

Article

A Comparative LCA of Aeroponic, Hydroponic, and Soil Cultivations of Bioactive Substance Producing Plants

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Abstract: Sustainable agriculture is currently trendy. It is supported not only for the urban environment but also as an innovation of conventional practices in order to increase the efficiency and quality of agricultural production. This study presents the results achieved within selected soil-less (hydroponic and aeroponic) systems. Then, it compares them, using the tool of comparative life cycle assessment (LCA), with the results of soil cultivation. The attention is directed towards biomass production and the content of bioactive substances, which can compensate for higher operating costs of soil-less cultivation systems. *Coffea arabica* has shown a significant increase of caffeine and theobromine contents, both in leaves and roots, as well as higher biomass yield during the aeroponic cultivation. On the contrary, *Senecio bicolor* evinced the results of a considerably increased growth in the hydroponic system, with no higher contents of alkaloid or flavonoids, except for the rutin concentration. The LCA results of the compared soil and soil-less systems showed that the consumption of fertilizers, diesel, and water in soil systems and of conventional electricity in aeroponics and hydroponics contributed mostly to their environmental burden. The major environmental impact categories are terrestrial ecotoxicity, human non-carcinogenic toxicity, and global warming. Therefore, in order to make the soil-less cultivation systems sustainable, these environmental aspects need to be considered deeply.

Keywords: soil-less; agriculture; life cycle assessment; *Coffea arabica*; *Senecio bicolor*; caffeine; rutin



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1. Introduction

Agricultural production systems worldwide have been facing unprecedented challenges: from an increasing demand related to growing population, rising hunger and malnutrition, to adverse climate change effects, such as droughts or floods, overexploitation of natural resources, loss of biodiversity in arable land areas, and food loss and waste. These challenges can undermine the world's capacity and ability to meet its needs now and in the future. Sustainable food and agriculture (SFA) processes are favourable not only for urban environments but also for conventional growing practices, as they increase the yield and quality of agricultural productions, such as nutrients content [1]. Furthermore, sustainable agriculture should go beyond its economic aspects, which means paying attention also to environmental and social impacts. It should not only regard increasing yields, but also provide new job opportunities for women, men, and youth in crop. Moreover, it should carefully consider livestock and other related production as well as in research and innovation and after-harvest activities such as storing, processing, and marketing [2]. Long-term impacts of human activities on arable land and rural landscape are also important. Around a quarter of arable land has been declared unproductive, infertile, and unsuitable to perform agricultural activities. What stands behind these issues are inadequate soil management, soil degradation, erosion and compaction, fast regional climate changes,

rapid urbanization, industrialization, fewer recovery chances of natural fertility, continuous cropping, frequent drought, less water management, water pollution, and the decrease in groundwater [3]. Under such circumstances, researchers suggested the solution of implementing currently accessible technologies under a controlled environment. Concerning this, the soil-less system is one of them [4]. Butler and Oebker [5] already reported in 1962 that the soil-less system is the method of plant cultivation without the use of soil within substrate culture. The soil-less system uses a minimum input but facilitates a multiple-plant harvesting with a maximum output. The concept of the soil-less culture seeks to offer an innovative solution to ensure the environmental and soil-less economic sustainability of food supplies with high nutritional quality [4]. Soil-less systems are preferably used to reduce soil pests and diseases that often affect monoculture. A further advantage of these systems is the purity of production associated with lower requirements for mechanization and service in harvesting, which can lower the impacts on the environment. At the same time, these systems make it possible to increase the production of nutrients or bioactive compounds in grown crops [4,6]. Bioactive compounds in plants are the compounds produced by plants having pharmacological or toxicological effects on man and animals, while nutrients elicit pharmacological or toxicological effects when ingested at high dosages [7]. Bioactive compounds, even when represented in small quantities, provide health benefits beyond the basic nutritional value [8]. Epidemiological studies have indicated that an increased consumption of foods or supplements rich in bioactive compounds with antioxidant activity and phenolic compounds, such as flavonoids and carotenoids, has a positive effect on human health and could diminish the risk of several civilisation diseases [9,10].

The definition soil-less encompasses all the systems that provide plant management under soil-less conditions in which the supply of water and minerals is carried out by a nutrient solution, with or without a growing medium (e.g., rockwool, peat, perlite, pumice, coconut fibre, etc.) [11]. Soil-less cultivation systems thus can be divided into: (i) systems in a liquid medium, which do not have other media for the support of plant roots; and (ii) systems in a solid medium, using a substrate to support the plants. In addition, the soil-less substrate cultures are classified into: (i) open systems (when the nutrient solution that drains from the roots is not reused); and (ii) closed systems (when the surplus nutrient solution is collected, corrected, and put back into the system) [12]. These systems fulfil the current needs of the circular economy (CE) concept.

Hydroponic and aeroponic systems can be proposed as two types of soil-less cultivation. Hydroponics are well-known systems, which include partial and/or complete plant root system immersion in the nutrient solution and drip irrigation involving a nutrient solution application to rhizosphere [4,13,14]. Hydroponic irrigation methods include: (i) drip irrigation, (ii) deep water culture, (iii) nutrient film technique, and (iv) flood and drain. In drip irrigation systems, a nutrient solution is fed into a variable growing medium that supports the root system. The deep water culture submerges roots in the nutrient solution, with plants supported by a membrane preventing aerial tissue immersion. The nutrient film method exposes the bottom of the root bed to a flowing nutrient solution whilst the top of the root bed remains exposed to air. Flood and drain systems immerse the root system with a nutrient solution for a period of time. Subsequently, this is drained and collected into a reservoir to aerate the root bed [15].

Aeroponics is, contrary to hydroponics, related to systems that expose plant roots to nutrient-containing aerosol droplets [15], which can be ensembled to solid particles or liquid droplets suspended in the gas phase [16]. The size of aerosol droplets depends on the used pressure level and inkjet size. The high-pressure atomisation method typically generated aerosol droplets of 10–100 μm [4,15]. Thus, (i) high pressure atomization and (ii) the aero-hydro system belong among aeroponic methods. The high pressured aeroponics atomizes the nutrient solution, which deposit on the root surface. The aero-hydro systems atomise the nutrient solution whilst exposing the lower root bed to recirculated nutrient solution [15]. Solution pumping used in both systems not only helps the nutrient solution circulation, but also supports the increased oxygen level in the root zone.

On the other hand, the soil-less systems are, in general, more sophisticated and can be economically unfavorable in terms of higher operating costs (especially due to electricity used for pumps and lighting). Depending on the energy source and yield of the plant species grown, they can be also environmentally questionable, as these systems can show greater negative impacts on the environment than conventional land planting. Thus, to operate the soil-less system sustainably, these aspects have to be considered.

Life cycle assessment (LCA) is a systems analysis methodology for the assessment of their environmental impacts covered by the ISO standards 14040:2006 and 14044:2006 [17,18]. It is a powerful method to understand the environmental impacts and flows of various systems [19]. A comparative LCA is often performed to evaluate and determine a better process, product, or system out of several compared. Concerning such LCA studies, it is highly important to apply coherent rules (e.g., system boundaries, source, and quality of metadata), as these studies can easily be swayed in favor of one product or process over another [20].

This paper presents the results achieved during the model aeroponic, hydroponic, and soil cultivations of bioactive substance producing plants such as *Cannabis sativa* (technical), *Coffea arabica*, and *Senecio bicolor*. Furthermore, it also shows a comparative assessment of these systems and provides information on major environmental impacts of operations of these cultivation systems. Finally, it highlights important factors of the soil-less systems' sustainability and economic feasibility.

2. Experimental

The soil-less systems tested in this study were: (i) the deep water culture (hydroponics) and (ii) the aero-hydro system (aeroponics), as given by Eldridge et al. (2020). For both types of cultivations, the RainForest 2 (GHE) system RF2, height 43 cm × diameter 46 cm hexagonal, max. 65 L, 12 V–26.5 W, 18 pot's, 7.6 cm diameter (Terra Aquatica, Fleurance, France) was used. The pots were filled by Hydroton (ceramic clay). Prior to their use, they were thoroughly washed by tap water and supplied together with the cultivation system units. A mixture of FloraGrow (N-P-K) and FloraMicro (N-Ca- trace minerals) (both Terra Aquatica, Fleurance, France) in concentrations of 0.5–1.8 and 0.5–1.2 mL·L^{−1}, depending on a growth phase, was used as a nutrient solution. Electric conductivity of the nutrient solution was kept in the range of 0.8–1.5 mS·cm^{−1}; pH at 6.5–8 (measured by the Multi 340i instrument; WTW, Xylem Analytics, Weilheim, Germany). Fertilizers were added once a week, depending on the water level in the cultivation vessel. During hydroponic cultivations, the water height was kept on its maximum operational volume of 50 L, which means the height of 32–33 cm measured from the bottom of the cultivation system; for aeroponic cultivations, volume was lowered to a minimal sustained operation volume of 20 L, corresponding to height of 13–14 cm (Figure 1). For each test, duplicates of cultivation systems were prepared (i.e., 36 pots in 2 cultivation vessels for each plant species).

The soil system cultivation used for the comparison in this study was done in ordinarily filled flowerpots. Round plastic pots of diameter 15 cm, made of polypropylene, 1.55 L (Arca, Bergamo, Italy), and the Forestina standard propagation substrate (Forestina, Mnichov, Czech Republic) were used. Nutrients (the same as for hydroponics/aeroponics) were added once a week starting from the seventh week of planting in the amount of 50 mL per pot. For each tested plant species, 16 control soil pots were prepared.

The following plant species were tested: (i) *Cannabis sativa* (technical hemp), (ii) *Coffea arabica*, and (iii) *Senecio bicolor*. Technical cannabis FEDORA 17 (Cannapio, Kettering, UK) was planted as seeds. Arabian coffee (Hornbach, Prague, Czech Republic) and *S. bicolor* (CULS Prague, Prague-Suchdol, Czech Republic) were planted as seedlings.

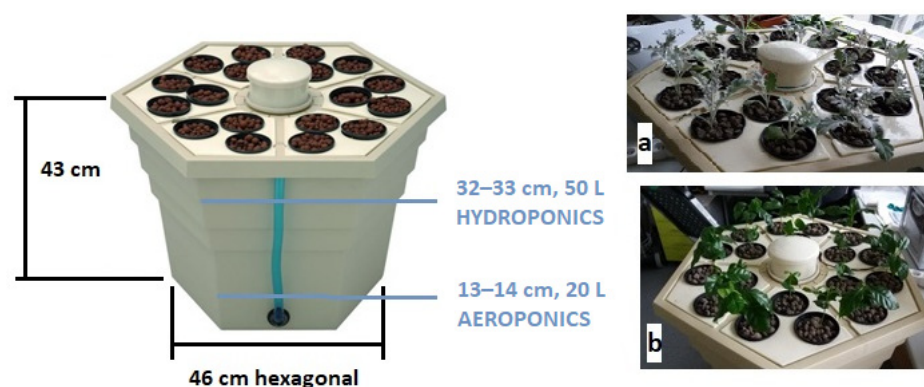


Figure 1. The used 18 pots' cultivation system: (a) hydroponics (deep water, 50 L water/nutrient, *S. bicolor*); (b) aeroponic (aero-hydro, 20 L water/nutrient, *C. arabica*).

All cultivation systems (one cultivation vessel or 8 soil pots) were lighted by a pair of TNeon TCL lamps, 55 W, 6500 K, luminous flux 7600 lm (Secret Jardin, Manage, Belgium) with a lightening period of 18 h light/6 h dark. The growing period varied from 6 months (*C. arabica*, *S. bicolor*) to 7 months (*C. sativa*, due to the need of extra time for seeds germination).

Analytical parts were performed at the end by the following procedures: (i) chlorophyll *a* + *b* and carotenoids according to Lichtenthaler [21] in ethanol (CAS: 64-17-5, for UV, 96%, Penta Chemicals, Prague, Czech Republic) extracted by a UV spectrophotometry, performed for a yield comparison with and without adding magnesium oxide (CAS: 1309-48-4, ACS reagent, 97%, Sigma-Aldrich, Prague, Czech Republic); (ii) total C/N analysis on the Primacs TOC/TN instrument (Skalar Analytical B.V., Breda, The Netherlands); (iii) alkaloids (caffeine, theobromine and theophylline) by a high-performance liquid chromatography coupled with a photo diode array detector (HPLC-PDA) at the ALS Czech Republic; and (iv) flavonoids (rutin, quercetin, naringenin, apigenin, kaempferol, chrysin, and galangin) by the same method (HPLC), but coupled with a coulometric array detector at the above-mentioned commercial laboratory. The biomass content was measured by weighing on the EMB 200-3 scale (Kern & Sohn, Balingen, Germany), both wet and dry. The dry biomass content (dry matter, DM) was calculated according to the EN 15934:2012 (E) [22] after the wet biomass was dried to a constant weight at 60 °C (depending on the dried plant biomass between 48–72 h).

3. Process Cultivation Results

Each of the plant species (i.e., technical *C. sativa*, *C. arabica* and *S. bicolor*) showed a different response to the tested cultivation methods.

Technical cannabis (*C. sativa*) demonstrated to be unsuitable for long-term cultivation, both in aeroponics and hydroponics, as plants suffered from broken and/or rotted stems. Similarly, their root systems decayed during the prolonged cultivation in both hydroponics and aeroponics. However, these systems, especially aeroponics, proved to be an appropriate method for germination and the hemp seedling preparation from untreated seeds (up to 0.5 m). The achieved germination rate was 98–99%. Such prepared hemp seedlings were also in an excellent growth state. When they were subsequently planted in soil pots, their blossom state came faster (by about one month) compared to the control plants (i.e., plants that germinated directly to soil pots).

Due to the worsening production of biomass and unachieved blossom and seeds in the tested hydroponic and aeroponic systems, the contents of chlorophyll *a* + *b*, carotenoids and total C/N were chosen for comparison (Table 1).

Table 1. Selected parameters of *C. sativa* (technical hemp)—soil vs. hydroponic cultivation.

Parameter ($\mu\text{g}\cdot\text{kg}^{-1}$)	Soil Cultivation				Hydroponic Cultivation			
	Leaf	SD	Stem	SD	Leaf	SD	Stem	SD
Chlorophyll <i>a</i>	244.310	± 28.784	97.962	± 13.803	313.379	± 23.307	109.755	± 7.242
Chlorophyll <i>b</i>	199.440	± 11.791	148.663	± 10.060	220.182	± 8.438	145.156	± 3.562
Carotenoids	30.652	± 7.312	2.802	± 0.348	45.015	± 3.974	2.189	± 0.955
Total C	40.59	± 0.23	39.92	± 0.09	39.80	± 0.57	41.56	± 1.22
Total N	4.60	± 0.01	1.51	± 0.01	4.81	± 0.06	1.81	± 0.06

Note: SD—standard deviation.

The hydroponic cultivation of technical hemp showed a higher content of both chlorophylls and carotenoids in the leaves, while practically the same in the stems. The total C/N content was comparable in both presented cultivation systems. Although, the achieved results are not yet fully interpretable regarding the mutual relationships, it would be interesting to further investigate the interconnection between hydroponics and specific nutrients supplements (e.g., humic acids, waste humolites) on bioactive substances contents including cannabinoids [23] and, at the same time, their influence of a blossom onset rate in young technical cannabis.

Contrary to the technical hemp, *C. arabica* was confirmed to be suitable for the aeroponic cultivation, incl. the long-term cultivation. Coffee plants grown in aeroponics were in a better state, were healthier, and had gained significantly more biomass, mainly in the leaves and roots (Figure 2, Table 2).

**Figure 2.** *C. arabica* grown in the aeroponic system: (a) upper plants aged 3.5 months; (b) aeroponic roots aged 3 months; (c) whole plants aged 6 months (the cultivation end).**Table 2.** Biomass of *C. arabica* (an average for one plant)—soil vs. aeroponic cultivation.

Dry Matter (DM)	Soil Cultivation		Aeroponic Cultivation	
	Mass (g)	Portion (%)	Mass (g)	Portion (%)
Leaves	2.31	39.8	36.91	65.7
Stem	1.29	22.3	9.28	16.5
Roots	2.20	37.9	10.01	17.8
Total biomass	5.80	100.0	56.20	100.0

Note: MU—measurement uncertainty of two simultaneous determination did not exceed 10% relative change.

The aeroponic coffee plants also showed a significant increase in the alkaloid content (caffeine and theobromine) in leaves and roots, contrary to the plants grown in the soil pots (Table 3). Regarding the significant increase in the caffeine content in leaves (soil 183 vs.

aeroponics $13,300 \text{ mg} \cdot \text{kg}^{-1}$) and roots (soil 22.3 vs. aeroponics $52.8 \text{ mg} \cdot \text{kg}^{-1}$) together with the higher biomass yield (leaves production is 16-times higher and roots 4.5-times higher in aeroponics), these systems proved to be efficient for the production of specific alkaloids (mainly caffeine, but also theobromine). Moreover, the roots produced in these aeroponic systems were completely clean, ready to be processed with no need of any additional washing process.

Table 3. Selected parameters of *C. arabica* (Arabian coffee)—soil vs. aeroponic cultivation.

Parameter ($\text{mg} \cdot \text{kg}^{-1}$)	Soil Cultivation				Aeroponic Cultivation			
	Leaf	Stem	Root	MU	Leaf	Stem	Root	MU
Caffeine	183	<10	22.3	$\pm 15\%$	13,300	94.6	52.8	$\pm 15\%$
Theobromine	<10	<10	<10	–	658	18.9	<10	$\pm 15\%$
Theophylline	<10	<10	<10	–	<10	<10	<10	–

Note: MU—measurement uncertainty (bioactive compounds measured in the accredited laboratory, SD not available).

The last plant species, *S. bicolor*, is generally considered an ornamental garden plant. However, this plant is also interesting for its specific substances content, mainly the flavonoid rutin. Rutin (or rutoside) can be considered as a bioactive compound with potential biological effects, such as in reducing a post-thrombotic syndrome or chronic venous insufficiency [24]. During the performed experiments, *S. bicolor* proved to be suitable for the cultivation under both conditions— aeroponic and hydroponic. Similarly to *C. arabica*, those plants grown in soil-less systems were healthier, more vital, and gained significantly more biomass (Figure 3, Table 4) in this case, including all plant parts, even stems.



Figure 3. *S. bicolor* grown in the hydroponic system: (a) upper plants aged 4 months; (b) hydroponic roots aged 4 months; (c) whole plants aged 6 months (the cultivation end).

Table 4. Biomass of *S. bicolor* (an average for one plant)—soil vs. hydroponic cultivation.

Dry Matter (DM)	Soil Cultivation		Hydroponic Cultivation	
	Mass (g)	Portion (%)	Mass (g)	Portion (%)
Leaves	15.14	70.26	205.28	64.43
Stem	4.27	19.81	65.95	20.70
Roots	2.14	9.93	47.38	14.87
Total biomass	21.55	100.0	318.61	100.0

Note: MU—measurement uncertainty of two simultaneous determination did not exceed 10% relative change.

Unlike coffee plants, *S. bicolor* grown in the hydroponic system showed neither an increase in the contents of alkaloids (caffeine, theobromine, theophylline) and flavonoids

(rutin, quercetin, naringenin, apigenin, kaempferol, chrysin, galangin) nor in the leaves and roots, except for the rutin concentration in the leaves of hydroponically cultivated plants (Table 5).

Table 5. Selected parameters of *S. bicolor*—soil vs. hydroponic cultivation.

Parameter (mg·kg ^{−1})	Soil Cultivation *				Hydroponic Cultivation			
	Leaf	Stem	Root	MU	Leaf	Stem	Root	MU
Alkaloids	<10	<10	<10	–	<10	<10	<10	–
Rutin	<1.0	<1.0	<1.0	–	114	<1.0	<1.0	±15%
Other flavonoids	<1.0	<1.0	<1.0	–	<1.0	<1.0	<1.0	–

Note: MU—measurement uncertainty (bioactive compounds measured in the accredited laboratory, SD not available); * The same results achieved for the aeroponic cultivation.

The achieved increase in the rutin content in hydroponically produced leaves (soil < 1.0 vs. hydroponics 114 mg·kg^{−1}) together with the higher biomass yield (leaves production 13.5-times higher in hydroponics than in soil pots) makes these systems advantageous for the production of this specific flavonoid.

4. Life Cycle Analysis

The life cycle assessment (LCA) was performed in the openLCA software (Green-Delta, Berlin, Germany) using the ecoinvent database, v.3.7.1:2021 (Ecoinvent, Zürich, Switzerland) in accordance with ISO standards 14040:2006 and 14044:2006 (both as latest amended) [17,18]. The LCA paid attention to and compared only operational stages of the tested cultivation processes (i.e., hydroponics/aeroponics/soil). The APOS unit model was used following the attributional approach, in which burdens are attributed proportionally to specific processes. The ReCiPe method (midpoint, H-hierarchist) was chosen for the life cycle impact assessment (LCIA). The main objective of this method is to provide a comprehensive LCIA method that combines the two most widely used ones, i.e., the Eco-Indicator 99 [25,26] (and the CML method [26,27] in the updated version [28,29]. The ReCiPe midpoint (H) method covers all important impact categories of the observed cultivation systems, such as land use, acidification and eutrophication, climate change, human toxicity, ecotoxicity, and resources depletion.

LCA analysis was set as two comparative studies, based on the results presented in the previous chapter. The first case study compared the soil and aeroponic cultivations of *C. arabica* and was aimed at the production of caffeine. The second one looked on the soil and hydroponic cultivations of *S. bicolor* with the target bioactive compound of rutin.

4.1. Soil vs. Aeroponics–Caffeine

The inputs and outputs of both compared processes, considered during the LCA study, are given below (Table 6). They were quantified for two function units (FU)—productions of (i) 1 kg of total dried biomass (DM) and (ii) 100 g of caffeine.

As it can be seen, the factors that play a significant role in the classical soil cultivation are land use and sources consumption, while in aeroponics electricity consumption and its origin play a significant role.

The following table (Table 7) shows the LCIA results of the compared systems. Each selected impact category is displayed in the rows and the variants of two compared cultivation systems are in the columns. The impact indicator is the unit of the LCIA category as defined by the used LCIA methods.

Table 6. Input and output parameters—soil vs. aeroponic cultivation (*C. arabica*, caffeine).

INPUTS	Soil Cultivation		Aeroponic Cultivation	
Land use (m ²)	13.23	15,795.16	0.8	9.13
Water (L)	155.7	185,888.67	140	1597.40
Fertiliser (kg)	0.383	457.64	0.365	4.165
Diesel fuel (MJ)	1.225 *	1462.52 *	–	–
Electricity (kWh)	–	–	232.78 **	2656.02 **
OUTPUTS	Soil cultivation		Aeroponic cultivation	
DM biomass (kg)	1.0	1193.89	1.0	11.41
Caffeine (g)	0.08376	100	8.7635	100

Input data note: * Included soil preparation operations (i.e., stubble cultivator, medium ploughing, dragging, rolling, application of liquid fertilizers); normative consumptions of diesel fuel for incl. operations taken from Syrový and Sarec [30]; calorific value of diesel fuel used 36.9 MJ·L^{−1} [31]. ** Considered a usage of two aeroponic pumps 26.5 W; operating time 24 h per 6 months.

Table 7. LCIA results—soil vs. aeroponic cultivation (ReCiPe, midpoint, H).

Impact Category Group	Indicator (Unit)	Cultivation Type; Functional Unit			
		SOIL	AEROPONICS	SOIL	AEROPONICS
		1 kg DM Biomass		100 g Caffeine	
Fine particulate matter formation	kg PM _{2.5} eq.	5.62075×10^{-4}	1.99861×10^{-1}	6.71133×10^{-1}	2.28042
Fossil resource scarcity	kg oil eq.	6.58010×10^{-2}	4.25355×10^1	7.85666×10^1	4.85330×10^2
Freshwater ecotoxicity	kg 1,4-DCB eq.	2.70041×10^{-2}	1.58050×10^1	3.22583×10^1	1.80335×10^2
Freshwater eutrophication	kg P eq.	8.86768×10^{-5}	3.28608×10^{-1}	1.05897×10^{-1}	3.74942
Global warming	kg CO ₂ eq.	2.33729×10^{-1}	2.04232×10^2	2.79073×10^2	2.33029×10^3
Human carcinogenic toxicity	kg 1,4-DCB eq.	6.83812×10^{-2}	1.86954×10^1	8.16503×10^1	2.13314×10^2
Human non-carcinogenic toxicity	kg 1,4-DCB eq.	1.19518	2.5554×10^2	1.42749×10^3	2.91579×10^3
Land use	m ² a crop eq.	5.54277×10^{-2}	2.83821	6.62142×10^1	3.23840×10^1
Mineral resource scarcity	kg Cu eq.	3.53651×10^{-3}	1.95616×10^{-1}	4.22427	2.23198
Ozone formation, Human health	kg NO _x eq.	1.53590×10^{-3}	3.42037×10^{-1}	1.83384	3.90265
Ozone formation, Terrestrial ecosystems	kg NO _x eq.	1.56136×10^{-3}	3.43982×10^{-1}	1.86423	3.92484
Terrestrial acidification	kg SO ₂ eq.	1.08699×10^{-3}	6.02547×10^{-1}	1.29792	6.87506
Terrestrial ecotoxicity	kg 1,4-DCB eq.	1.08699×10^{-3}	6.02547×10^{-1}	1.43704×10^3	1.15145×10^3
Water consumption	m ³	1.68531×10^{-1}	5.13912	2.01219×10^2	5.86373×10^1

Note: PM—particulate matter; 1,4-DCB—1,4-dichlorobenzene.

The following graphs provide the relative indicator results of both cultivation systems. For each indicator, the maximum result is set to 100% and the results of the other variants are displayed in relation to this result. The first graph shows the results for FU—the production of 1 kg DM biomass (Figure 4), the second one for FU—the production of 100 g caffeine (Figure 5).

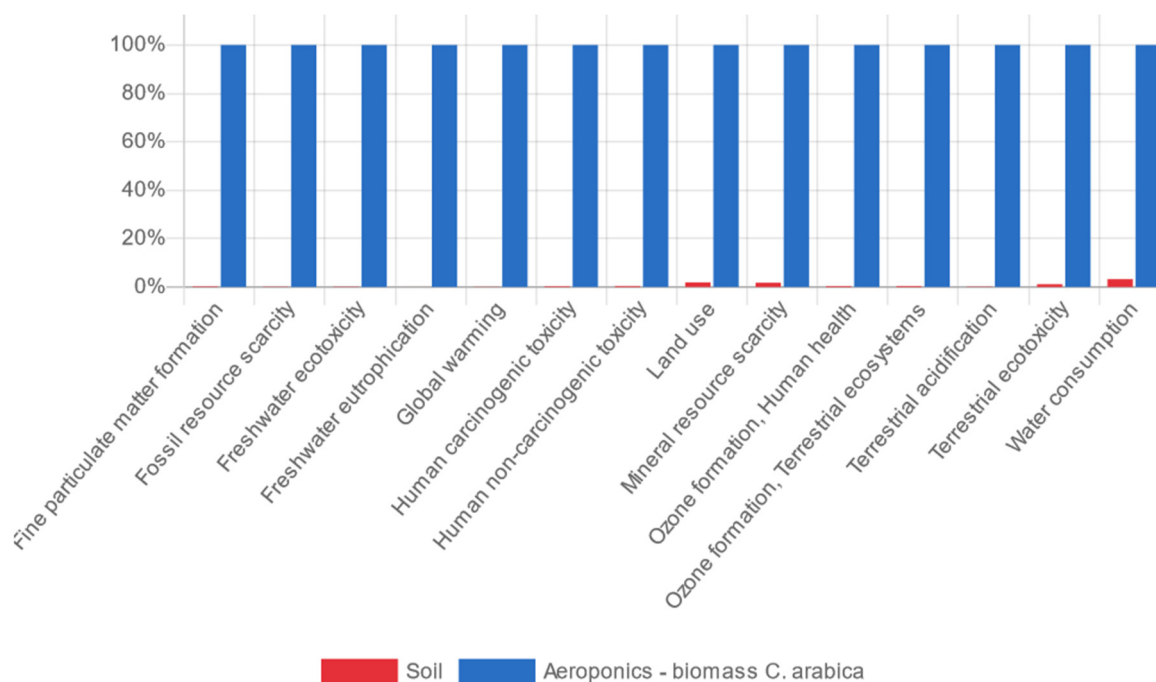


Figure 4. Relative indicator results—soil vs. aeroponic cultivation (1 kg DM biomass).

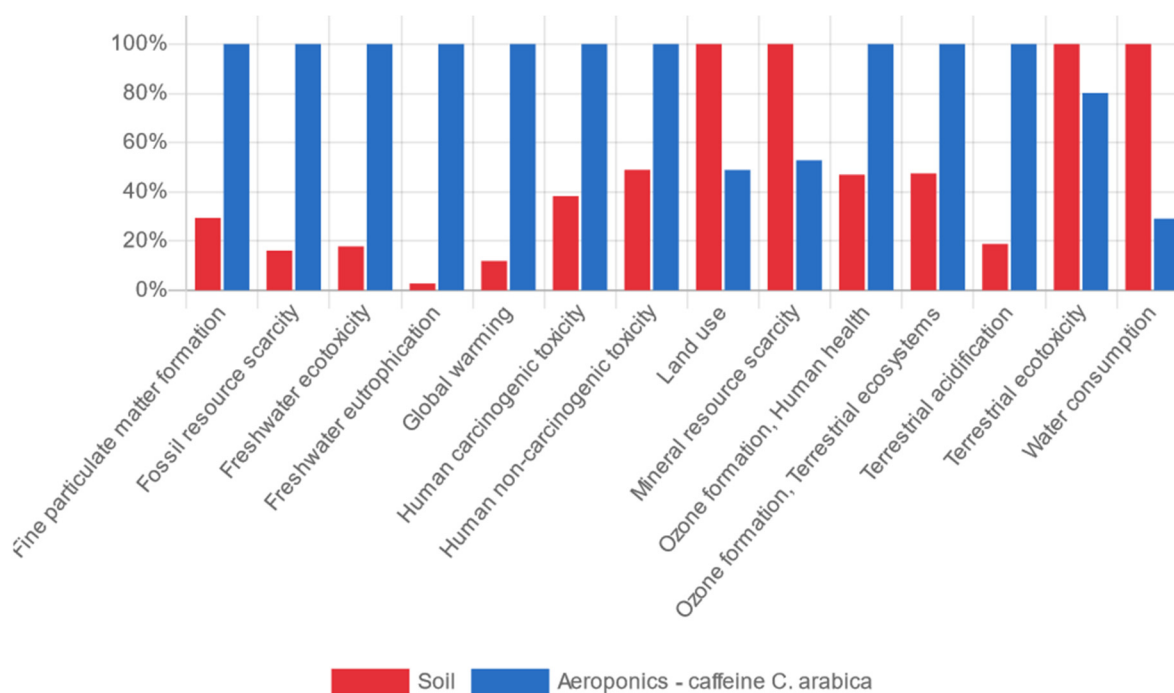


Figure 5. Relative indicator results—soil vs. aeroponic cultivation (100 g caffeine).

As obvious from the presented graphs of relative indicators, the results strongly depend on the used functional unit of LCA assessment. When comparing operating parameters of soil and aeroponic systems for the production of 1 kg of dry matter biomass, environmental indicators show significantly lower impacts in all monitored categories for the conventional soil cultivation. However, the aeroponic cultivation is becoming advantageous over the soil system, when considering the production of a bioactive substance—100 g caffeine—but only in some environmental impact categories, such as land use, mineral resource depletion, terrestrial ecotoxicity, and water consumption.

Concerning the soil cultivation, for both compared FU, the main inputs contributing to the process with the greatest environmental impacts on human non-carcinogenic toxicity, terrestrial ecotoxicity, global warming, and water consumption are related to the use of fertilizer, diesel oil, and water. Aeroponics is also connected with the major negative environmental impacts on human non-carcinogenic toxicity, terrestrial ecotoxicity and global warming, which are caused primarily by the use of conventional electricity (in the model used CZ production mix).

4.2. Soil vs. Hydroponics—Rutin

The inputs and outputs of both compared processes, considered during the LCA study are given below (Table 8). They were quantified for two function units—productions of (i) 1 kg of total DM biomass and of (ii) 1 g of rutin.

Table 8. Input and output parameters—soil vs. hydroponic cultivation (*S. bicolor*, rutin).

INPUTS	Soil Cultivation		Hydroponic Cultivation	
Land use (m ²)	3.6	3600	0.8	1.084
Water (L)	42.3	42,300	175.	237.13
Fertiliser (kg)	0.104	104.3	0.456	0.618
Diesel fuel (MJ)	0.333 *	333.	–	–
Electricity (kWh)	–	–	116.39 **	157.71 **
OUTPUTS	Soil cultivation		Hydroponic cultivation	
DM biomass (kg)	1.0	1000	1.0	1.355
Rutin (g)	0.001	1.0	0.7381	1.0

Input data note: * Included soil preparation operations (i.e., stubble cultivator, medium ploughing, dragging, rolling, application of liquid fertilizers); normative consumptions of diesel fuel for incl. operations taken from Syrový and Sarec [30]; calorific value of diesel fuel used 36.9 MJ·L^{−1} [31] (ACEA, ©2016). ** Considered a usage of one hydroponic pump 26.5 W; operating time 24 h. per 6 months.

As in the previous study, there are factors that play a significant role in the classical soil cultivation, land use and sources consumption. Regarding hydroponics, they relate primarily to electricity and water consumption.

The following table (Table 9) shows the LCIA results of the compared systems. As in the previous case, the impact categories are in the rows, the cultivation systems variants in the columns. Units of impact indicators are defined by the used LCIA methods.

The following graphs give the relative indicator results of both cultivation systems. For each indicator, the maximum result is set to 100% and the results of the other variants are displayed in relation to this result. The first graph shows the results for FU—the production of 1 kg DM biomass (Figure 6), the second one for FU—the production of 1 g rutin (Figure 7).

Corresponding to the previous study, the results of the comparison between the soil and hydroponic cultivation systems strongly depend on the LCA functional unit used. When comparing the operating parameters of the compared systems for the production of 1 kg of biomass dry matter, the monitored environmental indicators showed significantly lower impacts in all categories for the soil cultivation. The hydroponic system becomes more favourable than the soil system when the production of a bioactive substance—1 g of rutin—is considered. Using this FU, hydroponics performed better in most observed impact categories, except for fossil resource depletion, freshwater ecotoxicity and eutrophication, global warming, and terrestrial acidification.

Regarding both compared FU, in the conventional soil cultivation, the main inputs contributing to the process the greatest environmental impacts on terrestrial ecotoxicity, human non-carcinogenic toxicity, and global warming are the consumption of fertilizer, diesel oil, and water. Similarly, in the hydroponic system, the main negative environmental impacts on human non-carcinogenic toxicity, global warming, and terrestrial ecotoxicity

are caused primarily by the use of mix electricity (CZ production mix) and partially by the fertilizer consumption.

Table 9. LCIA results—soil vs. hydroponic cultivation (ReCiPe, midpoint, H).

Impact Category Group	Indicator (Unit)	Cultivation Type; Functional Unit			
		SOIL	HYDROPONICS	SOIL	HYDROPONICS
		1 kg DM Biomass		1 g Rutin	
Fine particulate matter formation	kg PM _{2.5} eq.	1.52756×10^{-4}	1.00045×10^{-1}	1.52815×10^{-1}	1.35563×10^{-1}
Fossil resource scarcity	kg oil eq.	1.78828×10^{-2}	2.12823×10^1	1.78884×10^1	2.88378×10^1
Freshwater ecotoxicity	kg 1,4-DCB eq.	7.33477×10^{-3}	7.91766	7.34925	1.07285×10^1
Freshwater eutrophication	kg P eq.	2.40914×10^{-5}	1.64350×10^{-1}	2.41124×10^{-2}	2.22696×10^{-1}
Global warming	kg CO ₂ eq.	6.35197×10^{-2}	1.02171×10^2	6.35403×10^1	1.38443×10^2
Human carcinogenic toxicity	kg 1,4-DCB eq.	1.85786×10^{-2}	9.38379	1.85869×10^1	1.27152×10^1
Human non-carcinogenic toxicity	kg 1,4-DCB eq.	3.24712×10^{-1}	1.28223×10^2	3.25172×10^2	1.73744×10^2
Land use	m ² a crop eq.	1.50552×10^{-2}	1.44870	1.50864×10^1	1.96303
Mineral resource scarcity	kg Cu eq.	9.60642×10^{-4}	9.96992×10^{-2}	9.62269×10^{-1}	1.35094×10^{-1}
Ozone formation, Human health	kg NO _x eq.	4.17455×10^{-4}	1.71201×10^{-1}	4.17561×10^{-1}	2.31979×10^{-1}
Ozone formation, Terrestrial ecosystems	kg NO _x eq.	4.24373×10^{-4}	1.72177×10^{-1}	4.24481×10^{-1}	2.33303×10^{-1}
Terrestrial acidification	kg SO ₂ eq.	2.95400×10^{-4}	3.01530×10^{-1}	2.95534×10^{-1}	4.08578×10^{-1}
Terrestrial ecotoxicity	kg 1,4-DCB eq.	3.26738×10^{-1}	5.11416×10^1	3.27404×10^2	6.92978×10^1
Water consumption	m ³	4.57844×10^{-2}	2.68338	4.57934×10^1	3.63602

Note: PM—particulate matter; 1,4-DCB—1,4-dichlorobenzene.

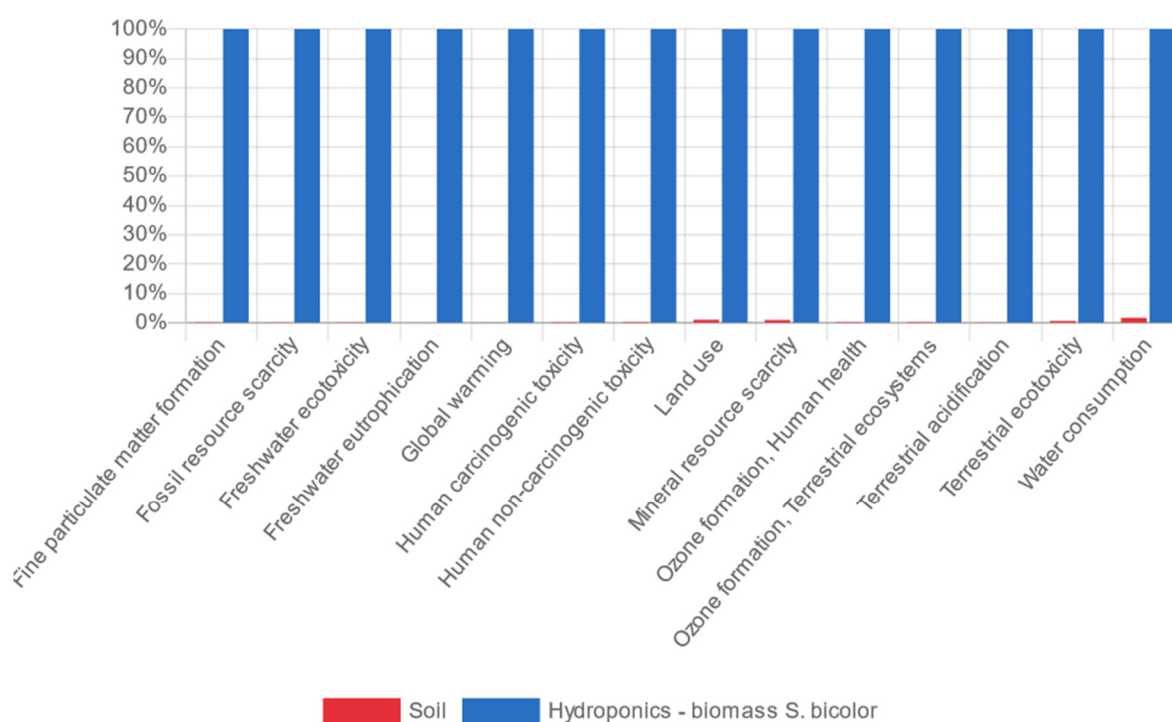


Figure 6. Relative indicator results—soil vs. hydroponic cultivation (1 kg DM biomass).

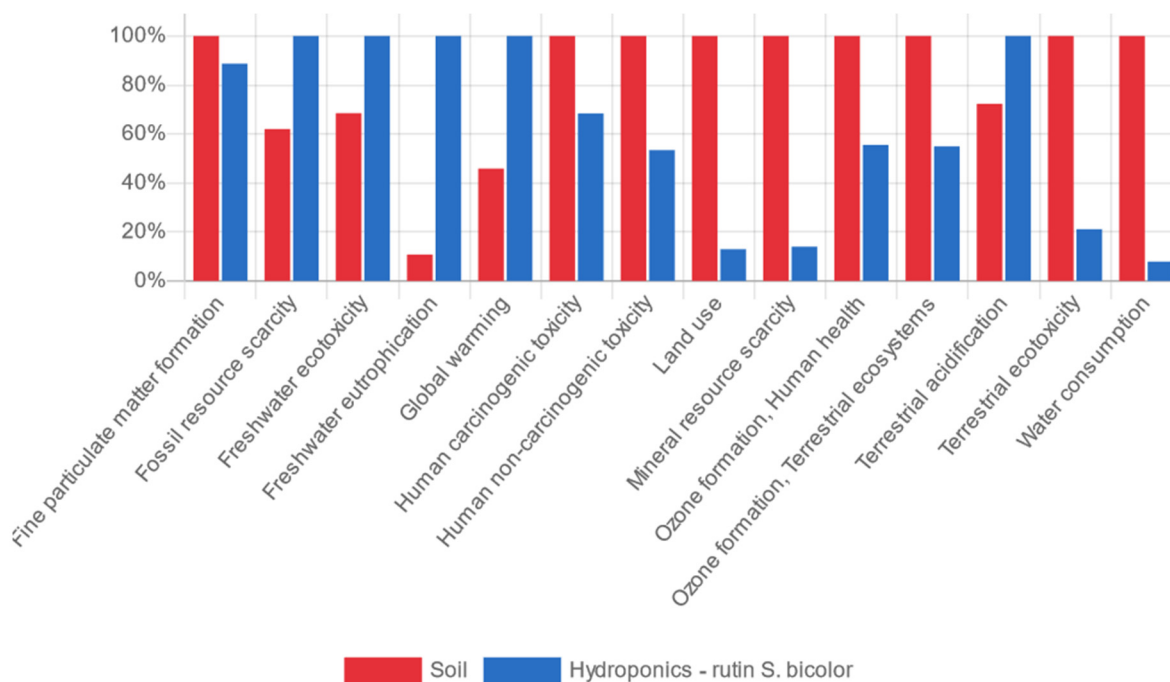


Figure 7. Relative indicator results—soil vs. hydroponic cultivation (1 g rutin).

5. Conclusions

Soil-less cultivation systems can be favourable for the production of bioactive substances. Their advantage lies primarily in higher production yield and purity of plant production, which eliminates the need for washing and other pre-treatment procedures before isolating bioactive substances. This can be beneficial for the overall costs of a cultivation process as well as for lowering its environmental impacts.

The present study shows the results achieved within hydroponic (the deep water culture), aeroponic (the aero-hydro system), and soil cultivations of the selected plant species (*C. sativa*; *C. arabica* and *S. bicolor*) that contain bioactive compounds (e.g., alkaloids and flavonoids), which can be commercially used. While the effect of the soil-less cultivation on the content of chlorophyll *a + b* and carotenoids is not clear, the efficacy of the soil-less systems has been confirmed for Arabian coffee and the caffeine content as well as for *S. bicolor* and the content of rutin. For both species, the yield of plant biomass significantly increased together with bioactive substance concentrations, mainly in leaves and partially also in roots.

In terms of the performed LCA comparative analysis, the consumption of fertilizers, diesel, and water in soil systems and of conventional electricity in aeroponics and hydroponics, which negatively contribute to the increase in terrestrial ecotoxicity, human non-carcinogenic toxicity, and global warming represent the most significant impact categories. It is assumed that the achieved negative impacts on the tested soil-less cultivation processes could be further reduced by several steps, such as: (i) the optimization of the bioactive substances production (higher concentrations of bioactive substances in the plant, e.g., leaf and root zone); (ii) the use of green energy sources, such as photovoltaics or wind; (iii) the use of environmentally friendly fertilizers, e.g., produced as a by-product or from waste products; and (iv) the use of a water recirculation system and minimization of water process loss.

The scaling up and expansion of soil-less cultivation systems for the production of bioactive substances, such as the tested aeroponics and hydroponics, waste valorisation, and process water recovery, should contribute to further reducing environmental impacts on these systems.

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