	1.1×10^1	3.6×10^1
	S1-L2	1.5×10^{-1}	6.7×10^{-3}	1.1×10^{-2}	4.6×10^{-3}	6.5×10^{-3}	1.7×10^1	6.6×10^0	2.1×10^1
	S2-L1	2.7×10^{-1}	1.3×10^{-2}	4.7×10^{-2}	1.7×10^{-2}	1.2×10^{-2}	2.0×10^1	1.2×10^1	3.8×10^1
	S2-L2	1.6×10^{-1}	7.4×10^{-3}	2.7×10^{-2}	9.9×10^{-3}	6.7×10^{-3}	1.8×10^1	6.8×10^0	2.2×10^1
WD	S1-L1	1.5×10^{-1}	1.1×10^{-2}	4.7×10^{-3}	7.1×10^{-4}	4.3×10^{-1}	1.8×10^0	1.0×10^0	3.4×10^0
	S1-L2	9.2×10^{-2}	6.5×10^{-3}	2.8×10^{-3}	4.2×10^{-4}	2.6×10^{-1}	1.6×10^0	6.2×10^{-1}	2.0×10^0
	S2-L1	1.6×10^{-1}	1.1×10^{-2}	1.1×10^{-2}	1.7×10^{-3}	4.6×10^{-1}	1.9×10^0	1.1×10^0	3.6×10^0
	S2-L2	9.5×10^{-2}	6.7×10^{-3}	6.3×10^{-3}	1.0×10^{-3}	2.7×10^{-1}	1.7×10^0	6.4×10^{-1}	2.1×10^0

Table A2. Cont.

Impact Category	Treatment	Growing Media	Flowerpot-1 Year Amortization	Fertilizers (NPK)	Minerals & Microelements	Tap Water	Electricity-Lighting	Electricity-Ventilation	Electricity-Dryers
HT	S1-L1	6.8×10^0	4.4×10^{-1}	3.7×10^{-1}	2.1×10^{-1}	5.8×10^{-1}	7.8×10^2	4.5×10^2	1.5×10^3
	S1-L2	4.1×10^0	2.6×10^{-1}	2.2×10^{-1}	1.3×10^{-1}	3.5×10^{-1}	7.2×10^2	2.7×10^2	8.9×10^2
	S2-L1	7.2×10^0	4.6×10^{-1}	1.0×10^0	4.7×10^{-1}	6.2×10^{-1}	8.3×10^2	4.8×10^2	1.6×10^3
	S2-L2	4.2×10^0	2.7×10^{-1}	6.1×10^{-1}	2.7×10^{-1}	3.6×10^{-1}	7.4×10^2	2.8×10^2	9.1×10^2
LD	S1-L1	6.8×10^{-1}	3.0×10^{-2}	9.4×10^{-3}	2.2×10^{-3}	4.7×10^{-3}	1.1×10^1	6.5×10^0	2.1×10^1
	S1-L2	4.1×10^{-1}	1.8×10^{-2}	5.6×10^{-3}	1.3×10^{-3}	2.8×10^{-3}	1.0×10^1	3.9×10^0	1.3×10^1
	S2-L1	7.3×10^{-1}	3.2×10^{-2}	3.5×10^{-2}	5.8×10^{-3}	5.0×10^{-3}	1.2×10^1	6.9×10^0	2.2×10^1
	S2-L2	4.2×10^{-1}	1.9×10^{-2}	2.0×10^{-2}	3.4×10^{-3}	2.9×10^{-3}	1.1×10^1	4.0×10^0	1.3×10^1

S1-L1: solution 1, lighting 1, S1-L2: solution 1, lighting 2, S2-L1: solution 2, lighting 1, S2-L2: solution 2, lighting 2, CCH: Climate change (kg CO₂ eq), TA: Terrestrial acidification (kg SO₂ eq), FE: Freshwater eutrophication (kg P eq), ME: Marine eutrophication (kg N eq), TE: Terrestrial ecotoxicity (kg 1.4-DCB), FX: Freshwater ecotoxicity (kg 1.4-DCB), WD: Water depletion (m³), HT: Human toxicity (kg 1.4-DCB), LD: Land use (m²a crop eq), “Fertilizers (NPK)” include NO₃[−], NH₄⁺, P₂O₅, and K₂O fertilizers. “Minerals & Microelements” include calcium carbonate, magnesium oxide, sulphite, and microelements (Fe, B, Cu, Zn, Mn, Mo). “Growing media” include stone wool, coconut fiber, and perlite, SimaPro 9.3.0.2 software; ReCiPe 2016 Midpoint (H) V1.09/World (2010) H; Cut-off System Model approach; Characterization model.

Table A3. Contribution analyses: Environmental load of nutrients only system per functional unit (1 kg of dried hemp inflorescence).

Impact Category	Treatment	Total	Inorganic Nitrogen Fertilizer as NO ₃	Inorganic Nitrogen Fertilizer as NH ₄	Inorganic Phosphorus Fertilizer as P ₂ O ₅	Inorganic Potassium Fertilizer as K ₂ O	Calcium Carbonate (CaCO ₃)	Magnesium Oxide (MgO)	Sulphite	Microelements (Fe, B, Cu, Zn, Mn, Mo)
CCH	S1-L1	3.92×10^{-1}	2.15×10^{-1}	1.15×10^{-2}	2.22×10^{-2}	5.43×10^{-2}	4.00×10^{-2}	3.26×10^{-2}	1.46×10^{-2}	1.43×10^{-3}
	S1-L2	2.35×10^{-1}	1.29×10^{-1}	6.90×10^{-3}	1.33×10^{-2}	3.25×10^{-2}	2.39×10^{-2}	1.95×10^{-2}	8.75×10^{-3}	8.55×10^{-4}
	S2-L1	7.46×10^{-1}	2.29×10^{-1}	1.22×10^{-2}	1.87×10^{-1}	1.26×10^{-1}	3.98×10^{-2}	6.69×10^{-2}	8.41×10^{-2}	1.31×10^{-3}
	S2-L2	4.35×10^{-1}	1.33×10^{-1}	7.12×10^{-3}	1.09×10^{-1}	7.31×10^{-2}	2.32×10^{-2}	3.90×10^{-2}	4.90×10^{-2}	7.65×10^{-4}
TA	S1-L1	1.92×10^{-3}	7.96×10^{-4}	4.26×10^{-5}	2.84×10^{-4}	1.63×10^{-4}	1.32×10^{-4}	4.55×10^{-5}	4.46×10^{-4}	7.80×10^{-6}
	S1-L2	2.97×10^0	4.77×10^{-4}	2.55×10^{-5}	1.70×10^{-4}	9.78×10^{-5}	7.89×10^{-5}	2.73×10^{-5}	2.67×10^{-4}	4.67×10^{-6}
	S2-L1	6.46×10^{-3}	8.45×10^{-4}	4.52×10^{-5}	2.40×10^{-3}	3.77×10^{-4}	1.31×10^{-4}	9.35×10^{-5}	2.56×10^{-3}	7.18×10^{-6}
	S2-L2	3.77×10^{-3}	4.92×10^{-4}	2.63×10^{-5}	1.40×10^{-3}	2.20×10^{-4}	7.65×10^{-5}	5.45×10^{-5}	1.49×10^{-3}	4.18×10^{-6}
FE	S1-L1	1.02×10^{-4}	2.99×10^{-5}	1.60×10^{-6}	3.24×10^{-5}	1.21×10^{-5}	1.04×10^{-5}	4.97×10^{-6}	1.04×10^{-5}	5.31×10^{-7}
	S1-L2	1.66×10^0	1.79×10^{-5}	9.57×10^{-7}	1.94×10^{-5}	7.27×10^{-6}	6.25×10^{-6}	2.98×10^{-6}	6.20×10^{-6}	3.18×10^{-7}
	S2-L1	4.15×10^{-4}	3.17×10^{-5}	1.69×10^{-6}	2.73×10^{-4}	2.80×10^{-5}	1.04×10^{-5}	1.02×10^{-5}	5.96×10^{-5}	4.89×10^{-7}
	S2-L2	2.42×10^{-4}	1.85×10^{-5}	9.87×10^{-7}	1.59×10^{-4}	1.63×10^{-5}	6.06×10^{-6}	5.95×10^{-6}	3.47×10^{-5}	2.85×10^{-7}
ME	S1-L1	3.21×10^{-5}	2.55×10^{-5}	1.36×10^{-6}	1.63×10^{-6}	1.11×10^{-6}	8.36×10^{-7}	3.11×10^{-7}	1.06×10^{-6}	3.33×10^{-7}
	S1-L2	1.10×10^{-1}	1.53×10^{-5}	8.16×10^{-7}	9.75×10^{-7}	6.65×10^{-7}	5.01×10^{-7}	1.87×10^{-7}	6.32×10^{-7}	2.00×10^{-7}
	S2-L1	5.26×10^{-5}	2.70×10^{-5}	1.45×10^{-6}	1.37×10^{-5}	2.56×10^{-6}	8.33×10^{-7}	6.39×10^{-7}	6.07×10^{-6}	3.07×10^{-7}
	S2-L2	3.07×10^{-5}	1.58×10^{-5}	8.43×10^{-7}	8.00×10^{-6}	1.49×10^{-6}	4.85×10^{-7}	3.73×10^{-7}	3.54×10^{-6}	1.79×10^{-7}
TE	S1-L1	4.12×10^0	1.63×10^0	8.74×10^{-2}	5.30×10^{-1}	1.07×10^0	4.44×10^{-1}	5.31×10^{-2}	2.44×10^{-1}	5.82×10^{-2}
	S1-L2	1.86×10^3	9.78×10^{-1}	5.23×10^{-2}	3.17×10^{-1}	6.40×10^{-1}	2.66×10^{-1}	3.18×10^{-2}	1.46×10^{-1}	3.49×10^{-2}
	S2-L1	1.08×10^1	1.73×10^0	9.27×10^{-2}	4.47×10^0	2.47×10^0	4.42×10^{-1}	1.09×10^{-1}	1.40×10^0	5.36×10^{-2}
	S2-L2	6.28×10^0	1.01×10^0	5.40×10^{-2}	2.61×10^0	1.44×10^0	2.58×10^{-1}	6.35×10^{-2}	8.19×10^{-1}	3.12×10^{-2}
FX	S1-L1	259×10^{-2}	1.09×10^{-2}	5.83×10^{-4}	3.08×10^{-3}	3.62×10^{-3}	3.86×10^{-3}	1.96×10^{-3}	1.53×10^{-3}	3.27×10^{-4}
	S1-L2	4.55×10^1	6.53×10^{-3}	3.49×10^{-4}	1.84×10^{-3}	2.17×10^{-3}	2.31×10^{-3}	1.18×10^{-3}	9.14×10^{-4}	1.96×10^{-4}
	S2-L1	6.35×10^{-2}	1.16×10^{-2}	6.19×10^{-4}	2.60×10^{-2}	8.36×10^{-3}	3.85×10^{-3}	4.03×10^{-3}	8.78×10^{-3}	3.01×10^{-4}
	S2-L2	3.70×10^{-2}	6.74×10^{-3}	3.60×10^{-4}	1.51×10^{-2}	4.87×10^{-3}	2.24×10^{-3}	2.35×10^{-3}	5.12×10^{-3}	1.75×10^{-4}
WD	S1-L1	5.44×10^{-3}	3.32×10^{-3}	1.78×10^{-4}	6.89×10^{-4}	5.44×10^{-4}	3.38×10^{-4}	8.60×10^{-5}	1.96×10^{-4}	8.85×10^{-5}
	S1-L2	4.64×10^0	1.99×10^{-3}	1.06×10^{-4}	4.13×10^{-4}	3.26×10^{-4}	2.02×10^{-4}	5.15×10^{-5}	1.17×10^{-4}	5.30×10^{-5}
	S2-L1	1.25×10^{-2}	3.53×10^{-3}	1.89×10^{-4}	5.81×10^{-3}	1.26×10^{-3}	3.36×10^{-4}	1.77×10^{-4}	1.13×10^{-3}	8.15×10^{-5}
	S2-L2	7.29×10^{-3}	2.06×10^{-3}	1.10×10^{-4}	3.39×10^{-3}	7.32×10^{-4}	1.96×10^{-4}	1.03×10^{-4}	6.56×10^{-4}	4.75×10^{-5}

Table A3. Cont.

Impact Category	Treatment	Total	Inorganic Nitrogen Fertilizer as NO ₃	Inorganic Nitrogen Fertilizer as NH ₄	Inorganic Phosphorus Fertilizer as P ₂ O ₅	Inorganic Potassium Fertilizer as K ₂ O	Calcium Carbonate (CaCO ₃)	Magnesium Oxide (MgO)	Sulphite	Microelements (Fe, B, Cu, Zn, Mn, Mo)
HT	S1-L1	5.84×10^{-1}	2.07×10^{-1}	1.11×10^{-2}	7.43×10^{-2}	8.16×10^{-2}	7.30×10^{-2}	9.55×10^{-2}	3.36×10^{-2}	7.73×10^{-3}
	S1-L2	1.88×10^3	1.24×10^{-1}	6.64×10^{-3}	4.45×10^{-2}	4.89×10^{-2}	4.37×10^{-2}	5.72×10^{-2}	2.01×10^{-2}	4.63×10^{-3}
	S2-L1	1.52×10^0	2.20×10^{-1}	1.18×10^{-2}	6.27×10^{-1}	1.89×10^{-1}	7.27×10^{-2}	1.96×10^{-1}	1.93×10^{-1}	7.11×10^{-3}
	S2-L2	8.83×10^{-1}	1.28×10^{-1}	6.86×10^{-3}	3.65×10^{-1}	1.10×10^{-1}	4.24×10^{-2}	1.14×10^{-1}	1.13×10^{-1}	4.14×10^{-3}
LD	S1-L1	3.43×10^{-3}	1.83×10^{-4}	2.88×10^{-3}	2.90×10^{-3}	1.06×10^{-3}	4.35×10^{-4}	6.54×10^{-4}	3.13×10^{-5}	3.43×10^{-3}
	S1-L2	2.05×10^{-3}	1.10×10^{-4}	1.72×10^{-3}	1.74×10^{-3}	6.37×10^{-4}	2.61×10^{-4}	3.92×10^{-4}	1.88×10^{-5}	2.05×10^{-3}
	S2-L1	3.64×10^{-3}	1.94×10^{-4}	2.43×10^{-2}	6.70×10^{-3}	1.06×10^{-3}	8.94×10^{-4}	3.76×10^{-3}	2.88×10^{-5}	3.64×10^{-3}
	S2-L2	2.12×10^{-3}	1.13×10^{-4}	1.41×10^{-2}	3.90×10^{-3}	6.17×10^{-4}	5.21×10^{-4}	2.19×10^{-3}	1.68×10^{-5}	2.12×10^{-3}

S1-L1: solution 1, lighting 1, S1-L2: solution 1, lighting 2, S2-L1: solution 2, lighting 1, S2-L2: solution 2, lighting 2, CCH: Climate change (kg CO₂ eq), TA: Terrestrial acidification (kg SO₂ eq), FE: Freshwater eutrophication (kg P eq), ME: Marine eutrophication (kg N eq), TE: Terrestrial ecotoxicity (kg 1.4-DCB), FX: Freshwater ecotoxicity (kg 1.4-DCB), WD: Water depletion (m³), HT: Human toxicity (kg 1.4-DCB), LD: Land use (m²a crop eq), SimaPro 9.3.0.2 software; ReCiPe 2016 Midpoint (H) V1.09/World (2010) H; Cut-off System Model approach; Characterization model.

Table A4. Normalization model for unit of production (FU = 1 kg of dried hemp inflorescence).

Impact Category	S1-L1	S1-L2	S2-L1	S2-L2
CCH	1.90×10^{-1}	1.31×10^{-1}	2.01×10^{-1}	1.35×10^{-1}
TA	1.05×10^{-1}	7.25×10^{-2}	1.12×10^{-1}	7.49×10^{-2}
FE	3.69×10^0	2.55×10^0	3.92×10^0	2.64×10^0
ME	3.44×10^{-2}	2.38×10^{-2}	3.65×10^{-2}	2.46×10^{-2}
TE	1.78×10^{-1}	1.22×10^{-1}	1.89×10^{-1}	1.27×10^{-1}
FX	2.61×10^0	1.81×10^0	2.77×10^0	1.86×10^0
WD	2.54×10^{-2}	1.74×10^{-2}	2.70×10^{-2}	1.80×10^{-2}
HT	1.54×10^1	1.07×10^1	1.64×10^1	1.10×10^1
LD	6.44×10^{-3}	4.44×10^{-3}	6.83×10^{-3}	4.59×10^{-3}

S1-L1: solution 1, lighting 1, S1-L2: solution 1, lighting 2, S2-L1: solution 2, lighting 1, S2-L2: solution 2, lighting 2, CCH: Climate change, TA: Terrestrial acidification, FE: Freshwater eutrophication, ME: Marine eutrophication, TE: Terrestrial ecotoxicity, FX: Freshwater ecotoxicity, WD: Water depletion, HT: Human toxicity, LD: Land use, ReCiPe 2016 Midpoint (H) V1.09/World (2010) method, normalization model, results are expressed in pt (points).

Table A5. Sensitivity analysis of the electricity mix composition on the total environmental impact per functional unit (1 kg of dried hemp inflorescence).

Treatment	Baseline (CZ 2022)	Lignite	Nuclear	Renewables
S1-L1	4.17×10^1	8.87×10^1	2.96×10^1	3.46×10^1
S1-L2	2.88×10^1	6.13×10^1	2.04×10^1	2.39×10^1
S2-L1	4.43×10^1	9.42×10^1	3.14×10^1	3.68×10^1
S2-L2	2.97×10^1	6.33×10^1	2.10×10^1	2.47×10^1

S1-L1: solution 1, lighting 1, S1-L2: solution 1, lighting 2, S2-L1: solution 2, lighting 1, S2-L2: solution 2, lighting 2, the “Baseline (CZ 2022)” scenario represents the actual Czech electricity mix in 2022, the “Lignite” scenario assumes a 25% increase in the share of lignite-based electricity with a corresponding reduction in nuclear power, the “Nuclear” scenario assumes a 25% increase in nuclear share with reduced lignite contribution, the “Renewables” scenario models a 25% increase in renewable energy, with proportional contributions recalculated among hydropower, pumped storage, biomass, biogas, wind, solar, and geothermal sources, while reducing lignite proportion accordingly, ReCiPe 2016 Endpoint (H) V1.11/World (2010) H/A method, Single score model, results are expressed in pt (points).

References

- Jami, T.; Rawtani, D.; Agrawal, Y.K. Hemp Concrete: Carbon-Negative Construction. *Emerg. Mater. Res.* **2016**, *5*, 240–247. [CrossRef]
- Crini, G.; Lichtfouse, E.; Chanet, G.; Morin-Crini, N. Applications of Hemp in Textiles, Paper Industry, Insulation and Building Materials, Horticulture, Animal Nutrition, Food and Beverages, Nutraceuticals, Cosmetics and Hygiene, Medicine, Agrochemistry, Energy Production and Environment: A Review. *Environ. Chem. Lett.* **2020**, *18*, 1451–1476. [CrossRef]

3. Yano, H.; Fu, W. Hemp: A Sustainable Plant with High Industrial Value in Food Processing. *Foods* **2023**, *12*, 651. [CrossRef] [PubMed]
4. Zimniewska, M. Hemp Fibre Properties and Processing Target Textile: A Review. *Materials* **2022**, *15*, 1901. [CrossRef]
5. European Commission Hemp—Crop Production and Plant-Based Products 2025. Available online: https://agriculture.ec.europa.eu/farming/crop-productions-and-plant-based-products/hemp_en (accessed on 16 July 2025).
6. Fischer, B.; Hall, W. Germany's Evolving Framework for Cannabis Legalization and Regulation: Select Comments Based on Science and Policy Experiences for Public Health. *Lancet Reg. Health Eur.* **2022**, *23*, 100546. [CrossRef]
7. Mirpoor, S.F.; Ibáñez-Ibáñez, P.F.; Giosafatto, C.V.L.; Del Castillo-Santaella, T.; Rodríguez-Valverde, M.A.; Maldonado-Valderrama, J. Surface Activity of Protein Extracts from Seed Oil By-Products and Wettability of Developed Bioplastics. *Food Hydrocoll.* **2023**, *145*, 109091. [CrossRef]
8. Rheay, H.T.; Omondi, E.C.; Brewer, C.E. Potential of Hemp (*Cannabis sativa* L.) for Paired Phytoremediation and Bioenergy Production. *GCB Bioenergy* **2021**, *13*, 525–536. [CrossRef]
9. Milan, J.; Michalska, A.; Jurowski, K. The Comprehensive Review about Elements Accumulation in Industrial Hemp (*Cannabis sativa* L.). *Food Chem. Toxicol.* **2024**, *184*, 114344. [CrossRef]
10. Padmavathiamma, P.K.; Li, L.Y. Phytoremediation Technology: Hyper-Accumulation Metals in Plants. *Water Air Soil Pollut.* **2007**, *184*, 105–126. [CrossRef]
11. Burczyk, H.; Grabowska, L.; Kołodziej, J.; Strybe, M. Industrial Hemp as a Raw Material for Energy Production. *J. Ind. Hemp* **2008**, *13*, 37–48. [CrossRef]
12. Amaducci, S.; Scordia, D.; Liu, F.H.; Zhang, Q.; Guo, H.; Testa, G.; Cosentino, S.L. Key Cultivation Techniques for Hemp in Europe and China. *Ind. Crops Prod.* **2015**, *68*, 2–16. [CrossRef]
13. Jin, D.; Jin, S.; Chen, J. Cannabis Indoor Growing Conditions, Management Practices, and Post-Harvest Treatment: A Review. *Am. J. Plant Sci.* **2019**, *10*, 925–946. [CrossRef]
14. Ampim, P.A.Y.; Obeng, E.; Olvera-Gonzalez, E. Indoor Vegetable Production: An Alternative Approach to Increasing Cultivation. *Plants* **2022**, *11*, 2843. [CrossRef] [PubMed]
15. Choi, H.G.; Moon, B.Y.; Kang, N.J. Effects of LED Light on the Production of Strawberry during Cultivation in a Plastic Greenhouse and in a Growth Chamber. *Sci. Hortic.* **2015**, *189*, 22–31. [CrossRef]
16. Engler, N.; Krarti, M. Review of Energy Efficiency in Controlled Environment Agriculture. *Renew. Sustain. Energy Rev.* **2021**, *141*, 110786. [CrossRef]
17. Moosavi-Nezhad, M.; Salehi, R.; Aliniaieifard, S.; Winans, K.S.; Nabavi-Pelesaraei, A. An Analysis of Energy Use and Economic and Environmental Impacts in Conventional Tunnel and LED-Equipped Vertical Systems in Healing and Acclimatization of Grafted Watermelon Seedlings. *J. Clean. Prod.* **2022**, *361*, 132069. [CrossRef]
18. Pinstrup-Andersen, P. Is It Time to Take Vertical Indoor Farming Seriously? *Glob. Food Secur.* **2018**, *17*, 233–235. [CrossRef]
19. Llewellyn, D.; Golem, S.; Foley, E.; Dinka, S.; Jones, A.M.P.; Zheng, Y. Indoor Grown Cannabis Yield Increased Proportionally with Light Intensity, but Ultraviolet Radiation Did Not Affect Yield or Cannabinoid Content. *Front. Plant Sci.* **2022**, *13*, 974018. [CrossRef]
20. Pedrazzi, S.; Santunione, G.; Mustone, M.; Cannazza, G.; Citti, C.; Francia, E.; Allesina, G. Techno-Economic Study of a Small Scale Gasifier Applied to an Indoor Hemp Farm: From Energy Savings to Biochar Effects on Productivity. *Energy Convers. Manag.* **2021**, *228*, 113645. [CrossRef]
21. Ely, K.; Podder, S.; Reiss, M.; Fike, J. Industrial Hemp as a Crop for a Sustainable Agriculture. In *Cannabis/Hemp for Sustainable Agriculture and Materials*; Agrawal, D.C., Kumar, R., Dhanasekaran, M., Eds.; Springer: Singapore, 2022; pp. 1–28, ISBN 978-981-16-8777-8.
22. Bernas, J.; Bernasová, T.; Nedbal, V.; Neugschwandtner, R.W. Agricultural LCA for Food Oil of Winter Rapeseed, Sunflower, and Hemp, Based on Czech Standard Cultivation Practices. *Agronomy* **2021**, *11*, 2301. [CrossRef]
23. Ruviaro, C.F.; Gianezini, M.; Brandão, F.S.; Winck, C.A.; Dewes, H. Life Cycle Assessment in Brazilian Agriculture Facing Worldwide Trends. *J. Clean. Prod.* **2012**, *28*, 9–24. [CrossRef]
24. Desaulniers Brousseau, V.; Goldstein, B.P.; Lachapelle, M.; Tazi, I.; Lefsrud, M. Greener Green: The Environmental Impacts of the Canadian Cannabis Industry. *Resour. Conserv. Recycl.* **2024**, *208*, 107737. [CrossRef]
25. Mills, E. Energy-Intensive Indoor Cultivation Drives the Cannabis Industry's Expanding Carbon Footprint. *One Earth* **2025**, *8*, 101179. [CrossRef]
26. Mills, E. The Carbon Footprint of Indoor Cannabis Production. *Energy Policy* **2012**, *46*, 58–67. [CrossRef]
27. Summers, H.M.; Sproul, E.; Quinn, J.C. The Greenhouse Gas Emissions of Indoor Cannabis Production in the United States. *Nat. Sustain.* **2021**, *4*, 644–650. [CrossRef]
28. Ahamed, M.S.; Sultan, M.; Monfet, D.; Rahman, M.S.; Zhang, Y.; Zahid, A.; Bilal, M.; Ahsan, T.M.A.; Achour, Y. A Critical Review on Efficient Thermal Environment Controls in Indoor Vertical Farming. *J. Clean. Prod.* **2023**, *425*, 138923. [CrossRef]

29. Dillis, C.; Butsic, V.; Georgakakos, P.; Portugal, E.; Grantham, T.E. Water Demands of Permitted and Unpermitted Cannabis Cultivation in Northern California. *Environ. Res. Commun.* **2023**, *5*, 025005. [\[CrossRef\]](#)
30. ISO 14040; Environmental Management–Life Cycle Assessment–Principles and Framework. International Organization for Standardization: Geneva, Switzerland, 2006.
31. ISO 14044; Environmental Management–Life Cycle Assessment–Requirements and Guidelines. International Organization for Standardization: Geneva, Switzerland, 2006.
32. Steubing, B.; Wernet, G.; Reinhard, J.; Bauer, C.; Moreno-Ruiz, E. The Ecoinvent Database Version 3 (Part II): Analyzing LCA Results and Comparison to Version 2. *Int. J. Life Cycle Assess.* **2016**, *21*, 1269–1281. [\[CrossRef\]](#)
33. Konvalina, P.; Neumann, J.; Hoang, T.N.; Bernas, J.; Trojan, V.; Kuchař, M.; Lošák, T.; Varga, L. Effect of Light Intensity and Two Different Nutrient Solutions on the Yield of Flowers and Cannabinoids in *Cannabis sativa* L. Grown in Controlled Environment. *Agronomy* **2024**, *14*, 2960. [\[CrossRef\]](#)
34. European Commission; Joint Research Centre; Institute for Environment and Sustainability. *International Reference Life Cycle Data System (ILCD) Handbook: General Guide for Life Cycle Assessment: Detailed Guidance*; Publications Office: Luxembourg, 2010.
35. Koch, P.; Salou, T. AGRIBALYSE®: Methodology, version 1.3; ADEME: Angers, France, 2013.
36. Tyszler, H.B.M.; van der Voet, E.; van Paassen, M.; Braconi, N.; Kuling, L.; Durlinger, B.; Gual, P. *Agri-Footprint 6: Methodology Report*; Parts 1–2; Blonk Sustainability: Gouda, The Netherlands, 2022.
37. Wernet, G.; Bauer, C.; Steubing, B.; Reinhard, J.; Moreno-Ruiz, E.; Weidema, B. The Ecoinvent Database Version 3 (Part I): Overview and Methodology. *Int. J. Life Cycle Assess.* **2016**, *21*, 1218–1230. [\[CrossRef\]](#)
38. Nemecek, T.; Bengoa, X.; Lansche, J.; Roesch, A.; Faist-Emmenegger, M.; Rossi, V.; Humbert, S. *Methodological Guidelines for the Life Cycle Inventory of Agricultural Products*; Version 3.5; World Food LCA Database (WFLDB); Quantis and Agroscope: Lausanne/Zurich, Switzerland, 2019.
39. Ministry of Industry and Trade of the Czech Republic. Renewable Energy Sources 2022–2023. Available online: https://mpo.gov.cz/assets/cz/energetika/statistika/obnovitelne-zdroje-energie/2024/12/Obnovitelne-zdroje-energie-2022-2023_web.pdf (accessed on 10 July 2025).
40. Oenergetice.cz. EnergoStat. Available online: <https://oenergetice.cz/energostat> (accessed on 10 July 2025).
41. Dijkman, T.J.; Basset-Mens, C.; Antón, A.; Núñez, M. LCA of Food and Agriculture. In *Life Cycle Assessment*; Hauschild, M.Z., Rosenbaum, R.K., Olsen, S.I., Eds.; Springer International Publishing: Cham, Switzerland, 2018; pp. 723–754, ISBN 978-3-319-56474-6.
42. Bernas, J.; Bernasová, T.; Gerstberger, P.; Moudrý, J.; Konvalina, P.; Moudrý, J. Cup Plant, an Alternative to Conventional Silage from a LCA Perspective. *Int. J. Life Cycle Assess.* **2021**, *26*, 311–326. [\[CrossRef\]](#)
43. Hauschild, M.Z.; Rosenbaum, R.K.; Olsen, S.I. (Eds.) *Life Cycle Assessment: Theory and Practice*; Springer International Publishing: Cham, Switzerland, 2018; ISBN 978-3-319-56474-6.
44. Hayashi, K.; Gaillard, G.; Nemecek, T. Life Cycle Assessment of Agricultural Production Systems: Current Issues and Future Perspectives. In *Good Agricultural Practice (GAP) in Asia and Oceania*; Food and Fertilizer Technology Center: Taipei, Taiwan, 2005.
45. Pérez, R.; Argüelles, F.; Laca, A.; Laca, A. Evidencing the Importance of the Functional Unit in Comparative Life Cycle Assessment of Organic Berry Crops. *Environ. Sci. Pollut. Res.* **2024**, *31*, 22055–22072. [\[CrossRef\]](#)
46. Meffo Kemda, M.; Marchi, M.; Neri, E.; Marchettini, N.; Niccolucci, V. Environmental Impact Assessment of Hemp Cultivation and Its Seed-Based Food Products. *Front. Environ. Sci.* **2024**, *12*, 1342330. [\[CrossRef\]](#)
47. Reichel, P.; Munz, S.; Hartung, J.; Präger, A.; Kotiranta, S.; Burgel, L.; Graeff-Hönninger, S. Impact of Three Different Light Spectra on the Yield, Morphology and Growth Trajectory of Three Different *Cannabis sativa* L. Strains. *Plants* **2021**, *10*, 1866. [\[CrossRef\]](#) [\[PubMed\]](#)
48. Zheng, Z.; Fiddes, K.; Yang, L. A Narrative Review on Environmental Impacts of Cannabis Cultivation. *J. Cannabis Res.* **2021**, *3*, 35. [\[CrossRef\]](#) [\[PubMed\]](#)
49. Holzapfel, P.; Bach, V.; Finkbeiner, M. Electricity Accounting in Life Cycle Assessment: The Challenge of Double Counting. *Int. J. Life Cycle Assess.* **2023**, *28*, 771–787. [\[CrossRef\]](#)
50. Šerešová, M.; Štefanica, J.; Vitvarová, M.; Zakuciová, K.; Wolf, P.; Kočí, V. Life Cycle Performance of Various Energy Sources Used in the Czech Republic. *Energies* **2020**, *13*, 5833. [\[CrossRef\]](#)
51. Barros, M.V.; Salvador, R.; Piekarski, C.M.; De Francisco, A.C.; Freire, F.M.C.S. Correction to: Life Cycle Assessment of Electricity Generation: A Review of the Characteristics of Existing Literature. *Int. J. Life Cycle Assess.* **2020**, *25*, 55–56. [\[CrossRef\]](#)
52. Bauer, S.; Olson, J.; Cockrill, A.; Van Hattem, M.; Miller, L.; Tauzer, M.; Leppig, G. Impacts of Surface Water Diversions for Marijuana Cultivation on Aquatic Habitat in Four Northwestern California Watersheds. *PLoS ONE* **2015**, *10*, e0120016. [\[CrossRef\]](#)
53. Butsic, V.; Brenner, J.C. Cannabis (*Cannabis sativa* or *C. Indica*) Agriculture and the Environment: A Systematic, Spatially-Explicit Survey and Potential Impacts. *Environ. Res. Lett.* **2016**, *11*, 044023. [\[CrossRef\]](#)
54. Hassanien, R.H.E.; Li, M.; Dong Lin, W. Advanced Applications of Solar Energy in Agricultural Greenhouses. *Renew. Sustain. Energy Rev.* **2016**, *54*, 989–1001. [\[CrossRef\]](#)

55. Liantas, G.; Chatzigeorgiou, I.; Ravani, M.; Koukounaras, A.; Ntinis, G.K. Energy Use Efficiency and Carbon Footprint of Greenhouse Hydroponic Cultivation Using Public Grid and PVs as Energy Providers. *Sustainability* **2023**, *15*, 1024. [[CrossRef](#)]
56. Parkes, M.G.; Azevedo, D.L.; Cavallo, A.C.; Domingos, T.; Teixeira, R.F.M. Life Cycle Assessment of Microgreen Production: Effects of Indoor Vertical Farm Management on Yield and Environmental Performance. *Sci. Rep.* **2023**, *13*, 11324. [[CrossRef](#)] [[PubMed](#)]
57. Poore, J.; Nemecek, T. Reducing Food's Environmental Impacts through Producers and Consumers. *Science* **2018**, *360*, 987–992. [[CrossRef](#)]
58. Jwaideh, M.A.A.; Sutanudjaja, E.H.; Dalin, C. Global Impacts of Nitrogen and Phosphorus Fertiliser Use for Major Crops on Aquatic Biodiversity. *Int. J. Life Cycle Assess.* **2022**, *27*, 1058–1080. [[CrossRef](#)]
59. Bartzas, G.; Zaharaki, D.; Komnitsas, K. Life Cycle Assessment of Open Field and Greenhouse Cultivation of Lettuce and Barley. *Inf. Process. Agric.* **2015**, *2*, 191–207. [[CrossRef](#)]

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