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Research Article

Mediterranean Cropping Systems: The Importance of Their Economic and Environmental Sustainability

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Abstract

The COVID-19 pandemic has drastically changed the lives of people, as well as the production and economic systems throughout the world. The flow of raw materials and products, the supply of labor and manpower, and the purchasing power have all been changed to the detriment of individual health and well-being. Such a situation requires placing even more emphasis on the search for virtuous agricultural systems compatible with the goals of economic and environmental development so clearly defined at the world level in the last decades. The present study aimed to assess the environmental and economic performance of some typical Mediterranean crops grown under different agronomical management regimes, such as strawberry, hazelnut, apricot tree, kiwifruit, peach, olive tree, and grapevine, to emphasize the importance of the mentioned issues even in the current pandemic situation. Life cycle assessment (LCA) was used to investigate the environmental profile of the studied crops, while lifecycle costing (LCC) was performed to assess and compare the economic aspects. From the environmental perspective, the hobby-organic olive systems were the most eco-friendly cropping systems, emitting 0.031 to 0.105 kg CO_2eq per kg olives, while the organic hazelnut system had the greatest impact (1.001 kg of CO_2eq per kg). Apricot, kiwifruit, and peach systems used N and P inputs most effectively, while strawberry systems efficiently used fossil fuels. Olive HO-2, kiwifruit, and peach cropping systems had the lowest budgets, with the costs amounted to 0.12 € kg^{-1} per fruit for Olive HO-2 and 0.28 € kg^{-1} per fruit for both kiwifruit and peach. On the contrary, organic strawberry cultivation was the most expensive (4.77 € kg^{-1}). The variability in results due to the large differences between contexts, such as landscape, technical knowledge, and crop management, characterized the studied agricultural systems. To easily identify sustainability classes and to diminish the impact of farming practices, a considerable effort should be expended to combine LCA with LCC, C sequestration estimates, and some other useful indicators for the environmental quality evaluation.

Keywords
Life cycle assessment; life-cycle costing; environmental standards; sustainability indicators

1. Introduction

The Sustainable Development Goals of the 2030 Agenda, established in 2015, were adopted as a universal call to counteract poverty, protect the earth, and improve the lives and prospects of everyone, everywhere. A total of 17 Goals and 169 Targets are intended to stimulate significant actions over the next ten years in areas of critical importance for humanity and the planet. This agenda aims to protect the latter from degradation using the systems of sustainable consumption and production to manage its natural resources and take urgent actions to combat climate change so that the needs of the present and future generations can be met [1]. Goal 2 and 15 are particularly of interest to agricultural and environmental sections. While the latter entirely focuses on the role played by agriculture for the use of resources, in the second goal, point 2.4 has the greatest significance [1].

In this context, according to the Paris Agreement [2], Italy has undertaken some measures to reduce the emissions of greenhouse gases in the atmosphere with the aim of keeping global warming below 2 °C compared to pre-industrial levels and to pursue the action aimed at limiting the temperature increase to 1.5 °C compared to pre-industrial levels. In particular, the circular economy is assumed as the basis for sustainable growth and, most importantly, for the reduction of greenhouse gas emissions. Thus, Italy has adopted a general document, as well as the circular economy strategic framework positions, called "Toward a model of circular economy for Italy", and a specific document on the indicators suggested to measure economic efficiency in terms of circular economy [3]. With regard to the latter, the increase in the use of methods to calculate the environmental footprints in the policies and programs relevant to the measurement or communication of environmental performance during the life cycle of products (Product Environmental Footprint-PEF) or organizations (Organization Environmental Footprint-OEF), seems very important. Furthermore, Italy already established a voluntary national scheme for the assessment and communication of the environmental footprint of products, called “Made Green in Italy”, based on the PEF method and aimed to promote high environmental qualification products [4].

The basis for the development of PEF and the Environmental Product Declaration (EPD) is life cycle assessment (LCA), a cradle-to-grave methodology to assess products, processes, services, activities, and systems. LCA was developed in the 1970s but standardized by the ISO 14040 series in the late 1990s [5]. Designed essentially for the industrial sector in recent years, it has been widely applied to the agricultural sector. LCA has been proven as a valuable tool to address the questions about the environmental impact of various agricultural production systems [6], resting on both the identification of the subsystems that contribute most to the total environmental impact of the systems and the comparison of products and processes with same functions [7-13]. Nienhuisen de Vreede, Kramer et al., van Woerden, Halberg et al., Foteinis and Chatzisymeon, and Ronga et al. [14-19] assessed the LCA profile of organic and conventional vegetables. Nicoletti et al. [20] and Villanueva-Rey et al. [21] applied LCA to investigate the environmental impact of organic/biodynamic and conventional wine-growing systems. A wide range of reviews of the challenges of LCA applications in the fruit-growing, specifically the olive-growing sector, can be found in the findings published by Cerutti et al. [22] and Espadas-Aldana et al. [23].

The actual COVID-19 pandemic caused the global trade to collapse, with a negative impact on the structure of the agricultural production that is not self-sufficient in Italy and the consequent difficulty in procuring raw materials for the production of basic goods. Furthermore, lockdown periods and border closures have caused a sudden shortage of labor, especially the seasonal workers [24].

Although COVID-19 likely represents a tremendous shock to the global economy, FAO argues that in the short term, the real cost of a healthy diet could increase due to the rising cost of perishable raw materials, which would have a particularly negative impact on low-income families and raise the price of progress toward sustainable development goals [25]. Therefore, the question of “How important is the environmental sustainability of agricultural products and practices in the current pandemic situation?” should be addressed.

Is LCA a useful assessment tool for agricultural systems or must it be combined with other sustainability indicators? Can the combination of these above-mentioned procedures help define sustainability classes for wise choices of agricultural plans by farmers? In line with the European Green Deal, it is very important to reduce the impact of farming practices. Hence, the present research was conducted with the aim to evaluate the environmental and economic sustainability of some typical Mediterranean crops such as strawberry, hazelnut, apricot, peach, kiwifruit vines, olive trees, and grapevines. Twenty-one cropping systems located in two regions of Italy, Campania and Basilicata, were specifically analyzed. The combination of LCA with additional environmental indicators and the Life Cycle Costing (LCC) method was used for the environmental and economic evaluation of the investigated cropping systems.

2. Description of the Analysed Cropping Systems

The study was carried out in Campania and Basilicata regions located in Southern Italy, where fruit growing represents one of the most important productive sectors. The analysed cropping systems were the following::

- Three strawberry growing systems including conventional (Strawberry C), integrated (Strawberry I), and organic (Strawberry O);
- Three hazelnut growing systems including conventional (Hazelnut C), integrated (Hazelnut I), and organic (Hazelnut O);
- Three apricot growing systems including two integrated (Apricot I-1, Apricot I-2) and one biodynamic (Apricot B);
- One integrated kiwifruit growing system (Kiwi I);
- One integrated peach growing system (Peach I);
- Six olive growing systems including two certified as organic (Olive O1, Olive O2), two integrated (Olive I-1, Olive I-2), and two organic-hobbyists (Olive HO-1, Olive HO-2);
- Four vineyards growing systems, including two organic (Grapevine O-1, Grapevine O-2), one integrated (Grapevine I), and one conventional (Grapevine C).

The main features of the investigated cultivations systems are represented in Table S1 and Table S2. Data were collected by direct interviews with farmers, with a specific data collection sheet, visiting farms, and consultation on field notebooks. The investigated crop systems differed in the average yield, the duration of the production process, the plant density, the training system (specific to each crop), the presence/absence of irrigation activities, covering and supporting structures, the types of pruning, management of pruning residues, fertilization, soil management, disease control, and harvesting (manual or mechanized) and cultivation methods (conventional, integrated, organic, biodynamic, and hobbyist). With respect to these methods, the integrated system is the most widely used in the studied contexts, and it produces high-quality crop yields. It particularly follows specific protocols [26] to manage fertilization and control pests and diseases using both chemical and natural products.

Moreover, although the biodynamic cultivation system is less widespread, it is an alternative form of organic agriculture that contributes to soil fertility, plant growth, and livestock care and treatment as ecologically interrelated tasks, emphasizing spiritual and mystical perspectives [27]. Hobby farming refers to agronomical systems managed by subjects external to agricultural activity (in terms of time and income) who dedicate their free time to crops cultivation [28].

3. Materials and Methods

A detailed analysis was performed to estimate the environmental impacts and calculate the production costs using the LCA approach, according to the ISO 14040-44:2006 [5]. Each of these two analyses was articulated in four interrelated phases, including the goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation.

3.1 Goal and Scope Definition

The aim of the analyses performed in the present study was to evaluate the environmental and economic sustainability of the production of several Mediterranean crops. Following the suggestions made by Maffia et al. [29], Pergola et al. [30], Cerutti et al. [31], and Milà i Canals et al. [13], the entire life cycle of each system was analyzed. Since each investigated cropping system had a specific duration of the production process, shown in Table S1 and Table S2, the reference period of the analysis was set to the end of each production cycle, except for the olive groves. In this case, only one year of the production process was studied because olive trees are secular, and therefore their cradle-to-grave life cycle assessment is out of the question. Moreover, olive tree explanting is forbidden in Italy, except when a) the physiological death of the plant and the permanent unproductivity or low productivity occur due to non-removable causes, b) the excessive plant density causes damage to olive groves, and c) olive trees felling becomes indispensable for the execution of land development schemes [32]. The four main stages of farming - soil preparation and trees plantation, trees growth phase, full production phase, and trees explant - were taken into account. Some crops referred only to one year of production (strawberries, due to their annual nature, and olive, as already explained), so to equate and better compare all the investigated crops, the analyses were also performed on one year of full production. The system boundaries (Figure 1) went from the extraction of raw materials of inputs and machines to the farm gate (fruit harvesting) because the main goal of the study was to compare the stages of agricultural production. All inputs, including fuel, lubricants, fertilizers, pest control products, water, materials for setting up the irrigation system, etc., were included considering their manufacturing processes. The transport of inputs was excluded from the analysis only due to the availability of missing datasets. As the functional unit (FU), the reference unit based on which all data were analysed and characterized [5], 1 kg of harvested fruits, as well as 1 hectare of the farmland, were chosen to improve the interpretation of environmental and economic results [29-31, 33].

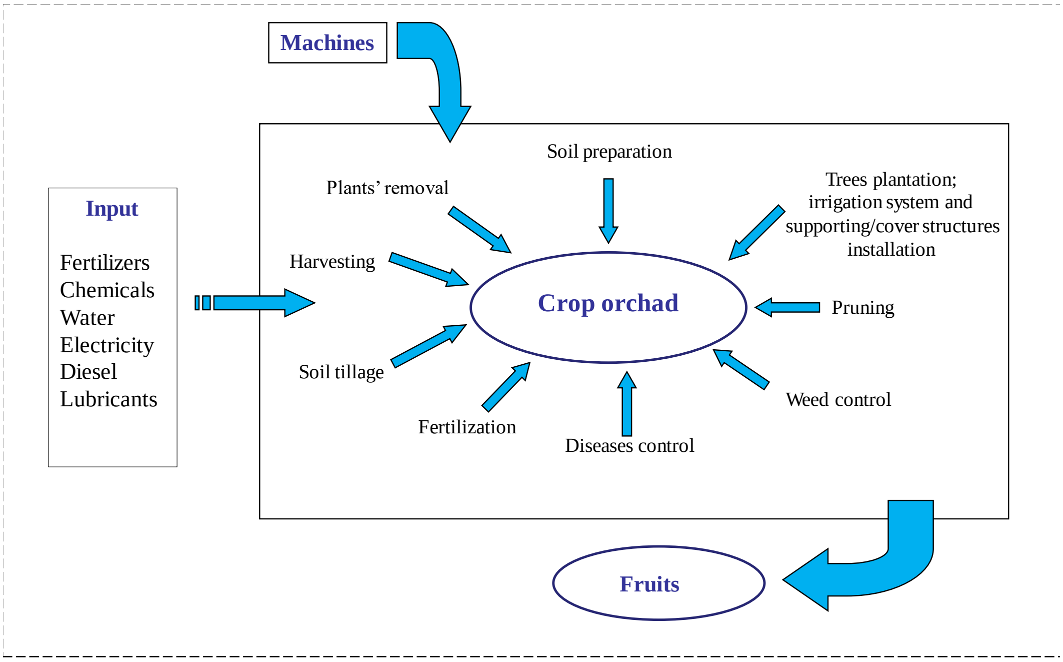

Figure 1 The system boundaries for the life-cycle assessment (LCA) and the life-cycle costing (LCC) analysis of the investigated cropping systems.

3.2 Life-Cycle Inventory

Primary data on the features of the investigated crops, amounts of fertilizers, chemicals, diesel fuel, water, and other items were collected *in situ* during the last five agricultural years within technology transfer/dissemination programs for some Italian (at national and regional levels) and European projects using a data collection sheet. The farming operations such as plantation (soil preparation, pre-plant fertilization, tree plantation, etc.), soil tillage, fertilization, disease control, irrigation, other operations specific to each crop, harvesting, and explants of trees at the end of their life cycle, were taken into account. Farm inputs used in the investigated cropping systems during each reference period are reported in Table S3 and Table S4. As in previous studies [29, 30], the use of primary data, in terms of material input types and the amounts used, should be given priority. Additionally, to estimate direct and indirect emissions, the active ingredient of each product, as well as the amounts of the consumed fuel, water, and energy, were calculated and used in the analyses for each operation as a standard practice in LCAs.

The calculation of direct emissions, especially those from fuel and lubricants, was performed using SimaPro’s LCI databases. For the estimation of those from fertilizers, as already explained in previous studies [29, 30], the no entire mineral balance study was undertaken. It is often difficult to calculate the exact rates of N released into the air and water because emission rates can greatly vary depending on soil type, climatic conditions, and agricultural management practices. However, nitrogen emissions from the cultivation were considered according to Brentrup et al. [34] and IPCC [35]. Emissions of synthetic pesticides released into the air, surface water, groundwater, and soil were estimated according to the method suggested by Hauschild [36], as reported in studies published by Maffia et al. [29], Pergola et al. [30], and Milà i Canals et al. [13].

The embodied emissions, namely secondary data, were extrapolated from international databases of scientific importance and reliability, like Ecoinvent 3 [37]. In particular, the extrapolation was done for the production of electricity, diesel, lubricants, fertilizers, and pesticides used in the investigated systems, along with the resulting emissions and the construction of agricultural vehicles and fixed structures such as irrigation systems and supporting and covering structures, as described in the study carried out by Pergola et al. [30].

3.3 Life Cycle Impact Assessment

The impact assessment was performed using SimaPro 8.02, with the problem-oriented CML method developed by the Institute of Environmental Sciences of the University of Leiden [38]. The impact categories, including abiotic depletion (AD), abiotic depletion (fossil fuels) ($AD_{\text{fossil fuels}}$), global warming potential (GWP) or climate change, photochemical oxidation (PO), ozone layer depletion (OLP), human toxicity (HT), freshwater aquatic ecotoxicity (FWE), marine aquatic ecotoxicity (MAE), terrestrial ecotoxicity (TE), acidification of air (AA), and eutrophication (EU), were considered according to the selected method.

3.4 Additional Environmental Indicators

As affirmed by Tabatabaie and Murthy [39], the use of LCA to estimate the environmental impacts in several categories is not always easy to understand for non-experts. Therefore, three additional indicators that may be more accessible to the general public and provide useful information about sustainability of crop production were included. These indicators are the nitrogen productivity (NP), phosphorous productivity (PP), and fossil-fuel productivity (FEP), which indicate the use efficiency of nitrogen ($\text{kg}_{\text{harvested fruit}}\text{N}_{\text{ha}}^{-1}$), phosphorous ($\text{kg}_{\text{harvested fruit}}\text{P}_{\text{ha}}^{-1}$), and fossil materials ($\text{kg}_{\text{harvested fruit}}\text{kgdieselha}^{-1}$), respectively, by each cropping system. To calculate these additional indicators, the same life cycle inventory described for LCA (Table S3 and Table S4) was used. The methodological details are reported in the study conducted by Tabatabaie and Murthy [39].

3.5 Production Cost Analysis

The Life Cycle Costing (LCC) method was applied to evaluate the production cost of the studied cropping systems. LCC is a complementary tool for an economic analysis of the operations comprising the supply chain of a product or service [40]. Additionally, it does not have a standardization framework, though the use of life cycle methods, like LCA, according to the ISO 14040-44:2006 can be extended to the economic aspects [5]. Therefore, to combine the LCC and LCA findings, the analysis was performed using the same system boundary (Figure 1), from soil preparation and trees plantation to trees explant, and the same life cycle inventory described for LCA (TableS3 and Table S4). 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 [41]. Therefore, 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, the analysis indicated the four main stages of the life cycle of crop farming, including soil preparation and trees plantation, trees growth, full production, and trees explant, when applied, as explained in Section 3.1. For each phase, the main types of cultivation management practices were identified, along with the associated fixed and variable costs. Consequently, to perform a complete economic analysis, which was consistent with the LCA analysis, and to understand the importance of each cost item, the cumulative costs of crop production were evaluated for each year considering the expenses throughout the whole life cycle of the systems related to materials, labor, services, quotas, and other duties. Materials included the cost of all non-capital inputs such as fertilizers, pesticides, herbicides, fuels, water, electricity, and other crop-specific requirements; labor included the cost of workers involved in farm production; quotas and services included machinery, equipment, depreciation costs, and interests in circulating and anticipation capital [42]. To calculate the total costs of each investigated crop during its production cycle, the annual costs related to 2020 were indexed and aggregated using rate anticipation ($1/q^{n}$), in which n refers to each year of cultivation and q represents an indexing factor, whose interest rate was assumed to be equal to 2%. All indexed costs were then added together. Further details on the above-mentioned methodologies are provided in a study conducted by Pergola et al. [43].

4. Results and Discussion

4.1 Environmental Impacts per kg of Fruit

Life cycle impacts per kg of the harvested fruit are presented in Table 1. The most eco-friendly crop systems were the hobby-organic olive orchards (Olive HO-1 and Olive HO-2) for all impact categories. Apricot B had the highest impact in the abiotic depletion category, mainly for the consumption of resources for the greenhouse construction. All Hazelnut orchards showed significant impacts on the categories of abiotic depletion$_{\text{fossil fuels}}$, global warming potential, freshwater, and marine aquatic ecotoxicity, photochemical oxidation, and eutrophication, mainly due to the fertilization and weed/disease control. Strawberry C was the most impactful cropping system in the ozone layer depletion category, essentially for the operation of soil sanitization. Kiwifruit I showed the largest impact on the human toxicity category, mainly due to the use of copper for disinfection of pruning wounds. Apricot B and Kiwifruit I systems had the greatest impacts in the terrestrial ecotoxicity category, for the presence of dispersion tubes made of zinc in the former and the use of copper in the latter. Grapevine C, along with Hazelnut C, were the most impactful systems, with regard to air acidification, caused mainly by fertilization.

Table 1 Total impacts per kg of product for the investigated cropping systems along the entire life cycle (AD: abiotic depletion; $AD_{\text{fossil fuels}}$: abiotic depletion fossil fuels; GWP: global warming potential; OLP: ozone layer depletion; HT: human toxicity; FWE: freshwater aquatic ecotoxicity; MAE: marine aquatic ecotoxicity; TE: terrestrial ecotoxicity; PO: photochemical oxidation; AA: air acidification; and EU: eutrophication)

	AD kg Sb eq	$AD_{\text{fossil fuels}}$ MJ	GWP kg CO_2eq	OLP kg CFC-11 eq	HT kg 1,4-DB eq	FWE kg 1,4-DB eq	MAE kg 1,4-DB eq	TE kg 1,4-DB eq	PO kg C2H4 eq	AA kg SO2 eq	EU kg PO4---eq
Strawberry C	0.000	7.104	0.382	0.000	0.317	0.118	403.132	0.002	0.000	0.003	0.005
Strawberry I	0.000	3.920	0.286	0.000	0.092	0.034	110.875	0.000	0.000	0.003	0.002
Strawberry O	0.000	7.373	0.410	0.000	0.353	0.201	527.620	0.001	0.000	0.003	0.003
Hazelnut C	0.000	7.234	0.917	0.000	1.119	0.507	1380.381	0.001	0.000	0.016	0.008
Hazelnut I	0.000	6.842	0.719	0.000	0.750	0.332	911.553	0.001	0.000	0.011	0.006
Hazelnut O	0.000	13.399	1.001	0.000	0.704	0.298	892.169	0.001	0.000	0.010	0.005
Apricot I-1	0.000	3.490	0.277	0.000	0.642	0.083	281.846	0.001	0.000	0.002	0.002
Apricot I-2	0.000	4.177	0.350	0.000	0.882	0.098	333.623	0.002	0.000	0.003	0.002
Apricot B	0.000	4.409	0.321	0.000	0.327	0.169	536.834	0.004	0.000	0.003	0.002
Kiwi fruit I	0.000	1.621	0.289	0.000	2.845	0.208	770.617	0.005	0.000	0.002	0.001
Peach I	0.000	1.408	0.136	0.000	0.024	0.006	40.295	0.000	0.000	0.002	0.000
Olive O1	0.000	1.514	0.109	0.000	0.464	0.072	219.344	0.001	0.000	0.001	0.001
Olive O2	0.000	1.645	0.119	0.000	0.660	0.061	205.778	0.001	0.000	0.001	0.001
Olive I-1	0.000	2.274	0.151	0.000	0.326	0.040	149.928	0.001	0.000	0.001	0.001
Olive I-2	0.000	1.933	0.126	0.000	0.308	0.050	151.384	0.001	0.000	0.001	0.000
Olive HO-1	0.000	1.028	0.105	0.000	0.023	0.006	15.105	0.000	0.000	0.001	0.000
Olive HO-2	0.000	0.434	0.031	0.000	0.017	0.005	10.532	0.000	0.000	0.000	0.000
Grapevine O-1	0.000	1.828	0.162	0.000	0.055	0.010	69.142	0.000	0.000	0.002	0.001

Grapevine O-2	0.000	2.756	0.197	0.000	0.984	0.087	318.517	0.002	0.000	0.002	0.001
Grapevine I	0.000	4.783	0.395	0.000	0.100	0.033	83.745	0.000	0.000	0.003	0.001
Grapevine C	0.000	5.291	0.647	0.000	0.671	0.284	790.993	0.001	0.000	0.014	0.005

With respect to GWP, the hobby-organic olive systems (Olive HO-2 and Olive HO-1) were confirmed to be the most sustainable crop systems, emitting CO_2 eq within the range of 0.031 to 0.105 kg per kg of olives (Figure 2). Conversely, the Hazelnut O system was found to be the most impactful (1.001 kg of CO_2 eq per kg), not due to the cultivation management but the lower productivity of this crop (2200 kg ha^{-1} year^{-1}). From the perspective of the life cycle, the most impactful crop systems per hectare were Grapevine C (119,797 kg of CO_2 eq ha^{-1}), Kiwifruit I (112,621 kg of CO_2 eq ha^{-1}), and Apricot B (109,245 kg of CO_2 eq ha^{-1}), due to fertilization in the first two cases, and soil preparation practices, including tree plantation, irrigation system, and installation of supporting/cover structures in the latter. Considering the annual impacts, Strawberry C was the most impactful cropping system (14,506 kg of CO_2 eq ha^{-1} year^{-1}).

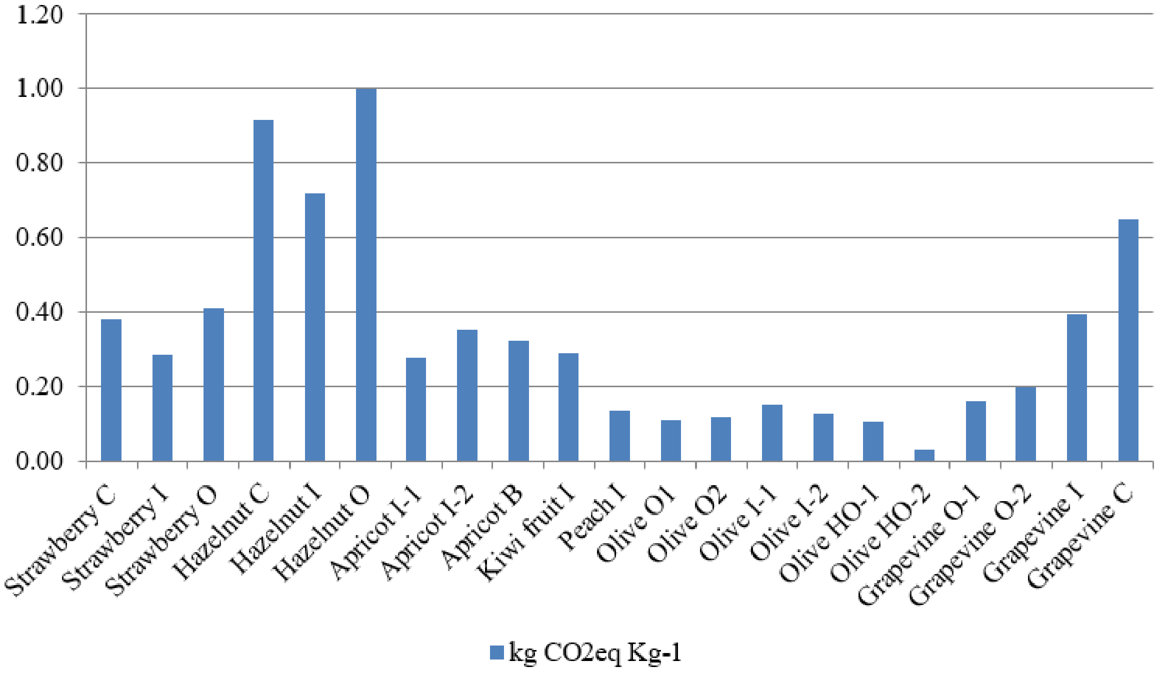

Figure 2 Estimation of global warming potential (GWP) for each cropping system.

According to these results, firstly, it needs to be taken into consideration that in LCA studies, the choice of FU is very important, and results of the analysis per 1 kg of product are not always reliable, since to equal impacts per hectare, the less productive crops result more impactful.. Secondly, differences in production practices and yields can cause large variation in GWP [39], but also the different methods for the calculation of emissions, the system boundaries (whether certain agronomical operations such as plantation, irrigation, and installation of supporting/cover structures should be considered or not), and the life span of cropping systems (whole production cycle *vs* 1 year of cultivation). For example, the impact per kg of the harvested apricots found in the present study was higher than the available data in the literature: Page et al. [44] reported that an intensive organic apple system impacted for 0.09 kg CO_2eq kg^{-1}, while a semi-intensive apple system had an impact of 0.11 kg CO_2eq kg^{-1}, and an organic kiwifruit system in New Zealand impacted for 0.13 kg CO_2 eq kg^{-1}. At the same time, CO_2 eq emissions per kg of product for the cultivation of kiwifruit were similar to those found for pears (0.140 kg CO_2 eq kg^{-1}) in a study published by Liu et al. [45]. Emissions per kg of peaches (0.124 kg CO_2eq kg^{-1}) were similar to those found for peach tree by Vinyes et al. [46] in Spain (0.139 kg CO_2eq kg^{-1}), by Milà i Canals et al. [13] for the cultivation of apples (0.120), and by Pergola et al. [44] in conventional cultivation of lemons and oranges (0.12 and 0.13 kg CO_2eq kg^{-1}, respectively), but less impacting than those found by Ingrao at al. [47] for an integrated peach orchard (0.23). $^{---}$ Emissions produced in olive systems (Olive HO-2 and Olive HO-1), ranging from 0.031 to 0.151 kg CO_2 eq kg^{-1}of olives, were lower than those reported in a review of 23 relevant LCA studies on olive oil production and olive trees cultivation (0.224 to 0.489 kg CO_2 eq kg^{-1} of olives), carried out by Espadas-Aldana et al. [23]. Tabatabaie and Murthy [39] observed that the GWP for strawberry production varied from 1.75 to 5.48 kg CO_2 eq kg^{-1} in California, Florida, North Carolina, and Oregon, while Mordini et al. [48] affirmed that in several countries, e. g., Spain, U. K., Japan, this value ranged from 0.27 to 3.99 kg CO_2 eq kg^{-1}. The strawberry cultivation in our experiment resulted in the production of emissions ranging from 0.286 to 0.410 kg CO_2 eq kg^{-1}, indicating more sustainable production than those found in other countries. With regard to the wine sector, Bosco et al. [49] reported that the agricultural phase covered an average of 22% of the total GWP per bottle, while the industrial phase was the relevant stage. Consistent with these data, Notarnicola et al. [50] and Point [51] observed that the agricultural phase accounted for 20%, while Gazullaet al. [52] reported it as the most relevant stage of the life cycle, covering almost 50% of GHG emissions associated with the whole life cycle of wine production. Our results are in line with those presented by Vázquez-Rowe et al. [53], except for Grapevine C, whose emissions (0.647 kg CO_2 eq kg^{-1} of grapes) made it more impactful. Finally, Volpe et al. [54] found that the cultivation of almond, hazelnut, and pistachio produced emissions of 2.30, 1.29, and 2.53 kg CO_2 eq kg^{-1} of fruit, respectively. However, lower emission levels were obtained by Sabzevariet al. [55] in a comparative environmental assessment of hazelnut production in three different orchard sizes (<1 ha, 1-3 ha, and >3 ha) in Iran (0.775, 0.666, and 0.750 CO_2 eq kg^{-1} of fruit, respectively). Under our experimental conditions, emissions produced from the hazelnut systems ranged from 0.719 to 1.001 CO_2 eq kg^{-1} of unshelled hazelnuts (Table 1).

Such results highlighted a need to harmonize the approaches to be followed in applying the LCA methodology within the agricultural sector.. The great variability in the agronomic technologies and practices used does not allow to define the standards above which crop systems have to be considered impacting. Moreover, special attention must be given to C sequestration by the whole agricultural systems, both soil and plants, and in particular, those consisting of perennial crops. Aguilera et al. [56] observed low levels of N_2O emissions associated with organic fertilizers and higher soil organic carbon (SOC) stocks in organically managed soils under Mediterranean climatic conditions. González-Sánchez et al. [57] found the C sequestration rates of 1.59 and 0.35 Mg C ha^{-1} in Spanish cover cropped orchards in short-term (<10 years) and long-term experiments (>10 years), respectively. Based on the CO_2 balance approach, calculated as the difference between the "global warming" impact category and the total C-CO_2 fixed by soil and trees in the studied systems, Pergola et al. [30] showed that the Ninfa Bio orchard (now Apricot B) was the most environmental sustainable system. Although the construction of the greenhouse resulted in a release of large amounts of CO_2 eq (124.6 tons ha^{-1}), the capacity of Apricot B to store CO_2 (204.3 tons of CO_2 ha^{-1}) made it very virtuous. In another research, we observed that Peach I, trained to transverse Y, sequestered on average 329 tons of CO_2 ha^{-1} (153 tons of CO_2 ha^{-1} in tree structures consisting of above-ground and below-ground parts and 176 tons of CO_2 ha^{-1} in the soil) in a 15-years period. The mean annual CO_2 sequestration by Peach I was 22 tons CO_2 ha^{-1} (12 tons of CO_2 ha^{-1} in soil). On the contrary, Kiwifruit I, trained to "Pergola", in 20 years, sequestered 425 tons of CO_2 ha^{-1} in total, 56% of which in the tree structures. Both crop systems seemed to be environmentally sustainable if their CO_2 storage capacities are compared to CO_2 eq released through their management systems (75 and 50 tons of CO_2 eq ha^{-1} for Kiwifruit I and Peach I, respectively). All these confirmed that soil carbon sequestration is an important and immediate strategy to remove atmospheric carbon dioxide and slow global warming [44]. Therefore, CO_2 emissions and sequestration, and other environmental indexes, like biodiversity [58, 59], should be considered to define adequate sustainability classes to look beyond the pandemic and build back better and more resilient food systems.

4.2 Environmental Impacts related to Agricultural Operations

The analysis of GWP for each cultivation operation showed that among the studied systems, the most impactful operations were irrigation and fertigation, fertilization, weed control, and soil tillage. Other detrimental factors for the environment were the irrigation system and the installation of supporting/covering structures, particularly when there were many plastic, zinc, and concrete elements, as in Apricot B and Strawberry systems; the presence of greenhouse was responsible for 63% of the total CO_2 eq emissions in the former and 20% (on average) in the latter.

The breakdown of impacts by production factors revealed that in 16 cropping systems, fuel consumption was the major cause of the total CO_2 eq emissions, being about 50% in Apricot I-1, Apricot I-2, Peach I, Olive O1, Olive O2, Olive I-1, Olive I-2, Olive HO-1, and Grapevine C, and more than 90% in the investigated hazelnut systems. The second most impactful item was fertilization, ranging from 30 to 40% of impacts in 7 cropping systems, including Apricot I-1, Apricot I-2, Peach I, Olive I-1, Olive I-2, Olive HO-1, and Grapevine C, and from 50 to 70% in other systems such as Strawberry I, Strawberry O, and Kiwi fruit I. Finally, materials were found to be another important cause of the release of emissions in both Apricot B and Strawberry systems (79 and about 30% of the total impacts, respectively). These emissions were especially due to the use of zinc structures in Apricot B and plastics in all Strawberry systems., Otherwise, Tabatabaie and Murthy [39] affirmed that materials, especially plastics, mostly contributed to GWP of strawberry production in all the considered States, including California, Florida, North Carolina, and Oregon, representing up to 80% of total emissions, while the production of fuel for machines was the second largest contributor to GWP.

4.3 Measuring Sustainability Using Additional Indicators

Figure 3 represents the additional simplified environmental indicators, NP, PP, and FFP productivity, which indicate crops productivity per input unit. Consequently, higher values corresponded to greater environmental sustainability. Under our experimental conditions, Peach I, Grapevine C, and Strawberry C were the cropping systems with the greatest N productivity. Among the cropping systems which use phosphorous, Apricot B, Kiwifruit I, and Peach I showed the highest P productivity. Therefore, Peach I seemed to be the system with the most effective use of fertilizers. With respect to diesel fuel productivity, Strawberry systems were the most sustainable ones.

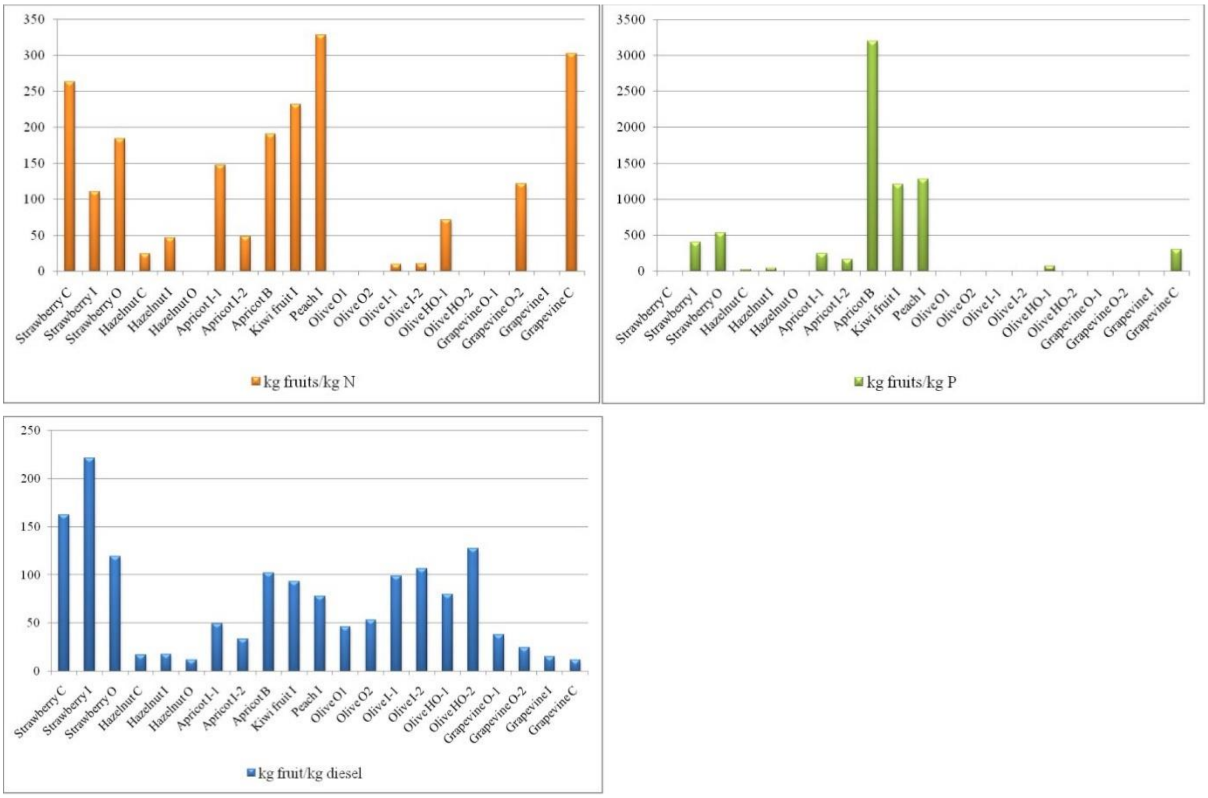

Figure 3 The additional simplified environmental indicators, including nitrogen productivity, phosphorous productivity, and fossil fuel productivity (per hectare) for each investigated cropping system

4.4 Cumulative Production Costs

Details on the production costs per kg of the harvested product are provided in Figure 4. Strawberry O was the most expensive cultivation system (4.77 € kg^{-1}), both in terms of the higher average production costs per hectare and the lower productivity, followed by the other Strawberry systems, as well as Hazelnut and Olive I-2 systems. On the contrary, Olive HO-2 (0.12 € kg^{-1}), Kiwifruit I (0.28 € kg^{-1}), and Peach I (0.28 € kg^{-1}) were the most cost-effective crop systems.$^{-}$. Moreover, on an annual basis, the three investigated Strawberry systems were confirmed to be the most expensive, with the highest average production costs (Figure 4).

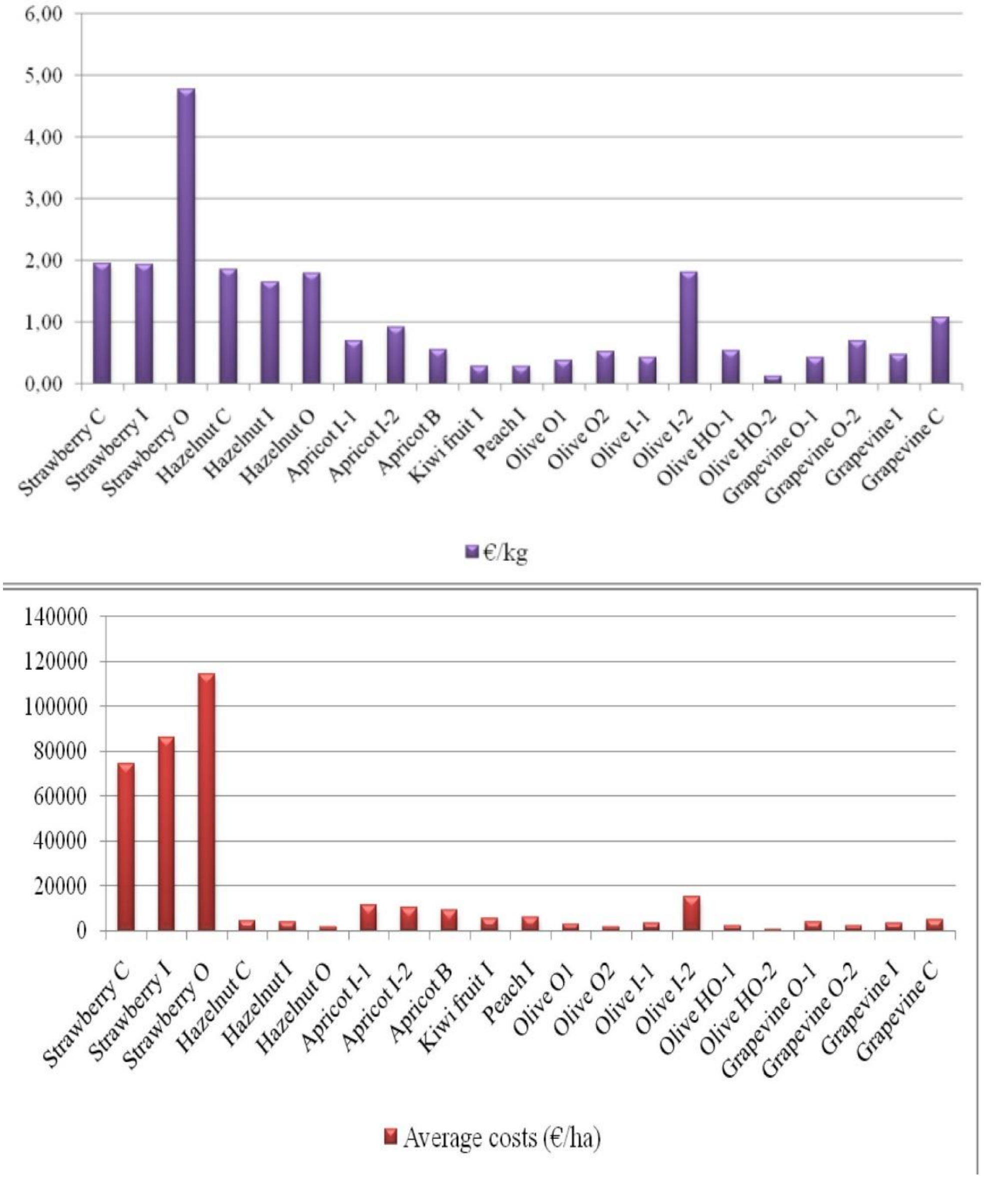

Figure 4 Cumulative production costs (per kg of product) and average production costs (per hectare) for each investigated cropping system

From a life cycle perspective, it would be expected that crops with longer production cycles show higher cumulative costs, but this assumption was not always true. The studied apricot systems, unlike other crops with longer production cycles , namely Hazelnut or Grapevine, showed highest cumulative costs (Figure 5). The phase of full production, on average, represented 80% of total cumulative costs. The disaggregation of costs among various agricultural operations, aimed to find more expensive production systems, showed significant differences between the crops. Differences in costs were observed among the Strawberry systems, for which only one year of the production cycle was studied. Particularly, harvesting and planting were the most expensive operations in Strawberry C and Strawberry I systems, representing more than 80% of the total costs, while in Strawberry O, harvesting, irrigation, and fertigation played the major parts. As already specified, in the studied olive systems, only one year of the whole production cycle was investigated. Harvesting, followed by pruning or nets costs, were the most important items in the less mechanized olive systems, including Olive O1, Olive O2, Olive I-2, and Olive HO-1, which made greater use of human labor. In Olive HO-2, characterized by minimal operations, and therefore, the most environmental sustainable system, the major cost was due to soil tillage. Conversely, in one of the two integrated systems, namely OliveI-1, fertilization and disease control were the most costly operations.

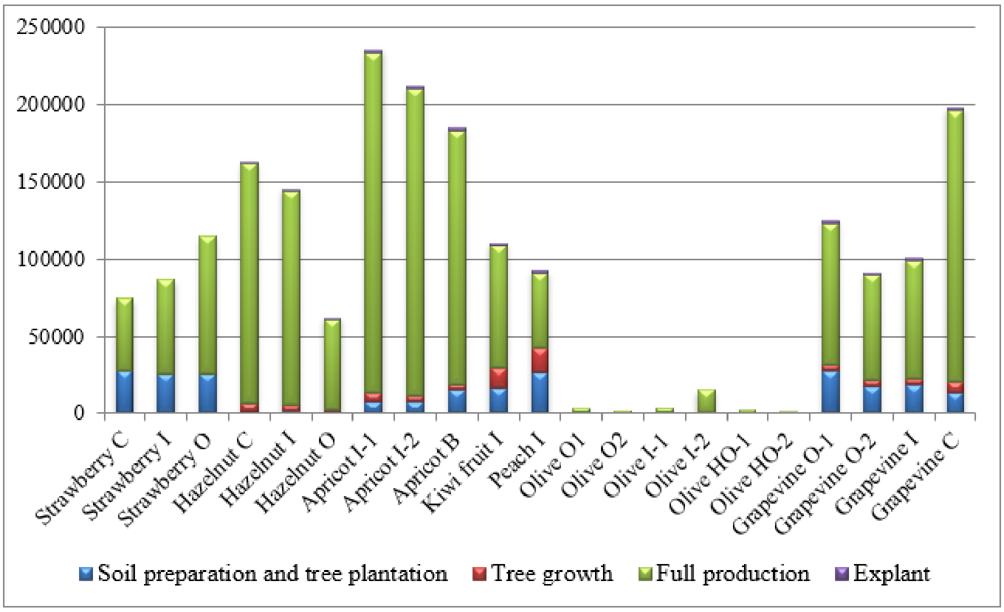

Figure 5 Cumulative production costs distinguished by agricultural phase for each investigated cropping system.

In the other investigated cropping systems, for which the entire life productive cycle was analyzed, the following operations were found to be more expensive:

- fertilization in Hazelnut C and Hazelnut I; pruning and soil tillage in Hazelnut O; pruning, manual fruit thinning, and irrigation in Apricot systems, representing more than 60% of total costs;
- pruning, fertigation, and harvesting in Kiwi fruit I, representing more than 77% of total costs; pruning, disease control, and harvesting in Peach I, accounting for 70% of total costs.

In the studied vineyards, the situation was very variable: pruning was the most expensive operation in Grapevine O-1, representing more than 50% of the total cumulative costs, harvesting in Grapevine O-2, pruning and fertilization in Grapevine I and Grapevine C.

In less mechanized cropping systems, the most expensive operations were those manually carried out (harvesting and pruning) due to the high labor costs; in highly mechanized systems, fertilization and disease control were the most costly operations, mainly due to the input costs (fertilizers and chemicals). It is noteworthy that in the current Covid-19 pandemic situation, restrictions on the movement of seasonal workers and other factors of production could increase the production costs.

Other significant cost items, highlighted by LCC, were soil preparation and trees or seedlings plantation, which were 20-30% of total costs (Figure 5). Particularly, the purchase of seedlings was the major cost item. This issue can be resolved by seedlings self-production from cuttings, as it happened in Hazelnut systems, in which this phase represented only 1% of total cumulative costs.

In agriculture, profitability is assessed as crop gross margin (GM), which is the difference between crop revenues and specific variable crop costs of farms [41, 60, 61]. But one aim of sustainable agriculture is higher productivity per production costs [62]. Therefore, Olive HO-2, Kiwifruit I, and Peach I were the most sustainable cropping systems, being able to produce more with the same costs (Figure 6).

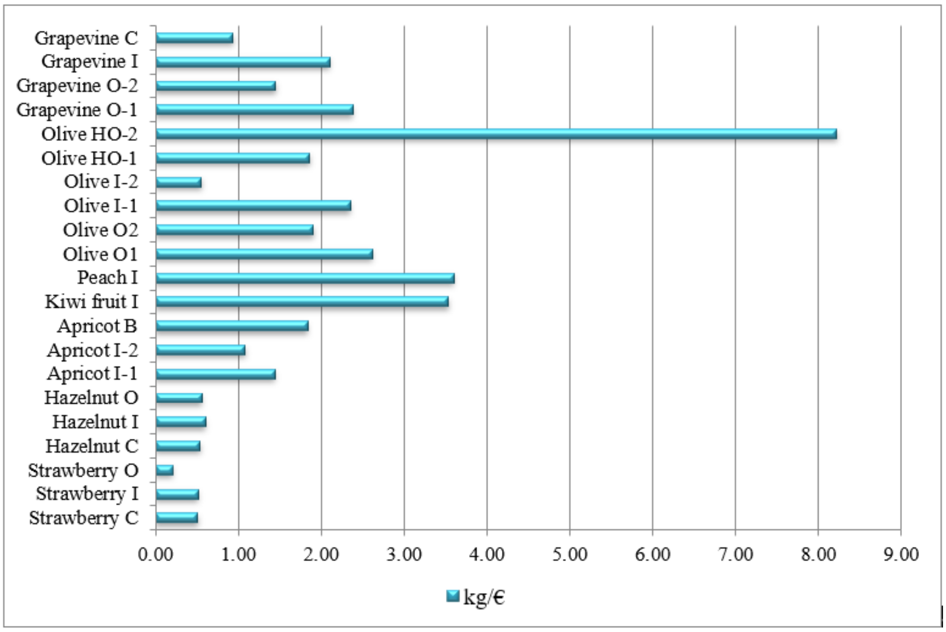

Figure 6 Cost productivity (product harvested for invested euro), calculated for each investigated cropping system.

5. Conclusion

The present study aimed to assess the environmental and economic sustainability of some typical Mediterranean cropping systems by combining LCA and LCC methods and developing additional environmental indicators to reiterate the importance of these issues also in the current pandemic situation.

As expected, the investigated crops performed very differently, due to both management systems and duration of the production cycle. Some crop systems, including hazelnut, grapevine, and strawberry were found to be more impactful, while others, like olive systems, were more sustainable. The organic systems, especially the hobbyist ones, were by far the most sustainable production systems. Apricot, Kiwifruit, and Peach systems were those that used N and P input in the most effective way, while Strawberry systems efficiently used fossil fuels. With regard to production costs, one of the two organic-hobbyist olive systems, along with Kiwifruit and Peach orchards, had the lowest costs per kg of product and the greatest productivity per cost unit.

Consequently, to define sustainability classes in agriculture and identify unsustainable cropping systems from environmental and economic perspectives, a more rigorous standardization of the LCA methodology and its combination with LCC and other environmental indicators are necessary because the agricultural landscape context varies and it is characterized by knowledge, production techniques, and management practices that are typical of production sites for each crop. The application of LCA methodology, however, remains a very important green marketing tool since it can provide the basis for eco-labels, such as EPD, which is repeatedly requested by end consumers due to their increased awareness and attention to environmental issues. At the same time, farmers/business owners must be encouraged to use LCA and LCC methods to find out how to reduce the environmental impacts on their farms and improve their economic conditions by lowering production costs.

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Additional Materials

The following additional materials are uploaded at the page of this paper.

1. Table S1: Main features of the investigated Mediterranean cropping systems.
2. Table S2: Main features of the investigated Mediterranean cropping systems.
3. Table S3: Farm inputs used in the investigated cropping systems in the reference period equal to the species productive cycle.
4. Table S4: Farm inputs used in the investigated cropping systems in the reference period equal to the species productive cycle.

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Competing Interests

The authors have declared that no competing interests exist.

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