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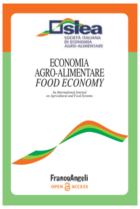

How environmentally sustainable are farms? An analysis in Southern Italy through the Life Cycle Assessment methodology

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Abstract

Promoting a sustainable economy through the digital and ecological transition of companies is one of the challenges of our century. Digital promises to reduce the ecological footprint of the agricultural sector by improving processes along the agri-food supply chains and enhancing the data generated in every single area of the value chain. One of the aims of the present research was to monitor farms in Southern Italy with the intention to evaluate the use in farm of digital technologies. A second aim was to estimate the environmental impacts and the social cost of pollution of different agricultural systems to identify the weak points in the cultivation phase. Then, more sustainable lines of intervention and alternatives in a green transition perspective were proposed. The study was carried out in three Italian regions of south of Italy and 46 cropping systems were analyzed and compared using the Life Cycle Methodology. According to the results, to date, only two farmers interviewed have started to adopt digital technologies. The comparison among the cultivation systems highlighted the greater sustainability of the organic ones. Those cropping systems characterized by a low use of resources and inputs, such as olive and hazelnut systems, were more sustainable than others. On the contrary, other systems had greater impacts due to the use of considerable quantities of materials (especially support and covering structures, as in table grapes systems, or plastic containers, as in strawberry systems). The

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disaggregation of the impacts by agricultural operations, in low material use systems, showed that the greatest impacts were due to fuel emissions, especially during the harvesting phase, and to fertilization and disease control. Hence, the need to increase organic cultivation and to carry out fertilizations using, instead of empirical approaches, modern digital and precision agriculture technologies able to consume fewer resources, reduce waste, and improve the quality of life.

Introduction

Digital technologies and environmental protection are the cornerstones of the Common Agricultural Policy (CAP) 2023-2027 (Guyomard *et al.*, 2023), whose fundamental objectives are to promote a smart and resilient agricultural sector, support care for the environment and climate action, stimulate growth and employment in rural areas. Achieving these objectives requires innovation from the primary sector, which helps to reduce environmental impact, increase productivity, reduce production costs, thus becoming a basic factor for improving sustainability (Moreno *et al.*, 2024).

The latest report from the Smart Agrifood Observatory highlights that the agriculture 4.0 market in Italy grew in 2022, reaching over 2 billion euros and recording a growth of +31% compared to 2021. Even the surface cultivated with 4.0 solutions has grown (from 6% in 2021 to 8% in 2022). Furthermore, the report shows that 65% of the market value is made up of connected machinery and monitoring and control systems for vehicles and equipment. Remote monitoring systems for crops, land and infrastructure are also growing strongly (+15% compared to 2021) (Aa.Vv., 2023).

The last few years have been complex for the European agri-food sector, especially due to the increase in the cost of raw materials and the severe drought that hit the entire European territory in 2022. Thus, to face the new challenges, farms are using digital technologies (agriculture 4.0), especially those related to improving efficiency and therefore reducing the use of the main production inputs (Patel and Bhatia, 2024). Referring to agri-food processing firms, 82% of these have used or experimented with at least one digital solution. Food traceability, production, logistics and quality control (of both raw materials and the finished product) are the areas where firms are innovating the most (Aa.Vv., 2023).

Many authors claim that the new technologies of Industry 4.0 can completely revolutionize agriculture, ensure greater food production using few resources, reduce losses and waste food with overall improved environmental implications (Shepherd *et al.*, 2020; Lezoche *et al.*, 2020; Galanakis *et al.*, 2021). The application of new digital technologies (cyber-physical systems, the Internet of Things, cloud computing, advanced manufacturing solutions and big data analysis) (Leone *et al.*, 2021) would seem to lead to an improvement in the overall farm performance (Warner and Wäger, 2019). According to Abbate *et al.* (2023), the use of digital technologies can help control the impact of agricultural activities on soil and air quality, reduce the use of natural resources, pollutants, and CO_2 eq emissions, thus providing long-term economic, environmental, and social benefits.

In this context, it is important to evaluate how sustainable agri-food systems/supply chains are from an environmental point of view, in order to choose the right innovation that makes them capable of improving themselves and being truly green. The answer lies in the Life Cycle Assessment (LCA) methodology, which has been applied for years in various sectors, including the agri-food sector (De Backer *et al.*, 2009; Haas *et al.*, 2000; Brentrup *et al.*, 2001; Brentrup *et al.*, 2004; Nemecek *et al.*, 2024), which many agricultural producers already rely on to identify the weak link in the supply chain in order to adopt less impactful alternatives. We read in many places that "digital promises to reduce the ecological footprint of the agri-food sector", but this will only be possible by having a good collection of data, studies, and research on the impacts of the different production systems available.

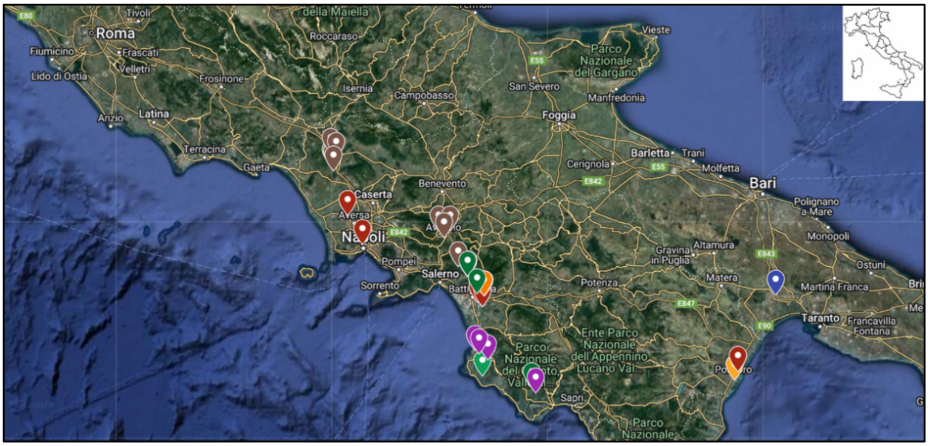
In line with what has been said, one of the aims of this research were to understand if farms located in Southern Italy are using digital technologies. A second aim was to estimate the environmental impacts and the social cost of pollution of different agricultural systems to identify the weak point in the cultivation phase and propose more sustainable lines of intervention and alternatives in a green transition perspective.

1. Materials and methods

1.1. *Description of the Analyzed Cropping Systems*

The study was carried out in Campania, Basilicata, and Apulia regions (Southern Italy) (Figure 1), where fruit growing represents one of the most important productive sectors.

Figure 1 - Study area (Campania, Basilicata, and Puglia regions - Southern Italy) and position of the cropping systems under study



The analyzed cropping systems were the following:

- three apricot growing systems including two integrated (Apricot INT1, Apricot INT2) and one biodynamic under greenhouse (Apricot B);
- eight strawberry growing systems under greenhouse including one conventional (Strawberry CON), five integrated (Strawberry INT1 - Strawberry INT5), and two organics (Strawberry OR1 and Strawberry OR2);
- one integrated kiwifruit growing system (Kiwi INT);
- one integrated peach growing system (Peach INT);
- twenty-one hazelnut growing systems including one conventional (Hazelnut CON), sixteen integrated (Hazelnut INT1 - Hazelnut INT16), and four organics (Hazelnut OR1 - Hazelnut OR4);
- six olive growing systems including two certified as organic (Olive OR1 and Olive OR2), two integrated (Olive INT1 and Olive INT2), and two organic-hobbyists (Olive HO1 and Olive HO2);
- four vineyards growing systems for wine grapes, including two organics (Grapevine OR1 and Grapevine OR2), one integrated (Grapevine INT), and one conventional (Grapevine CON);
- two vineyards growing systems for table grapes, including one organic (GRTable OR1) and one conventional (GRTable CON).

The main features of the investigated growing systems were collected by direct interviews with farmers, using a specific data collection sheet, visiting farms, and consultation on field notebooks. The cropping systems investigated differed in the:

- average yield (variable from a minimum of 1,000 kg per hectare per year, in two integrated hazelnut systems, to a maximum of 52,500 kg per hectare per year, in one of the two organic strawberry systems);
- duration of the production process (annual in the strawberry growing systems and multi-yearly in the others);
- plant density (from a minimum of 150 plants ha^{-1} in olive growing systems to a maximum of 75,000 plants ha^{-1} in strawberry growing systems);
- training system (specific to each crop and therefore multi stem, transverse ipsilon, vase, double guyot, espalier, free, awning, etc.);
- presence/absence of irrigation activities, covering and supporting structures;
- types of pruning (manual or mechanized);
- management of pruning residues (burned in the field, removed and burned in the open air, shredded in the field, composted, removed and burned in plants);
- fertilization (green manure, organic, natural, mineral);
- soil management (harrowing, milling, absent);
- disease control (natural products, conventional products, absent);
- harvesting (manual or mechanized);
- cultivation methods (conventional, integrated, organic, biodynamic, and hobbyist).

With respect to the cultivation methods, the integrated system was the most widespread in the studied areas, and it produced high-quality crop yields. It particularly followed specific protocols (MIPAF, 2008) to manage fertilization and control pests and diseases using both chemical and natural products.

More specifications on the systems analyzed can be found in Pergola *et al.* (2011, 2014, 2017, 2021, 2022, 2023, 2024) and Maffia *et al.* (2020).

1.2. *Quantification of the environmental impacts*

The LCA methodology was used to assess the environmental impacts of the cropping systems under study according to the ISO 14040-44 (ISO, 2006 a,b) through the main LCA standardized phases (goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation).

1.2.1. Goal and scope definition

The goal of the analyses was to estimate and compare the environmental impacts of 46 cropping systems in order to 1) understand if the analyzed farms were using digital technologies to be more sustainable and if there were differences between organic, integrated, and conventional systems; 2) identify for each analyzed system (or groups of systems) the most impactful agricultural operation to try to realize how a LCA study can help in finding the optimal solution to adopt.

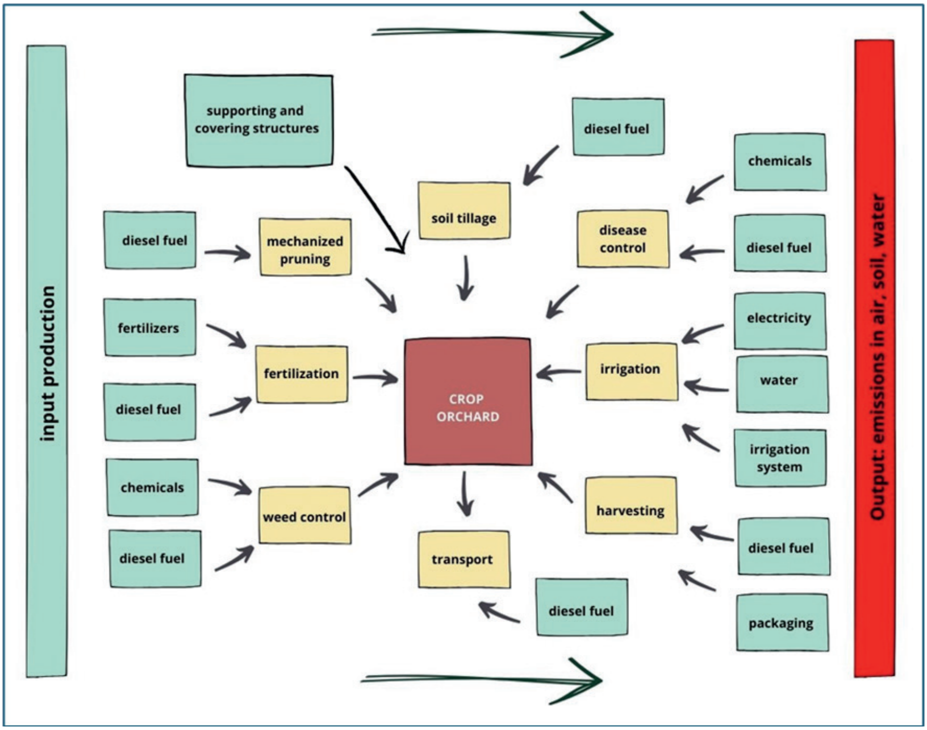
To achieve these aims, the reference period of the analysis was set to the end of one productive year and both the functional unit (the reference according to which all inputs and outputs were processed to allow comparison between systems or alternatives) (ISO, 2006) and the system boundaries were defined. The function of the systems under observation was the production of fruits, consequently, the basis for the comparison of the different systems, namely the functional unit (FU) of the service delivered, should have been the production of one kilo of fruits, as reported in other LCA studies (Coppola *et al.*, 2022; Cerutti *et al.*, 2011; Seda *et al.*, 2011). Anyway, to achieve the research aims and to better compare the analyzed systems, one hectare of cultivated land was used as FU. Indeed, it is well known that using production (1 kg) as FU can lead to errors given that less productive systems (such as organic ones) often have a greater impact per unit of product (Coppola *et al.*, 2022). Referring to the system boundaries (namely the operations and processes considered in the analysis), they went from the extraction of raw materials to the farm gate: it was a cradle to farm gate study which considered only the agricultural phase (Figure 2).

Thus, the analysis considered the production of input (fertilizers, chemicals, diesel fuel, electricity, water, etc.); the production of materials (irrigation systems; supporting and covering structures; packaging) and the following agronomical operations: soil tillage; mechanized pruning; fertilization; weed control; disease control; irrigation; harvesting and transport of the harvested products to the farm. No type of cut-off (mass, energy or economic) has been applied, namely processes contributing minimally (1%) to total impacts have not been excluded. The analysis did not consider input and materials transportation (due to lack of appropriate data), and buildings, machines and tools used in accordance with the product category rules of the different analyzed products.

1.2.2. Life cycle inventory

Primary data on the features of the investigated crops, quantity and type of materials used for irrigation systems and for support and covering structures (when present), amounts of fertilizers, chemicals, diesel fuel, water, and other items were collected in situ during the last agricultural years within technology transfer/dissemination programs within some Italian (at national and regional levels) and European projects using a data collection sheet. For

Figure 2 - The system boundaries of the LCA analysis



each operation, direct and indirect emissions were calculated considering the active ingredients of each product used. Specifically, direct emissions from fuel were taken from SimaPro's LCI databases (Ecoinvent v.3; Agri-footprint 5), while those from nitrogen fertilizers (emissions of ammonia and dinitrogen monoxide), as in other studies (Pergola *et al.*, 2017; Maffia *et al.*, 2020; Maffia *et al.*, 2022; Pergola *et al.*, 2023; Pergola *et al.*, 2024), were accounted considering the emission factors proposed by Bouwman (1995), Brentrup *et al.* (2000), and IPCC (2006). Referring to synthetic pesticides, direct emissions were estimated considering the amount of each active ingredient and following the methodology suggested by Hauschild (2000).

The embodied emissions, namely secondary data, were extrapolated from international databases of scientific importance and reliability, like Ecoinvent v.3.

1.2.3. Life cycle impact assessment

The software SimaPro 9.02 was used to perform the impact assessment according to the Environmental Prices' method developed by CE Delft (de Bruyn *et al.*, 2018). In particular, this method expresses the environmental impacts, depending on the impact category, in kg of substances emitted, square meters or cubic meters, but also in monetary units (euros). The characterization step was based on ReCiPe (2008) Midpoint, hierarchist perspective (RIVM *et al.*, 2016), with the exception of climate change, based on the IPCC 2013 values for a 100-year timeframe. The following impact categories were considered: climate change (CC); ozone depletion (OD); terrestrial acidification (TA); freshwater eutrophication (Feu); marine eutrophication (Meu); human toxicity (HT); photochemical oxidant formation (POF); particulate matter formation (PMF); terrestrial ecotoxicity (Tec); freshwater ecotoxicity (FEc); marine ecotoxicity (MEc); ionizing radiation (IR); agricultural land occupation (ALO); urban land occupation (ULO); natural land transformation (NLT); water depletion (WD); metal depletion (MD); fossil depletion (FD).

After assessing the environmental impacts (which represented the characterization phase of the analysis), the normalization of the results was performed by the estimation of the social cost of pollution. In particular, the loss of economic welfare, that occurs when one additional kilogram of the pollutant finds its way into the environment, was calculated by expressing the total impact as the sum of euros per kilogram pollutant (de Bruyn *et al.*, 2018). The environmental prices were not available for some impact categories (natural land transformation, water, metal, and fossil depletion), so they were not considered in this final step.

2. Results and discussion

Interviews with farmers showed that almost all analyzed farms to date have not adopted digital technologies useful to manage soil, water and crops (remote sensing based on satellites or drones) or farm and supply chains (Brunori, 2022). The electric forklifts, only found in the farm hosting the kiwifruit and peach systems and used for moving the harvested product, can be considered as a beginning of ecological transition. Furthermore, the capitalistic farms accommodating the Olive OR2, Kiwi INT, and Peach INT systems can be considered in transition, as they are starting to use decision support systems for disease control, irrigation networks with meteorological stations included, and grass cover control with autonomous driving with hybrid engine (diesel/electric).

The environmental analysis involved 46 systems that were very different from each other, especially in terms of crop type and cultivation system. Thus, to facilitate the presentation of the results, the systems analyzed were grouped by cultivation system. Tables 1a and 1b report the environmental impacts of organic crop systems and show that, referring to most of the impact categories (ozone depletion, terrestrial acidification, freshwater eutrophication, marine eutrophication, human toxicity, photochemical oxidant formation, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, agricultural land occupation and natural land transformation), the Olive OH2 system had the lowest impacts. This was included in a small, purely hobby farm that carried out no fertilization and no disease control operations, but performed manual pruning, temporary natural grass cover, disk harrowing, and manual harvesting using electric shakers (Maffia *et al.*, 2020). Therefore, the unique impacts were linked to the movement of agricultural machinery in the field and to the transport of the harvested olives to the farm. Concerning climate change, particulate matter formation, and metal depletion, Strawberry OR2 was the most sustainable. This was an organic system which used solarization for soil disinfestation, biological fight for pest control, and corrugated boxes as packaging recycled at the end-of-life. Furthermore, the Grapevine OR2 was the least impacting system for the following impact categories: ionizing radiation, urban land occupation and water depletion. It was characterized by the use of chestnut poles, galvanized wire, and reeds rods as support structures; manual pruning; pruning residues used as soil mulching; organic fertilization every three years; permanent natural grass and subsequent shredding; disease control by synthetic products/resistance promoters; and manual harvesting.

On the contrary, GRTable OR1 system (organic table grapes cultivation with the “tendone” training system, a particular Apulian training system with double horizontal roofs and a planting distances of 2,5 X 2,5 meters) had the least impacts only on the category “fossil depletion” (Tables 1a and 1b).

Twenty-five integrated systems were also analyzed, but Table 2 shows only the environmental impacts of the most sustainable integrated systems and those of the most impactful ones. Data were much more variable than those observed in the organic systems. Indeed, some hazelnut systems (Hazelnut INT4, Hazelnut INT5; Hazelnut INT13; Hazelnut INT14; Hazelnut INT16) were very sustainable with respect to several impact categories. In particular, Hazelnut INT16 (an integrated hazelnut cultivation on embankments characterized by manual pruning, removal of pruning residues and their burning in the open air; annual and mineral fertilization; weed control by shredding; no soil cover management; disease control through the use of conventional products; and mechanized harvesting) stood out as the most sustainable integrated system in 8 of the 18 impact categories.

Table 1a - The environmental impact of organic systems (apricot, strawberry, and hazelnut) per *hectare*

Impact category	**Unit of measurement**	**Apricot**	**Strawberry**		**Hazelnut**			
		B	**OR1**	**OR2**	**OR1**	**OR2**	**OR3**	**OR4**
Climate Change	kg CO_2 eq	2778	8699	–972	1235	1173	1952	1387
Ozone Depletion	kg CFC-11 eq	0	0	0	0	0	0	0
Terrestrial Acidification	kg SO_2 eq	18	53	26	8	8	16	15
Freshwater Eutrophication	kg P eq	2	2	7	0	0	0	0
Marine Eutrophication	kg N eq	1	2	5	3	0	1	1
Human Toxicity	in kg 1,4-DB eq	4728	2734	9983	406	233	391	372
Photochemical Oxidant Formation	kg NMVOC	19	31	7	12	10	17	12
Particulate Matter Formation	kg PM10 eq	10	18	–10	4	4	7	6
Terrestrial Ecotoxicity	kg 1,4-DB eq	1	3	37	0	0	0	0
Freshwater Ecotoxicity	kg 1,4-DB eq	372	495	664	64	16	27	45
Marine Ecotoxicity	kg 1,4-DB eq	332	434	610	56	14	24	40
Ionizing Radiation	kBq U235 eq	429	882	1815	86	46	81	61
Agricultural Land Occupation	in m^2 $year^{-1}$	304	319	28134	868	189	320	233
Urban Land Occupation	in m^2 $year^{-1}$	275	884	97459	118	44	76	66
Natural Land Transformation	m^2	1	1	1	0	0	0	0
Water Depletion	m^3	3969	146	3334	5	3	5	4
Metal Depletion	kg Fe eq	1313	9214	–6508	208	117	202	194
Fossil Depletion	kg oil eq	308	4368	2087	373	315	540	397

Table 1b - The environmental impact of organic systems (olive, grapevine, and grape table) per *hectare*

Impact category	Unit of measurement	Olive				Grapevine		GRTable
		OR1	OR2	HO1	HO2	OR1	OR2	OR1
Climate Change	kg CO_2 eq	1065	591	855	314	1227	182	66495
Ozone Depletion	kg CFC-11 eq	0	0	0	0	0	0	1
Terrestrial Acidification	kg SO_2 eq	7	10	5	2	12	10	739
Freshwater Eutrophication	kg P eq	0	0	0	0	0	0	12
Marine Eutrophication	kg N eq	0	0	0	0	1	0	39
Human Toxicity	in kg 1,4-DB eq	425	154	176	68	626	245	26011
Photochemical Oxidant Formation	kg NMVOC	10	5	7	3	12	4	288
Particulate Matter Formation	kg PM10 eq	4	3	3	1	5	3	284
Terrestrial Ecotoxicity	kg 1,4-DB eq	21	16	0	0	0	24	95
Freshwater Ecotoxicity	kg 1,4-DB eq	79	22	19	7	80	22	558
Marine Ecotoxicity	kg 1,4-DB eq	236	145	17	6	70	211	526
Ionizing Radiation	kBq U235 eq	69	32	54	20	87	19	54
Agricultural Land Occupation	in m^2 $year^{-1}$	206	94	144	60	271	111	16704
Urban Land Occupation	in m^2 $year^{-1}$	88	35	62	23	92	21	27302
Natural Land Transformation	m^2	0	0	0	0	0	0	7
Water Depletion	m^3	4	2	3	8	3	–4	4573
Metal Depletion	kg Fe eq	236	80	90	35	304	89	1153
Fossil Depletion	kg oil eq	322	150	251	95	186	–361	–16600

Strawberry INT3 (strawberry cultivation in which the plants were grown on rows made ex novo during the production cycle, according to the ordinary cultivation techniques and supplemented by seven root applications – via fertigation – of compost tea produced on-farm) and Strawberry INT5 (strawberry cultivation in which the plants were grown on rows already used in the previous production cycle and in which the ordinary cultivation techniques were carried out together with seven root applications – through fertigation – of compost tea produced on-farm) were the most impactful systems among the integrated ones: the first regarding climate change, photochemical oxidant formation, agricultural land occupation, water depletion, and fossil depletion; the second regarding ozone depletion, marine eutrophication, human toxicity, freshwater ecotoxicity, marine ecotoxicity, ionizing radiation, urban land occupation, and natural land transformation (Table 2).

Among the conventional systems, Grapevine CON (a conventional vineyards characterized by chestnut poles, galvanized poles, PVC wire as support structures; manual pruning; pruning residues used as soil mulching; mineral fertilization performed every three years; temporary natural grass cover and disk harrowing; disease control by conventional products; manual harvesting) proved to be the least impactful system in reference to almost all impact categories, except for freshwater eutrophication, human toxicity, freshwater ecotoxicity, and marine ecotoxicity for which the greatest sustainability was recorded for Hazelnut CON system (a conventional hazelnut cultivation characterized by manual pruning; shredding of pruning residues on field; annual and mineral fertilization; weed control by shredding and rarely use of glyphosate; milling and harrowing operations; disease control through the use of conventional products; and mechanized harvesting). On the contrary, GRTable CON (a conventional table grapes cultivation with the "tendone" training system and a planting distances of 2,5 X 2,5 meters) was the most impactful system among the conventional ones (but also overall among all the systems analyzed). At the same time, Strawberry CON (a conventional strawberry cultivation in which the plants were grown on rows made ex novo and managed during the production cycle according to the ordinary cultivation techniques) was the most impactful towards the following categories: terrestrial ecotoxicity, marine ecotoxicity, ionizing radiation, and fossil depletion (Table 3).

Table 2 - The environmental impact of integrated systems per *hectare*

Impact category	Unit of measurement	Strawberry			Kiwi	Hazelnut				
		INT 1	INT 3	INT 5	INT	INT 4	INT 5	INT 13	INT 14	INT 16
Climate Change	kg CO_2 eq	7949	11431	11068	5186	1377	1276	1726	1810	1880
Ozone Depletion	kg CFC-11 eq	0	0	0	0	0	0	0	0	0
Terrestrial Acidification	kg SO_2 eq	135	64	63	51	16	22	9	16	12
Freshwater Eutrophication	kg P eq	1	6	6	1	7	0	0	0	0
Marine Eutrophication	kg N eq	5	4	6	2	0	1	1	1	1
Human Toxicity	in kg 1,4-DB eq	1230	14545	14641	2208	360	252	388	185	241
Photochemical Oxidant Formation	kg NMVOC	18	52	49	17	6	9	9	6	4
Particulate Matter Formation	kg PM10 eq	20	18	18	13	4	6	4	4	3
Terrestrial Ecotoxicity	kg 1,4-DB eq	3	389	393	495	0	0	0	0	0
Freshwater Ecotoxicity	kg 1,4-DB eq	175	1232	1261	439	16	23	48	23	26
Marine Ecotoxicity	kg 1,4-DB eq	153	6540	6546	4383	14	21	50	25	23
Ionizing Radiation	kBq U235 eq	505	1689	1701	135	36	64	138	61	28
Agricultural Land Occupation	in m^2 $year^{-1}$	366	805	785	364	102	162	169	107	43
Urban Land Occupation	in m^2 $year^{-1}$	1256	378358	378404	301	39	70	134	49	24
Natural Land Transformation	m^2	1	2	2	1	0	0	0	0	0
Water Depletion	m^3	119	9095	9088	20	4	6	237	6	9
Metal Depletion	kg Fe eq	–1253	–251	–57	1104	73	122	144	86	70
Fossil Depletion	kg oil eq	3539	5434	5069	–29	326	351	516	262	222

Table 3 - The environmental impact of conventional systems per *hectare*

Impact category	**Unit of measurement**	**Strawberry CON**	**Hazelnut CON**	**Grapevine CON**	**GRTable CON**
Climate Change	kg CO_2 eq	7046	2594	1384	63703
Ozone Depletion	kg CFC-11 eq	0	0	0	1
Terrestrial Acidification	kg SO_2 eq	54	51	10	456
Freshwater Eutrophication	kg P eq	2	1	1	12
Marine Eutrophication	kg N eq	3	2	1	26
Human Toxicity	in kg 1,4-DB eq	3998	1056	1512	26092
Photochemical Oxidant Formation	kg NMVOC	29	16	14	289
Particulate Matter Formation	kg PM10 eq	10	12	6	248
Terrestrial Ecotoxicity	kg 1,4-DB eq	379	1	0	96
Freshwater Ecotoxicity	kg 1,4-DB eq	437	230	321	524
Marine Ecotoxicity	kg 1,4-DB eq	5937	225	279	498
Ionizing Radiation	kBq U235 eq	1070	175	93	118
Agricultural Land Occupation	in m^2 $year^{-1}$	443	310	271	12179
Urban Land Occupation	in m^2 $year^{-1}$	836	203	125	27635
Natural Land Transformation	m^2	1	1	1	6
Water Depletion	m^3	1592	17	7	4573
Metal Depletion	kg Fe eq	–1621	549	922	1156
Fossil Depletion	kg oil eq	4522	689	305	–16339

Given the heterogeneity of the analyzed systems, the characterization phase allowed us to make only a few considerations. Indeed, the comparison just presented highlighted, among different crops, those which by their nature can be considered more sustainable than others (as olive and hazelnut systems) because linked to a management characterized by a low use of resources and inputs. On the contrary, other systems (like strawberries and table grapes) require the use of considerable quantities of items, especially support and covering structures. The system with the least impact was Olive OH2, a hobby system whose production was not intended for sale, but only for family consumption. On the contrary, in the panorama of farms that sold their products both on local, national and even international markets, the situation was more complex and did not allow the most virtuous or impactful system to be identified.

Therefore, to better compare the results, the normalization of them through the estimation of the total cost of pollution was very useful. Among the organic systems, GRTable OR1 was the most impactful system; among the conventional ones, the table grape system, while, among the integrated ones, strawberries, followed by kiwifruits, appeared the less sustainable systems (Figure 3).

Figure 3 - Comparison of the total impact (cost of pollution) of the systems analyzed divided by cultivation method

However, the comparison among cultivation systems (organic, integrated, and conventional) allowed us to highlight the greater sustainability of organic systems. This was clearly noticeable where it was possible to compare the cultivation of the same crop under organic and integrated/conventional management (as occurred for apricot, grapevine, table grapes, hazelnut, olive, and strawberry). The total cost of pollution of the different systems analyzed widely highlighted this finding (Table 4). Therefore, the first step for the ecological transition in agriculture is the conversion of cultivation systems to organic. Indeed, increasing the European Union's agricultural land dedicated to organic farming by at least 25% by 2030 is one of the objectives of the Farm to Fork Strategy (European Commission, 2020).

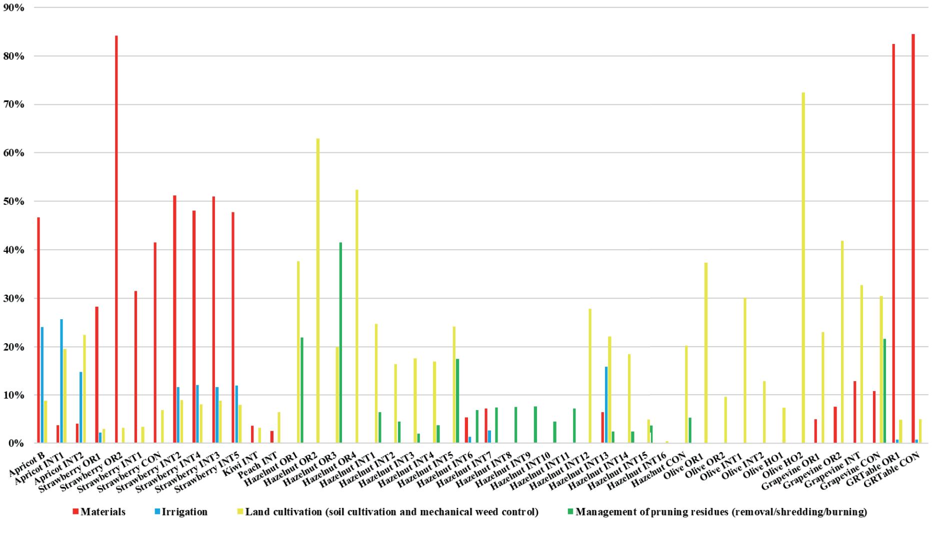
Table 4 - The cost of pollution of the cropping system analyzed

System	Euros	System	Euros
Apricot B	1240	Hazelnut INT4	444
Apricot INT1	2150	Hazelnut INT5	492
Apricot INT2	2013	Hazelnut INT6	577
Grapevine OR1	501	Hazelnut INT7	495
Grapevine OR2	454	Hazelnut INT8	754
Grapevine CON	621	Hazelnut INT9	745
Grapevine INT	875	Hazelnut CON	1204
GRTable OR1	25486	Olive HO1	253
GRTable CON	29732	Olive HO2	94
Hazelnut OR1	493	Olive OR1	414
Hazelnut OR2	345	Olive OR2	258
Hazelnut OR3	618	Olive INT1	514
Hazelnut OR4	506	Olive INT2	239
Hazelnut INT1	888	Strawberry OR1	2111
Hazelnut INT10	663	Strawberry OR2	1098
Hazelnut INT11	522	Strawberry INT1	2661
Hazelnut INT12	651	Strawberry INT2	6995
Hazelnut INT13	420	Strawberry INT3	6780
Hazelnut INT14	418	Strawberry INT4	7016
Hazelnut INT15	430	Strawberry INT5	6798
Hazelnut INT16	369	Strawberry CON	5155
Hazelnut INT2	627	Kiwi INT	5852
Hazelnut INT3	501	Peach INT	1126

At the same time, however, within the hazelnut systems, some integrated systems were found to be more environmentally sustainable than other organic ones. This was the case of INT16, INT14, INT13, INT15, INT4, and INT5 when they were compared to Hazelnut OR1 (Table 4). Consequently, from an ecological transition perspective, field management according to the principles of integrated agriculture has also proven to be a valid alternative. In fact, it is a production strategy based on the principles of awareness and analysis, guaranteed and maintained through technical preparation, constant updating of skills, technical adequacy of the tools, and "integrated" intervention strategies (which combine prevention, monitoring and targeted intervention). In this sense, the meaning of the term "integrated" combines the concepts of sustainable and safe.

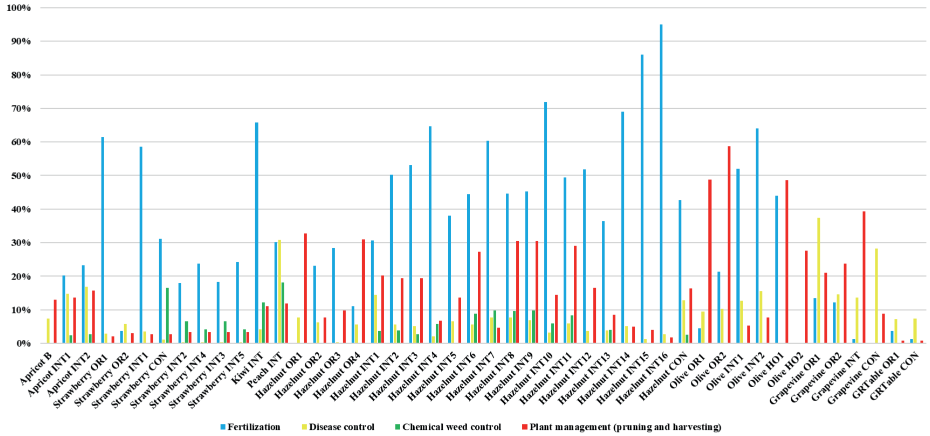
The disaggregation of the impacts by individual operation/item, reported in Figures 4 and 4bis, highlighted that materials represented the greatest impact in those systems adopting important support (such as the cultivation of table grapes) and coverage structures (such as the cultivation of apricot trees under greenhouse - Apricot B) and making use of significant quantities of packaging (for example plastic containers in the production of strawberries). Consequently, the impact of the production of the different materials used in the analyzed systems represented 84% of the total impact in GRTable CON and in Strawberry OR2, 82% in GRTable OR1, and 50% in other Strawberry systems (Figure 4).

Figure 4 - Contribution of the cultivation operations on the total cost of pollution in the different systems analyzed



On the contrary, in other systems (such as some olive and hazelnut systems) the greatest impacts were due to emissions from fuels, especially during the harvesting phase, while in others (Strawberry OR1, Strawberry INT1, Kiwi INT, Hazelnut INT2, Hazelnut INT3, Hazelnut INT4, Hazelnut INT7, Hazelnut INT12, Hazelnut INT14, Hazelnut INT15, Hazelnut INT16, Olive INT1, Olive INT2) the use of fertilizers and other disease control products caused 50% to 80% of impacts (Figure 4bis).

Figure 4bis - Contribution of the cultivation operations on the total cost of pollution in the different analyzed systems



The results obtained by the LCA analysis could be useful for farmers, farmer associations, and technicians to identify the best cultivation techniques or the weak link in agricultural production, in order to reduce emissions and, consequentially, to make their contribution to the ecological transition. In particular, the analysis just conducted makes it clear to what extent the systems under study are more or less sustainable and how much there is still to be done. Surely today farmers cannot produce without having an impact, but they can intervene by bringing improvements in production processes and cultivation techniques, using, for example, digital innovations to make the various agricultural products more sustainable. Thus, satellite guidance technologies, the precision in cultivation operations and data management for the reduction of packaging, synthetic products, water, and waste seem to be the most widespread solutions at the moment, which could be widely applied in systems that make extensive use of plastic containers, fertilizers, pesticide and other chemical products. In this regard, as reported in Abbate *et al.* (2023), precision agriculture techniques appear to be important for reducing resource waste, pollution and increasing quality of life, thus contributing to the achievement of sustainable development goals (Bhakta *et al.*, 2019). The Internet of Things (IoT) is at the heart of smart agriculture and, according to Wu and Ma (2020), can convert and improve conventional agriculture by lowering costs, reducing emissions, and increasing efficiency and quality. Therefore, intelligent water management, smart temperature, humidity and lighting control system of greenhouses, based on various IoT, including sensors and cloud, can provide crops with the precise amount of resources they need, improving their fertility and avoiding waste and environmental pollution (Abbate *et al.*, 2023). At the same time, there are several examples in the agricultural sector of cloud-based platforms for acquiring and managing data. Indeed, Manna *et al.* (2020) demonstrated how a new type of Decision Support Systems (DSS) built on the open-source Geospatial Cyberinfrastructure (GCI) platform could serve as a critical web-based operational tool for olive farming by better connecting productivity and environmental sustainability. In the viticulture sector, Terribile *et al.* (2017) showed that a new geospatial DSS, developed on a GCI platform, can provide a web-based operational tool for high quality viticulture providing operational support for farmers, farmer associations and decision makers involved in the viticulture landscape. At the same time, these digital technologies should be analyzed on a case-by-case basis in order to identify the best digital innovation to introduce into the farm, without neglecting a cost-benefit analysis that takes into account the real economic possibilities of the various farmers to understand whether they are able to bear these costs.

Conclusions

The research, through the analysis of different cropping systems, aimed to highlight the importance of conducting an LCA study to quantify sustainability of crop productive chains, identify the most impactful operations and find the best technical solution. In short, the results showed the greater sustainability of organic cultivation and how the production of materials (used in support and covering structures and in packaging), mineral nitrogen fertilization, fuel consumed during harvesting and the use of disease control products are the most impactful items, whose damage in some cases can represent up to 80% of the total impact. Hence the need to find less impactful alternatives. However, if mineral fertilizers and synthetic pesticides can be replaced with natural products (on-farm compost, biological control), it seems more difficult to replace the other items (materials and fuel), for the functions they must perform. The difficulty of introducing digital technologies is demonstrated by the fact that, at the moment, of the farms analyzed, only two are in transition and are starting to adopt these technologies to be less impactful and consume fewer resources. Consequentially, the effect of this transition can only be verified in the coming years.

Furthermore, the results of the present research represent a contribution to the literature on LCA studies in agriculture, but at the same time they should be refined with economic analyses, to understand the profitability of farms, and social sustainability analyses, in order to have a complete picture and give the best operational indications to both farmers and policy makers. At the same time, there is the need to spread the use of the LCA methodology in the agricultural sector to quantify the impacts of the farms and consider it the starting point for the dual green and digital transition. For this purpose, it would be appropriate to increase the statistical base of the agricultural phase of the different analyzed systems for the creation of benchmarks to have elements of comparison for each crop and between cultivation systems. Only in this way the most virtuous farms, from an environmental, social and economic point of view, could be supported and rewarded, for example with more targeted CAP aids.

Finally, there is also the need to extend the evaluation to post-harvest and to the different types of processed products, with particular reference to small farms, and introduce carbon sequestration into the evaluation. This could help to think the agricultural sector in terms of carbon balance and not to evaluate it only through the "lens" of the impacts and damage it causes, but also from a more positive perspective.

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