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Environmental Impacts of Conventional versus Organic Eggplant Cultivation Systems: Influence of Electricity Mix, Yield, Over-Fertilization, and Transportation

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Abstract: We report a comparative environmental study of organic and conventional open-field eggplant cultivation systems under Mediterranean (northern Greece) climatic conditions. Actual life cycle inventory (LCI) data were collected from local farm systems. Using life cycle assessment (LCA), organic eggplant cultivation exhibited better environmental performance per unit area (24.15% lower total environmental footprint compared to conventional cultivation), but conventional cultivation performed better per unit of mass (28.10% lower total environmental footprint compared to organic cultivation). The conventional system attained higher scores in eutrophication (up to 37.12%) and ecotoxicity (up to 83.00%) midpoint impact categories, due to the use of chemical fertilizer and pesticide. This highlights the need for spatially explicit LCA that accounts for local environmental impacts at the local scale. For both cultivation systems, the main environmental hotspot was groundwater abstraction for irrigation owing to its infrastructure (drip irrigation pipes and pump) and electricity consumption from the fossil fuel-dependent energy mix in Greece. Excessive addition of soil fertilizer greatly affected the environmental sustainability of both systems, especially conventional cultivation, indicating an urgent need for fertilizer guidelines that enhance environmentally sustainable agricultural practice worldwide. Results were sensitive to lower marketable fruit yield, with the organic system performing better in terms of environmental relevance with respect to maximum yield. When renewable energy sources (RES) were used to drive irrigation, both systems exhibited reductions in total environmental footprint, suggesting that RES could help decarbonise the agricultural sector. Finally, eggplant transportation greatly affected the environmental sustainability of both cultivation systems, confirming that local production and consumption are important perquisites for environmental sustainability of agricultural products.

Keywords: life cycle analysis; agricultural sector; non-organic farming; renewable energy; aubergine; nightshade

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1. Introduction

In recent years, the share of organic agriculture has been on the rise in most EU member states. This increase is driven by a steadily growing demand for organic products, with 12.6 million hectares farmed as organic in 2017 [1], up from 9.6 million in 2011 [2]. Furthermore, organic retail sales reached €34.3 billion in 2017, making the EU the second largest consumer of organic food in the world [1]. This increase could be, at least partly, attributed to EU policies for environmental protection and rural development [3] and to the preference of certain consumers for products produced using natural substances and processes [4]. Currently, the share of total utilised agricultural area occupied by organic farms (i.e., existing organically farmed areas and areas in process of conversion) in the EU-28 is 7% [1]; therefore, ample space exists for further expansion of organic farming.

As the share of the total utilised agricultural area occupied by organic farming keeps increasing, agricultural planners progressively require appropriate, reliable data at all levels of the organic food supply chain [5]. Without proper planning, uncontrolled increase in agricultural activity can adversely affect ecological diversity [6]. The EU Horizon 2020 framework programme for research and innovation has prioritised the need to strengthen research on conventional and organic agriculture, highlighting the lack of comprehensive data [2]. Key missing elements from the literature concern data on the environmental sustainability of organic and conventional agricultural systems and their main environmental hotspots. Such data would be useful in supporting harmonized agricultural policies for land reform and in restructuring the agricultural sector.

Comprehensive tools, such as life cycle assessment (LCA), enable assessment of the environmental sustainability of the agricultural sector and identification of its main environmental hotspots. LCA can estimate environmental impacts of a system, product, or process throughout its lifespan [7] and is considered a robust decision support tool for environmental sustainability assessments that has seen application in the food industry, notably to agricultural products [8]. It also provides reliable, holistic quantification of net environmental impacts from a macro-perspective and can be used by farmers, decision makers, policy makers, and researchers to examine different options [4].

Given that organic and conventional cultivation systems rely on different inputs and agricultural practices, substantial variations exist from an environmental perspective. Data on the environmental sustainability of agricultural crops are vitally important in promoting the adoption of "greener" agricultural practices and policies worldwide. To date, various studies have examined the environmental sustainability of certain fruits, including tomato [9], apple [10], coffee fruit [11], banana [12], strawberry [13], and pepper [4]. For conventional eggplant cultivation, two studies in Guilan province, Iran, have proposed that a 26% reduction of greenhouse gas (GHG) emissions can be achieved through energy optimization when using the data envelopment analysis (DEA) approach [14] and also the corresponding environmental impacts when using artificial neural networks [15]. Furthermore, a highly diverse vegetable multi-cropping system (22 crop species, including eggplant) was examined in Fengqiu County, Henan Province, China and, in general, its environmental impacts were lower compared to a conventional wheat/maize rotation system [16]. The environmental sustainability of greenhouse, but not open-field, cultivation of eggplant has also been investigated in north China [17]. The present study increases this rich repository of information by examining the environmental sustainability of organic and conventional eggplant-fruit farm systems in a Mediterranean setting, identifying their main environmental hotspots, and the impacts of marketable fruit yield, transportation, over-fertilization, and electricity mix used during cultivation.

2. Methodology

2.1. Goal

The goal of the present LCA study is to estimate the environmental sustainability and main environmental hotspots of organic and conventional open-field eggplant cultivation systems in northern Greece, (Mediterranean setting). Eggplant (*Solanum melongena*), also known as aubergine or brinjal, is an edible fruit species; the Langadas eggplant variety is traditionally cultivated in northern Greece. However, even though both organic and conventional eggplant cultivation methods are popular in Greece, their environmental sustainability under local climatic conditions remains largely unknown. Furthermore, eggplant cultivation requires irrigated water, and so an environmental assessment of both organic and conventional systems should include a sensitivity analysis of energy mix needed for irrigation. In order to acquire transparent and reproducible results, we follow ISO 14040:2006, which provides a framework and guidelines for standardized LCAs [4]. The results of the present LCA study will be of interest to researchers, farmers, political decision makers, and agricultural policy-makers.

2.2. System Boundary

A cradle-to-gate (farm) approach is used, starting from seedling planting and ending at harvesting of the eggplant fruit. The main processes are as follows:

(a) Seedling growing. In practice, this is undertaken within greenhouses to ensure stable temperature and humidity conditions. Given that similar inputs are used in both cases, this process is excluded from the LCA boundary.

(b) Seedling planting and eggplant harvesting. These are undertaken manually (no machinery or energy input) in both organic and conventional cases, and as such they are not expected to affect the results. Therefore, seedling planting and eggplant harvesting are external to the system boundary. However, the eggplant seeds are included in the system boundary.

(c) Post-harvesting activities, such as eggplant packaging. These are similar in both cultivation systems and thus are not included in the boundaries. However, eggplant fruit transportation to the main sale points, one of the main post-harvesting activities, is examined in the section on sensitivity analysis.

Figure 1 shows the system boundary, which includes the inputs, outputs, and processes considered during environmental modelling. Land use is taken into account in both systems, but not land use change, because both systems are assumed cultivated in existing agricultural land.

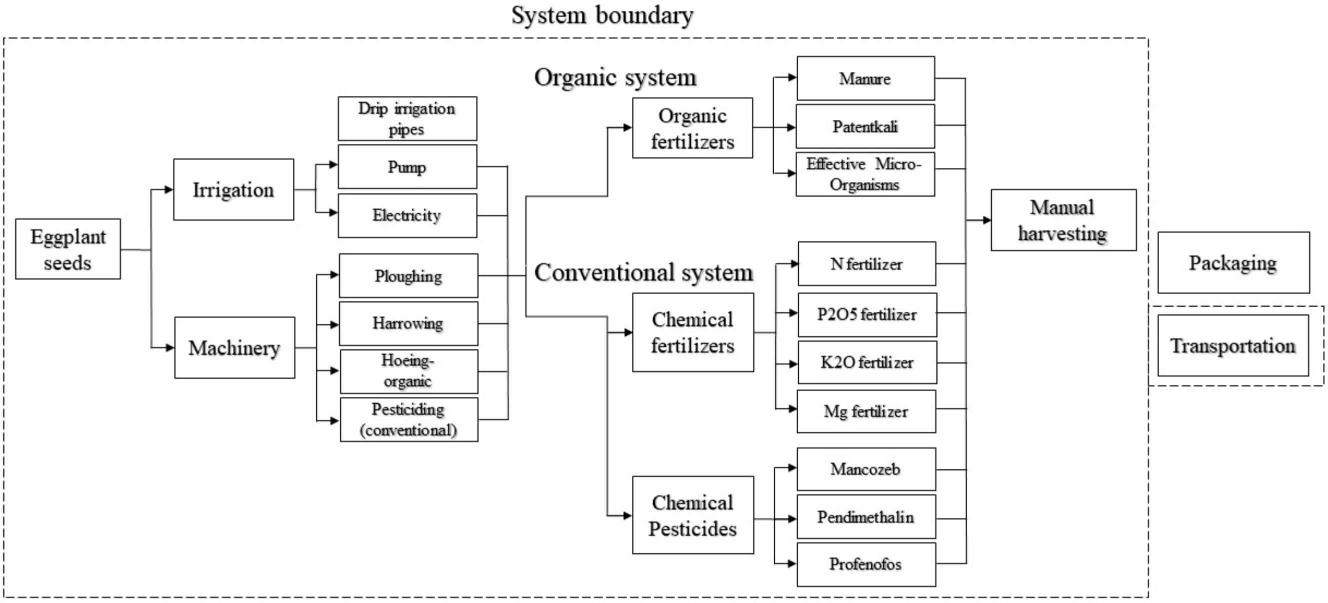

Figure 1. System boundary of the organic and conventional open-field eggplant cultivation systems under study.

2.3. Functional Unit

Noting previously reported sensitivity to choice of functional unit (FU) [18], the environmental performance of organic and conventional open-field eggplant cultivation is estimated using two functional units (FUs): one per unit of area (1000 m^2 of cultivation area), and the other per product unit (1000 kg or 1 t of marketable eggplant fruit yield). Marketable yield is the yield that reaches the market for sale. In general, the sale of organic eggplant fruit is less restricted by shape irregularities and surface imperfections than its conventional counterpart [4].

2.4. Data Collection

Life cycle inventory (LCI) data were collected through personal communication with a farmer operating a typical conventional farm system, and a farmer operating a certified organic eggplant farm system. Both systems involved were open-field cultivation and were situated in Anthemountas basin in northern Greece, i.e., subject to Mediterranean climatic conditions (mean annual temperature 15.1 °C and mean annual precipitation 451 mm, with the majority (70–80%) occurring during winter [19]. Specifically, the Anthemountas basin spans 374 km^2 [20], its soil pH is 5.5 to 7.0 [21] and land use in the area mainly comprises agriculture [19], with the water demand primarily met by groundwater abstraction (>1000 boreholes are in the area) [20]. For both cultivation systems, inventory data were collected by interviewing farmers from a representative certified organic and a representative conventional vegetable farm. Both farms were identified by the local agriculturist, and eggplant fruits, among other vegetable fruits, have been cultivated in these farms for more than two decades [4]. It should be noted that the cultivation practices in the area are representative for northern Greece and other Mediterranean areas, where intense agriculture takes place. As a result, high nitrate concentrations both in groundwater (up to 162.0 mg·L^{-1}) and in surface waters (39.0 mg·L^{-1}), have been reported in the area, and these can be traced back to the use of chemical fertilizers (mainly to nitrified ammonium-based synthetic urea) [19]. In the studied cultivation systems, eggplant seedling transplantation to the field was achieved manually, in rows spaced from 80 to 120 cm apart, commencing in late March. Although seedling spacing typically ranges from 50 to 80 cm, it is usually denser in organic systems than conventional systems because the plants tend to grow shorter. In northern Greece, popular eggplant varieties (cultivars) include the 'Emi', 'Tsakoniki', and 'Langadas', with the latter yielding elongated, cylindrical shaped, dark purple fruit without any characteristic colour stripes [22].

In the conventional system, the field is usually nourished by chemical NPK fertilizer, with about 40% applied to the field before seedling planting and the remainder after planting by diluting fertilizer in water and then feeding it to the plants by drip irrigation [23]. Ammonia and nitric acid are the primary constituents of many nitrogen-containing fertilizers, potassium sulphate and potassium chloride (both mining products) are the primary constituents of potassium fertilizer, and phosphate fertilizers originate mostly from phosphate rock and/or phosphoric acid [24]. In the conventional system, spray application of pesticide, fungicide, and insecticide usually takes place four times in total, depending on hydrometeorological factors, such as rain frequency and temperature. Herein, both fertilizer and pesticide are taken to be market processes, and an average global transport model is applied. Information on chemical fertilizer was taken from the Agri-footprint LCI database for NPK compound fertilizer.

In the organic system, the field is fertilized with manure, along with effective microorganisms, and Patentkali® (K+S Minerals and Agriculture GmbH - Bertha-von-Suttner-Str. 7-34131 Kassel, Germany), before seedling transplantation (Table 1). We assume manure to be a residual product of the animal production system (i.e., it does not include emissions from the animal production system). This is often the case and is also how the Agri-footprint LCI database handles manure. This is similar with ecoinvent's cut-off system model, where primary material production is allocated to primary users without attributing any environmental credits from recyclable materials, i.e., recyclable materials are burden-free and only the impacts of the recycling processes are ascribed to the recycling processes. The mean utilisable amount of N, P, and K per tonne of manure was taken to be 2.15, 1.12, and 2.85 kg, respectively [25]. Manure was ascribed a mean transportation distance of 30 km, using a EURO 3 emissions standards truck, which was assumed to return empty. For the eggplant seeds, LCI data on seed production for barley grain, included in the ecoinvent LCI database, were taken as proxy LCI data. For effective microorganisms employed in organic agriculture, an existing process for fodder yeast, also contained in the ecoinvent database, was used as a proxy. Specifically, the process corresponds to the treatment of whey by fermentation, which is a multioutput process that delivers: (i) ethanol (95% in H_20), (ii) yeast paste, and (iii) protein concentrate from whey fermentation as co-products.

Table 1. Inputs for Organic and Conventional Eggplant Cultivation Systems, Normalized per 1000 m^2 of Cultivation Area.

Cultivation Procedure (Input)		**Cultivation System**		**Source**	**LCI Database**
		Organic	**Conventional**		
	Land Use (m^2a)	1000		-	-
Seedling	Eggplant seeds, gr	25	20	Field investigation	Agri-footprint 5
Irrigation *	Electric pump (rated power, kW)	22			Ecoinvent 3.6
	Electricity, MJ m^{-3}	0.813			
	Water, m^3	550	600	Field investigation	Input from nature
Machinery (times/year)	Ploughing	1	1	Field investigation	Ecoinvent 3.6
	Harrowing	1	1	Field investigation	Ecoinvent 3.6
	Hoeing	8	2	Field investigation	Ecoinvent 3.6
	Pesticiding	0	4	Field investigation	Ecoinvent 3.6
Fertilizers (kg)	Manure	8000	-	Field investigation	Agri-footprint 5
	Effective microorganisms	1	-	Field investigation	
	Patentkali® (30% K_2O, 10% MgO and 42.5% SO_3)	10	-	Field investigation	Ecoinvent 3.6
	N fertilizer	-	25	Field investigation	Agri-footprint 5
	P_2O_5 fertilizer		22	Field investigation	Agri-footprint 5
	K_2O fertilizer		24	Field investigation	Agri-footprint 5
	Mg fertilizer		6	Field investigation	Ecoinvent 3.6
	Ca fertilizer (limestone)		6	Field investigation	Agri-footprint 5
Emission factors	EF1 (N addition and N mineralised)	0.010		[26]	Emission to air
	$EF_{3PRP, CPP}$ (for cattle, poultry and pigs)	0.02		[26]	Emission to air
	EF_4 (N volatilisation and re-deposition)	0.010		[26]	Emission to air
	EF_5 (leaching/runoff)	0.0075		[26]	Emission to water
	$Frac_{GASF}$ (volatilisation from synthetic fertiliser)	0.10		[26]	Emission to air
	$Frac_{GASM}$ (volatilisation from all organic N fertilisers applied, and dung and urine deposited by grazing animals)	0.20		[26]	Emission to air
	Phosphorous (run-off from eroded soil to water)	0.01		Adapted from [25]	Emission to water
	CO_2 emission from liming	0.12		[26]	Emission to air
Fungicide (kg)	Mancozeb	-	0.08	Field investigation	Ecoinvent 3.6
	Emission to soil (Mancozeb)	-	0.0652	[27]	Emission to soil
	Emission to water (Mancozeb)	-	0.0068	[27]	Emission to water
	Emission to air (Mancozeb)	-	0.008	[27]	Emission to air
Herbicite (kg)	Pendimethalin	-	0.18	Field investigation	Ecoinvent 3.6
	Emission to soil (Pendimethalin)	-	0.1467	[27]	Emission to soil
	Emission to water (Pendimethalin)	-	0.0153	[27]	Emission to water
	Emissions to air (Pendimethalin)	-	0.018	[27]	Emission to air
Insecticide (kg)	Organochlorine insecticide	-	0.3	Field investigation	Agri-footprint 5
	Emission to soil (Profenofos)	-	0.2445	[27]	Emission to soil
	Emission to water (Profenofos)	-	0.0255	[27]	Emission to water
	Emission to air (Profenofos)	-	0.03	[27]	Emission to air
Mean yield (t)	Marketable fruits	3 (2–4)	5.5 (4.5–6.5)	Field investigation	-

* LCI data for irrigation were extracted from ecoinvent database.

Table 1 lists the mean data collected for the reference period 2014–2020 covered by the present study. During this period, no weather or climate extremes were observed and so the data were deemed typical for both cultivation systems under local conditions.

2.5. Life Cycle Impact Assessment (LCIA) Methodology

The software program SimaPro 9 (PRé Sustainability B.V., Stationsplein 121, 3818 LE Amersfoort, The Netherlands), version 9.1.1.1, was used for the environmental modelling, applying the LCA methodology described in ISO 14040:2006 [4]. SimaPro is widely used by both academia and industry, and offers the user a large menu of life cycle impact assessment (LCIA) methods, including single- and multi-issue methods, which can be used to calculate impact assessment results [28]. Here, ReCiPe 2016 (version 1.1), a robust, harmonised multi-issue LCIA method and the successor of Eco-indicator 99 and CML-IA methods [29], was applied at both mid- and end-point levels. ReCiPe 2016 expresses results as eighteen midpoint impact categories, which can then be multiplied by damage factors, normalized, weighted, and further aggregated into three endpoint categories and then into a single score.

ReCiPe 2016 uses eighteen midpoint impact categories (Table 2) to express results at midpoint level. After midpoint was reached, these categories were translated into three endpoint damage categories, expressing damage to human health (DALY), ecosystems (species $*$ year), and resources (USD2013) [30]. These damage categories were also aggregated into a single score, used to compare the different systems. In ReCiPe, data uncertainty is handled in a similar way as in Eco-indicator 99, using the following versions of cultural perspective theory [22], i.e., (i) the individualist (I), based on short-term interest; (ii) the hierarchist (H), based on the most common policy principles; and (iii) the egalitarian (E), the most precautionary perspective [28,31]. The H perspective is a consensus model, as often encountered in scientific models, including ReCiPe's default model [4,28], and therefore was adopted here.

Table 2. The Eighteen Categories that ReCiPe 2016 Used at Midpoint Level [30].

No	Midpoint Impact Category Name	Unit
1	Global warming	kg CO_2 eq
2	Stratospheric ozone depletion	kg CFC11 eq
3	Ionizing radiation	kBq Co-60 eq
4	Ozone formation, human health	kg NO_x eq
5	Fine particulate matter formation	kg $PM_{2.5}$ eq
6	Ozone formation, terrestrial ecosystems	kg NO_x eq
7	Terrestrial acidification	kg SO_2 eq
8	Freshwater eutrophication	kg P eq
9	Marine eutrophication	kg N eq
10	Terrestrial ecotoxicity	kg 1,4-DCB
11	Freshwater ecotoxicity	kg 1,4-DCB
12	Marine ecotoxicity	kg 1,4-DCB
13	Human carcinogenic toxicity	kg 1,4-DCB
14	Human non-carcinogenic toxicity	kg 1,4-DCB
15	Land use	m^2a crop eq
16	Mineral resource scarcity	kg Cu eq
17	Fossil resource scarcity	kg oil eq
18	Water consumption	m^3

In this LCA study, the attributional LCA (ALCA) modelling approach was selected over the consequential (CLCA). The latter aims to describe how environmentally relevant flows will alter in response to a change attribute related to a given decision, wheras ALCA describes the environmentally relevant physical flows to and from a life cycle and its subsystems [32]. The goal of the present LCA study is to examine comprehensively the environmental impacts of two different cultivation systems, i.e., conventional and organic, for open field eggplant cultivation, and therefore ALCA was employed to estimate and compare the environmental footprints of these cultivation systems. Finally, in this LCA study sensitivity analysis was also employed, which can be considered as a systematic process that is undertaken to estimate the influence of selected flows/parameters on the FU [4]. To this end, a separate section was also included, where the influence of (i) marketable fruit yield, (ii) fertilizer overuse, (iii) electricity mix, and (iv) eggplant fruit transportation means and distance is discussed. The effect of electricity mix was examined because electricity is the main driver of the irrigation process, and so the use of renewable energy sources to compile the energy mix can have a decisive effect on the LCA results [4]. Here, the existing energy mix was assumed to be replaced with solar energy, which is abundant in Greece.

2.6. Assumptions and Limitations

The following assumptions and limitations are associated with the analysis:

i. Mean LCI data were sourced from two open-field eggplant cultivation systems in northern Greece, one a typical conventional system and the other a certified organic system for the reference period 2014–2020 (the time interval covered by this work). The data are assumed generally representative of eggplant cultivation in northern Greece and in areas with similar climatic conditions.
ii. Eggplant field cultivation begins in late March (seedling planting) and stops in November, under the climatic conditions considered.
iii. Average technology was assumed, with information on machinery required during cultivation taken from SimaPro's LCI databases.
iv. In both systems, water is assumed to be pumped from drilled wells (i.e., groundwater) using electric submersible pumps and then fed to the fields by drip irrigation. To model this, ecoinvent's LCI dataset for Spanish irrigation water was modified to fit the local setting, as suggested by [33]. More specifically, irrigation was assumed to be entirely by groundwater abstracted using submersible electric pumps. Electricity was assumed to originate solely from Greece's fossil-fuel-dependent energy mix, as obtained from the ecoinvent 3.6 database, i.e., ~31% lignite, ~23% natural gas, ~10 hydro, ~9 wind, ~8% oil, plus electricity imports and other sources). Infrastructure (drip irrigation pipes, brass, cast iron, steel, etc.) and electric pump (22 kW rated power) were assumed the same as for Spanish irrigation.
v. Data on mean (airborne and waterborne) nitrogen and (waterborne) phosphorous emissions were obtained from the literature [25,26]. Values of nitrogen emissions and of CO_2 emissions from limestone were taken directly from the Intergovernmental Panel on Climate Change (IPCC) Tier 1 approach [26].
vi. An emission factor of 2.4% for phosphorous run-off from eroded soil to water has been suggested by [25] for Swiss conditions. However, during the eggplant cultivation period in Greece, rainfall is scarce and so an emission factor of 1% for phosphorous run-off from eroded soil to water was used.
vii. Typical emissions from pesticide application were estimated based on a previous study [27] that found that 85% of the total amount of pesticide applied in a field enters the soil (of which 10% forms run-off as waterborne emission, 5% is retained by plants, and 10% is emitted into the atmosphere (airborne emission).
viii. Carbon dioxide (CO_2) fixation in eggplant fruit is biogenic in origin, and therefore external to system boundary.

3. Results and Discussion

3.1. ReCiPe at Midpoint Level

First, the ReCiPe LCIA method was applied at midpoint level and per unit of area (1000 m^2 of cultivation area), in order to gain a robust, in-depth understanding of the environmental impact of each cultivation system. Figure 2 presents a comparison between organic and conventional cultivation systems using ReCiPe's 18 midpoint impact categories (Characterization) expressed per unit of area FU. Conventional eggplant cultivation makes a larger contribution than organic cultivation in most midpoint impact categories, in particular human carcinogenic toxicity and human non-carcinogenic toxicity, where organic agriculture showed 83.00% and 60.57% lower scores than conventional agriculture, respectively. Furthermore, organic cultivation attained 27.07% and 38.12% lower scores than conventional agriculture in freshwater and marine ecotoxicity impact categories, respectively. However, organic agriculture has a larger effect in land-use impact category (7.44% higher score than conventional agriculture), reflecting the use of effective microorganisms. As mentioned above, the proxy LCI data for the effective microorganisms were based on the treatment of whey by fermentation, and therefore the impact on land use is traced back in animal feed and specifically the land that is required for animal feed cultivation. Nonetheless, as shown in Figure 3, the normalised scores of land use are very low, suggesting an overall low influence on the environmental performance of both cultivation systems. Furthermore, organic agriculture's larger scores in the ozone formation categories (48.57%), fine particulate matter formation (10.49%), and terrestrial acidification (8.33%) impact categories can be attributed to: (i) the manure loading and spreading process, which is responsible for a high load of airborne emissions, including fine particulate matter; and (ii) high ammonia emissions from manure volatilisation. The overall larger contribution of the conventional system across impact categories is mainly attributed to use of chemical fertilizer and pesticide.

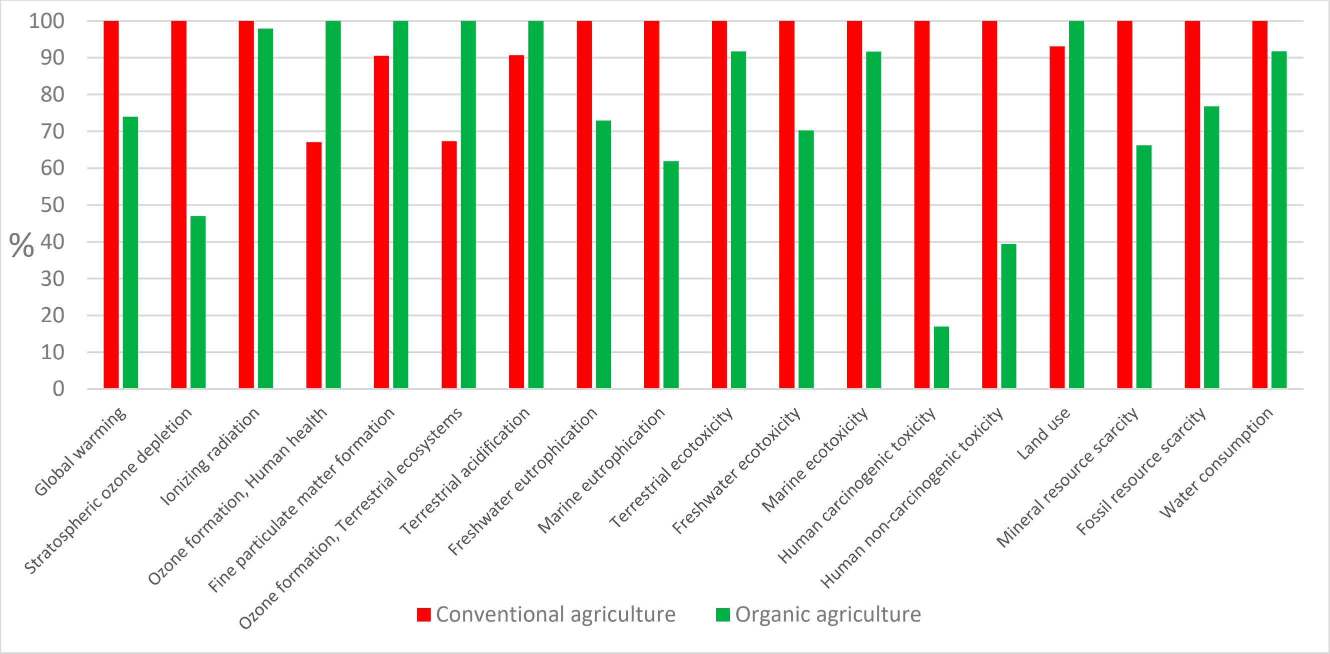

Figure 2. Contribution of each cultivation system to each midpoint impact category (characterization).

Normalization is used to identify the relative importance and magnitude of each midpoint impact category. Reference numerical scores based on normalization factors express the total impact occurring in a reference year and region for a certain impact category (e.g., climate change, eutrophication, etc.) [34]. Here, ReCiPe's global normalization factors for the reference year 2010 were used. Figure 3 shows that the highest normalized scores for both cultivation systems in descending order are for midpoint impact categories of marine ecotoxicity, freshwater ecotoxicity, human carcinogenic toxicity, and human non-carcinogenic toxicity. It also should be noted that ReCiPe 2016 does not yet include normalization factors for Europe, where the normalized results could be substantially different. In the absence of such factors for Europe, we believe the global normalization factors can provide a pragmatic proxy.

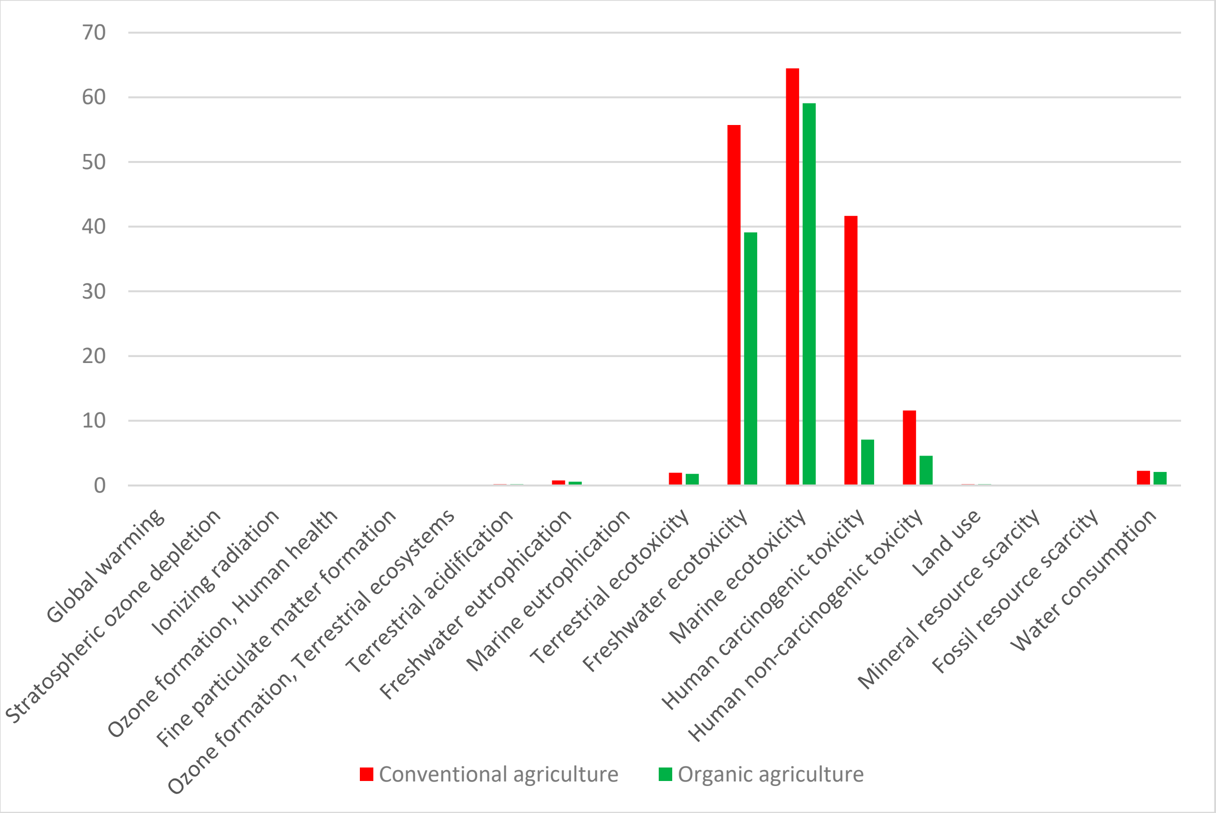

Figure 3. ReCiPe 2016 normalized scores for conventional and organic cultivation of 1000 m^2 field eggplant.

In both systems, the main contributor to the aforementioned categories is the irrigation process. As would be expected, the irrigation stage affects the midpoint impact category of water consumption. Irrigation also has a large impact on the toxicity impact categories, notably on freshwater and marine ecotoxicity. Underlying causes of high scores in these categories include: (i) use of brass fittings in the pipping system; (ii) use of copper in manufacture of the water pump; and (iii) electricity consumption from the fossil-fuel-dependent energy mix. In Greece, electricity is fossil-fuel-dependent, with associated extraction (e.g., spoil generated from lignite mining) and burning (e.g., toxic and hazardous airborne emissions) processes contributing to the aforementioned toxicity categories [4]. Brass and copper required for irrigation have a large influence on the toxicity impact categories because of burning of fossil fuel during metals production and notably the disposal of tailings (e.g., sulfidic tailings) with associated emissions of toxic and acidifying pollutants to air, soil, and water [35]. In the study of Nabavi-Pelesaraei and Amid (2014), the use of diesel fuel during conventional eggplant cultivation was the main environmental hotspot [14], whereas Sadeghzadeh et al. (2015) observed that the global warming potential (GWP) category was most important environmental index for conventional eggplant production [15]. Finally, for greenhouse eggplant cultivation in the north China Plain, Xu et al. (2018) noted a high potential for eutrophication and water and soil contamination [17]. However, the comparison between different LCA studies cannot be direct because, among others, different cultivation practices, FUs, system boundaries, assumptions and limitations, and LCIA methods are used [36].

Higher scores of the conventional system compared to its organic counterpart were partly attributed to: (i) slightly larger water input, and (ii) chemical fertilizer and pesticide production, and field application. In the conventional system, fossil fuels are required for fertilizer production (e.g., natural gas is consumed during ammonia production) and harmful emissions are released with relatively high global warming potential (nitrous oxide (N_2O) airborne emissions during ammonia production) [24]. Furthermore, phosphate fertilizer is usually produced from mined phosphate rock or energy intensive synthetically produced phosphoric acid [24], contributing to greenhouse gas emissions and fossil energy depletion. In the conventional system, pesticide emissions greatly affect the toxicity impact categories, in particular, the freshwater ecotoxicity and human non-carcinogenic toxicity categories. In both systems, the impact on eutrophication impact categories is primarily attributed to organic or synthetic fertilizer emissions to air, water, and soil [33]. The larger impact of the conventional system on freshwater and marine ecotoxicity (Figure 1) occurs because synthetic fertilizer production is a fossil-fuel-intensive process, where indirect emissions affect the eutrophication impact categories.

3.2. ReCiPe at Endpoint Level

To directly compare conventional with organic eggplant cultivation systems, the results are examined at endpoint level. We consider ReCiPe's three damage categories, i.e., human health, ecosystems, and resources. For easier comparison, the endpoint results for each cultivation system were aggregated into a single score. Figure 4 shows that the annual environmental footprint per unit of area (1000 m^2 of cultivation area) is 40.29 Pt and 30.56 Pt for conventional and organic systems. Therefore, in terms of per unit of area FU, the organic system exhibits a 24.15% lower total environmental footprint compared to the conventional system. The damage category with highest score in both cultivation systems is human health, followed by biodiversity (ecosystems), whereas resource availability has a very low score in both systems. The score in the human health damage category is mainly affected by emissions originating from fossil fuel extraction and burning for electricity production required to drive the irrigation process. Chemical fertilizer production, an energy intensive process where harmful emissions are also released, contributes to the higher score of the conventional system in this category. Airborne emissions from fertilizer application in both systems affect scores in the human health category, because of the significant implications of ammonia emissions on human health [37].

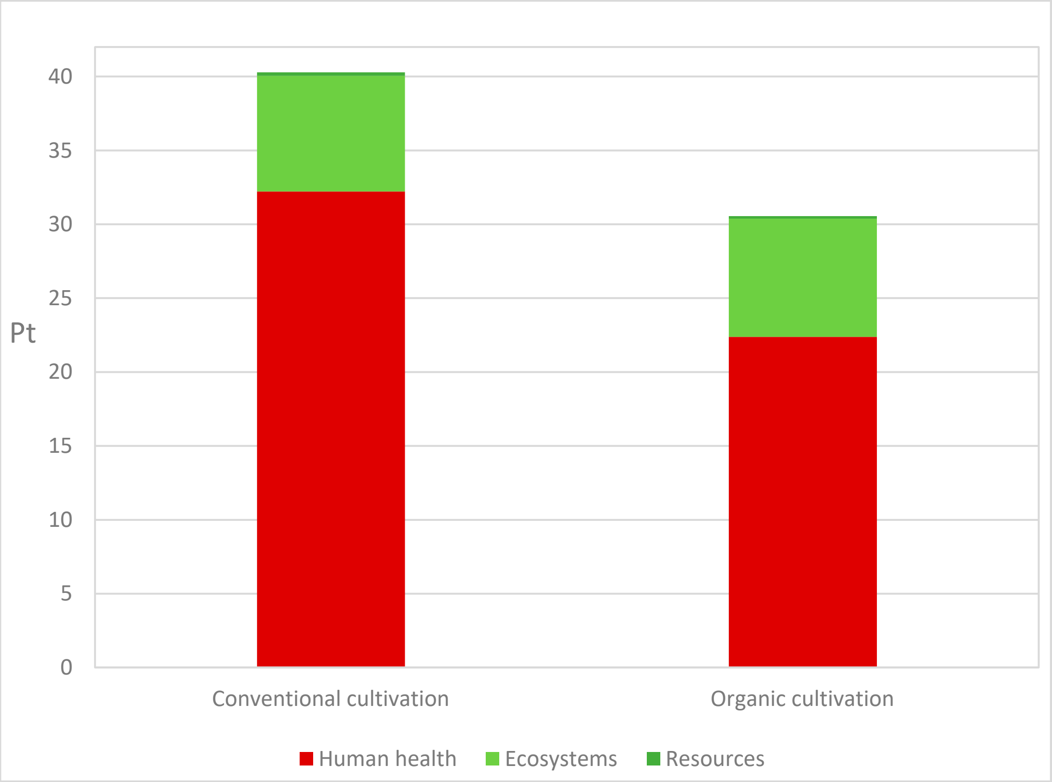

Figure 4. Comparative analysis, at endpoint level, between conventional and organic open-field eggplant cultivation per unit of area (1000 m^2).

As for the human health damage category, electricity consumption during the irrigation process affects the scores in the ecosystems damage category. Emissions from fossil-fuel extraction and burning contribute partly to the eutrophication and acidification midpoint-impact categories, thus affecting the ecosystems damage category. Furthermore, emissions (such as ammonia) from organic (manure) and chemical fertilizer also contribute to the ecosystems damage category. For example, common, fast-growing species thrive in nitrogen-rich environments and out-compete more sensitive, smaller, or rarer species, whereas ammonia pollution also impacts biodiversity through the loss of sensitive and rare species and their habitats (e.g., through soil acidification, direct toxic damage to leaves, and alteration of the susceptibility of plants to frost, drought, and pathogens) [37].

Finally, in both systems the irrigation process was primarily responsible for damage in the resource availability category. Irrigation infrastructure (e.g., pumps) and electricity consumption, where large amounts of fossil fuels are mined (e.g., lignite in Greece) and burned, are the main contributors. Furthermore, in conventional systems, the use of chemical fertilizer contributes to damage in this category, given that large amounts of fossil fuel are required for fertilizer production [24] and mining of phosphate reserves leads to resource depletion [18].

Nonetheless, when results are expressed using per unit of mass FU, i.e., 1 tonne of marketable fruit yield, then the findings differ significantly (Figure 5). This is attributed to the much higher mean yield of conventional cultivation (5.5 t) compared to that of organic cultivation (3 *t*). As a result, the conventional system has a lower environmental footprint of 7.32 Pt per tonne of produce than that of its organic counterpart of 10.18 Pt per tonne of produce. Therefore, in terms of per unit of area FU, the conventional system exhibits a 28.10% lower total environmental footprint compared to the organic system. This is in accordance with previous studies, where it has been suggested that organic farming practices generally have positive impacts on the environment per unit of area, but not necessarily per product unit, due to lower yield and the requirement to enhance land fertility [18]. Herein, the mean yield of organic open-field eggplant cultivation was about 45% lower than conventional cultivation, leading to a higher environmental footprint per unit of mass. A sensitivity analysis was therefore carried out to examine the effect of changes in marketable fruit yield on the environmental sustainability of both cultivation systems. Furthermore, the influences on environmental sustainability of over-fertilization, of introducing renewable energy to drive the irrigation process, and of fruit transportation were also examined.

3.3. Sensitivity Analysis

3.3.1. Marketable Fruit Yield

First, the effect of changes in the marketable fruit yield is examined for worst- and best-case scenarios (minimum and maximum yields, respectively). Here, changes in marketable fruit yield only affect the per unit of mass FU, and not the per area FU. For the worst-case scenarios (2 and 4.5 t in the organic and conventional systems, respectively), conventional eggplant cultivation has a much smaller footprint of 8.80 Pt/t compared to organic cultivation of 15.28 Pt/t. In the best-case scenario (4 and 6.5 t in the organic and conventional systems, respectively), both cultivation systems enjoy a large reduction in total environmental footprint, i.e., 6.09 Pt/t for conventional cultivation and 7.64 Pt/t for organic cultivation. From the foregoing, it appears that organic systems are more sensitive, in terms of environmental relevance, to changes to their total marketable yield.

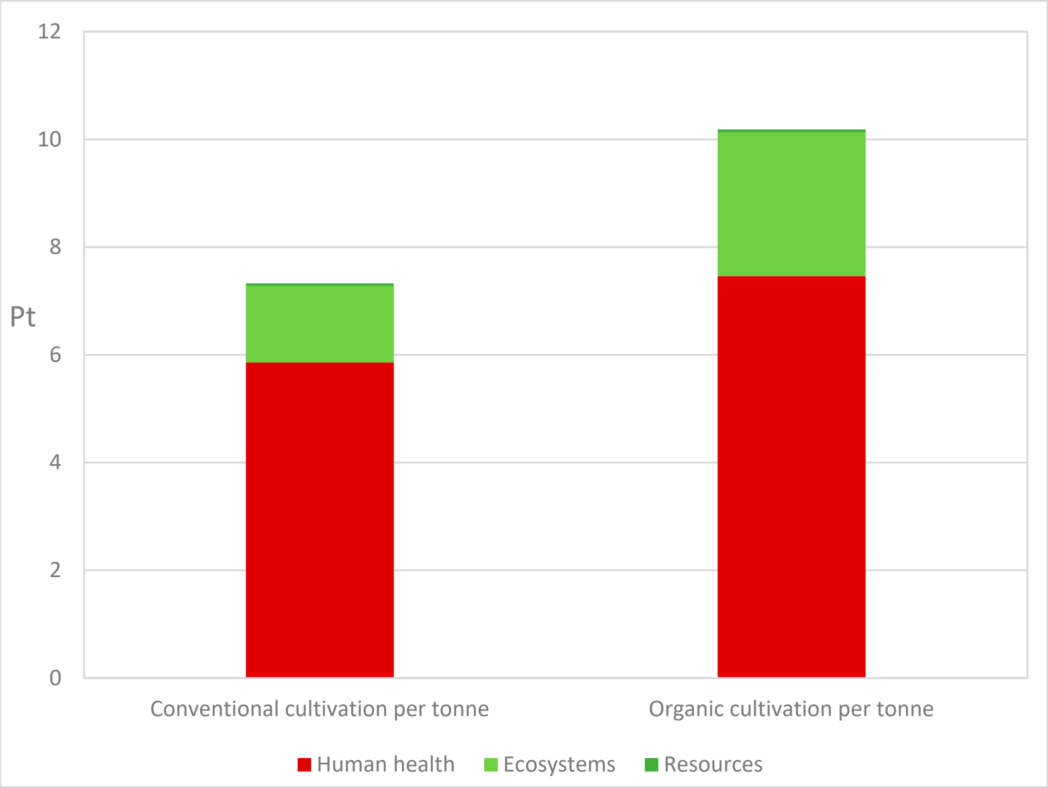

Figure 5. Comparative analysis at endpoint level between conventional and organic open-field eggplant cultivation per unit of mass (1 t of marketable eggplant fruit yield).

3.3.2. Fertilizer Overuse

Overuse of chemical and organic fertilizer is a global problem worldwide, with direct and indirect repercussions, such as increased total cost and higher emissions, primarily attributed to nitrogen application. Different amounts of fertilizer are used in different geographical areas, notably between countries. For example, use of chemical fertilizer in Japan is higher than in Germany and much higher than in the USA. Moreover, the guidelines for eggplant cultivation in Ibaraki Prefecture, Japan, allow higher doses of fertilizer (20 t/ha of manure, 370 kg/ha of nitrogen, 280 kg/ha of P_2O_2, and 270 kg/ha of K_2O) [38] than Greece (see Table 1). Therefore, it is difficult to estimate the exact amount of over-fertilization, and thence to estimate the additional fertilizer emissions to the environment. However, it is the intention of the present scenario-based analysis to illustrate possible pathways and point towards future outcomes rather than to make accurate predictions [39]. We therefore assumed that the selected threshold amounts of organic and chemical fertilizers are sufficient to cover all growing needs and that any additional quantities contribute to over-fertilization.

The effect of fertilizer overuse was examined by adding 50% more fertilizer to each system, which was assumed to be the over-fertilized amount. Manure was treated as a residue of the livestock supply chain, and so only relevant emissions from its field application were included in the analysis. Trivial amounts of crop residue are left behind in the field because non-marketable fruit ends up in landfill or is used as an animal (pig) feedstock (external to the system boundary). Therefore, the fertilizing potential of crop residue was not included in the analysis. It has been reported that when cattle manure is over-applied in the field, 80% of nitrogen leaches from the soil to the surrounding environment [38]. This consequence of over-fertilization was therefore adopted in both systems, with the focus solely on additional nitrogen content. It was assumed that 80%

of this surplus is lost as ammonia, and from this amount, 20% was taken as waterborne emission and the remainder as airborne emission [25].

In both cases, over-fertilization strongly increases environmental impact, particularly for conventional cultivation, which is associated with chemical fertilizer production. For the per area FU, 75.0% and 69.1% higher total environmental footprints were observed for over-fertilized conventional and organic systems. These very large increases in total environmental footprint are mainly due to increased ammonia emissions in both systems and are merely indicative of the impact of fertilizer overuse. Other emissions, such as phosphorous leaching, are also expected to occur, thus further affecting the environmental sustainability of both cultivation systems, particularly the conventional. Chemical fertilizer can also be associated with high levels of natural radioactivity [40]. Excessive use of fertilizer and pesticide in conventional systems is known to have major consequences on indigenous natural resources in different areas of the European Union (EU) [41].

Our results suggest that there is a need for proper fertilizer guidelines to support sustainable agriculture practice worldwide.

3.3.3. Electricity Mix

We now investigate the effect of the electricity mix used to drive the irrigation process, and consider the scenario whereby electricity is solely provided by renewable energy sources (RES). Electricity in Greece presently relies on fossil fuels [4], and so use of a sustainable electricity mix could substantially reduce the environmental impact of both cultivation systems. Here, solar energy was assumed to be produced from 3 KWp single-Si panels mounted on slanted roofs, for which LCI data are available in the ecoinvent database for Greece. With solar energy used to drive the irrigation process, then the per area total environmental footprint of conventional and organic agriculture reduced by about 13.5 and 16%. The score in the damage to human health category was lower for this scenario primarily because it avoids fossil fuel extraction and burning, and associated harmful emissions. These results suggest that RES can help decarbonise both organic and conventional cultivation systems.

3.3.4. Eggplant Fruit Transportation

Finally, by extending the system boundary, the effect of eggplant transportation, from the field up to the consumer, was examined. Specifically, after manual harvesting, eggplant fruit is transported in crates to the central vegetable market of Thessaloniki. Three scenarios are considered. The first two involve a mean transportation distance of 60 km: Scenario 1, fruit directly transported by a small refrigerator truck (3.5–7.5 metric tonne); and Scenario 2 fruit first transported by a small refrigerator truck to a main hub (20 km from the field), then moved to larger refrigerator truck (7.5–16 metric tonne), and finally transported to the central vegetable market (40 km). After transportation to the central vegetable market, we assume the fruit is either sold to local business, with no additional transportation ascribed, or bought wholesale and transferred for consumption elsewhere. In Scenario 3, the total transportation distance of the larger refrigerator truck is increased to 320 km. In all scenarios, EURO 4 refrigerator trucks were taken as the mean transport technology following Greek standards, and the fruit crates treated as external to the system boundary. Table 3 list the transportation scenarios and their effect on increasing the per mass total environmental footprint, compared to a reference scenario where transportation is external to the system boundary. Transportation can have a large effect on the total environmental footprint of both cultivation systems, particularly the conventional system, when the results are expressed per unit of mass. Furthermore, transportation can be an environmental hotspot in cases involving small trucks/lorries and/or long transportation distances. Comparison between Scenario 1 and Scenario 2 shows that vehicle type, i.e., small versus large truck, greatly affects the environmental sustainability of the two systems, with the smaller the vehicle, the larger the impact. In Scenario 3, the total environmental footprint increases by up to 51.4% in the conventional cultivation system, suggesting that transportation can be a major environmental hotspot. If small trucks are used to transfer eggplant fruit over long distances, then the total environmental footprint will increase significantly, with the resulting environmental footprint from transportation being even larger for conventional than organic cultivation. Finally, due to the lower total environmental footprint of conventionally grown eggplant fruit per unit of mass, compared to its organic counterpart, transportation has a larger effect on environmental sustainability, as observed across the examined scenarios (Table 3).

Table 3. Eggplant Transportation Scenarios and Their Effect on the Environmental Sustainability per Tonne of Conventional and Organic Eggplant Production.

Scenario	Distance (km)	Capacity (t)	Emissions Standard	Conventional System *	Organic System *
1	60	3.5–7.5	EURO 3	19.9%	14.0%
2	20 60	3.5–7.5 7.5–16	EURO 3 EURO 3	12.2%	8.6%
3	20 320	3.5–7.5 7.5–16	EURO 3 EURO 3	51.4%	36.3%

* Percentage increase compared to reference scenario of no transportation.

In short, it appears that local production and consumption offer a more sustainable strategy for agricultural products, given that the type of vehicle and the overall transportation distance greatly affect the environmental sustainability of both conventional and organic cultivation systems.

4. Conclusions

By comparing the environmental footprint and main environmental hotspots of organic and conventional open-field eggplant cultivation systems under Greek conditions, the findings of the present study could support more environmentally sustainable practices for both cultivation systems worldwide. LCA methodology and sensitivity analysis were employed to assess the total environmental impacts of both systems and alternative options for more sustainable cultivation practices. Evaluations of the environmental performance of each cultivation system were dependent on the chosen functional unit, i.e., per unit of area (1000 m^2) or per unit of mass (1 t of marketable eggplant fruit yield). Organic cultivation of eggplant presented a lower total environmental footprint than conventional cultivation when the per unit of area functional unit was used. However, when using the per unit of mass functional unit, conventional cultivation then presented a lower total environmental footprint than organic. Owing to the use of chemical fertilizer, conventional eggplant cultivation had higher scores in the midpoint impact categories for eutrophication and ecotoxicity, indicating the need to introduce spatially explicit LCA methods that account for impact at regional and local scales.

Irrigation was the main environmental hotspot in both cultivation systems. Chemical fertilizer production and application had an appreciable effect on the conventional system, whereas manure loading and spreading affected the organic system. Sensitivity analysis revealed that the results were sensitive to changes in marketable fruit yield, particularly for organic cultivation. Excessive application of fertilizer had a negative effect on the environmental sustainability of both systems, particularly conventional cultivation, indicating that strict guidelines for fertilizer are urgently needed to support sustainable agriculture practice worldwide. Use of renewable energy sources (RES) to drive irrigation led to a lower total environmental footprint, confirming the importance of RES in decarbonising agricultural activities. Finally, transportation greatly affected the environmental sustainability of both systems, with impact depending on vehicle type; the smaller the vehicle, the larger the impact, and total distance, with the longer the distance, the larger the environmental impact. These suggest that local production and consumption are key to sustainable agricultural practice in eggplant cultivation.

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References

1. European Commission. *Organic Farming in the EU—A Fast Growing Sector*; Agriculture and Rural Development, Ed.; European Commission: Brussels, Belgium, 2019; p. 12.
2. European Commission. *Action Plan for the Future of Organic Production in the European Union*; European Commission: Brussels, Belgium, 2014.
3. European Commission. *Council Regulation (EC) No 834/2007 of 28 June 2007 on Organic Production and Labelling of Organic Products and Repealing Regulation (EEC) No 2092/91*; The Council of the European Union: Brussels, Belgium, 2007.
4. Chatzisymeon, E.; Foteinis, S.; Borthwick, A.G.L. Life cycle assessment of the environmental performance of conventional and organic methods of open field pepper cultivation system. *Int. J. Life Cycle Assess.* **2017**, *22*, 896–908. [CrossRef]
5. European Commission. *Facts and Figures on Organic Agriculture in the European Union*; European Commission: Brussels, Belgium, 2013.
6. Abu, S.; Chandra, U.; Das, S.; Chettri, D. Advancements in Agriculture Strategies and Environmental Impact: A Review; SSRN. 2020, p. 15. Available online: https://ssrn.com/abstract=3516438 (accessed on 18 March 2021).
7. Trovato, M.R.; Nocera, F.; Giuffrida, S. Life-Cycle Assessment and Monetary Measurements for the Carbon Footprint Reduction of Public Buildings. *Sustainability* **2020**, *12*, 3460. [CrossRef]
8. Del Borghi, A.; Moreschi, L.; Gallo, M. 3—Life Cycle Assessment in the Food Industry. In *The Interaction of Food Industry and Environment*; Galanakis, C., Ed.; Academic Press: Cambridge, MA, USA, 2021; pp. 63–118.
9. Bosona, T.; Gebresenbet, G. Life cycle analysis of organic tomato production and supply in Sweden. *J. Clean. Product.* **2018**, *196*, 635–643. [CrossRef]
10. Zhu, Z.; Jia, Z.; Peng, L.; Chen, Q.; He, L.; Jiang, Y.; Ge, S. Life cycle assessment of conventional and organic apple production systems in China. *J. Clean. Product.* **2018**, *201*, 156–168. [CrossRef]
11. Giraldi-Díaz, M.R.; Medina-Salas, D.; Castillo-Gonzalez, E.; Leon-Lira, R. Environmental Impact Associated with the Supply Chain and Production of Grounding and Roasting Coffee through Life Cycle Analysis. *Sustainability* **2018**, *10*, 4598. [CrossRef]
12. Coltro, L.; Karaski, T.U. Environmental indicators of banana production in Brazil: Cavendish and Prata varieties. *J. Clean. Product.* **2019**, *207*, 363–378. [CrossRef]
13. Valiante, D.; Sirtori, I.; Cossa, S.; Corengia, L.; Pedretti, M.; Cavallaro, L.; Vignoli, L.; Galvagni, A.; Gomarasca, S.; Pesce, G.R.; et al. Environmental impact of strawberry production in Italy and Switzerland with different cultivation practices. *Sci. Total Environ.* **2019**, *664*, 249–261. [CrossRef]
14. Nabavi-Pelesaraei, A.; Amid, S. Reduction of greenhouse gas emissions of eggplant production by energy optimization using DEA approach. *Elixir Energy Environ.* **2014**, *69*, 23696–23701.
15. Ahmad Sadeghzadeh, M.Y.-O.; Ashkan, N.-P. Modeling and Sensitivity Analysis of Environmental Impacts for Eggplant Production using Artificial Neural Networks. *Biol. Forum Int. J.* **2015**, *7*, 375–381.
16. Li, L.; Wu, W.; Giller, P.; O'Halloran, J.; Liang, L.; Peng, P.; Zhao, G. Life Cycle Assessment of a Highly Diverse Vegetable Multi-Cropping System in Fengqiu County, China. *Sustainability* **2018**, *10*, 983. [CrossRef]
17. Xu, Q.; Hu, K.-L.; Li, J.; Han, H.; Yang, H.-F. Life Cycle Environmental Impact Assessment on Different Modes of Greenhouse Vegetable Production in the North China Plain. *Huan Jing Ke Xue* **2018**, *39*, 2480–2488. (In Chinese) [PubMed]
18. Tuomisto, H.L.; Hodge, I.D.; Riordan, P.; Macdonald, D.W. Does organic farming reduce environmental impacts? A meta-analysis of European research. *J. Environ. Manag.* **2012**, *112*, 309–320. [CrossRef] [PubMed]
19. Kazakis, N.; Matiatos, I.; Ntona, M.; Bannenberg, M.; Kalaitzidou, K.; Kaprara, E.; Mitrakas, M.; Ioannidou, A.; Vargemezis, G.; Voudouris, K. Origin, implications and management strategies for nitrate pollution in surface and ground waters of Anthemountas basin based on a δ15N-NO3− and δ18O-NO3− isotope approach. *Sci. Total Environ.* **2020**, *724*, 138211. [CrossRef]
20. Kazakis, N.; Voudouris, K.; Vargemezis, G.; Pavlou, A. Hydrogeological regime and groundwater occurence in the Anthemountas River Basin. *Bull. Geol. Soc. Greece* **2013**, *47*, 711–720. [CrossRef]
21. Foteinis, S.; Chatzisymeon, E. Life cycle assessment of organic versus conventional agriculture. A case study of lettuce cultivation in Greece. *J. Clean. Product.* **2016**, *112*, 2462–2471. [CrossRef]

22. Krommydas, K.; Mavromatis, A.; Bletsos, F.; Roupakias, D. Suitability of CMS-based Interspecific Eggplant (Solanum melongena L.) Hybrids as Rootstocks for Eggplant Grafting. *J. Agric. Ecol. Res. Int.* **2018**, *15*, 1–15. [CrossRef]
23. Plant Protection. Eggplant: Fertilizing Guide for Open Field and Greenhouse Cultivation (In Greek). Plant Protection 2019. Available online: https://plantpro.gr/post/505 (accessed on 18 March 2021).
24. Kool, A.; Marinussen, M.; Blonk, H. *LCI Data for the Calculation Tool Feedprint for Greenhouse Gas Emissions of Feed Production and Utilization—GHG Emissions of N, P and K Fertilizer Production*; Consultants, B., Ed.; Blonk Consultants: Gouda, The Netherlands, 2012.
25. Audsley, E.; Alber, S.; Clift, R.; Cowell, S.; Crettaz, P.; Gaillard, G.; Hausheer, J.; Jolliet, O.; Kleijn, R.; Mortensen, B.; et al. Harmonisation of Environmental Life Cycle Assessment for Agriculture. In *Community Research and Technological Development Programme in the Field of "Agriculture and Agro-Industry, including Fisheries" AIR 3*; Directorate-General for Agriculture and Rural Development (DG AGRI): Brussels, Belgium, 1997; p. 107.
26. De Klein, C.; Akiyama, H.; Bernoux, M.; Chirinda, N.; del Prado, A.; Kasimir, A.; MacDonald, J.D.; Ogle, S.M.; Regina, K.; van der Weerden, T.J. N2O Emissions from Managed Soils, and CO2 Emissions from Lime and Urea Application. In *2006 IPCC Guidelines for National Greenhouse Gas Inventories*; Intergovernmental Panel on Climate Change: Geneva, Switzerland, 2006.
27. Fusi, A.; Bacenetti, J.; Fiala, M.; Azapagic, A. Life Cycle Environmental Impacts of Electricity from Biogas Produced by Anaerobic Digestion. *Front. Bioeng. Biotechnol.* **2016**, *4*, 26. [CrossRef]
28. Various authors, PRé Sustainability. *SimaPro Database Manual, Methods Library*; Version: 4.15; PRé Sustainability B.V: Amersfoort, The Netherlands, 2020.
29. Goedkoop, M. *ReCiPe 2008: A Life Cycle Impact Assessment Method which Comprises Harmonised Category Indicators at the Midpoint and the Endpoint Level*, 1st ed.; (version 1.08), Report I: Characterisation; Dutch Ministry of the Environment: The Hague, The Netherlands, 2013; p. 133.
30. Huijbregts, M.A.J.; Steinmann, Z.J.N.; Elshout, P.M.F.; Stam, G.; Verones, F.; Vieira, M.; Zijp, M.; Hollander, A.; van Zelm, R. ReCiPe2016: A harmonised life cycle impact assessment method at midpoint and endpoint level. *Int. J. Life Cycle Assess.* **2017**, *22*, 138–147. [CrossRef]
31. Thompson, M.; Ellis, R.; Wildavsky, A. *Cultural Theory*; Westview Press: Boulder, CO, USA, 1990; p. 296.
32. Finnveden, G.; Hauschild, M.Z.; Ekvall, T.; Guinee, J.; Heijungs, R.; Hellweg, S.; Koehler, A.; Pennington, D.; Suh, S. Recent developments in Life Cycle Assessment. *J. Environ. Manag.* **2009**, *91*, 1–21. [CrossRef]
33. Nemecek, T.; Kagi, T. Life cycle inventories of agricultural production systems. Agroscopereckenholz-tänikon research station ART, Zurich and Dubendorf. In *Ecoinvent Report No. 15*; Agroscope Reckenholz-Tanikon Research Station (ART): Dubendorf, Switzerland, 2007.
34. Benini, L.; Mancini, L.; Sala, S.; Manfredi, S.; Schau, E.; Pant, R. Normalisation method and data for Environmental Footprints. In *EUR—Scientific and Technical Research Reports*; European Union: Luxembourg, 2014; p. 113.
35. Nuss, P.; Eckelman, M. Life Cycle Assessment of Metals: A Scientific Synthesis. *PLoS ONE* **2014**, *9*, e101298. [CrossRef]
36. Ioannou-Ttofa, L.; Foteinis, S.; Moustafa, A.S.; Abdelsalam, E.; Samer, M.; Fatta-Kassinos, D. Life cycle assessment of household biogas production in Egypt: Influence of digester volume, biogas leakages, and digestate valorization as biofertilizer. *J. Clean. Product.* **2021**, *286*, 125468. [CrossRef]
37. Guthrie, S.; Giles, S.; Dunkerley, F.; Tabaqchali, H.; Harshfield, A.; Ioppolo, B.; Manville, C. *The Impact of Ammonia Emissions from Agriculture on Biodiversity—An Evidence Synthesis*; RAND Europe: Cambridge, UK, 2018; p. 76.
38. Matsuura, E.; Komatsuzaki, M.; Hashimi, R. Assessment of Soil Organic Carbon Storage in Vegetable Farms Using Different Farming Practices in the Kanto Region of Japan. *Sustainability* **2018**, *10*, 152. [CrossRef]
39. Kouloumpis, V.; Stamford, L.; Azapagic, A. Decarbonising electricity supply: Is climate change mitigation going to be carried out at the expense of other environmental impacts? *Sustain. Product. Consump.* **2015**, *1*, 1–21. [CrossRef]
40. Ugolini, R.C.E.; Trotti, F. Use of Fertilizers in Agriculture: Individual Effective Dose Estimate. *Environments* **2020**, *7*, 7. [CrossRef]
41. Fanelli, R. The Spatial and Temporal Variability of the Effects of Agricultural Practices on the Environment. *Environments* **2020**, *7*, 33. [CrossRef]