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Resource Use and Environmental Impacts of Seed and Vegetative Globe Artichoke Production in Mediterranean Environments: A Cradle-to-Farm Gate Analysis

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Abstract: Globe artichoke is propagated by seed (seed propagated, SP) or by plant (vegetative propagated, VP). To date, there is a lack of knowledge of how the propagation system affects the life cycle resource use and environmental performance of globe artichoke production. We combined energetic, exergetic, and environmental life cycle assessment (LCA) to explore "cradle-to-farm gate" resource use and environmental impacts of Mediterranean globe artichoke production using VP and SP. The cumulative energy and exergy were calculated using cumulative energy demand (CED) and cumulative exergy extraction from the natural environment (CEENE). The environmental impacts classified in different impact categories were assessed using the ReCiPe 2016 method. The functional units were 1 ton of artichoke heads (reflecting production efficiency) and 1 ha of cropped land (reflecting production intensity). The results show that the VP globe artichoke generate 14% lower CED (64,212 vs. 75,212 MJ ha^{-1}) and 17% lower CEENE (88,698 vs. 106,664 MJ$_{ex}$ha^{-1}) per 1 ha of land while 1 ton of product generates higher impact: 29% CED (5384.4 MJ vs. 4178.5 MJ ton^{-1}) and 25% CEENE (7391.5 vs. 5927 MJ$_{ex}$ ton^{-1}). On a mass basis, SP artichokes had lower water consumption (−18%), freshwater and marine ecotoxicity (−47%), and stratospheric ozone depletion (−32%), but a higher global warming (+19%), fossil (+36%) and mineral scarcity (+39%), and human toxicity-related impacts (+27%). At the endpoint level, VP globe artichoke has higher damage to human health (+13.4%) and ecosystem quality (+20.5%), but lower to resource availability (−24.5%). The single-score LCA analysis indicated that SP globe artichokes generate a 24% higher impact per 1 ha (1911.3 vs. 1452.7 points) but 14% less per unit of product (106 vs. 121.1 points). For both systems, water and fertilizer should be used more carefully and efficiently since the application of irrigation, fuel, and fertilizers were the major contributors to total environmental damage.

Keywords: life cycle assessment (LCA); energy and exergy analysis; sustainability; artichoke propagation; growing techniques

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1. Introduction

Globe artichoke (*Cynara carduncul*u L. var. *scolymus* (L.) is an important vegetable crop that has spread globally in recent years due to its use in modern functional foods as well as in pharmaceuticals [1,2]. Globe artichokes can also be phytotoxic [3] and have antimicrobial effects [4]. Worldwide, more than 1.5 million tonnes of globe artichokes are produced per year [5]. In 2020 [5], Italy was the largest producer of artichokes with around 378,000 tons (39,420 ha), followed by Egypt (296,899 tons over 16,546 ha), Spain (199,940 tons over 14,490 ha), and Peru (131,882 tons over7028 ha); a significant production is also supplied by Algeria (119,636 tons over 5792 ha), the United States (45,722 tons over 2914 ha), and Argentina (111,853 tons over 3900 ha).

Traditionally, the globe artichoke is propagated vegetatively by using offshoots or rhizome parts, which are frequently self-produced by farmers at the end of the production cycle [6]. Vegetative propagation is quite problematic, particularly with a low rate of multiplication, the potential spread of parasites and infections, as well as the high labor required [7]. Earliness, high yield, and good quality products are the main criteria targeted by farmers [8]. In recent years, seed propagated artichoke has gained popularity providing uniformity, resource efficiency [9], high yield, disease resistance, and profitability [10–12]. However, the cost of seeds utilized for SP is generally higher than offshoots utilized for VP (0.23 €/seed vs. 0.08 €/offshoots). Moreover, the SP necessitates the use of a nursery to produce seedlings in an artificial growing medium (peat moss, perlite, vermiculite, and sand) in a controlled environment, such as a greenhouse, where most or all of the growth-limiting factors can be manipulated [13]. Nursery production is, without a doubt, one of the agricultural activities where the integration of environmental and economic policies is particularly difficult [14]. Previous research [15,16] has shown that the nursery phase can have a significant effect on the environmental impacts of crop production. In general, artichoke production has a larger material footprint and significantly lower productivity [17]. Ensuring a transition towards more sustainable production and consumption patterns requires a holistic approach and life cycle thinking to take into account all relevant interactions from a supply chain perspective [18].

Life Cycle Assessment (LCA) is a comprehensive, structured, and internationally standardized methodology for analyzing the environmental impact of a product or process over its entire "life cycle" and provides insight into ways to mitigate the impacts [19]. The LCA framework can be used to determine areas of greatest impact and compare reduction strategies for agricultural production systems [20]. The scientific literature on the LCA of agricultural products is particularly rich. Recently, applications have been widely used to highlight differences in fertilization and irrigation management practices [21], conventional and organic cultivation systems [22], open-field and greenhouse production systems [23,24], and various greenhouse typologies [25]. We found that there were only very few LCA-based studies of artichoke cultivation. Lo Giudice et al. [26] analyzed Sicilian artichoke production and improvement potential in terms of energy supply through the use of biofuels and the possibility of recycling PVC tubes. Martin-Gorriz et al. [17] analyzed artichoke cultivation in the region of Murcia (south-east Spain) and evaluated several impact mitigation interventions (e.g., replacing herbicide treatmentwith mulching, deficit irrigation, and the use of manure in place of mineral fertilizer). Canaj et al. [27] used a monetized LCA to quantify the external environmental costs of artichokes irrigated with groundwater and reclaimed water.

Artichokes are an excellent agricultural product, with the market expected to continue an upward consumption trend over the next decade [28]. However, the resource use and environmental impacts of globe artichoke cultivation under the propagation systems are usually not acknowledged. Thus, it is essential to understand relative and absolute environmental performance along with any associated trade-offs in key areas of environmental concern.

We applied energetic, exergetic, and environmental life cycle assessment to estimate the resource use and environmental impacts of seed propagated (SP) and vegetative-propagated (VP) globe artichoke in Mediterranean environments. As for performance indicators, the cumulative energy demand (CED), cumulative exergy extraction from the natural environment (CEENE), and twenty-one environmental impact categories deriving from ReCiPe 2016 model were quantified. The main contribution of the study is to generate life cycle inventory dataand provide a multi-indicator assessment of the effects of propagation systems on the environmental performance of globe artichoke production in the Mediterranean environments.

2. Materials and Methods

2.1. LCA Framework

The LCA methodology comprises four methodological phases: goal and scope definition, inventory, impact assessment, and interpretation. Details of LCA and methodological choices in this study are summarized in Table 1.

Table 1. LCA steps and details about this study.

Stage	Definition	This Study
Goal and scope definition	Specifies the intended purpose of the study, the targeted audience, the application, and the methods and databases.	• Goal: Exploring the impact of globe artichoke cultivation using seed and vegetative propagation. • Type of LCA: Attributional • Level of LCA: Detailed • System boundaries: Cradle-to-farm gate • Functional unit: 1 ton of globe artichoke heads at the farm exit gate and 1 ha of cultivated land. • The intended audience: farmers, technicians, and agriculture researchers. • Co-product allocation: not performed
Life cycle Inventory	The life cycle inventory (LCI) represents a compilation of resource use and emissions related to the functional unit.	• Primary input data collection: Farm and industry data • Secondary data collection: LCI databases • Off-farm emissions: all inputs up to the harvest of the crop. • On-farm emission considered ○ Soil direct and indirect N_2O emission ○ Nitrate nitrogen leaching loss ○ Ammonia volatilization ○ Phosphorus, surface water (P from erosion) ○ Phosphate, surface water (PO_4^{3-} from run-off) ○ Phosphate, groundwater (PO_4^{3-} leaching) ○ Diesel emission to air ○ Pesticide emissions
Life cycle impact assessment (LCIA).	Assess all potential effects of material usage, water, and energy within the environmental releases.	• Life cycle impact assessment models: ○ CED (Energy use) ○ CEENE (Exergy use) ○ ReCiPe 2016 (Environmental impacts), LCIA steps: characterization, normalization, weighting ○ Indicators quantified: 24 • Modeling of the investigated systems: OpenLCA v1.10.3 • LCA Database: EcoInvent 3.1
LCA interpretation	Identify, quantify, check, and evaluate information from the results of the LCI and/or the LCIA.	Insights into production efficiency and production intensity of globe artichoke propagation techniques following a cradle-to-farm gate perspective.

2.1.1. Goal, Scope, Functional Unit, System Boundaries, and Assumptions

The first phase of an LCA study consists of defining the goal and the scope of the study. We applied an attributional LCA to analyze the environmental impacts of globe artichoke cultivation. The system boundary (Figure 1) was defined in a from a cradle-to-farm-gate perspective, to include all the agricultural activities specifically required for artichoke production, such as pre-plant field preparation, artichoke planting, and artichoke harvesting. The plantlets are produced at local nurseries (greenhouses) and then transplanted in the field. In VP, the offshoots are produced by the farmers. The offshoots are removed by cutting the rhizome of the mother plant with a sharp knife and then transplanting the cuttings in the field. The phases of product distribution, processing, and consumption were excluded because they were considered outside of the focus and scope of the study. The functional unit of analysis was the production of 1 ton of globe artichoke heads under each strategy. A second functional unit is one hectare of cultivated land.

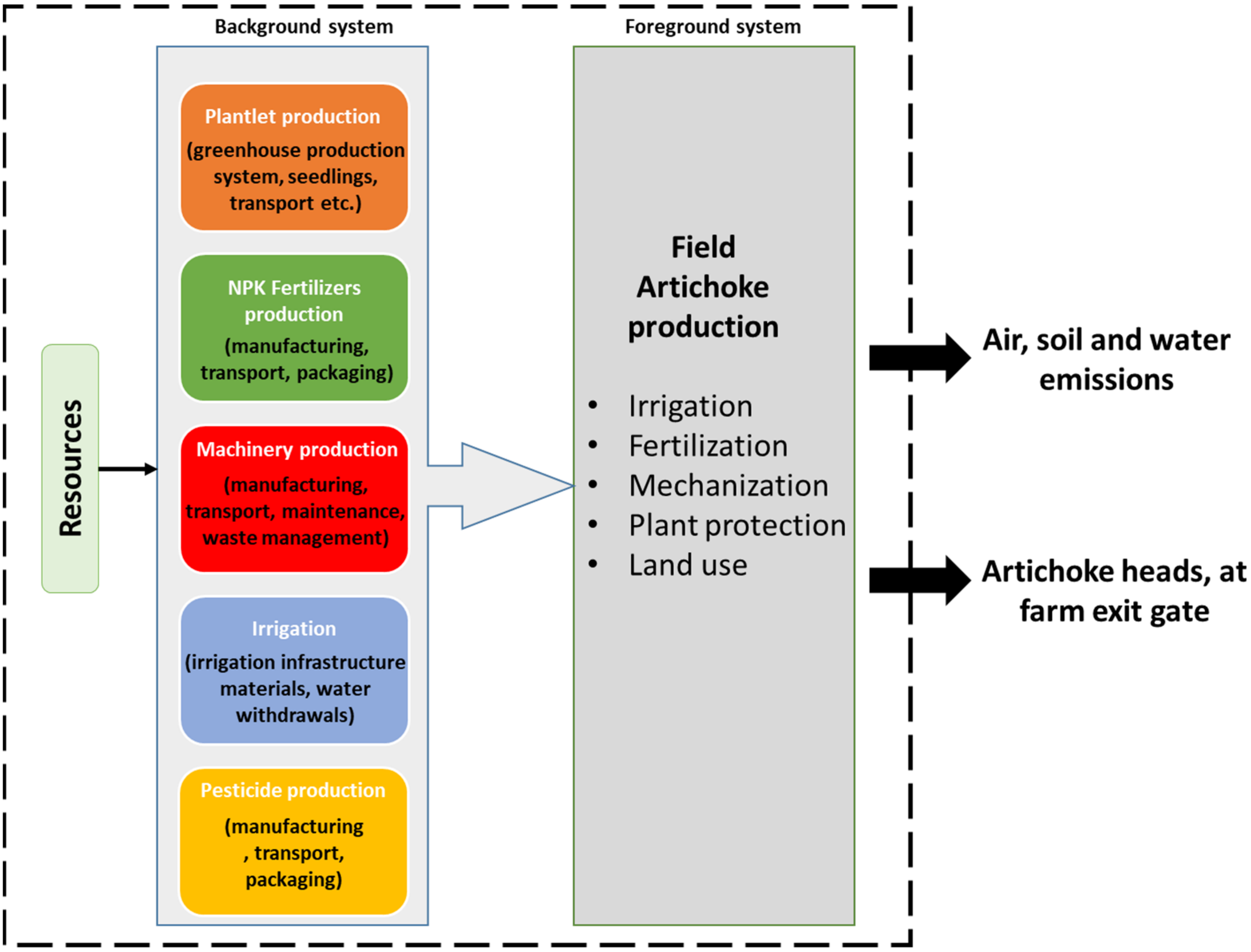

Figure 1. LCA system boundary for the globe artichoke production.

2.1.2. Inventory Data

Table 2 shows major inputs for both propagation systems for 1 ton of globe artichoke heads at the farm exit gate. The foreground input data (crop yield, seeds, water, fertilizers, pesticides, diesel consumption, and human labor) were obtained from a survey carried out with 20 local farms and technical support of 10 local nurseries in the Apulia region. Inventory data on the amount of energy and materials entering the system under examination were verified by expertise in terms of quality and reliability. The inventory data were calculated for average productivity of 18 and 12 tonnes ha^{-1} for SP and VP, respectively. For SP globe artichokes, the greenhouses considered are steel-frame structures made of solar glass (4 mm) with a lifetime of fifteen years and a greenhouse frame lifetime of twenty years. The cumulative amount of material needed for one hectare of the greenhouse (including auxiliary equipment and a climate control system) is 7165 kg of glass, 2800 kg of aluminum, 3.8 m^3 of concrete, and 14,100 kg of steel. These flows were allocated to the amount of land needed for artichoke plants considering 250 seedlings m^{-2} and 60 cells seedling $tray^{-1}$. The amount of packaging needed was estimated to be a 150 g polystyrene foam slab per 60 cells seedling tray. For every 300 seedling trays, 1 m^3 of peat moss is used and is composed of 50% of blonde peat, 40% black peat, and 10% coconut fiber. Fertilizer requirements considered for seedlings were 175 g N (nitrogen), 111 g P (phosphorus), and

111 g K (potassium) per 7000 plants. Transport from nursery to farm gate is carried out by a light commercial vehicle with an average distance of 30 km.

Table 2. Inventory input data for globe artichoke per 1 ton of artichoke heads at the farm exit gate.

Input-Output	Unit	Seed-Propagated (SP)	Vegetative Propagated (VP)
Seedlings	n.	388	833
Aluminum	kg	0.43	-
Concrete	m^3	6.11×10^{-4}	-
Stainless steel	kg	2.19	-
Solar glass for the greenhouse structure (4 mm)	kg	1.17	-
Low-density polyethylene (LDPE)	kg	0.08	-
Polyvinyl chloride (PVC)	kg	1.67×10^{-3}	
Polyester	kg	0.006	-
Peat moss, horticultural use	m^3	0.023	-
Polystyrene foam for trays	kg	0.972	-
Transport, freight, light commercial vehicle	ton km^{-1}	0.389	-
Irrigation water, groundwater	m^3	500	583
Electricity irrigation, Italian grid network	kWh	94	109
Nitrogen-based fertilizers	kg N	15.1	20
Urea, as N	kg N	6.0	8
Ammonium nitrate, as N	kg N	4.5	6
Nitrogen fertiliser, as N	kg N	4.5	6
Phosphorus-based fertilizers	kg P_2O_5	8.3	10
Potassium-based fertilizers	kg K_2O	8.3	12.5
Fuel for farm operations	MJ	1074.3	1289.2
Pesticides, unspecified (mix of fungicides, herbicides, and insecticides)	kg	0.56	0.8
Human labor	hour	13.6	35

In the calculation model, we accounted for the on-site environmental emissions from different practices, i.e., combustion of fossil fuels by the tractor, irrigation engines, and application and decomposition of fertilizers (Table 3). The considered nitrogen based environmental emissions from fertilizers were direct dinitrogen monoxide emissions (0.01 kg N_2O-N), indirect N_2O from atmospheric deposition (0.01 kg N_2O-N/kg NH_3-N) and leaching/runoff (0.0075 kg N_2O-N/kg NO_3-N), nitrate–nitrogen leaching loss (0.2 kg NO_3-N/kg N), ammonia volatilization (0.1 kg NH_3-N/kgN), and nitrous oxide (0.21 kg NOx/kg N_2O). The phosphate emissions included phosphates PO_4^{3-} leaching to groundwater (0.07 kg/ha/a), runoff to surface water (0.175 kg/ha/a for open arable land), and phosphorous (P) emissions through water erosion to surface water. IPCC [29] estimated that the application of 1 kg nitrogen fertilizers results in an emission of 1% of N_2O into the air (0.01 kg N_2O-N/kg N), where 10% of the total nitrogen applied is emitted from the soil as NH_3, while 20% of N fertilizers (expert judgment) leaches deeper down into the soil. Phosphorus leachate was calculated based on the equations suggested by Nemecek and Kagi [30]. For urea application, the emission is 1.57 kg CO_2/kg urea-N [30]. Pesticide emissions were calculated from the Ecoinvent database. Emissions from human labor were calculated considering a coefficient of 0.7 kgCO_2 h^{-1} of work [31]. The Ecoinvent database was used for all of the background processes (production of plastics, glass, electricity, fertilizers, fuels, etc.).

Table 3. On-farm (foreground) emissions for 1 ton of seed propagated (SP) and vegetative propagated (VP) globe artichoke heads at the farm exit gate.

Output	Unit	SP	VP
Fertilizer emissions			
Ammonia, to air	kg	1.82	1.52
Dinitrogen monoxide, to air	kg	0.295	0.245
Nitrogen oxides, to air	kg	0.049	0.041
Carbon dioxide, fossil, to air (urea)	kg	9.42	12.56
Phosphates, to water	kg	0.0178	0.0148
Phosphorus, to water	kg	0.1005	0.081
Nitrates, to water	kg	13.2	11
Diesel fuel emissions			
Ammonia, to air	kg	5.02×10^{-4}	6.02×10^{-4}
Benzo(a)pyrene, to air	kg	7.53×10^{-7}	9.04×10^{-7}
Cadmium, to air	kg	2.51×10^{-7}	3.02×10^{-7}
Carbon dioxide, fossil, to air	kg	78.4	94.1
Carbon monoxide, fossil, to air	kg	0.286	0.343
Chromium, to air	kg	1.26×10^{-6}	1.51×10^{-6}
Copper, to air	kg	4.26×10^{-5}	5.12×10^{-5}
Dinitrogen monoxide, to air	kg	3.01×10^{-3}	3.61×10^{-3}
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin, to air	kg	1.50×10^{-12}	1.80×10^{-12}
Methane, fossil, to air	kg	4.03×10^{-3}	4.83×10^{-3}
Nickel, to air	kg	1.76×10^{-6}	2.11×10^{-6}
Nitrogen oxides	kg	1.11	1.33
NMVOC, non-methane volatile organic compounds, unspecified origin, to air	kg	0.13	0.156
PAH, polycyclic aromatic hydrocarbons, to air	kg	8.43×10^{-5}	1.01×10^{-4}
Particulates, <2.5 µm, to air	kg	0.101	0.122
Particulates, >10 µm, to air	kg	6.75×10^{-3}	8.10×10^{-3}
Particulates, >2.5 µm, and <10 µm, to air	kg	4.50×10^{-3}	5.40×10^{-3}
Selenium, to air	kg	2.51×10^{-7}	3.02×10^{-7}
Human labor			
Carbon dioxide, fossil, to air	kg	9.53	24.5
Pesticide emissions			
Avermectin B1, to soil	kg	0.0040	0.0060
Cadusafos, to soil	kg	5.6	8.3
Chlorothalonil, to soil	kg	9.7	14.3
Chlorpyrifos, to soil	kg	0.84	1.25
Diquat dibromide, to soil	kg	0.42	0.63
Emamectin benzoate, to soil	kg	0.015	0.022
Indoxacarb, to soil	kg	0.11	0.16
Mancozeb, to soil	kg	2.520	3.735
Methomyl, to soil	kg	0.945	1.401
Paraquat, to soil	kg	0.361	0.535
Spinosad, to soil	kg	1.176	1.743

2.1.3. Life Cycle Impact Assessment (LCIA)

Typical LCIA resource accounting methods were used to evaluate resource use. The Cumulative Energy Demand (CED) [32] was used to quantify the direct and indirect primary energy use throughout the life cycle. The Cumulative Exergy Extraction from the Natural Environment (CEENE v3.0) [33] quantifies exergy "taken away" from natural ecosystems. Environmental impacts were assessed through the ReCiPe 2016 Midpoint and Endpoint hierarchist (H). ReCiPe2016 [34] produces eighteen (18) midpoint indicators (e.g., global warming, water consumption, toxicity, eutrophication, etc.) and three (3) endpoint indicators (human health, ecosystem quality, and resource scarcity). These endpoints were further normalized and weighted using European normalization references to obtain overall environmental performance indicators in the form of one dimensionless single indicator (a so-called single score). We used weighted results not to make comparative claims (statistical uncertainties are higher), but to help non-LCA experts understand the meaning of LCA results and to gain an understanding of the overall environmental sustainability globe artichoke cultivation under each propagation system. The openLCA 1.10.3 software (https://www.openlca.org/, accessed date 3 May 2022) was used and the Ecoinvent v.3.1 [35] database was accessed for the modeling of the investigated systems.

3. Results

3.1. Energetic and Exergitic Performance

The results of CED and CEENE analysis of both propagation systems are reported in Table 4. The CED was computed at 75,212 MJ ha^{-1} and 64,212 MJ ha^{-1} for SP and VP, respectively. For 1 ton of product, the CED was 4178.5 MJ ton^{-1} and 5384.4 MJ ton^{-1}, respectively. As a result, using 1 ha as FU, the SP has on average 29% lower CED while per 1 ton of product, the CED is reported 14% higher. Analyzing the process contributions for SP, the highest CED was chemical fertilizers with 1603.6 or 38.4% of total CED (Figure 2). The largest amount of fertilizers CED was caused by nitrogen based-fertilizers with 25% of the total CED (1037.3 MJ ton^{-1}). Mechanization contributed 1346.7 MJ ton^{-1} or 32.2% of total CED, while electricity for irrigation contributed 871.2 MJ ton^{-1} or 20% of total CED. Other input/processes have a much lower contribution. In the VP system, a similar pattern was observed, although with some notable differences in CED partitioning due to yield differences.

Table 4. Cradle-to-farm gate cumulative energy demand (CED) and cumulative exergy extraction from the natural environment (CEENE) for seed and vegetative propagated globe artichoke. SD denote standard deviation.

Propagation System	CED (MJ)		CEENE (MJ_{ex})	
	1 ha	1 ton	1 ha	1 ton
Seedpropagated (SP)	75,212 [SD 11,285.5]	4178.5 [SD 675.1]	106,664 [SD 13,812]	5927 [SD 826.2]
Vegetative propagated (VP)	64,212 [SD 6820.4]	5384.4 [SD 586.4]	88,698 [SD 8530.7]	7391.5 [SD 711]

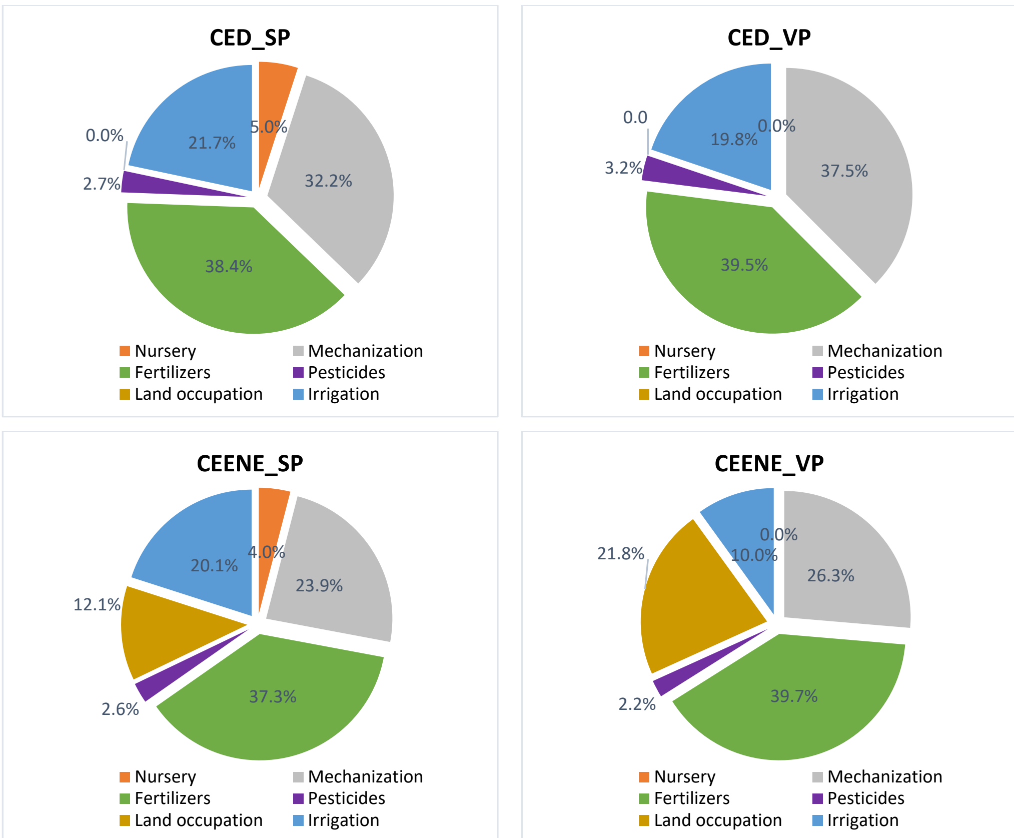

Figure 2. The process contribution to total CED and CEENE impacts for seed propagated (SP) and vegetative propagated (VP) globe artichoke.

The results of exergy analysis results reveal that cumulative exergy extraction from the natural environment (CEENE) in SP and VP systems is 5927 MJ ton^{-1} and 7391.5 MJ ton^{-1}, respectively. This means that the SP has on average 25% lower CEENE per 1 ton of product and 17% higher per unit of area. Based on results, fertilizers are the highest exergy consumer among all inputs and make up more than 37% of each category approximately for both scenarios (Figure 2). For CEENE, impacts related to the land occupation (exergy loss related to land use) contributed from 12.1% to 21.8% for SP and VP, respectively.

3.2. Environmental Performance

Figure 3 shows some of the life environmental impacts per 1 ton of product of each artichoke cultivation system demonstrating high variations in life cycle impacts (See Table S1 for detailed results). For 1 ha, VP globe artichokes had from 0.7 to 81% fewer impacts due to less water–energy–fertilizer input, while for 1 ton of product the environmental impacts varied, reflecting different resource inputs and yield achieved. Despite the higher crop productivity, generally, SP globe artichokes had global warming potential (+19%), higher human toxicity (+27%), ozone formation (+2%), ionizing radiation (+33%), mineral (+39%) and fossil resource scarcity (+36%) than the VP (Figure 3). This was mainly because of the production of the structure and facility materials used in the nursery stage sharing 41% of GWP, 47% of human toxicity, 46% of ionizing radiation, 53% of fossil fuel scarcity, and 54% of mineral resource scarcity. The nursery contributed from 0.3% to 79% of all midpoint impact categories in the SP system. High emissions are associated with the production of steel, plastics, and glass, materials that are used for the construction of the greenhouse. The VP globe artichokes had a higher freshwater and marine ecotoxicity (+47%), terrestrial ecotoxicity (+49%), marine eutrophication (+47%), ozone depletion (+32%), water consumption (+18%), and terrestrial acidification (+5%). The VP has a higher fertilizer and water intensity for the given productivity. Fertilization was the main hotspot for global warming, particulate matter, terrestrial acidification, ozone depletion, and water consumption. Mechanization had the greatest contribution to ozone formation due to fuel combustion emission. Irrigation to the water consumption as a result of irrigation water and ionizing radiation due to electricity for water pumping.

The environmental impact was further considered in three damage categories (Figure 4): human health (HH), ecosystem quality (EQ), and resource availability (RA). The endpoint analysis shows that the VP globe artichoke has higher damage to HH (+13.4%) and EQ (+20.5%), but lower damage to RA (−24.5%). For 1 ha, VP has 24% higher damage to HH and 20% to EQ, but 50% lower to RA.

The findings according to the ReCiPe endpoint single score (aggregated index representing all indicators) are illustrated in Figure 5. The single score presents a perception of the sustainability of each system using a single metric measured in points (Pt). The total environmental impact per ton of product was 106.2 and 121.1 Pt for SP and VP, respectively. For 1 ha of land, the impacts were 1911.3 and 1452.7 Pt for SP and VP, respectively. Overall, the results indicated that SP globe artichoke has a 24% higher total environmental impact per unit area (1 ha) but 14% lower total environmental impact per unit of product (1 ton). Mechanization, irrigation, and fertilization also represents a significant burden for both propagation techniques. This is mainly due to the fuel consumption for farming operations, water consumption for irrigation, and greater use of synthetic fertilizers. With SP, the nursery phase was responsible for 15.4% of the total environmental impact. The endpoint category with the most significant impact is human health with a 90% share. For the sub-system, the greatest impacts are generated from on-farm emissions generating 53% and 65% of total impact per SP and VP, respectively. The impacts on human health are explained mainly by water consumption, followed by particulate matter and global warming potential (Figure 5). For ecosystem quality, the principal impacts are due to water consumption and global warming.

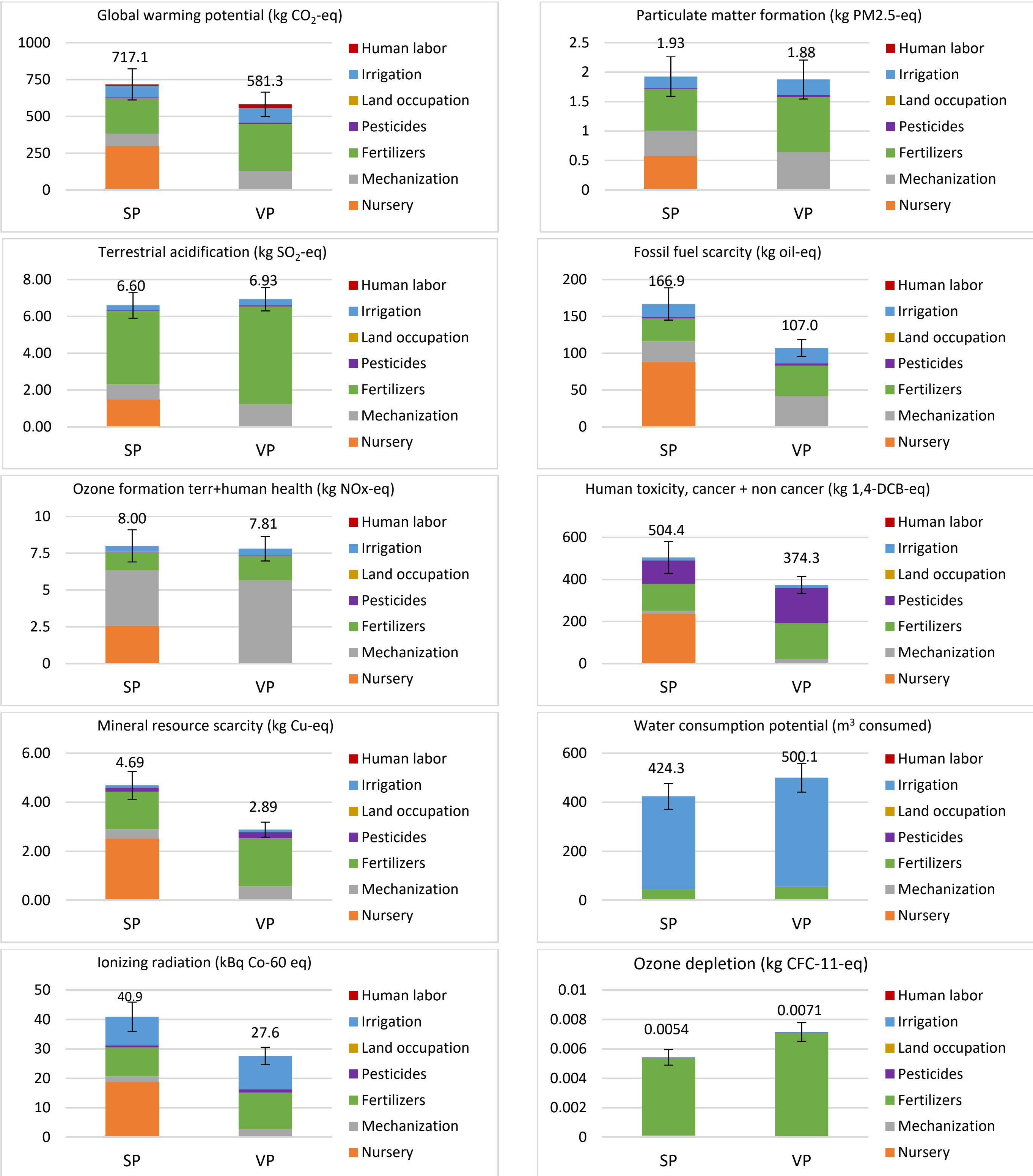

Figure 3. Cradle-to-farm gate ReCiPe 2016 midpoint impacts for 1 ton of seed propagated (SP) and vegetative propagated (VP) globe artichoke.

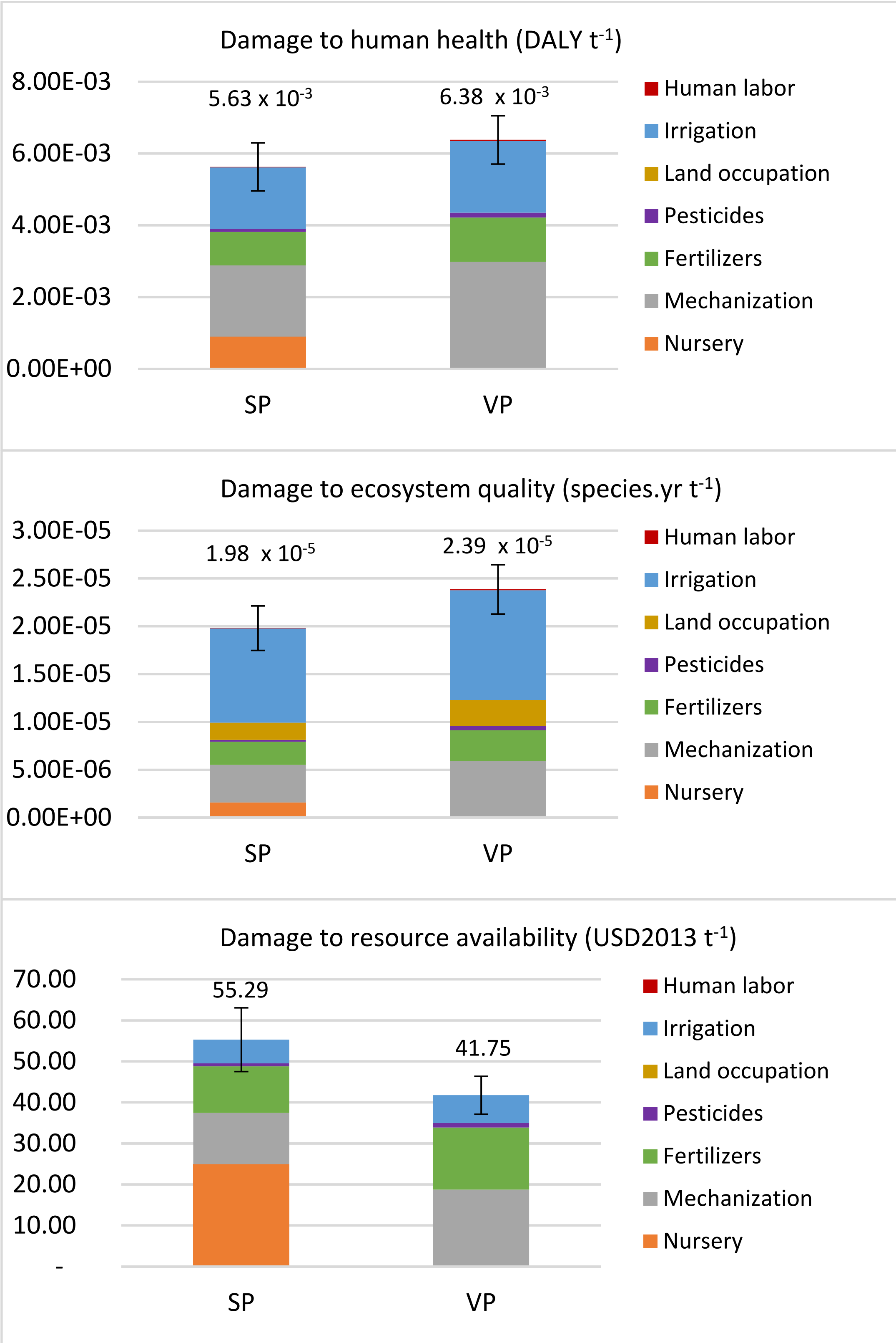

Figure 4. Cradle-to-farm gate ReCiPe 2016 endpoint impacts for 1 ton of seed propagated (SP) and vegetative propagated (VP) globe artichoke.

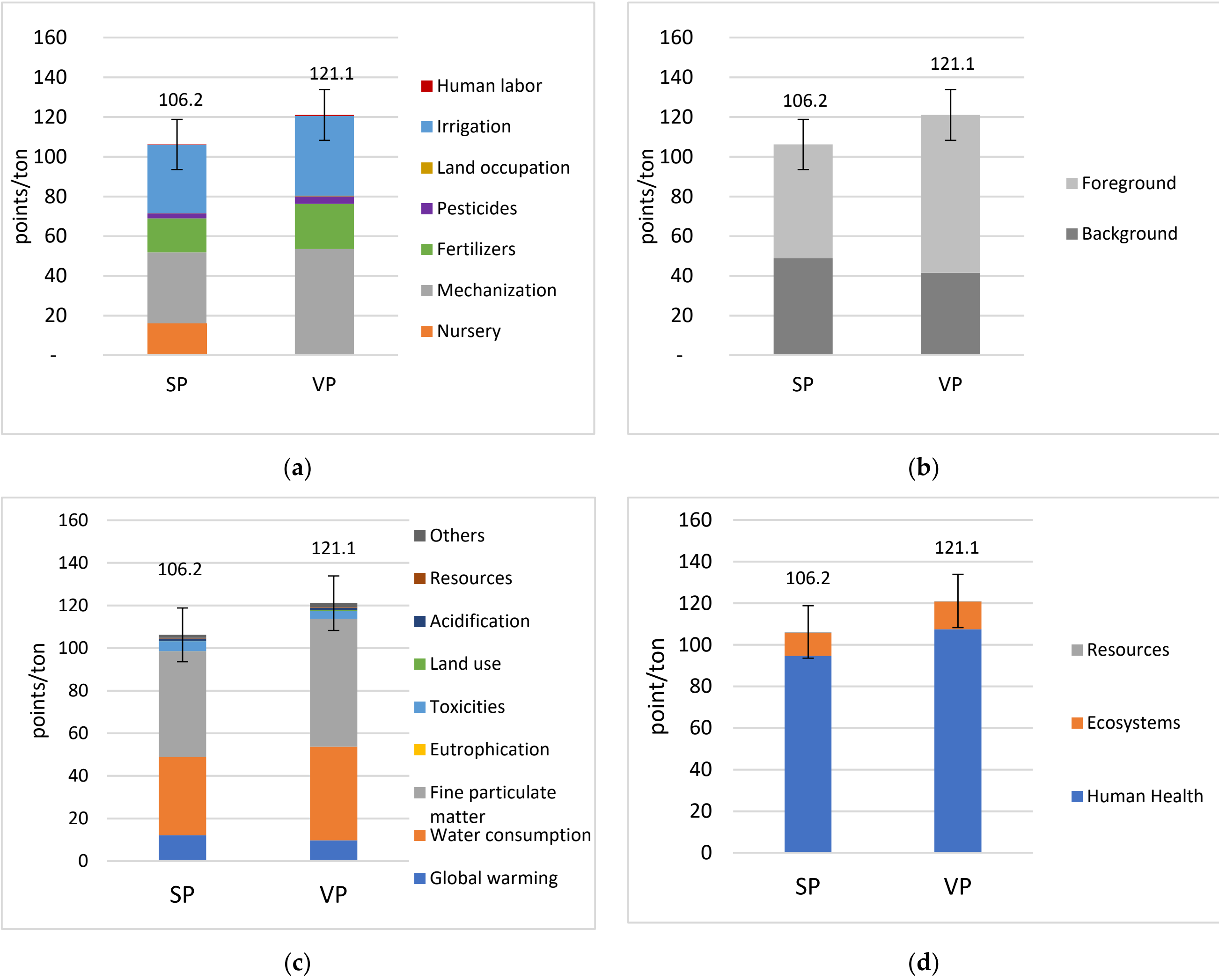

Figure 5. Cradle-to-farm gate ReCiPe single-score (in points) at different levels: (**a**) process, (**b**) subsystem, (**c**) midpoint indicator, and (**d**) endpoint indicator contribution.

4. Discussion and Concluding Remarks

The market is expected to continue its upward consumption trend over the next decade, driven by rising global demand for artichoke. Currently, the seed propagated varieties taking over the Italian national and international markets offer a high yield and quality. However, the seed propagated globe artichoke has a higher demand for inputs and infrastructure for seed growing, conditioning, and distribution. Thus, it is necessary to understand the relative potential for synergies or tradeoffs between yield and multiple environmental sustainability indicators. LCA is a time-tested methodology helping to identify hotspots, assess the environmental sustainability of crop production, and benchmark the product systems from a holistic perspective.

We conducted a cradle-to-gate energetic, exergitic, and environmental life cycle assessment (LCA) to investigate the resource use and environmental impacts of seed propagated (SP) and vegetative propagated (VP) globe artichoke production in the Mediterranean environment. Our assessment provided a complete picture of the environmental performances of globe artichokes for 1 ton of product (mass-based) and 1 ha of cultivated area (area-based), allowing us to capture the trade-offs between resource inputs, productivity, and environmental impacts. The results show VP has a lower farming intensity (i.e., lower CED and environmental impact per 1 ha of land); however, results on mass-basis show a wide variation due to the diversity of practices and influence of the yield level. Seed propagated artichoke had a lower CED, CEENE, terrestrial acidification, water consumption, freshwater and marine ecotoxicity, marine eutrophication, and stratospheric ozone depletion but a higher global warming effect, resource scarcity, and toxicity-related impacts. At the endpoint level, VP globe artichoke has higher damage to human health and ecosystem quality but lower resource availability.

We compared the LCIA results with other studies. The global warming potential for 1 ton of artichokes is reported at 189 kg CO_2-eq in Sicilia [26], and 860 kgCO_2-eq in Spain [17]. Martin-Gorriz et al. [36] reported that annual GHG emissions were 12.01 tonnes CO_2 ha^{-1} in Southeast Spain. Solinas et al. [37] estimated the carbon footprint of cardoon systems ranging from 140 to 200 kg CO_2-eq kg ton^{-1}. Energy input in Jerusalem artichoke production in China [38] was estimated at 39,870 to 40,956 MJ ha^{-1}. Martin-Gorriz et al. [17] results were 860 kgCO_2-eq. Martin-Gorriz et al. [17] reported a water consumption of 960 m^3, acidification potential of 4.59 kg SO_2-eq, and eutrophication potential of 1.96 kgPO_4 eq. The differences between our results and other studies can be explained by the different demand of energy, pesticides, fertilizers, and water. Nevertheless, our findings are in agreement with previous LCA studies [17,26,39] demonstrating that, in the case of artichoke production, the largest sources of impact are the production of fertilizers, irrigation, and diesel fuel. The impacts of globe artichoke can be reduced by increasing crop yield and seedling production per unit area, reduction of fertilizer rates, optimizing irrigation, prolongation of the anticipated life span of the greenhouse, as well as increasing the availability of its recycling service regionally and globally. The adoption of precise farming strategies and tools may provide the basis for more efficient use of critical inputs (fertilizers, water, and fuel) and reduce environmental impacts. The ability of smart farming to reduce environmental impacts is demonstrated in rice [40], olives [41], zucchini [42], and vineyard [43] production.

Many LCA studies [24,44,45] highlight that greenhouse cultivation is regarded as having heavier environmental burdens compared with traditional open-field practices. In contrast, other studies have concluded that greenhouses are an eco-friendly production method. Finally, the aggregation of environmental impacts into a single score indicated that SP has a 24% higher total environmental impact per unit area but 14% lower total environmental impact per unit of product. It has been shown that low-yield farming can often result in higher impacts per unit product, while high-yield farming raises other concerns because it is expressed as per unit area [46]. Our findings confirm that performance is dependent on the choices of the functional unit and that future LCAs on globe artichoke propagation systems should include land and productivity functional units.

Despite its higher resource intensity, seed propagated globe artichokes have 33% higher productivity and gross production value (EUR 6300 and EUR 4200 ha^{-1} for SP and VP considering an average selling price value of EUR 0.3/flower head). Yet, the ovules (VP) are cheaper than seeds (SP). Since trade-offs exist between system-level inputs and outputs, an integrated research approach for quantifying synergies and tradeoffs among multiple indicators and systems is further recommended. Joint LCC (Life Cycle Costing) and LCA (Life Cycle Assessment) approaches can be used to further evaluate the eco-efficiency of globe artichoke cultivation.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy12071605/s1, Table S1. ReCiPe 2016 midpoint and endpoint impacts of seed and vegetatively propagated globe artichoke for 1 ton of product and 1 hectare of cropped land.

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