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The Olive-Oil Chain of Salerno Province (Southern Italy): A Life Cycle Sustainability Framework

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Abstract: Agriculture, and the related food systems, represents one of the sectors that use most of the available water resources and is responsible for a large part of the greenhouse gases increase in Earth's atmosphere. The aim of the present research was to estimate the three dimensions of sustainability—identified by the 2030 Agenda—of the olive oil supply chain in a typical production area within Campania Region (South Italy), through the analysis of seven different olive oil systems: four certified as organic, two of which irrigated (BIO1, BIO2, BIO-IRR1, BIO-IRR2); two integrated (INT1, INT2); and one hobbyist (HOBB). The novelty of the research was the broad-spectrum sustainability evaluation of these systems, through the estimation of their water and carbon footprints, and some economic and social aspects, to classify them in sustainability classes. So, the Life Cycle Thinking approach was used to quantify the environmental impacts and the social issues, as well as the costs of production of 1 litre of packed oil produced. Environmental impacts were assessed thought the life cycle assessment methodology, with a focus on the global warming and the water footprint, using the SimaPro 9.0 software and Hoekstra methodology, respectively. The cost production evaluation was performed by the life cycle costing methodology, while a primordial approach of social sustainability estimation was built identifying the stakeholders involved and suitable impact categories. Results showed that, per litre of oil, HOBB and BIO2 were the systems that emitted less CO_2 eq (0.73 and 1.50 kg, respectively); BIO-IRR1 and BIO1 were the systems with the smallest water footprint (2.97 and 3.65 m^3, respectively); HOBB and BIO1 were the systems with the lowest production costs (3.11 and 3.87 €, respectively). From a social point of view, INT1 and INT2 were the most pro-social systems. Overall, BIO1 was in absolute the most sustainable system under the various aspects considered. Hence the need to spread more and more (a) organic production methods, characterized by the use of self-produced fertilizers (on-farm compost); (b) more efficient machines use, for saving fuel; (c) balanced nitrogen fertilization to lower the water footprint.

Keywords: water footprint; life cycle assessment; life cycle costing; social lca; olive oil sustainability; life cycle thinking

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Citation: Maffia, A.; Palese, A.M.; Pergola, M.; Altieri, G.; Celano, G. The Olive-Oil Chain of Salerno Province (Southern Italy): A Life Cycle Sustainability Framework. *Horticulturae* **2022**, *8*, 1054. https://doi.org/10.3390/horticulturae8111054

Academic Editor: Giuseppe Ferrara

Received: 3 October 2022
Accepted: 3 November 2022
Published: 9 November 2022

1. Introduction

With the publication of the 2030 Agenda, the United Nations have inaugurated a new season for global growth by publishing a document that revolves around 17 Sustainable Development Goals (SDGs), addressed to all countries, to all companies and to all individuals, to satisfy the needs of the present without compromising the possibilities of future generations. The success of the program will depend on the ability to combine in a balanced way the three dimensions to which the SDGs refer: economic growth, social inclusion, and environmental protection [1].

Objective 6 aims to ensure water availability and its sustainable management as well as sanitation facilities for all. This because of the recently acquired awareness that anthropogenic action is strongly altering water resources, even though water is a renewable good, capable of self-purifying and returning available simply by following its cycle. However, this risks not happening anymore as more water is consumed than is available. Agriculture is one of the sectors that uses most of the available water resources, whose demand has increased enormously over the past few decades. The total withdrawal of water from underground and surface sources went from 580 km^3 in the early 1900s to 3900 km^3 in 2010 [2]. Of these, about 70% is used in agriculture, mainly for irrigation, with even very significant differences between countries and regions of the world [3]. Furthermore, the impact of food systems on water has been addressed more recently also with respect to other issues, such as GHG emissions [4,5]. So, for Gibin et al. [6] the available scientific knowledge is still limited, and it is important to develop case studies.

The need for a more conscious and rational use of water resources has driven the guidelines of the European Commission (EC), first through the Water Directive 2000/60/EC, and then in the definition of the Common Agricultural Policy (CAP) towards 2020 [7], with the aim to combine the competitiveness of the agricultural system and the protection of natural resources. Other communications on water scarcity and drought [8], as well as the "Blueprint" document for the protection of European water resources [9], have led to an expansion of the conditionality criteria of aid to incentivize water saving in agriculture. Hence the need to identify, on the one hand, cultivation techniques able to a) reduce and/or avoid losses of water stored in the soil by direct evaporation or by crops; b) increase the water use efficiency; c) reduce the period in which the crop remains in unfavorable climatic conditions. On the other hand, the identification of production systems that allow to optimize water resources [10], which can include the application of protein hydrolysates [11], use of wastewaters for irrigation [12,13], remote sensors [14], all tools to better face the increasing and impressive water scarcity in many agricultural areas of the world.

Objective 13 of the SDGs is aimed at taking urgent measures to combat climate change and its consequences that occur with ever increasing intensity in different ways: heat waves, abundant rainfall, storms, and storm surges. Obviously, climate change and water depletion are closely linked, and measures are needed to mitigate the damage [10].

The investigation field of the present research is the olive sector: is the olive-oil chain sustainable from an environmental, economic, and social point of view?

Olive tree (*Olea europaea* L) is cultivated in the Mediterranean basin since ancient times and its cultivation has always been linked with the diet, the culture, and the economy of many areas of this context [15]. Moreover, today the olive sector is still a key element of the European Union (EU) [16]. Referring to Italy, olive growing has always boasted the primacy of guaranteeing an oil of excellent quality. According to data relating to the sixth agricultural census (the seventh will be available in January 2023), the olive-growing area in Italy is equal to 1,147,505 hectares. The Puglia region has the largest surfaces (392,150 ha), followed by Calabria (183,400 ha), Sicily (157,586 ha), Tuscany (83,525 ha), Lazio (80,181 ha) and finally Campania (75,334 ha). These regions guarantee 77% of the national production [17]. National olive growing is made up of 37% of competitive farms and 67% of marginal farms [18] Nonetheless, Italy accounts for 15% of world olive production compared to 45% for Spain, and is also the second exporter, thanks to the traditional role of the oil industry, which is an international leader [19].

Almost everywhere, but above all in Spain, Fernández-Lobato et al. [15] point out that the increased olive oil demand has caused the intensification and expansion of olive groves, with the consequent increasing use of chemical fertilizers and pesticides, irrigation, increased tree density, weed control with herbicides, and mechanical harvesting [20,21]. Such intensification process has resulted in simplified landscapes with olive groves with low-nature-value, driving greater negative environmental impacts, particularly in the form of soil erosion, run-offs to water bodies, increased rates of soil fertility loss, degradation of habitats and landscapes, and over-exploitation of scarce and vulnerable water resources [15]. In particular, reduced rain during summer and water scarcity for irrigation could be faced with applications of organic products (humic and fulvic substances, protein hydrolisates, weed extracts, etc.) to ameliorate the water stress tolerance of the plants [11] or even to reduce some negative effects of chemical products [22,23]. Not to mention the increasing costs of such type of olive grove management, i.e., the world economic and energetic situation. On the contrary, in Italy the degradation processes, above all soil erosion, can be attributed to the abandonment of olive groves, which are characterized by parcel fragmentation that directly affects production costs [24], the frequent tillage per year, and the empirical soil fertilization performed without considering the plant needs [25].

As said by Fernández-Lobato et al. [15], Stillitano et al. [26], and De Luca et al. [27], impacts may vary significantly as a result of the practices and techniques employed as well as with the analysis techniques adopted in studying these impacts. For Maffia et al. [28] the life cycle assessment (LCA) is an adequate methodology to analyze the whole life cycle of a product or service, and for Fernández-Lobato et al. [15] it is the most solid approach for the assessment of the environmental sustainability of the olive oil sector. Indeed, LCA has proven to be a valuable tool to address questions on the environmental impact of various agriculture production systems, relating to both the identification of the subsystems that contribute most to the total environmental impact and the comparison of products and processes with the same function [29–37]. A wide review of LCA applications for the olive oil sector can be found in Espadas-Aldana et al. [38].

According to Pellegrini et al. [39], an aggregate and multidimensional indicator of water usage is water footprint (WF), which quantifies the different types of water consumption as a function of space and time. A review of water footprint studies in agriculture, with a brief focus on olive production and processing, can be found in Pellegrini et al. [39].

The present work is the continuation and the evolution of a previous research in which some olive oil production systems, representative of Salerno Province (Campania region), were analyzed and evaluated from an environmental point of view. The LCA methodology was used to quantify different impact categories. The novelty of the present research was to evaluate the environmental (above all water footprint), economic and social sustainability of the olive-oil supply chain in the province of Salerno, through the analysis of 1 litre of packed oil produced in seven different olive systems: two certified as organic (BIO1, BIO2), other two certified as organic and irrigated (BIO-IRR1 and BIO-IRR2), two integrated (INT1, INT2), and one hobbyist (HOBB). The Life Cycle Thinking (LCT) approach was used as tool for all analyses.

2. Study Area and Systems Description

The study was carried out within Salerno Province (SA) where there are 38,420 olive farms [28]. The analyzed production systems are in Cilento, Alburni and Valle di Diano National Park (namely BIO1, BIO2, BIO-IRR1, BIO-IRR2, HOBB) and in Monti Picentini Regional Park (INT1 and INT2, which fall in the same farm). The farms were chosen with different characteristics such as to reflect the olive-oil scenario of the area, mainly characterized by traditional olive growing often conducted only for hobby purposes.

The main features of the studied systems are reported in Table 1. They were collected through visits to the farms, direct interviews with farmers using a specific collection sheet, and consultation of field notebooks. As in Maffia et al. [28], the olive orchard systems differed mainly for cultivar (*Salella*, *Leccino*, *Frantoiana*, *Rotondella*, *Ogliarola* and *Carpellese*), cultivation system (organic vs. integrated), and presence/absence of the irrigation system.

Among the analyzed farms, the organic cultivation system was the most present, albeit in different ways. Common to all organic farms was the use of fertilizers and pesticides of natural origin and two of these farms irrigated the olive groves (namely BIO-IRR1, BIO-IRR2). INT1 system, on the other hand, applied an integrated cultivation system, used synthetic fertilizers and pesticides, and also applied an herbicide (glyphosate) for the management of grass cover. On the contrary, INT2 system, despite using an integrated cultivation method, did not carry out chemical weeding but used synthetic products for fertilization and plant protection. Other important differences between the systems analyzed concerned the final destination of pruning residues and the methods of harvesting. Particularly, BIO1 and INT2 shredded pruning residues in the field, BIO-IRR1 reused about 20% of them to produce bundles, while the others removed them from the field for other uses: BIO2 used them in composting as structuring material, the other farms as firewood. Harvest methods varied for system to system as function of farm size. Table 1, reporting details on harvest type and its duration, highlighted that the majority of the systems (BIO1, BIO2, BIO-IRR1, BIO-IRR2) performed mechanized harvest with a mechanical shaker pulled by tractors different in capacity and power. On the contrary, the hobby system and INT2 carried out the manual harvest with the help of an electric shaker and manual combs, respectively. INT2 differed from the other systems because it carried out a preliminary operation aimed at covering the ground with sheets, sewn with special machines before the harvesting. For the presence of this preliminary operation, in this system the harvest lasted longer (400 h). Systems differed in terms of productivity too. In particular, BIO-IRR2 produced the most olives per hectare (8500 kg/ha) (Table 2).

Table 1. Technical and agronomic characteristics of the analyzed systems.

Orchard Characteristics	BIO1	BIO2	BIO-IRR1	BIO-IRR2	INT1	INT2	HOBB
Cultivar	*Salella Leccino Frantoiana*	*Rotondella Salella*	*Pisciottana Frantoio Rotondella Leccino*	*Pisciottana Frantoio Ogliarola Carpellese*	*Rotondella*	*Leccino Frantoio Carpellese*	*Rotondella Ogliarola*
Planting density (trees ha^{-1})	156 (8 × 8)	277 (6 × 6)	277 (6 × 6)	277 (6 × 6)	400 (5 × 5)	333 (5 × 6)	333 (5 × 6)
Soil texture	Clayey	Clayey	Franco-clayey	Franco-clayey	Sandy	Clayey	Franco-Sandy
Trees age (years)	Secular	Secular	Secular	Secular	80	30	Secular
Cultivation system	Certified organic	Certified organic	Certified organic	Organic regenerative agriculture	Integrated	Integrated	Organic
Pruning method				Manual			
Pruning residues management	Used as soil mulching	Composting	80% Used as soil mulching, 20% wood bundles	Used as soil mulching	Firewood	Used as soil mulching	Firewood
Irrigation	NO	NO	YES	YES	NO	NO	NO
Fertilization	Annual/ organic	Annual/ organic	Annual/ organic	Annual/ organic	Annual/ mineral	Annual/ mineral	Annual/ organic
Soil management/ weed control	Temporary natural grass cover-Disk harrowing	Temporary natural grass cover-Disk harrowing	Green manure-Disk harrowing	Grazing-Disk harrowing	Glyphosate-Disk harrowing	NO	NO
Disease control	Organic products	Organic products	Organic products	Organic products	Convention al products	Convention al products	NO
Harvesting method			Mechanized		Manual	Mechanized	Manual

Table 2. Farm inputs and outputs used in the analyzed systems.

	BIO1	BIO2	BIO-IRR1	BIO-IRR2	INT1	INT2	HOBB
Fertilizers (kg ha^{-1})							
Ferti Field (organic nitrogen)					800	800	
Compost	400	500	10,000	5000			
Biofertilizer			80				
NPK							300
Chemicals (kg ha^{-1})							
Bordeaux mixture	3						
Lime		1.5					
kaolin	1	1.5		10			
Vitabor	1.5						
Copper, Sulfur, Zeolite		1					
Idrofloral					6.5	6.5	
Iperion					9	9	
Boron	1				2	2	
Epik					1.2	1.2	
Spinosad				3			
Manisol			3	5			
Abies-Cu			2				
Glifosate					4		
Seeds			30				
Human labour (h ha^{-1})	257	85	187	102	501	120	186
Machinery (h ha^{-1})	117	69	89	98	134	106	130
Diesel (kg ha^{-1})	181	66	176	275	81	80	54
Water (l ha^{-1})			6400	10,000			
Olives average yield (kg ha^{-1} year^{-1})	8300	3500	8400	8500	8000	8500	4300

3. Materials and Methods

The LCA approach, according to the ISO 14040-44 [40,41], was used to estimate environmental impacts, water footprint, social sustainability, and production costs of the systems under study. LCA analysis was articulated in its four interrelated phases: goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation.

The present research intended to estimate and compare the environmental impacts of seven olive oil systems to classify them in sustainability classes, according to the model identified by Schau et al. (2016) [42], and detect the olive systems needing improvement. WF, social and economic aspects were also estimated. The study was "cradle to grave", namely from the extraction of raw materials up to the production of the final product (olive oil). The planting phase of the olive orchards was excluded, as foreseen by the relative PCR (product category rules) 2010:07 version 3.0 "Virgin olive oils and its fractions" [43] (PCR, 2017), since the analyzed orchards were secular or in any case planted for more than 25 years.

3.1. Environmental Impact Assessment

The environmental analysis was carried out with the LCA methodology. The study intended to assess different impact categories, above all global warming, to classify the analyzed systems in sustainability class and to identify operations, processes, and systems more impactful. Referring to sustainability classification, Schau et al. [42] reports the methods and results of a screening study carried out in the context of developing the Product Environmental Footprint Category Rules (PEFCR) (category-specific guidance for calculating and reporting life cycle environmental impacts of products) for olive oil. The representative product for the screening study has been modelled as a virtual olive oil that is based on the average mix of different types of olive oils consumed in Europe and considering the major agricultural and olive oil processing technologies. One of the results of the screening was the individuation of LCA performance classes for olive oil production. Relative to climate change, the following classes were individuated: A-Best (lower than 3.31 kg CO_2 eq L^{-1}); B (from 3.31 to 3.74 kg CO_2 eq L^{-1}); C (from 3.74 to 5.30 kg CO_2 eq L^{-1}); D (from 5.30 to 8.00 kg CO_2 eq L^{-1}); and E (higher than 8.00 kg CO_2 eq L^{-1}).

Two functional units, namely the reference on the basis of which all data were analyzed and characterized [40,41], were chosen: on the one hand, one litre of oil produced, as established by the relative PCR, including its primary and secondary packaging in glass bottles (capacity of 0.1–0.25–0.75–1 L) and in tins (capacity of 3 and 5 L); on the other hand, the surface unit (1 hectare) with the aim to improve environmental results interpretation [44–46].

The system boundaries, as shown in Figure 1, started from the olive tree cultivation, and ended with the olive oil sale. They included all the activities characteristic of the olive oil supply chain, divided into upstream (input production; agronomic operations for olive tree cultivation; olives harvesting and their transport to the olive oil mill; production of primary and secondary packaging material), core (processing of olives into oil, its storage, bottling and packaging), and downstream activities (product distribution and end of life of inputs and materials).

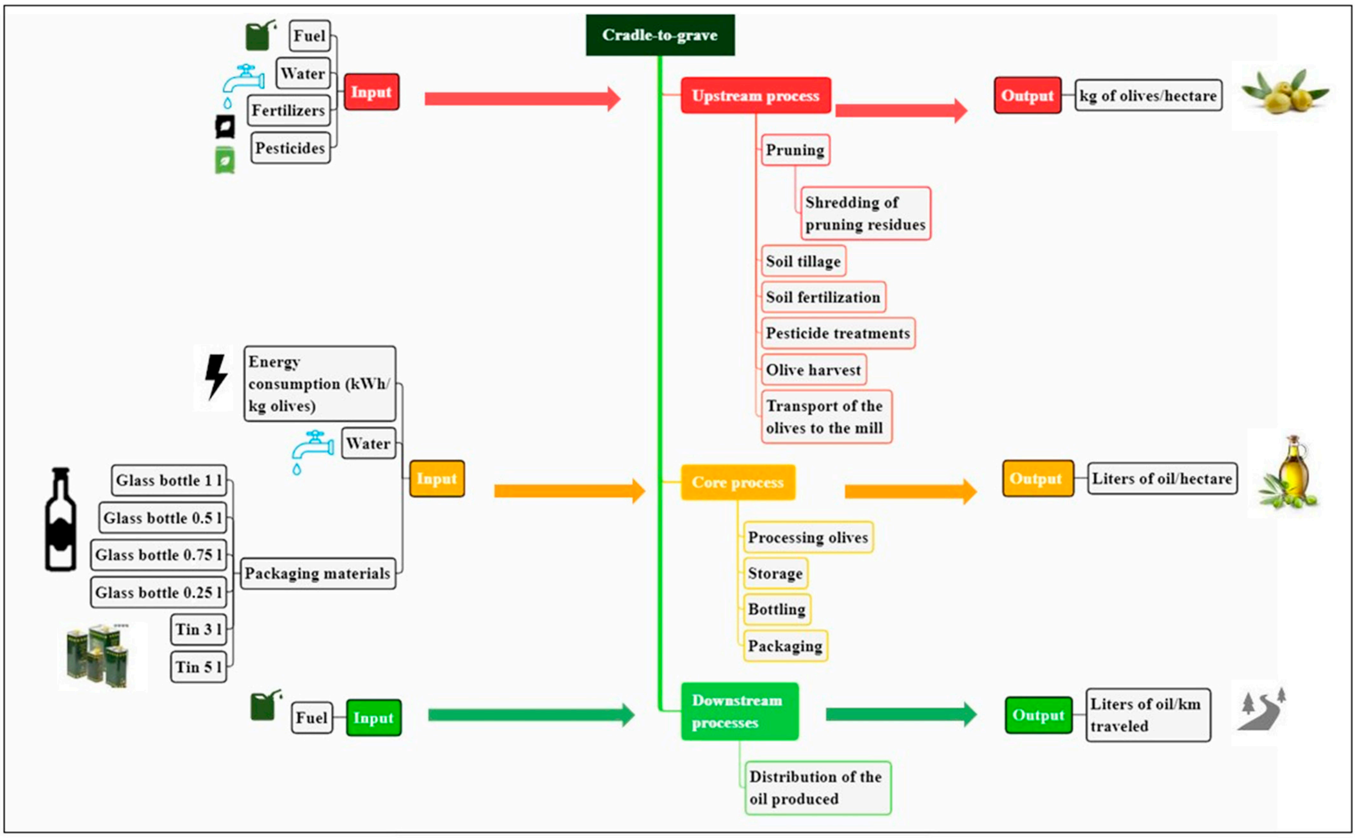


Figure 1. System boundaries for all analyses: life cycle assessment (LCA), Water footprint (WF), Life Cycle Costing (LCC), Social Life Cycle Assessment (SLCA).

Data (features of the studied orchard systems, amount of fertilizers, chemicals, fuels, water and other items) were collected in situ from 2016 to 2020 and those used in this research represent an average of these last five agricultural years. All this to overcome the problem associated with the alternate bearing (cycle of high yields followed by extremely low yields), typical of olive tree, and make data free of temporal variability.

Farm features are reported in Table 1 and farm inputs used in the examined systems are shown in Table 2. Priority was given to using primary data in terms of input material typologies and amounts used (Table 2). Additionally, to estimate direct and indirect emissions, the active ingredient of each product, and the amount of fuel and energy consumed, were calculated, and used in the analysis for each operation as a standard practice in LCAs. All specifications can be viewed in Maffia et al. [28] and Pergola et al. [45].

The impact assessment was performed using SimaPro 9, with the problem oriented CML method [47]. The following impact categories were considered according to the selected method: abiotic depletion (AD); abiotic depletion (fossil fuels) (AD fossil fuels); global warming potential (GWP) or climate change; photochemical oxidation (PO); ozone layer depletion (ODP); human toxicity (HT); freshwater aquatic ecotoxicity (FWE); marine aquatic ecotoxicity (MAE); terrestrial ecotoxicity (TE); air acidification (AA) and eutrophication (EU).

3.2. Water Footprint

WF was performed as established by Hoekstra et al. [48]. The concept of WF, introduced by Hoekstra et al. [49] and subsequently elaborated by Hoekstra and Chapagain [50], provides a framework to analyze the link between human consumption and the appropriation of the globe's freshwater.

The main reference standards for the assessment and calculation of the WF are reported in the international standard UNI EN ISO 14046: "Environmental management—Water Footprint, principles, requirements and guidelines" [51]. This standard makes it possible to adopt a unified and standardized calculation methodology to obtain evaluations of a high technical level, capable of offering results that can be easily communicated to the final consumer and potentially comparable between similar studies: the evaluation according to the principles indicated by the technical standard includes all potential environmental impacts associated with the use of the water resource, called "water footprint profiles". On the other hand, the "Water Footprint Assessment Manual" [48] provides operational guidelines for the WF calculation. The latter is the sum of three WF components: blue, green and grey WF as in the formula below:

$$WFP_{\,product}: WF_{blue} + WF_{green} + WF_{grey}$$

The blue WF refers to the volume of surface and groundwater consumed as a result of the production of a good. The consumptive water use can be: water evaporated; water incorporated into the product; water which does not return to the same catchment area; water which does not return in the same period. Evaporation is generally the most significant component [48]. The green WF refers to the rainwater consumed, which does not flow or refill groundwater but is stored in the soil or temporarily remains above the soil or vegetation [48]. Most of the world's agricultural production is based on green water consumption [52]. Therefore, this variable includes the water lost by evapotranspiration plus the amount of water incorporated in the plant biomass and represents the water used by the crop to grow.

The grey WF of a product refers to the volume of freshwater that is required to assimilate the load of pollutants to meet specific water quality standards. The concept of the grey WF was born from the awareness that the extent of water pollution can be expressed in terms of the volume of water needed to dilute the pollutants so that they become harmless [48].

According to Hoekstra et al. [48], the total water footprint of the analyzed olive systems was calculated as the sum of the green, blue, and grey components (Figure 2).

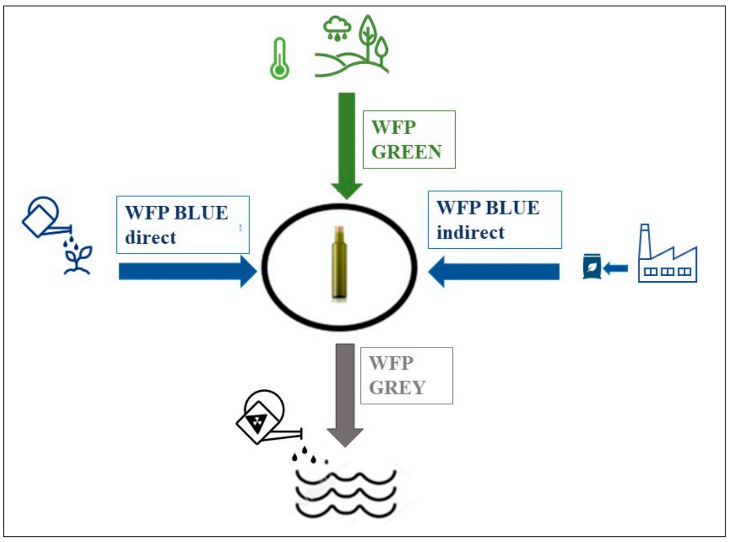


Figure 2. Schematization of the water footprint components: green, blue and grey.

Particularly, the green WF (WF_{green}, m^3 kg^{-1} and m^3 L^{-1}) was calculated as follows:

$$WF_{product,\ green} = CWU_{green}/Y$$

where:

CWU_{green} (m^3 ha^{-1}) is the crop green water use and Y is the yield in kg ha^{-1}. Particularly, CWU_{green} is calculated according to the following formula:

$$CWU_{green} = 10\ X\ \sum_{d=1}^{lgp} ETgreen$$

namely, by accumulation of daily evapotranspiration (ET_{green}, mm day^{-1}) over the complete growing period and lgp stands for length of growing period in days (1 year). According to Pellegrini et al. [39], ET_{green} was calculated as the minimum of Crop Water Requirement (CWR, mm $year^{-1}$) and effective precipitation (P_{eff}, mm $year^{-1}$):

$$CWU = 10\ X\ \sum_{\boldsymbol{d=1}}^{\boldsymbol{lgp}} \boldsymbol{ETc}$$

where CWR was calculated from both Crop Evapotranspiration (Etc, mm day^{-1}) and the growing period length in days (*lgp*).

The blue component (WF_{blue}, m^3 kg^{-1} and m^3 L^{-1}) is calculated in a similar way as:

$$WF_{\ product,\ blue} = CWU_{blu}/Y$$

and:

$$CWU_{blue} = 10\ X\ \sum_{\boldsymbol{d=1}}^{\boldsymbol{lgp}} \boldsymbol{ETblue}$$

where ET_{blue} was estimated from Irrigation Requirement (IR) rates as the minimum between IR (m^3 $year^{-1}$) and the irrigation volume (I_{eff}, m^3 ha^{-1} $year^{-1}$) [39]. IR was calculated as a constant value for the analyzed systems according to the following equation:

$$IR = \max\ (0;\ CWR\text{-}P_{eff})$$

The blue component also includes a portion of water incorporated in the product that does not return to the same catchment area. Therefore, the following elements were added to the ET_{blue}:

- the fraction of water directly consumed by the farm during irrigation, fertilization and phytosanitary treatments;
- the fraction of water indirectly used by the farm, i.e., the amount of water necessary for the production of the inputs used (fertilizers, chemicals, diesel) (Figure 2).

Following Hoekstra et al. [48], the grey component was calculated as:

$$WF_{product,\ grey} = [(\boldsymbol{\alpha\ X\ AR})/(\boldsymbol{C\ max} - \boldsymbol{C\ nat})]/Y$$

where:

AR is the chemical application rate to the field per hectare (kg ha^{-1});

α is the leaching-run-off fraction;

cmax is the maximum acceptable concentration for the pollutant considered (kg m^{-3});

cnat is the natural concentration for the pollutant considered (kg m^{-3});

Y is the crop yield (kg ha^{-1}).

Pollutants are fertilizers (nitrogen, phosphorus and more), pesticides, and insecticides. As recommend by Hoekstra et al. [48], we considered only the most critical pollutant: nitrogen fertilizers, for which a leaching rate of 0.1 is assumed for BIO-IRR1, BIO-IRR2, BIO1 and BIO2 systems, being located on flat soils, and of 0.25 for INT1 and INT2 systems since they are located in particularly sloping soils [48,52–55].

Generally, the estimation of evapotranspiration is done indirectly by means of models that uses climate data (ET_c and P_{eff}), soil properties and crop characteristics as inputs. In the present study, the FAO free application CROPWAT 8.0 [56] was used for the calculation of Et_c, IR and I_{eff} needs for the entire cultivation cycle. In particular, the software allows to calculate the CWU, which is based on the water needs of a crop.

So, a "Cradle-to-grave" study was carried out to calculate the WF, stopping at the farm's gates, namely to the oil transformation phase and, as required by UNI-ISO [51], the following items were considered and included in the analysis:

(a) quantity of water directly used in phytosanitary treatments; fertilizations; irrigation; washing of the olives and milling;
(b) water indirectly used in the manufacture of inputs;
(c) types of water resources used, distinguished between rainwater and irrigation water;
(d) forms of water use: evaporation; transpiration; product integration; release in river basins or at sea; moving water from one type of water resource to another water resource;
(e) climatic conditions of the production areas of the olive-growing systems analyzed.

Referring to this latter point, the weather stations closest to the systems under study were chosen, and the climatic data of the 2019–2020 agricultural year were obtained at the Regional Agrometeorological Center of the Campania Region.

3.3. Production Cost Analysis

The Life Cycle Costing (LCC) method was applied to evaluate the production cost of the studied olive systems. LCC, also known as life cycle cost analysis, is an economic evaluation methodology that considers all costs and cash flows of a project, product, or service during its life cycle [57,58] from initial investment costs through to operation, maintenance and disposal [59,60].

LCC is a complementary tool of LCA [61] and its first standard dates back to 2008, containing the theoretical basis of this methodology, but the use of life cycle methods, such as LCA, according to ISO 14040-44 [40,41], can be extended to the economic aspects. Therefore, to combine the LCC and LCA findings, the analysis was performed using the same system boundary (Figure 1), and the same life cycle inventory described for LCA (Table 2). As stated in Maffia et al. [28], farms can differ markedly in terms of the source of production factors, such as labor and machinery. Indeed, some farms rely on family labor (often uncompensated) and purchased machinery, while others make great use of hired labor and rented machinery [62]. Therefore, the analysis was based upon the assumption that the production techniques of all the investigated cropping systems are quite the same and all the studied farms pay for the labor and machinery. For each phase (agronomic practices for olive tree cultivation; olives harvesting and their transport to the olive oil mill; processing of olives into oil; its storage, bottling and packaging) the main types of cultivation management practices were identified, along with the associated fixed and variable costs. Consequently, to perform an economic analysis consistent with the LCA, each cost item (materials: costs of all non-capital inputs such as fertilizers, pesticides, herbicides, fuels, water, electricity, and other crop-specific requirements; labor: cost of workers involved in farm production; quotas and services: machinery, equipment, depreciation costs, and interests in circulating and anticipation capital) [63] were collected in situ from 2016 to 2020 and then averaged.

3.4. Social Life Cycle Assessment

The Social Life Cycle Assessment (SLCA) is an integration to the analysis methodologies described up to now. Indeed, the SLCA adds the assessment of the social sustainability (namely, potential social impacts: the probable positive or negative consequences for human well-being of organizations' activities or behaviors linked to use of the product) [64] of a process or product to the assessment of costs and environmental impacts [65] throughout its life cycle. As stated by [66], the Guidelines for SLCA of Products [67] represents the largest reference to develop SLCA, where it is defined as a technique of assessment of social and socioeconomic aspects of products and their positive and negative impacts (and potential impacts) along their life cycles [68].

SLCA has not yet been standardized in an international standard due to the nature of social impacts that do not depend only on the processes themselves, but also on the behavior and context of actors [69]. So, it follows the steps proposed by ISO 14040 [41] for environmental LCA [64,68,70]. Like the LCA framework, SLCA includes four phases: 1. definition of the goal and scope of the study; 2. data inventory (collecting data and significant information); 3. social impact assessment; 4. interpretation of results.

If ISO indications, describing in detail the techniques to be used to analyze the social life cycle, have not yet been provided, SLCA Guidelines [67] have proposed a methodology for developing an inventory identifying five stakeholder categories: workers (fair wages, working hours, job security, child labor, equal job opportunities/discrimination in the workplace); consumers (feedback mechanisms, consumer privacy, product end-of-life responsibility, transparency); local community (access to goods and resources, relocation and migration, local employment, living conditions); society (contribution to economic development, technological development, commitment to problems linked to sustainability) and value chain actors (promotion of social responsibility, relations with suppliers, respect for intellectual property) [66,69–72]. With regard to impact categories, the mains are: protection of human rights; working conditions; welfare and safety of workers; socio-economic repercussions on local communities and on society in general. All this because among the other objectives, the SLCA tends to evaluate variations in people's life expectancy, consequences on their health, variations in employment, education [72].

At the same time, the impact that a product and/or a service has on society, on the contrary to the analysis of environmental impact, differs greatly in relation to the context in which the farm is inserted. So, for the present research the authors conceived and designed a data collection useful for evaluating social sustainability thinking to the socio-economic and cultural context of the surveyed territory, leaving out the impact categories that do not concern Italy, such as child labor and the protection of human rights, because already normally provided for by national legislation. As shown in Table 3 workers, suppliers, the community, and consumers were considered among the different categories of stakeholders that affect the olive-oil supply chain. For each type of stakeholder, five categories of impact were chosen (Table 3), which were assigned a score given in relation to compliance with the parameter considered. The score varies from a minimum of 1 to a maximum of 5.

Table 3. Social Life Cycle Assessment: stakeholder categories and impact categories considered.

Stakeholders	Impact Categories				
Workers	Safety	Remuneration	Equity of treatment	Protected category workers	Foreign workers
Suppliers	Fair Payments	Compliance with delivery times	Respect for human rights throughout the supply chain	Absence of corruption	No abuse of power
Community	No impact on health due to the proximity of the plants	No movement of the community due to the proximity of the plants	Philanthropic activities of the farm	Interactions with local authorities	Farm participation in local events
Consumers	Product safety	Product transparency	No damage due to the consumption of products	Possibility to track the purchased product	Any discounts for fragile categories

4. Results

4.1. Environmental Impacts

Results of the environmental analysis, referring to the functional unit (1 litre of oil) are shown in Table 4. The hobby system was the most sustainable for all impact categories; on the contrary, BIO-IRR1 and BIO-IRR2 were the most impactful in terms of resource consumption (abiotic depletion), global warming and human toxicity; referring to marine eco-toxicity, INT2 was the most impactful followed by BIO-IRR2.

Table 4. Environmental impacts per litre of olive oil produced by each analyzed system (AD: abiotic depletion; AD-fossil fuels: abiotic depletion fossil fuels; GWP: global warming potential; PO: photochemical oxidation; ODP: ozone layer depletion; HT: human toxicity; FWE: fresh water aquatic ecotoxicity; MAE: marine aquatic ecotoxicity; TE: terrestrial ecotoxicity; AA: air acidification; EU: eutrophication).

Impact Categories	Unit	BIO1	BIO2	BIO-IRR1	BIO-IRR2	INT1	INT2	HOBB
AD	kg Sb eq	0.001	0.000	0.006	0.009	0.001	0.001	0.000
AD-fossil fuels	MJ	33.394	13.586	58.525	65.800	46.597	36.567	8.354
GWP	kg CO_2 eq	2.649	1.504	3.045	4.067	3.389	2.634	0.734
ODP	Kg CFC-11 eq	0.000	0.000	0.000	0.000	0.000	0.000	0.000
HT	kg 1,4-DB eq	3.540	4.305	20.000	27.019	3.687	3.102	0.030
FWE	kg 1,4-DB eq	0.736	0.421	20.980	29.372	1.067	0.880	0.007
MAE	kg 1,4-DB eq	3219	1685	24824	34228	4483	3938	35
TE	kg 1,4-DB eq	0.007	0.007	0.023	0.030	0.006	0.007	0.000
PO	kg C_2H_4 eq	0.001	0.000	0.001	0.001	0.001	0.001	0.000
AA	kg SO_2 eq	0.045	0.016	0.033	0.041	0.040	0.041	0.005
EU	kg $PO_4{}^{3-}$ eq	0.007	0.003	0.028	0.036	0.008	0.008	0.001

To better compare the different analyzed systems (different mainly for cultivar, planting density and cultivation system, as shown in Table 1), and to identify the most impacting steps that need improvements in terms of sustainability, a focus on global warming (GW) was carried out. Figure 3 shows that among the seven analyzed systems, BIO-IRR2 emitted the most CO_2 eq per litre of oil (4.1 kg of CO_2 eq L^{-1}), followed by INT1 (3.4 kg CO_2 eq L^{-1}) and BIO-IRR1 system (3.0 kg CO_2 eq L^{-1}). On the contrary, the hobby system was confirmed to be the least impacting system with 0.73 kg of CO_2 eq L^{-1}.

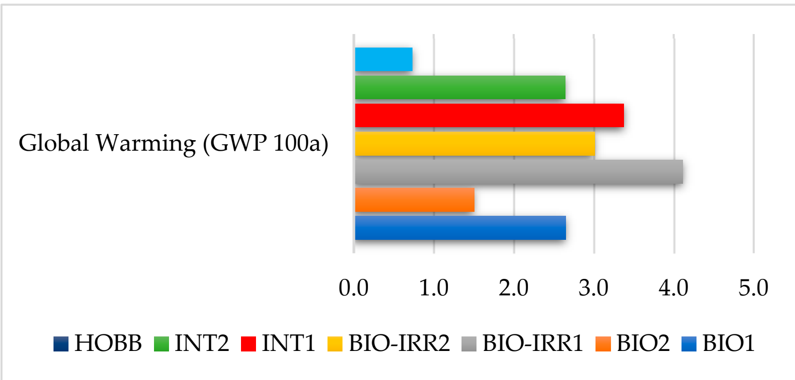
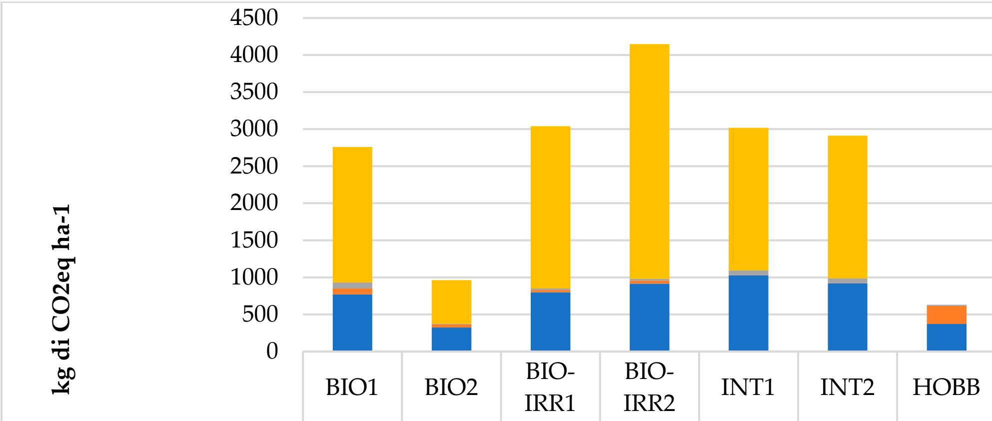


Figure 3. Global Warming of the entire life cycle in terms of kg of CO_2 eq per litre of bottled oil produced.

The GW analysis per hectare confirmed the sustainability of the hobby system and the major impacts of the BIO-IRR2 system (Figure 4).

The breakdown by single phase (Figure 4) showed that the most impacting phase, when present, was the packaging, followed by the agricultural phase, transport and lastly the processes that take place in the oil mill (milling, bottling and storage). Indeed, in all the analyzed systems, the impact of packaging represented more than 60% of the total impact. In particular, the analyzed farms respected market needs and demands, usually regional and national, but in some case international too. So, they used certain formats in place of others. Systems using the primary packaging showed the following behaviors: BIO1 used mainly the 3-litre tin (70%) and only a bit of the bottles; BIO2 used mostly 0.5 and 0.7-litre bottles (80%) and minimally the tins; BIO-IRR1 used mainly both tin formats (70%) and BIO-IRR2 principally the 5-litre tin (80%); INT1 and INT2 clearly prefer the 5-L tin (70%) too, and limitedly the bottles. Dark glass bottles were used to delay the oxidation processes favored by the light. HOBB system, which did not sell the oil, did not resort to any type of packaging but used a single plastic container for oil transport from the oil mill to the farm. Finally, only INT1 and INT2 used the secondary packaging, and specifically a recycled cardboard box with a 3-litre capacity.



	BIO1	BIO2	BIO-IRR1	BIO-IRR2	INT1	INT2	HOBB
Packaging	1827	589	2189	3166	1924	1925	0
Oil mill phase	80	8	22	24	61	61	16
Transportation Field - Oil mill	80	41	30	41	3	3	245
Agricultural phase	771	323	798	916	1030	922	370

Figure 4. Global Warming per phase of the production process. Values per hectare.

The agricultural phase refers to the operations of pruning, fertilization, weed control, irrigation, and harvesting. The analysis showed that, with reference to this phase, INT1 and INT2 were the most impacting systems (1030 kg of CO_2 eq ha^{-1} and 922 kg of CO_2 eq ha^{-1}, respectively) while BIO2 and HOBB were the most sustainable ones (323 kg of CO_2 eq ha^{-1} and 370 kg of CO_2 eq ha^{-1}, respectively) (Figure 4). Referring to INT1, the greatest impact was due to the two treatments of disease control (weed control with glyphosate) and fertilization with synthetic products. The INT2 system, at the same time, carried out a fertilization with synthetic products and four treatments of disease control.

BIO-IRR1 and BIO-IRR2, the only two irrigated systems among those analyzed, showed emissions of 798 kg of CO_2 eq ha^{-1} and 916 kg of CO_2 eq ha^{-1} respectively. Particularly, they owed most of their impact to soil tillage (shredding, green manuring, harrowing). Irrigation in these systems accounted for less than 10% of the impact of the agricultural phase.

4.2. Water Footprint

WF results are presented here first disaggregated among its components (green, blue, and grey) and then as total water consumption.

4.2.1. Green Water Footprint (WF_{green})

Table 5 reports yields and ET_{green} for the analyzed systems, and the WF_{green} expressed as m^3 per 1 kg of olives harvested and per 1 litre of olive oil produced.

Differences in WF_{green} between systems were due, on the one hand, to ET_{green}, essentially dependent on crop water requirement and rainfall specific of the production areas, and on the other hand to the yield of each analyzed system. So, Table 5 shows that the BIO2 system consumed more green water both for kg of olives harvested and for litre of olive oil produced (0.72 m^3 and 4.8 m^3, respectively), followed by the two INT systems. As expected, irrigated systems (BIO-IRR1 and BIO-IRR2) consumed less green water (Table 5).

Table 5. Green Water Footprint (WF_{green}) of the analyzed systems (ET_{green}: evapotranspiration).

Systems	Yield (kg Olives)	ET_{green} ($m^3\ ha^{-1}$)	WF_{green}	
			$m^3\ kg_{olives}{}^{-1}$	$m^3\ L_{oil}{}^{-1}$
BIO1	8300	2522	0.304	2.532
BIO2	3500	2522	0.721	4.804
BIO-IRR1	8400	2110	0.251	2.093
BIO-IRR2	8500	2110	0.248	2.069
INT1	8000	3790	0.474	3.644
INT2	8500	3790	0.446	3.430
HOBB	4300	2110	0.491	2.453

4.2.2. Blue Water Footprint (WF_{blue})

The WF_{blue} refers essentially to the volume of surface and groundwater consumed and was calculated from ET_{blue} plus the direct fraction (the water used in the treatments, irrigation, and milling process) and the indirect fraction (the water used in the manufacture of the different inputs used). Table 6 shows that BIO2 system, once again, consumed more blue water (0.27 $m^3\ kg^{-1}$ olives and 1.8 $m^3\ L^{-1}$ olive oil). Contrary to what one would expect, irrigated systems (BIO-IRR1 and BIO-IRR2) instead consumed less WT_{blue} (both 0.03 $m^3\ kg^{-1}$ olives and 0.2 $m^3\ L^{-1}$ olive oil), this because although they consumed water directly through irrigation, they had the lowest ET_{blue} per hectare (140 $m^3\ ha^{-1}$) (Table 6).

Table 6. Blue Water Footprint (WF_{blue}) of the analyzed systems. (ET_{blue}: evapotranspiration; Direct fraction: the water used in the treatments, irrigation, and milling process; Indirect fraction: the water used in the manufacture of the different inputs used).

Systems	Yield (kg Olives)	ET_{blue} ($m^3\ ha^{-1}$)	Direct Fraction ($m^3\ ha^{-1}$)	Indirect Fraction ($m^3\ ha^{-1}$)	Total ET_{blue} ($m^3\ ha^{-1}$)	WF_{blue}	
						$m^3\ kg_{olives}{}^{-1}$	$m^3\ L_{oil}{}^{-1}$
BIO1	8300	954	6.1	3.1	963	0.12	0.967
BIO2	3500	954	5.1	2.1	961	0.27	1.831
BIO-IRR1	8400	140	68.8	2.2	211	0.03	0.209
BIO-IRR2	8500	140	105.7	3.5	249	0.03	0.244
INT1	8000	1839	6.3	1.3	1847	0.23	1.776
INT2	8500	1839	6.4	1.3	1847	0.22	1.671
HOBB	4300	954	4.0	1.2	959	0.22	1.115

4.2.3. Grey Water Footprint (WF_{grey})

According to Hoekstra et al. [48], the grey component of WF was calculated considering only nitrogen fertilizers as they are the most critical fertilizers. Precisely, the use of nitrates in agriculture, usually at the base of nitrogen organic and chemical fertilizers, represented an important source of pollution in Europe, which was why in the 1990s the Nitrates Directive [73] took shape, which aims to control, improve, and protect the quality of surface and groundwater from pollution by nitrates from agricultural sources (mainly fertilizers and livestock effluents). Except to INT1 and INT2, which used synthetic fertilizers, fertilizers distributed in the other systems were all of natural origin, deriving from on-farm composting and livestock effluents (as in the case of BIO-IRR2).

As previously seen, WF_{grey} refers to the volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards. BIO-IRR2 was the system with the highest value of this component per kg of product (0.19 and 1.5 m^3, respectively) essentially due to the higher quantity of nitrogen used (240 kg ha^{-1}) (Table 7). At the same time, BIO2 was the system with the lowest WF_{grey} value (0.01 $m^3\ kg^{-1}$ olives and 0.06 m^3 $litre^{-1}$ olive oil) (Table 7).

Table 7. Grey Water Footprint (WF_{grey}) of the analyzed systems (α: the leaching run-off fraction; C*max*: the maximum acceptable concentration for the pollutant considered).

Systems	Yield (kg Olives)	Nitrogen Kg ha^{-1}	α	C max (kg m^3)	WF_{grey}	
					m^3 kg$_{olives}$$^{-1}$	m^3 L$_{oil}$$^{-1}$
BIO1	8300	10	0.10	0.015	0.02	0.152
BIO2	3500	12	0.10	0.015	0.01	0.064
BIO-IRR1	8400	120	0.10	0.015	0.10	0.667
BIO-IRR2	8500	240	0.10	0.015	0.19	1.569
INT1	8000	64	0.25	0.015	0.13	1.113
INT2	8500	64	0.25	0.015	0.13	0.629
HOBB	4300	24	0.10	0.015	0.04	0.187

4.2.4. Total Water Footprint (WF)

Total WF, differentiated between its components, is shown in Table 8. BIO2 was the system with the highest WF equal to 1.005 m3 kg^{-1} olives, followed by INT1 (0.839 m^3 kg^{-1} olives). On the contrary, BIO-IRR1 was the system with the lowest WF (0.388 m^3 kg^{-1} olives).

Table 8. Total WF broken down by its components (green, blue and grey) in the analyzed systems. Values are expressed in m^3 kg^{-1} olives.

Systems	WF GREEN	WF BLUE	WF GREY	Total WF
	m^3 kg^{-1} Olives			
BIO1	0.304	0.116	0.018	0.438
BIO2	0.721	0.275	0.010	1.005
BIO-IRR1	0.251	0.025	0.100	0.376
BIO-IRR2	0.248	0.029	0.188	0.466
INT1	0.474	0.231	0.134	0.838
INT2	0.446	0.217	0.126	0.789
HOBB	0.491	0.223	0.037	0.751

In BIO2, WF_{green} represented more than 70% of total WF, while in the other systems it represented more than 50%. However, this value transcends the farm's water use efficiency, as it was strongly influenced by climatic conditions. The WF_{blue} accounted for nearly 30% of the total WF in all analyzed systems, except in the irrigated systems, where this component represented only 7%, even if they used water to irrigate. At the same time, in these systems WF_{grey} was the second major component affecting WF, for the use of a consistent amount of nitrogen per hectare.

4.3. Economic Analysis

The life cycle analysis of the production of a bottle of olive oil also involved the analysis of the average annual costs, considering both fixed and variable costs, per hectare and per litre of oil. INT1 was the most expensive production system per hectare, followed by INT2, BIO-IRR2 and BIO-IRR1 (Table 9). In all systems, bottling and labelling were the most expensive operations representing from 21% (INT1) to 30% (BIO1) of the total costs. The second most expensive operation differed from system to system: in BIO1 and INT2 it was represented by the operations carried out in the oil mill; in BIO2, BIO-IRR1 and INT1 by the harvesting; in BIO-IRR2 by the disease control. A separate case was the HOBB system, where the most expensive operations were soil management and weed control and the other generic farm costs.

Table 9. Costs broken down by operation and by analyzed olive system. Values are in euro per hectare (€ ha^{-1}).

Operation	BIO1	BIO2	BIO-IRR1	BIO-IRR2 € ha^{-1}	INT1	INT2	HOBB
Farm Costs (Insurance, Taxes, Consortium Contributions, Interest on Working Capital, Overheads)	543	546	564	566	718	718	552
Pruning	343	380	328	242	444	444	227
Pruning residues management	275	31	249	230	82	82	29
Soil management and weed control	256	78	777	377	450	329	823
Fertilization	48	70	250	375	740	740	311
Disease control	72	152	403	1093	514	514	0
Harvesting	333	696	833	562	956	578	300
Oil mill	830	350	750	800	800	850	430
Bottling and Labelling	1152	850	1195	1248	1240	1250	0
Total	3853	3154	5349	5494	5945	5506	2672

Systems showing the highest production costs were those that made greater use of the market for the purchase of variable factors, especially synthetic fertilizers (INT1 and INT2) and pesticides (INT1), or carried out more operations (BIO-IRR1) or even carried out a mechanized harvesting. In systems that used compost, in some case self-produced (BIO-IRR1 e BIO-IRR2), fertilization represented on average 6% of total cost production.

The analysis of the costs per litre of oil confirmed the greater cost-effectiveness of HOBB and BIO1 systems (3.11 € L^{-1} and 3.87 € L^{-1}, respectively), while BIO2 system, characterized by the lowest yield (525 l ha^{-1} year^{-1}) was the most expensive (6.01 € L^{-1}) (Table 10).

Table 10. Final results of the analyzed systems.

Systems	GWP	WF		SLCA	Costs	
	kg CO_2 eq $L_{oil}{}^{-1}$	m^3 $kg^{-1}{}_{olives}$	m^3 $L_{oil}{}^{-1}$	%	€ ha^{-1}	€ $L_{oil}{}^{-1}$
BIO1	2.65	0.44	3.65	78	3853	3.87
BIO2	1.50	1.00	6.70	79	3154	6.01
BIO-IRR1	3.05	0.38	2.97	76	5349	5.31
BIO-IRR2	4.07	0.47	3.88	76	5494	5.39
INT1	3.39	0.84	6.53	86	5945	5.72
INT2	2.63	0.79	5.73	86	5506	4.98
HOBB	0.73	0.75	3.76	37	2672	3.11

4.4. Social Analysis

INT1 and INT2 were the most pro-social systems, reporting a score equal to 87% of the total points attributable (Figure 5). Specifically, these two systems fell both into a farm well integrated into the economy of the area under study, that employed above all socially disadvantaged people, characterized by a low level of literacy and education. The systems in question also had the largest number of non-EU employees, ensuring their social inclusion.

With respect to suppliers, all analyzed farms adopted correct behavior. They respected payment deadlines, delivery times, human rights along the entire supply chain. Furthermore, they were characterized by the absence of corruption and abuse of power, all important factors if we think that the studied territory falls within Campania, one of the Italian regions with the highest crime rate [74].

All the analyzed farms took part in all the commercial and social events organized by the institutions of the various territories in which they reside, becoming an active part of the socio-economic context in which they act.

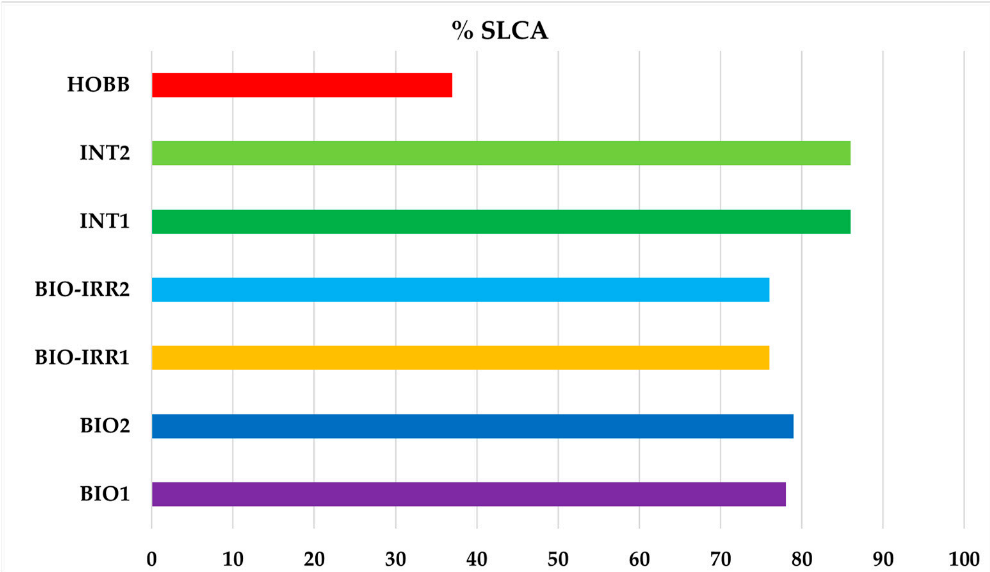


Figure 5. Distinction of the analyzed systems by percentage of Social Life Cycle Assessment (SLCA) sustainability.

Regarding the relationship with the final consumer, no farms among those analyzed guaranteed the consumer the possibility to trace the product along the entire supply chain and this is to the detriment of future customers, who are increasingly attentive to the healthiness of the products and their traceability. At the same time, however, all the analyzed farms, except the hobby one, sell their product on the regional and the national market, but some also on the international one, so they carry out chemical-physical analyses of the oil, guaranteeing its safety.

5. Discussion

In the light of the results obtained, the following reference framework emerged: HOBB and BIO2 were the systems that emitted less CO_2 eq; BIO-IRR1 and BIO1 were the systems with the smallest water footprint; from a social point of view, INT1 and INT2 were the most sustainable systems; and referring to costs per litre of oil, HOBB and BIO1 were the systems with the lowest production costs (Table 10). Overall, BIO1 was in absolute the most sustainable system under the various aspects considered, namely a certified organic system characterized by: manual pruning; pruning residues used as soil mulching; annual organic fertilization with on-farm compost; disease control with organic products; temporary natural grasses as ground cover and weed control by one disk harrowing; mechanized harvesting.

The adoption of organic production systems has proven effective in reducing the impacts and costs related to fertilization and the use of cover crops can enhance soil quality and biodiversity [75]. The results show that the integrated systems (INT1 and INT2) incurred higher fertilization costs due to the higher costs of synthetic fertilizers. Hence the need to encourage farms to self-produce production factors as much as possible (e.g., on-farm composting of agricultural residues) since, from the study carried out, systems that use organic fertilizers or self-produced soil improvers showed significantly lower impacts and production costs than the others.

The agricultural phase, the second most impactful step of the entire analyzed olive oil chain, showed another drawback due to the emissions and the related environmental impacts linked to the use of diesel that powers agricultural machinery.

Packaging was the first impactful phase. The LCA analysis showed that the impact of packaging, when present, was more than 60% of the total impact. In particular, the 3-litre tin, in addition to being the type of packaging most used by the farms under study, was also the most impactful one (on average 2.11 kg of CO_2 eq L^{-1}). So, as an environmental saving intervention it is suggested to replace 3 and 5 litre tins with alternative envelopes less impacting, as the Bag-in-box, whose emissions amount to 0.159 kg of CO_2 eq L^{-1}.

Another aim of this research, one of its novelties, was the classification of the seven analyzed olive oil systems, as already pointed out very different from each other (Table 1), in sustainability classes such as the model described by Schau et al. [42]. According to this classification, BIO1, BIO2, BIO-IRR1, INT2 and HOBB systems fall into category A (BEST). The INT1 system is placed in class B and the BIO-IRR2 system in category C, whose impact was essentially due to the packaging, and in particular to the predominant use of 5-litres tins.

Furthermore Schau et al. [42] affirmed that olive production takes place in areas where water resources are limited and full volumes of irrigation of olive groves (about 3000 m^3 ha^{-1} $year^{-1}$) has major contribution to the water withdrawal in those areas. At the same time, as mentioned earlier, the use of alternative waters for olive irrigation can be a tool to be considered to face water scarcity [12,13]. On the contrary, the results of the present research showed that emergency irrigation, which BIO-IRR1 and BIO-IRR2 systems used and that was equal to a maximum of 100 m^3 ha^{-1} $year^{-1}$, did not involve an important environmental and economic detriment, but contributed to a more balanced growth of the crop. Moreover, the WF values found in this study were lower than those of other researches and, WF_{green} was the most important component of WF [39,76–79]. Indeed, as said by Raluy et al. [80], WF results vary significantly within the same tree type for the different local edaphoclimatic conditions, tree management models as well as methodological choices adopted in the WF calculation. At the same time, the calculation of the WF for orchard trees seem to be important for accounting/inventory of the green water component, the impact assessment of the green water component, to choose the better estimation method used for the ET, and the spatial and time resolutions. So, the procedure to calculate the green water consumption can influence the results and, therefore, efforts should be made to harmonize the inherent concepts [80].

Differently from the blue and green water components which are strictly dependent on climatic conditions, the grey component, reaching from a minimum of 27% (BIO-IRR1) to a maximum of 40% (BIO-IRR2) of the total water footprint, is the only one which the producer can control. So, in the analyzed systems it is recommended to adopt a balanced organic fertilization to limit the release of nitrogen pollutants into the water, maybe by also adopting cover crops during winter-spring for nitrogen nutrition and slow mineral release for the olive roots or the use of composts [81].

The social analysis, one of the three pillars in the evaluation of sustainability [65], was the absolute novelty of this research. According to this analysis, all the studied systems are positively integrated in the territory in which they operate. Though SLCA is widely applied in different sectors (agriculture, bioenergy, transport, water management, chemical products, electronics, etc.) mainly in non-European countries [64], there is still a long way to reach the scientific maturity of this procedure [68]. Indeed, SLCA allows to identify key issues, assesses, and tells the story of social conditions in the production, use and disposal of products [71]. On the other hand, critical questions remain to be resolved concerning methods, framework, paradigms, and indicators [64] to compare different products or products belonging to the same product sector and make improvements where necessary. Arcese et al. [71] stated that there is the need to develop impact subcategories to assess a) the contribution of the effects on the society of the link between production and territory, very strong in the agri-food sector; b) the socio-economic impact of the product quality on consumers, in terms of usage experience. To our knowledge, this is difficult to do due to the extreme variability of the contests in which the various firms operate, above all in the agriculture context.

6. Conclusions

This research wants to give a contribution in the development of case studies in the olive oil sector on the applicability and usefulness of footprinting tools to promote the spread of sustainable agricultural systems from an environmental, economic, and social point of view, encouraging producers to improve the efficiency of production processes.

Some considerations addressed in the discussion section emerged from the analyses, ranging from the need to spread more and more (a) organic production methods, characterized above all by the use of self-produced fertilizers (on-farm compost); (b) the use of more efficient machines, for saving fuel; (c) a more balanced nitrogen fertilization to lower the water footprint.

Nowadays it is impossible to think to produce without polluting or consuming resources. Hence the need to develop estimative methodologies of economic, social and carbon balance, to understand if an analyzed system is actually impacting and therefore needs improvements or is already per itself sustainable, because it stores carbon, provides for improvement actions, and so on.

Author Contributions: Conceptualization, G.C.; methodology, A.M. and M.P.; software, A.M. and M.P.; validation, G.C.; formal analysis, A.M.; investigation, G.A.; resources, G.C.; data curation, A.M.; writing—original draft preparation, M.P.; writing—review and editing, A.M. and A.M.P.; visualization, G.C., G.A., A.M.P., A.M. and M.P.; supervision, G.C. and M.P.; project administration, G.C.; funding acquisition, G.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The research was partially supported by "PSR Campania Region 2014–2020, Modelli Project". We are grateful to Paola De Conciliis, Giuseppe Cilento, Edmondo Soffritti, Angelo Petolocchio, and Mario Di Bartolomeo for giving us access to their field data.

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

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