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Environmental Assessment of an Innovative High-Performance Experimental Agriculture Field

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Abstract: To increase food availability, optimizing production systems and reducing burdens related to human activities is essential in a scenario of population growth and limited natural resources. In this context, the life cycle methodology can represent a valuable asset for assessing the environmental performance of agricultural products and services. This study sought to investigate and characterize potential impacts of an experimental tomato field at the University of Perugia and evaluate if the production increment obtained using high-reflective mulching compensated for the emissions caused by this extra component. The first-year crop campaign was the baseline reference to measure the system's efficiency. A CML baseline method applied demonstrated that the covered field (F1) was associated with more than 23 kg CO_2 eq emissions (25% attributed to the mulch) in comparison to about 18 kg CO_2 eq of the non-covered sector (F2). In addition, electronic components and drainage systems were linked with most toxicity indicators. However, the F1 field's higher productivity compensated for the mulch impact, resulting in 9% lower CO_2 equivalent emissions per kg yield in the first year and 18% lower each year for 30 years. The results encourage application of this approach in urban contexts with several benefits.

Keywords: life-cycle assessment; agricultural systems; high-reflective materials; circular economy; experimental field; greenhouse gases

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1. Introduction

According to the Food and Agriculture Organization of the United Nations [1], by 2050, ongoing population growth will result in a world population of 10 billion, producing a massive demand for food, while worldwide resources remain limited. This, together with major concerns about the environmental impacts (EI) of agricultural production, are currently driving research and development in the food industry towards more sustainable production practices. As well as using natural resources, the sector is responsible for 20% of CO_2 emissions (related to climate change) [2].

Strategies to improve production can vary between more technological advances such as biotechnology manipulation and investment in new machinery [3], traditional use of pesticides and fertilizers, and more sustainable approaches, such as the practices of culture rotation and mixed crops, the use of pollinators and anaerobic digesters, and the application of mulches [4]. Such approaches can be combined to contribute to climate mitigation by enabling carbon sequestration, as experimentally tested by 105 farmers in Finland [5].

Mulch covers are extensively employed in agriculture. The method helps maintain suitable soil temperature and to control humidity, inhibits erosional processes and nutrient losses, and improves water management [6,7]. Given the widespread application of mulch covers, much research has focused on assessing the environmental impacts of the practice [8–10] and developing more sustainable materials for its application [6]. Blanco et al. reported that, in Italy alone, around 350,000 to 400,000 tons of plastic per year are consumed for mulching in agriculture [11].

Life cycle assessment (LCA) is increasingly used to assess the ecological sustainability of food production systems [12–14], including in agriculture [15–18].

Del Borghi et al. evaluated LCA and site management techniques (precision agriculture methods) as a means of improving the energy and ecological performances of beans, peas, sweet corn, and tomatoes [19]. The environmental assessment found that water use was critical for the system's performance in terms of production and impacts. The coordinated application of a holistic management tool and a holistic analysis tool, such as LCA, jointly can support the development of sustainable agriculture practices.

Gaillard et al. reviewed the LCA literature and highlighted as relevant barriers, geographical factors, adaptation of the method from the industrial sector to agriculture, and lack of knowledge concerning the LCA method [17]. Significant progress in LCA research in the agricultural sector is particularly needed [20–22]. Stoessel et al. developed a Swiss reference database of several types of fruit and vegetable that are produced or imported [20]. The study concluded that seasonality and local production could reduce emissions, if dependence on fossil-fuel-heated greenhouse structures was reduced. Using LCA, Urbano et al. compared eight scenarios of tomato production for urban consumption, finding, unexpectedly, that zero-kilometer culture in greenhouses showed the worst environmental performance, and concluding that the efficiency of all the systems involved in the production chain was crucial for sustainability [23].

This study sought to assess the potential ecological impact of an experimental field at the University of Perugia. LCA was applied to identify focal areas for future improvement and to evaluate if the crop production method was able to amortize particular impacts in the short- and long-term. The system implemented a high reflective mulching membrane that enhanced the culture productivity, while optimizing land and water use. In the campaign described by Manni et al., the mulch improved tomato production by about 20%, contributed to soil temperature control and water management, and increased the incidence of light, while lowering the superficial air temperature [7].

Previous research has demonstrated the effects of different mulch colors on the development of plants [24–28], and has indicated that choice of the most appropriate membrane should involve consideration of its optical performance, interaction with the soil, and the design of the field beds. Decoteau et al. studied the influence of mulch color on the yield of tomato crops. The authors showed that tomatoes grown with red mulch produced earlier marketable yields and less foliage [25]. Decoteau [26] demonstrated that alteration of the microclimate by use of a white mulch resulted in higher productivity than use of a black cover. Fortnum et al. evaluated the effect of mulch cover on tomatoes infected by *Meloidogyne incognita*. The yields obtained on areas with white and red mulches were almost double those of areas covered with a black mulch during a spring campaign [27]. Finally, Tarara studied the effect of black membranes on the local microclimate as a strategy to improve horticultural crop production. Modification of the microclimate above ground was related to a higher soil temperature and greater reduction in evaporation. The mulch also influenced the rate of heat conduction through the ground beneath it [29].

2. Methodological Approach

The life cycle assessment method used to determine the potential environmental impacts of the investigated field followed ISOs 14040 and 14044 [30,31]. It was composed of four mandatory steps presented in the following sections: goal and scope definition (Section 2.1), inventory analysis (Section 2.2), impact assessment (Section 2.3), and interpretation (Section 4).

Boundaries were defined to achieve the study aims, and data was collected from the team responsible for the experimental site implementation, including technical drawings and field measurements, as well as literature, to complement the inventory. The fluxes were calculated with SimaPRO 8.4.0.0 software (by Pré-Consultants), considering processes and materials from the ecoinvent v3.3 database [32].

This work implemented an attributional and process-based life cycle model, considering the unit component inputs and the corresponding outputs to represent the current situation [33]. The flows were expressed using the impact categories of the midpoint-oriented CML baseline method, which enables the identification of crucial "hotspots" based on several relevant environmental indicators.

2.1. Goal and Scope Definition

2.1.1. Objectives and Functional Unit

This study sought to assess the environmental impact of two comparable systems implemented in an experimental field at the University of Perugia, by identifying critical steps and assessing their performance. Two time-frames were considered: for the first year and for thirty years, evaluating if any gains in productivity compensated for the impacts associated with the initial mulch impacts.

In LCA studies, the functional unit is the reference basis for measuring products, services, and activities, while the reference flow is the amount of activity or product required to achieve the functional unit [34]. The functional unit here is expressed by area (in m^2), attributing hotspots to the components for one kg of fresh tomato, enabling comparison in terms of productivity. Gaillard et al. listed twelve studies using two functional units for agricultural systems [17].

2.1.2. System Description and Boundaries

The field was located between the Engineering Faculty of the University of Perugia and the Centro Interuniversitario di Ricerca sull'Inquinamento da Agenti Fisici "Mauro Felli" (CIRIAF).

The field comprised 12 beds with 12 plants, each covered by a highly reflective membrane, and two beds without cover, with 12 plants each, for a total surface area of 120 m^2, with a 15% slope (Figure 1). The high-reflective-mulch-covered area was more extensive because previous experiments required air temperature measurement at different locations, with the uncovered area as a control [7].

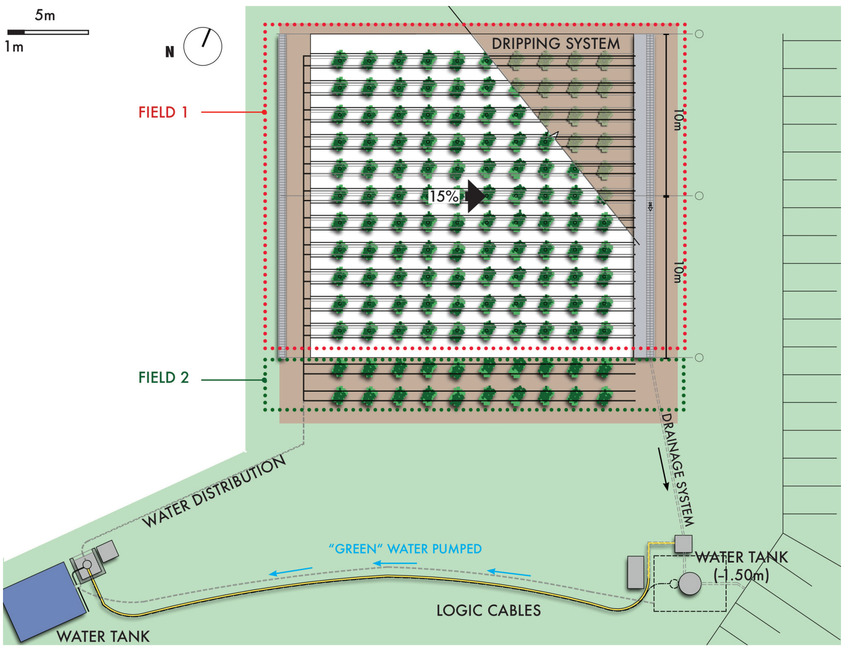

Figure 1. Field plan of the system.

The rainwater collected by the membrane was gravity-drained and stored in an underground tank. This water was pumped to a tank about 1.5 m higher and later distributed by dripping. In addition, the field had sensors for water flow monitoring and the automation systems. All methodological details are described in the inventory analysis in Section 2.2.

The materials required for constructing the field were considered in the analysis, including their transportation and the energy used to operate the field. The inputs for each cropping cycle were also considered.

The inputs were considered based on a cradle-to-gate system, corresponding to upstream processes [35]), i.e., from the site construction with the materials and energy flows up to the tomato crop, as in Figure 2. The selected boundaries were explicitly identified to allow direct comparison between the two agricultural systems, rather than processes involved in the subsequent distribution.

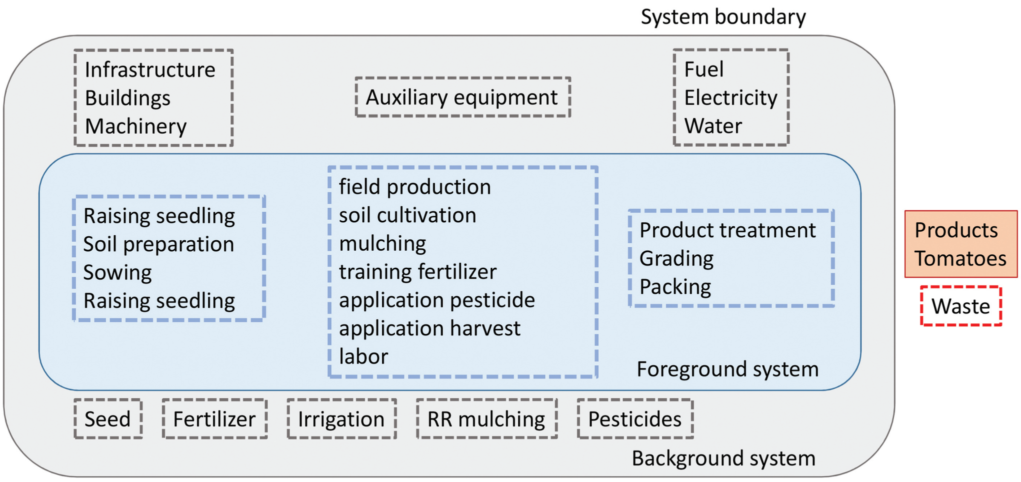

Figure 2. System boundaries scheme according to [17,20,36].

2.2. Life Cycle Inventory

The fundamental flows in the product system were listed and included in the SimaPro analysis to calculate the respective natural resources and emissions.

Two different fields were modeled (Table 1). Field 1 (F1) was 100 m^2 and corresponded to the area covered by the high-reflective mulching membrane, while Field 2 (F2) was 20 m^2 and comprised the uncovered part.

Table 1. Allocation (% area), lifespan (in years), and number of life cycles (n LC) for 1 year and for 30 years.

Inputs	Alloc	(%)	Lifespan	Field 1 n LC	Field 2 1 Year	Field 1 n LC	Field 2 30 Years
Connection parts (PVC)	83	17	15	1	1	3	3
Mulch FPO/TPO	100	-	30 [37]	1	-	1	-
Drip irrigation (PE)	83	17	5	1	1	6	6
Drainage	83	17	10	1	1	3	3
Logic system	83	17	10	1	1	3	3
Logic system cables	83	17	15	1	1	2	2
Pressure system	83	17	10	1	1	3	3
Pumping system	83	17	15	1	1	2	2
Tomato	83	17	1 [38]	1	1	30	30
Water storage	83	17	10	1	1	3	3
Outputs (yield, kg)				Field 1 821	Field 2 113	Field 1 24,630	Field 2 3390

For the life cycle calculations, the lifespan of the materials was evaluated applying a conservative approach, according to the reference study by [38], based on expert experience and site conditions.

All inputs are summarized at the end of Section 2.2, Table 2.

Table 2. Summarised inputs.

	Materials		**Unit**
Connection PVC	Polyvinylchloride production, bulk polymerisation (EU)	2.22	kg
	Bitumen adhesive compound, hot (EU), production	4.45×10^{-3}	kg
	Limestone, crushed, washed (GLO) market	0.12	kg
	Processes		
	Extrusion, plastic pipes (EU), production	2.34	kg
	Transport, freight, light commercial vehicle (GLO) market	0.03	tkm
	Transport, freight, lorry > 32 metric ton, EURO4 (GLO) market	0.60	tkm
Drainage	**Materials**		
	Polyvinylchloride production, bulk polymerisation (EU), Alloc Def, U	7.04	kg
	Bitumen adhesive compound, hot (EU), production	0.01	kg
	Limestone, crushed, washed (GLO) market	0.38	kg
	Concrete, normal (GLO) market	0.37	m^3
	Cast iron (GLO) market	220.00	kg
	Processes		
	Extrusion, plastic pipes (EU), production	7.43	kg
	Transport, freight, light commercial vehicle (GLO) market	0.09	tkm
	Transport, freight, lorry > 32 metric ton, EURO4 (GLO) market	1.89	tkm
Drip irrigation	**Materials**		
	Polyethylene, linear low density, granulate (EU), production	6.63	kg
	Polyethylene, linear low density, granulate (EU), production	31.98	kg
	Processes		
	Extrusion, plastic pipes (EU), production	6.63	kg
	Extrusion, plastic pipes (EU), production	31.98	kg
	Transport, freight, light commercial vehicle (GLO) market for	0.46	tkm
	Transport, freight, lorry > 32 metric ton, EURO4 (GLO) market	9.85	tkm
Logic system	**Materials**		
	Electronics, for control units (EU), production	4.52	kg
	Polypropylene, granulate (GLO) market for	16.00	kg
	Battery cell, Li-ion (GLO) market for	0.15	kg
	Processes		
	Injection moulding (EU), processing	16.00	kg
	Transport, freight, lorry, unspecified (GLO) market for	4.52	tkm
Logic cables	**Materials**		
	Polyethylene pipe, corrugated, DN 75 (GLO) market for	21.00	m
	Cable, data cable in infrastructure (GLO) market for	21.00	m
	Cable, three-conductor cable (GLO) market for	21.00	m
Mulch FPO/TPO	**Materials**		
	Fleece, polyethylene (EU), production	209.10	kg
	Processes		
	Electricity, low voltage (IT) market for	2.34	kWh
	Transport, freight, lorry 16-32 metric ton, EURO3 (GLO) market for , Alloc Rec, U	88.20	tkm
Pressure system	**Materials**		
	Steel, low-alloyed (GLO) market for	9.00	kg
	Cast-iron (GLO) market for	1.30	kg
Pumping System	**Materials**		
	Cast-iron (GLO) market for	10.00	kg
	Cable, three-conductor cable (GLO) market for	19.00	m

Table 2. *Cont.*

Tomato	**Materials**		
	Nitrogen fertiliser, as N (GLO) market for	0.40	kg
	Tomato seeding	168.00	p
	Glyphosate (GLO) market for	0.70	kg
	Phosphate fertiliser, as P2O5 (GLO) market for	0.20	kg
	Potassium fertiliser, as K2O (GLO) market for	0.60	kg
	Polyethylene, high density, granulate (GLO) market for	2.40×10^{-3}	kg
	Processes		
	Electricity, low voltage (IT) market for	0.33	kWh
	Transport, passenger car, large size, diesel, EURO 4 (GLO) market for	15.00	km
	Transport, passenger car, large size, diesel, EURO 4 (GLO) market for	10.00	km
	Blow moulding (GLO) market for	2.40×10^{-3}	kg
Tomato seeding	**Materials**		
	Tap water (EU without Switzerland) market for	0.75	kg
	Peat moss (GLO) market for	3.00×10^{-4}	m^3
	Processes		
	Electricity, low voltage (IT) market for	237.00	Wh
Water Storage	**Materials**		
	Polyethylene, high density, granulate (GLO) market for	290.00	kg
	Injection-moulding (EU), processing	290.00	kg

2.2.1. Mulching Membrane FPO/TPO

A flexible multilayered polyolefin roofing membrane system with a global density of 1.7 kg/m^2 was placed above the ground facing the white top layer for 123 m^2.

A 20 m long and 1.05 m width roll was placed in the field. The cut sections were heat-treated with a tool that consumed 0.019 kWh/m^2. The estimated installation time was 12 h. The lifespan of the membrane was 30 years [37].

The following inputs were considered in the model:

- Material: "Fleece, polyethylene RER, production, Alloc Def, U";
- Process: "Electricity, low voltage IT, market for, Alloc Def, U";
- Process: "Transport, freight, lorry 16–32 metric ton, EURO3 GLO, market for, Alloc Def, U (420 km Ponte di Piave—Perugia [39])".

2.2.2. Water Source

The system included two polyethylene water tanks with a 5000 L capacity [40]. The one above the ground (145 kg) was directly connected to the dripping system and distributed water from the second tank (green water) or, if necessary, from the municipal water network. In the following, the list of the materials used as inputs for modeling the water tank are presented:

- Material: "Polyethylene, high density, granulate GLO, market for, Alloc Def, U";
- Material: "Replaceable bladder autoclave for sanitary water AS-25 model [41], steel, low-alloyed GLO, market for, Alloc Def";
- Material: "Two "T" valves [42] in cast-iron (Cast-iron GLO, market for, Alloc Def, U)".

2.2.3. Pumping System

The system included two pumps, type CTM 61/A [43]. A pump near the above-ground tank distributed water to the dripping system. A pump underground pumped the rainwater, i.e., "green water" to the first tank. Both were electric-powered systems, with a total weight of 5 kg and 0.33 kW of power. A total of 19 m of cables was needed to supply the energy for the system.

The following inputs were used for modeling the pumping system:

- Material: "Cast-iron GLO, market for, Alloc Def, U";

- Material: "Cable, three-conductor cable GLO, market for, Alloc Def, U".
- Process: "Electricity, low-voltage IT, market for, Alloc Def, U".

2.2.4. Drip Irrigation

The water dripping distribution system was primarily above ground, with small segments underground, protecting the tube from people treading on it. The main distribution net (39 m) was made of polyethylene tubes with a diameter Ø of 25 mm [44]. The system was modeled as follows:

- Material: "Polyethylene, linear low density, granulate RER, production, Alloc Def, U";
- Process: "Extrusion, plastic pipes RER, production, Alloc Def, U".

The drip-irrigation system (267 m) Ø 20 mm was a polyethylene tube that delivered 2 L/h water to each plant with regularly spaced small emitters (33 cm) [45] and was modeled using the following inputs:

- Material: "Polyethylene, linear low density, granulate RER, production, Alloc Def, U";
- Process: "Extrusion, plastic pipes RER, production, Alloc Def, U".

Finally, the irrigation system was closed with 26 pieces of polyethylene end flush (40 g each) connected to the tubes by means of 26 polyethylene parts (50 g each) [46], modeled as follows:

- Material: "Polyethylene, linear low density, granulate RER, production, Alloc Def, U";
- Process: "Extrusion, plastic pipes RER, production, Alloc Def, U".

2.2.5. Drainage

A 7.5 m long drainage pipe removed rainwater from the concrete gutter to the underground tank by gravity.

- Material: "Polyvinylchloride, bulk polymerised RER, polyvinylchloride production, Alloc Def, U";
- Material: "Bitumen adhesive compound, hot RER, production, Alloc Def, U";
- Material: "Limestone, crushed, washed GLO, market for, Alloc Def, U".

The drainage system also included two 10m-long floor concrete gutters summing to 0.37 m^3 of concrete (15 cm depth, 10 cm width, and 6 cm thickness). A cast-iron grid protected these gutters with 0.5 × 0.13 m and 5.5 kg segments, totaling 220 kg.

2.2.6. System Controls

There were two 53 × 53 cm (8 kg) inspection boxes for the electrical and telecommunication system installations, consisting of:

- Material: "Polypropylene, granulate GLO, market for, Alloc Def, U";
- Process: "Injection-moulding RER, processing, Alloc Def, U".

The system also included two sensors and a router (LR-MB-10 La Passerelle Wi-Fi/LORA TM), each with an estimated weight of 300 g [47], two water-flow monitors (560 g each) [48], four AA battery-charged soil-moisture and temperature-measuring devices, of 5 g each (Easylog USB data loggers), and 12 thermocouples (Lutron BTM-4208SD) with a total weight of 2.3 kg. The impacts of all these components were calculated using the following inputs:

- Material: "Polyethylene pipe, corrugated, DN 75 RER, production, Alloc Def, U";
- Material: "Cable, data cable in infrastructure GLO, market for, Alloc Def, U";
- Material: "Battery cell, Li-ion RoW, production, Alloc Def, U";
- Material: "Control units RER, production, Alloc Def, U".

2.2.7. Tomatoes

The experimental field was treated with herbicide (2 m offset from the field) in a proportion of 0.015 kg/mm^2 (total 46.4 m^2, 0.7 kg). Later, about 7 g of fertilizer was applied to each plant for an estimated labor time of 2 h for a total of 1.20 kg. The proportion considered was N_2, P_2O_5, and K_2O_3.

For the tomatoes, 168 plants (15–20 cm) of "*Solanum lycopersicum* L." were transplanted and manually placed within the 50 mm mulch holes during 4 h of labor.

For each plant, 0.0003 mm^3 of peat was included, according to the ecoinvent method [32]. The water included for the greenhouse step was 0.00075 m^3. The infrastructure of the greenhouse was excluded.

The electricity operation assumed was 0.30 kWh/t of tomato [38]. With respect to productivity, a non-optimized plant grew 4.7 kg [7] of tomatoes or 789.6 kg for 168 plants, totaling 0.237 kWh.

For the cropping cycle, the water consumed was collected exclusively from the system ("green water"), totaling 0.2 m^3 per day [7]. According to [36], green water is not accounted for as part of irrigation water, since it does not represent any environmental impact. Therefore, the calculations do not include water.

According to the first campaign, the 144 mulch-covered plants grew 821 kg of tomatoes (about 5.7 kg each), while the 24 plants without the mulch grew 113 kg of tomatoes (about 4.7 kg each). The total amount of tomatoes collected was 934 kg.

2.3. Life Cycle Impact Assessment

Emission flows obtained in the life cycle inventory were organized and allocated into impact categories associated with specific environmental issues [49].

The impacts were selected according to the most important aspects of agricultural systems. According to Caffrey and Veal, this sector contributes to numerous environmental impacts, including land-use change, greenhouse gas (GHG) emissions, eutrophication, ecotoxicity, and harms to human health [15].

Blanco et al. reported studies using the Center of Environmental Science (CML) methodology developed by Leiden University [11]. The CML baseline involves a problem-oriented approach recommended for simple LCA studies and is often used in studies related to agricultural activities [22].

The indicators considered were: abiotic depletion (in kg antimony equivalents/kg extraction); abiotic depletion for fossil fuels (in MJ per kg of m^3); global warming potential for a time horizon of 100 years (in kg carbon dioxide equivalent/kg emission); ozone layer depletion (in kg CFC-11 equivalent/kg emission); human toxicity; freshwater aquatic ecotoxicity; marine aquatic ecotoxicology and terrestrial ecotoxicity (all in 1,4-dichlorobenzene equivalents/kg emission); photochemical oxidation (in kg ethylene equivalents/kg emission); acidification (in kg SO_2 equivalents/kg emission); and eutrophication (in kg PO_4 equivalents per kg emission).

3. Results

3.1. One Year Life Cycle—Global Warming Potential Gases

During the first year of implementation, assessment of the total global warming potential (GWP) for Fields 1 and 2 was 2330 kg CO_2 eq and 351 kg CO_2 eq, respectively. The difference related mainly to the area was adjusted once the emissions by area were assessed and attributed to the mulch component of the F1 system.

Table 3 shows the GWP per system component. Most of the absolute emissions in both fields were associated with the water storage systems (more than 30%), the drainage system (more than 20%), and the plants. The membrane contributed about 24.65% of the CO_2 eq emissions in F1 for one year of operation. The main factors responsible for these results were the polyethylene in the membrane, the water tank, and the cast-iron grid that protected the gutter.

Table 3. GWP for F1 and F2 in the first year.

Emissions kg CO_2 eq	Total		/m^2		Contribution	
	Field 1	**Field 2**	**Field 1**	**Field 2**	**Field 1**	**Field 2**
Connection parts (PVC)	4.61	0.92	0.05	0.05	0%	0%
Mulch FPO/TPO	574.18	-	5.74	-	25%	-
Drip irrigation (PE)	72.58	14.52	0.73	0.73	3%	4%
Drainage + concrete	509.25	101.85	5.09	5.09	22%	29%
Logic system	145.53	29.11	1.46	1.46	6%	8%
Logic system cables	99.86	19.97	1.00	1.00	4%	6%
Pressure system	15.98	3.20	0.16	0.16	1%	1%
Pumping system	87.51	17.50	0.88	0.88	4%	5%
Tomato	46.02	9.20	0.46	0.46	2%	3%
Water storage system	774.13	154.83	7.74	7.74	33%	44%
1 year	2329.65	351.09	23.30	17.55	100%	100%

3.2. One Year Life Cycle—Other CML Indicators

Figure 3 shows the impacts of the system on each of the indicators. The mineral resources' abiotic depletion (kg Sb eq) was high for most of the metallic-component (e.g., copper and printed wiring board) systems.

The indicator, marine aquatic ecotoxicity, had the absolute highest values compared to all indicators. Most impacts in this category were associated with the logic system, the cabling, and the pumping system, mainly due to the metallic components. The human toxicity and the marine aquatic ecotoxicity indicators showed a similar profile, while the terrestrial ecotoxicity (kg 1,4-DB eq) indicator increased in the drainage system due to the cast-iron grid.

Ozone depletion could be attributed to water storage due to the injection molding, pumping and logic systems associated with the copper in the cabling, and to the drainage systems, primarily due to the iron casting.

Freshwater aquatic ecotoxicity was higher in the cabling and pumping systems. Abiotic depletion (MJ) related to fossil source use stood out in the water storage systems and the mulch, which was mainly composed of high-density polyethylene.

Photochemical oxidation, acidification, and eutrophication were high in almost all categories, except for the plants, the pressure system, irrigation, and the connection pieces.

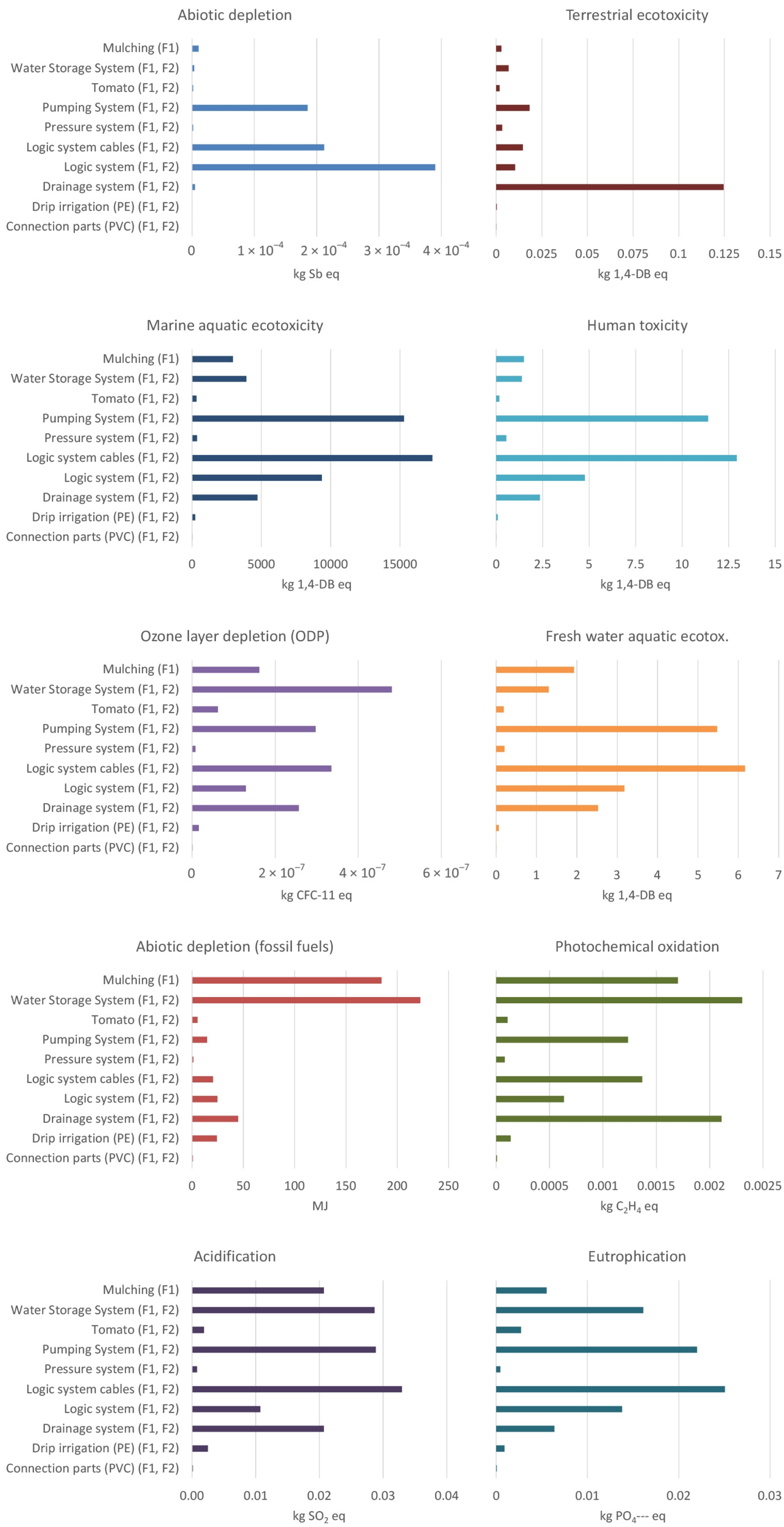

Figure 3. Values per m^2 in both fields for the first year calculated with SimaPro 8.4.0.0.

3.3. Thirty Year Life Cycle—Global Warming Potential Gases

Comparing the total global warming gas emissions for F1 and F2 resulted in 7797 kg CO_2 eq (683.81 kg CO_2 eq for mulch maintenance) and 1308 kg CO_2 eq, respectively, for a total of 30 years.

Table 4 shows the emissions per system component. The systems that impacted the most were the same as in the first year: the water storage systems (more than 30%), followed by the drainage system (more than 20%), and the tomato plants (around 20%). The membrane contribution dropped to 16% of the CO_2 eq emissions in F1.

Table 4. GWP for F1 and F2 for thirty years.

Emissions kg CO_2 eq	**Total**		**/m^2**		**Contribution**	
	Field 1	**Field 2**	**Field 1**	**Field 2**	**Field 1**	**Field 2**
Connection parts (PVC)	13.84	2.77	0.14	0.14	0%	0%
Mulch FPO/TPO	574.18	-	5.74	-	8%	-
Drip irrigation (PE)	435.48	87.12	4.35	4.36	6%	7%
Drainage + concrete	1527.68	305.61	15.28	15.28	21%	23%
Logic system	436.57	87.33	4.37	4.37	6%	7%
Logic system cables	199.72	39.95	2.00	2.00	3%	3%
Pressure system	47.93	9.59	0.48	0.48	1%	1%
Pumping system	175.01	35.01	1.75	1.75	2%	3%
Tomato	1380.56	276.18	13.81	13.81	19%	21%
Water storage system	2322.29	464.57	23.22	23.23	33%	36%
30 years	7113.25	1308.13	71.13	65.41	100%	100%

3.4. Thirty-Year Life Cycle—Other CML Indicators

Figure 4 reports the overall environmental impacts of the other indicators used in the CML method. As can be seen, in terms of the 30-year life cycle, abiotic depletion was more relevant for the electronic parts, cabling, and pumping.The marine ecotoxicity indicator contributed most to the cabling, pumping, electronics, drainage, mulching membrane, and water systems impacts. As for the first year, the drainage system stood out for terrestrial toxicity. Human toxicity was higher in the systems containing a large number of metallic parts.

Figure 4 also shows the prominent role played by the water storage, pumping, and drainage systems in ozone depletion. However, a large proportion of the impact was associated with the tomato plants and the mulch membrane. The abiotic depletion related to non-renewable sources was higher in the water system, mulching, dripping irrigation, plants, and drainage systems.

The photochemical oxidation indicator was mainly affected by the water and drainage systems. Therefore, acidification could be attributed to water storage, cabling, pumping, electronics system, and tomato plants. Finally, eutrophication was mainly caused by the tomato inputs, cabling, water storage, and electronic and pumping systems.

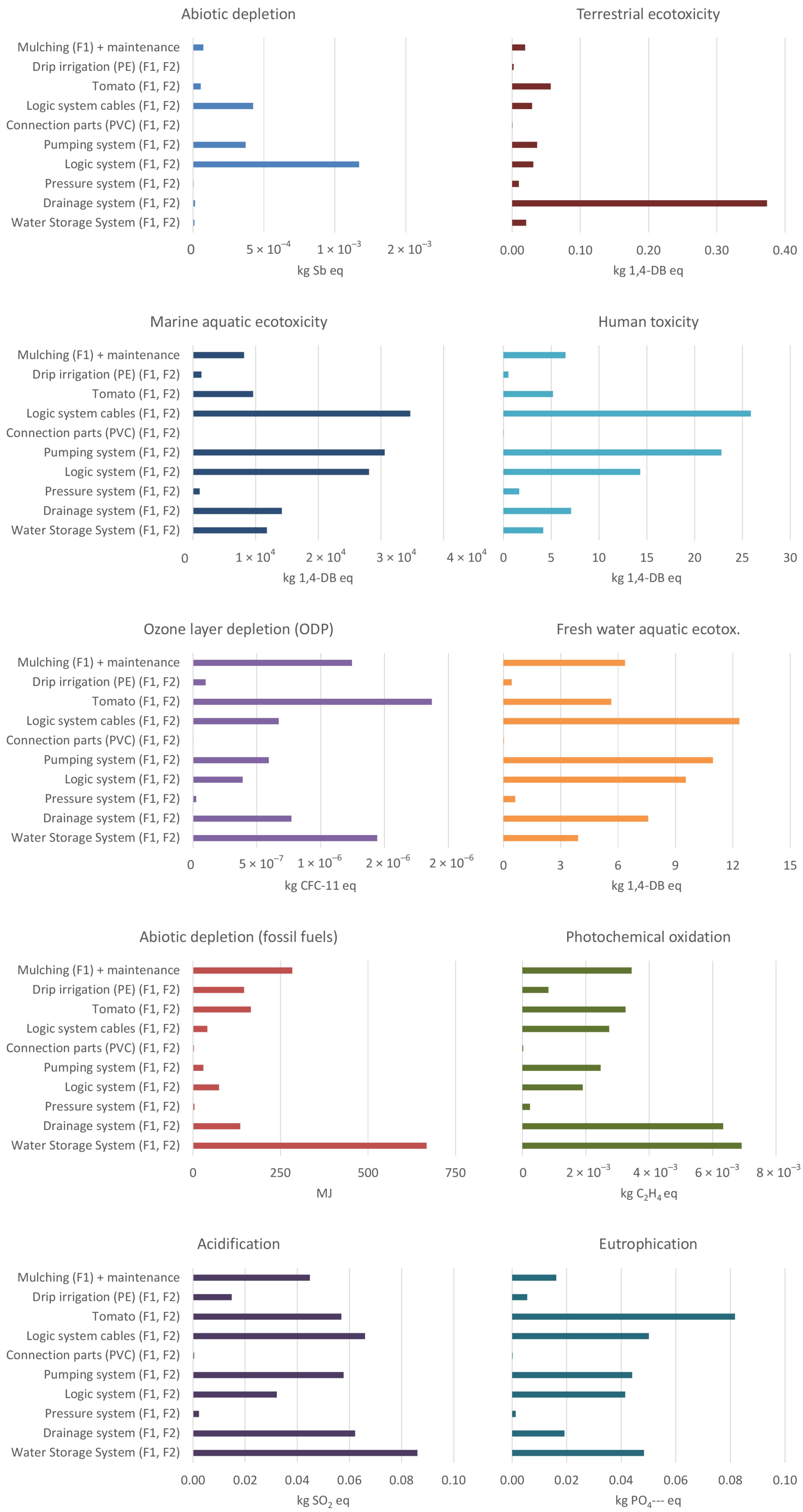

Figure 4. Values per m^2 in both fields for thirty years calculated with SimaPro 8.4.0.0.

4. Discussion

Fields 1 and 2 were analyzed in terms of area and yield. The area calculation allowed us to determine which system impacted the most, while the emissions attributed per kg of yield enabled understanding of which system was more sustainable.

Beer studied the impacts of polyolefin production and the related end-life stages [50]. As explained by the author, the service life should be considered to evaluate the impact generated by a specific system. Indeed, the environmental impact of the mulch membrane, responsible for almost 25% GWP during the first year, reduced to two-thirds of this fraction after 30 years.

Figure 5a,b shows the first-year GWP, comparing the global value and the emissions per square meter and kg of tomatoes. The respective emissions per square meter were 23.30 kg CO_2 eq and 17.56 kg CO_2 eq. Considering that the productivity of F1 was 20% higher than F2 (821 kg of tomatoes against 113 kg), a share of the 2.84 kg CO_2 eq and 3.11 kg CO_2 eq could be attributed to each kg of tomatoes produced by F1 and F2, respectively.

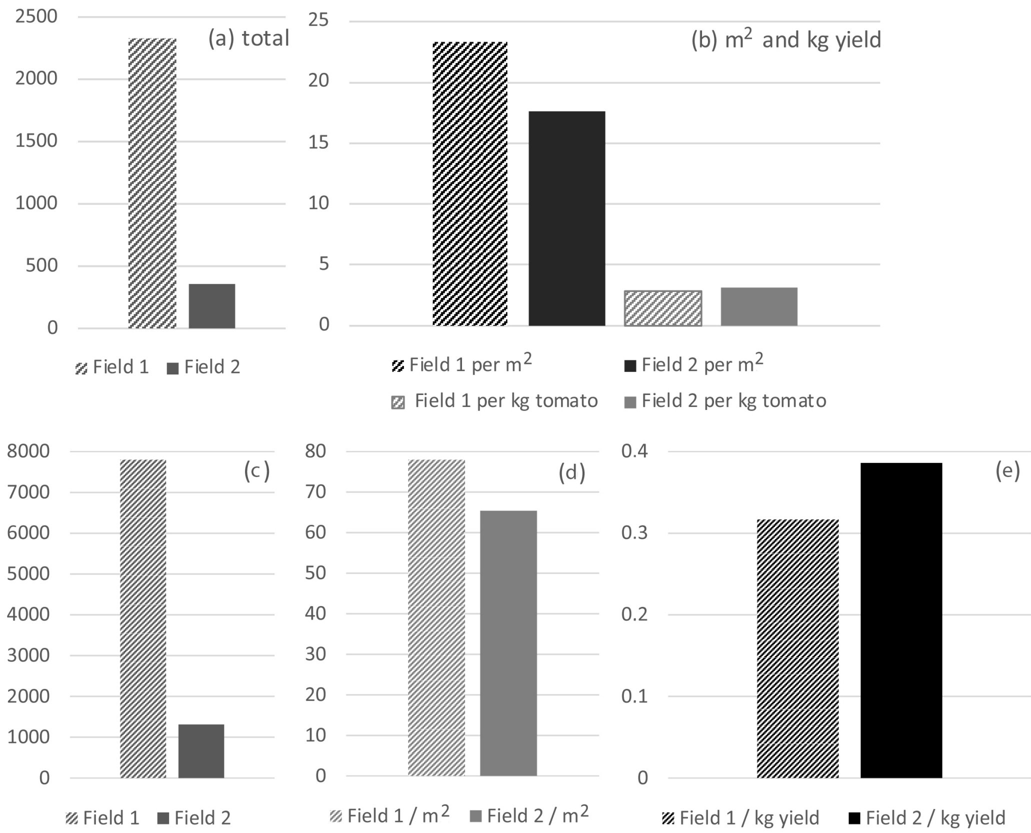

Figure 5. Emissions in kg CO_2 eq.: (**a**) total emissions for F1 and F2; (**b**) emissions per area (m^2) and kg of yield on the first year. (**c**) Total emissions for F1 and F2; (**d**) emissions per area (m^2); (**e**) emissions per kg of yield, during 30 years.

Both these values were high if compared to those reported in the Agribalyse that reported greenhouse gas emissions for one season for one kg of tomato as 0.51 kg CO_2 eq/kg [51]. In this case, 59.4% of the emissions were attributed to agriculture (farm gate).

Two factors determined the difference. First, all the emissions were credited in just one year of the crop, while most components have a much longer service life. Second, the experimental field was not optimized regarding water storage sizes and the number of control systems associated with the research study.

The GWP calculations for 30 years are presented in Figure 5c–e. The emissions per square meter were 78 kg CO_2 eq and 65 kg CO_2 eq for the F1 and F2, respectively.

The 20% higher production demonstrated by F1 during the entire life cycle of the field allowed us to evaluate the performance according to productivity. Since 821 kg and 113 kg GWP emissions per year were obtained in the two cases, 0.29 kg CO_2 eq were associated with each tomato kg in F1, and 0.39 kg CO_2 eq were associated with each tomato kg in F2.

The results regarding the yield are subject to uncertainty. Therefore, it is essential to evaluate the effect of mulching color aging on tomato production. In addition, crop production can vary with the temperature and sun availability, which are unpredictable weather conditions.

Paolini et al. [52] tested the effect of aging on several high reflective surfaces. The authors found that the surfaces decreased reflectance with time, in the case of polyolefin samples, mainly due to soiling and weather conditions. In two years, a surface with more than 0.80 decreased by 0.14 in Rome and 0.22 in Milan. This represented a significant loss in energy savings. In another study, Paolini et al. [53] found that, after 2.5 years, the loss could be more than 0.25 for highly reflective surfaces.

Dominguez-Delgado et al. [54] also reported the aging effect of cool roofs. From the research results discussed by the authors, it is possible to conclude that most reflectivity losses occurred in the first year. It was also possible to restore 90 to 100% of the initial values by power-washing [54]. Akbari [55] found that power-washing effectively reconstituted reflectivity in PVC membranes.

In our study, similar aging could represent a loss in production due to effects on plant light access and soil temperature. However, there are no equivalent studies that have evaluated degradation over 30 years with this application or the eventual productivity reduction when employing this sort of material as an agricultural mulch. Furthermore, both experiments reported in [52] were performed in cities more markedly affected by pollution than the engineering field at the University of Perugia. Therefore, the soiling aspect would be of greater significance if applied in an urban context.

Our life cycle assessment assumed that the yield was constant each year, even if, with time, the reflectivity dropped. Twenty-nine cycles of two hours of pressured water washing were included to restore the first-year conditions [54]. The use of "K 7 Premium full control plus", rented (60 km travel) once a year, with a performance area equal to 6 m^2/h, consumption of 600 L of water per hour, and 3000 W consumption were assumed [56].

Another relevant consideration is that land-use transformation and land occupation were not included. For agricultural systems, land change is an essential indicator [15], since natural areas are converted to plantations causing a reduction in biodiversity and landscape profile. However, the field under investigation was implemented in a small area inside a parking area. In this specific case, the implementation of the culture had more benefits in terms of land modification (converting to a green area) and aesthetic components [15].

Limitations

The research was limited by the information available on the materials employed. Therefore, the representativeness of the study is limited to the study field and the known suppliers. Furthermore, some assumptions were made based on research, i.e., literature, documents, catalogs, and a high-quality database (ecoinvent).

Nonetheless, there are some claims that can be made regarding the nature of the system under the spotlight. Alhashim et al. [22] and Caffrey discussed the complexity of agricultural systems and the absence of a consolidated methodology to evaluate the most critical issues related to these activities [15].

The lack of production system details and data gaps make the LCA method time-consuming and increase uncertainty in the results. However, the growing availability of certified products will contribute to reconstructing resource flows and supply chains, improving the accuracy of studies.

Beer studied the durability of polyolefin roof membranes considering the effects of UV [50]. The research showed that the material was stable with respect to the effects of chemical and biological agents, and resistant to aging factors such as radiation, water, and high temperature. However, deformation due to heat was an issue that was highlighted. The author reported a lifespan of 20 to 30 years dependent on exposure conditions. The study also investigated the ecological performance of the product regarding energy resources, GHG, acidification, eutrophication, and ozone-forming potential, concluding that polyolefin was less harmful across indicators compared to the other two extensively employed systems.

Autonomous water consumption was considered for the system that used the mulch-collected water to irrigate F1 and F2 indiscriminately. A dedicated connection to the network should be considered in a separate system. However, since the fields were in close contact, it was not reasonable to consider them to be separated in terms of water management.

5. Conclusions

The study investigated the potential environmental impact of an experimental agricultural site at the University of Perugia. Apart from hotspots, the productivity difference between a field implementing a high reflective mulch membrane and a common culture was evaluated.

As expected, the results show that the more complex F1, equipped with an extra component, had a higher environmental impact since the high reflective mulch contributed to emissions. Nonetheless, the emissions related to this component were reduced through the service life, while the benefits of the water savings and higher plant productivity made the final product in F1 more sustainable.

However, the significant reduction in the final emissions per kg of tomatoes did not consider possible decreases in productivity due to stains, weather conditions, eventual plant infections, malfunctioning system parts, etc.

Overall, the monitoring equipment, electric cabling, and the gutter grid were responsible for most toxicity effects. Using a grid with a bio-based and lighter material (feasible since the area is not a high traffic path), and shortening the distances covered by the cables, would reduce the impacts. Regarding the thermoplastic polyethylene water tanks, bio-based plastic substitution could decrease the emissions. For the mulch, the assumption of product trading is not so simple since it could affect the performance in reflection and the possibility of restoring the original characteristics by cleaning. Substituting the mulch yearly also represents more material employed, more labor (with transportation and energy for replacement), and disposed products.

The results from the first campaign appear promising for urban farming applications. With respect to food systems, it is possible to reduce the transportation factor, obtain plants according to seasonality, and manage rainwater. Increasing the albedo in urban areas could also benefit the microclimate and the effects of building scale. Such a system associated with green roof assemblies could improve thermal performance, reducing the need for active systems.

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Abbreviations

The following abbreviations are used in this manuscript:

CIRIAF	Interuniversity Research Centre for Pollution and Environment—Mauro Felli
CML	Centrum voor Milieukunde
EI	Environmental impacts
F1	Field 1
F2	Field 2
GHG	Greenhouse gases
GLO	Global
GWP	Global warming potential
LCA	Life cycle assessment
MDPI	Multidisciplinary Digital Publishing Institute
PE	Polyethylene
PVC	Polyvinyl chloride
RER	Europe
RoW	Rest of the world

References

1. FAO. *The Future of Food and Agriculture: Trends and Challenges*; Technical Report; Food and Agriculture Organization of the United Nations: Rome, Italy, 2017.
2. FAOSTAT. *The Contribution of Agriculture to Greenhouse Gas Emissions*; FAOSTAT: Rome, Italy, 2021.
3. Edgerton, M.D. Increasing crop productivity to meet global needs for feed, food, and fuel. *Plant Physiol.* **2009**, *149*, 7–13. [CrossRef] [PubMed]
4. Eisenstein, M. Sustainable Nutrition: Outlook. *Nature* **2020**, *588*, S58–59. [CrossRef] [PubMed]
5. Mattila, T.J.; Hagelberg, E.; Söderlund, S.; Joona, J. How farmers approach soil carbon sequestration? Lessons learned from 105 carbon-farming plans. *Soil Tillage Res.* **2022**, *215*, 105204. [CrossRef]
6. Agrobiofilm Consortium. Compostable Films for Agriculture. 2013, p. 160. Available online: http://www.agrobiofilm.eu/temps/docs/10_13_15_25_handbook_agrobiofilm.pdf (accessed on 12 November 2020).
7. Manni, M.; Di Giuseppe, A.; Petrozzi, A.; Nicolini, A.; Rossi, F.; Cotana, F. High-reflective Mulching Membrane for a Sustainable Development: Monitoring Campaign. *E3S Web Conf.* **2020**, *197*, 08012. [CrossRef]
8. Bamber, N.; Jones, M.; Nelson, L.; Hannam, K.; Nichol, C.; Pelletier, N. Life cycle assessment of mulch use on Okanagan apple orchards: Part 1—Attributional. *J. Clean. Prod.* **2020**, *267*, 121960. [CrossRef]
9. Bos, U.; Makishi, C.; Fischer, M. Life cycle assessment of common used agricultural plastic products in the EU. *Acta Hortic.* **2008**, *801 Pt 1*, 341–349. [CrossRef]
10. Chi, T.; Chen, K.j.; Marsh, T.L. Application of biodegradable mulches in crop production: A life cycle assessment. In Proceedings of the Agricultural & Applied Economics Association Annual Meeting, Atlanta, GA, USA, 21–23 July 2019.
11. Blanco, I.; Ingrao, C.; Siracusa, V. Life-cycle assessment in the polymeric sector: A comprehensive review of application experiences on the Italian scale. *Polymers* **2020**, *12*, 1212. [CrossRef]
12. Cadillo-Benalcazar, J.J.; Renner, A.; Giampietro, M. A multiscale integrated analysis of the factors characterizing the sustainability of food systems in Europe. *J. Environ. Manag.* **2020**, *271*, 110944. [CrossRef]
13. Meier, M.S.; Stoessel, F.; Jungbluth, N.; Juraske, R.; Schader, C.; Stolze, M. Environmental impacts of organic and conventional agricultural products—Are the differences captured by life-cycle assessment? *J. Environ. Manag.* **2015**, *149*, 193–208. [CrossRef]
14. Cerutti, A.K.; Beccaro, G.L.; Bruun, S.; Bosco, S.; Donno, D.; Notarnicola, B.; Bounous, G. Life cycle assessment application in the fruit sector: State of the art and recommendations for environmental declarations of fruit products. *J. Clean. Prod.* **2014**, *73*, 125–135. [CrossRef]
15. Caffrey, K.R.; Veal, M.W. Conducting an agricultural life-cycle assessment: Challenges and perspectives. *Sci. World J.* **2013**, *2013*, 472431. [CrossRef] [PubMed]
16. Clune, S.; Crossin, E.; Verghese, K. Systematic review of greenhouse gas emissions for different fresh food categories. *J. Clean. Prod.* **2017**, *140*, 766–783. [CrossRef]

17. Hayashi, K.; Gaillard, G.; Nemecek, T. Life Cycle Assessment of Agricultural Production Systems: Current Issues and Future Perspectives. In Proceedings of the International Seminar on Technology Development for Good Agriculture Practice in Asia and Oceania, Ibaraki, Japan, 25–28 October 2005; pp. 98–110.
18. Coletto, L.; Frezza, A.; Elsayed, M.; Nicoletto, C.; Sambo, P.; Bona, S. Using LCA to assess environmental impact of processing tomato production: First approach. *Acta Hortic.* **2012**, *936*, 79–86. [CrossRef]
19. Del Borghi, A.; Tacchino, V.; Moreschi, L.; Matarazzo, A.; Gallo, M.; Arellano Vazquez, D. Environmental assessment of vegetable crops towards the water-energy-food nexus: A combination of precision agriculture and life cycle assessment. *Ecol. Indic.* **2022**, *140*, 109015. [CrossRef]
20. Stoessel, F.; Juraske, R.; Pfister, S.; Hellweg, S. Life cycle inventory and carbon and water foodprint of fruits and vegetables: Application to a swiss retailer. *Environ. Sci. Technol.* **2012**, *46*, 3253–3262. [CrossRef]
21. Haas, G.; Wetterich, F.; Geier, U. Life cycle assessment framework in agriculture on the farm level. *Int. J. Life Cycle Assess.* **2000**, *5*, 345–348. [CrossRef]
22. Alhashim, R.; Deepa, R.; Anandhi, A. Environmental impact assessment of agricultural production using lca: A review. *Climate* **2021**, *9*, 164. [CrossRef]
23. Urbano, B.; Barquero, M.; González-Andrés, F. The environmental impact of fresh tomatoes consumed in cities: A comparative LCA of long-distance transportation and local production. *Sci. Hortic.* **2022**, *301*, 111126. [CrossRef]
24. Gordon, G.G.; Foshee, W.G.; Reed, S.T.; Brown, J.E.; Vinson, E.L. The effects of colored plastic mulches and row covers on the growth and yield of okra. *HortTechnology* **2010**, *20*, 224–233. [CrossRef]
25. Decoteau, D.; Kasperbauer, M.; Hunt, P. Mulch surface color affects yield of fresh-market tomatoes. *J. Am. Soc. Hortic. Sci. (USA)* **1989**, *114*, 216–219. [CrossRef]
26. Decoteau, D.R. Leaf area distribution of tomato plants as influenced by polyethylene mulch surface color. *HortTechnology* **2007**, *17*, 341–345. [CrossRef]
27. Fortnum, B.A.; Decoteau, D.R.; Kasperbauer, M.J. Colored mulches affect yield of fresh-market tomato infected with Meloidogyne incognita. *J. Nematol.* **1997**, *29*, 538–546. [PubMed]
28. Decoteau, D.; Kasperbauer, M.; Daniels, D.; Hunt, P. Plastic Mulch Color Effects on Reflected Light and Tomato Plant Growth. *Sci. Hortic.* **1988**, *34*, 169–175. [CrossRef]
29. Tarara, J.M. Microclimate modification with plastic mulch. *HortScience* **2000**, *35*, 169–180. [CrossRef]
30. *ISO 14040:2006*; Environmental Management—Life Cycle Assessment—Principles and Framework; Technical Report. International Organization for Standardization: Geneva, Switzerland, 2006.
31. *ISO 14044:2006*; Environmental Management—Life Cycle Assessment—Requirements and Guidelines; Technical Report. International Organization for Standardization: Geneva, Switzerland, 2006.
32. Wernet, G.; Bauer, C.; Steubing, B.; Reinhard, J.; Moreno-Ruiz, E.; Weidema, B. The ecoinvent database version 3. *Int. J. Life Cycle Assess.* **2016**, *21*, 1218–1230. [CrossRef]
33. Ekvall, T. Attributional and Consequential Life Cycle Assessment. In *Sustainability Assessment at the 21st Century*; IntechOpen: Rijeka, Croatia, 2020; Volume 32, pp. 137–144. [CrossRef]
34. Curran, M.A. Life Cycle Assessment: A review of the methodology and its application to sustainability. *Curr. Opin. Chem. Eng.* **2013**, *2*, 273–277. [CrossRef]
35. EPD International AB. *Prepared and Preserved Vegetable and Fruit Products, Including Juice*; Technical Report; EPD International: Stockholm, Sweden, 2019.
36. Nemecek, T.; Bengoa, X.; Rossi, V.; Humbert, S.; Lansche, J.; Mouron, P. World Food LCA Database: Methodological Guidelines for the Life Cycle Inventory of Agricultural Products. Version 3.5. 2019, p. 88. Available online: https://simapro.com/wp-content/uploads/2020/11/WFLDB_MethodologicalGuidelines_v3.5.pdf (accessed on 30 December 2020).
37. Polyglass SpA. *Environmental Product Declaration*; Technical Report; Polyglass SpA: Ponte di Piave, Italy, 2016.
38. Torrellas, M.; Antón, A.; López, J.C.; Baeza, E.J.; Parra, J.P.; Muñoz, P.; Montero, J.I. LCA of a tomato crop in a multi-Tunnel greenhouse in Almeria. *Int. J. Life Cycle Assess.* **2012**, *17*, 863–875. [CrossRef]
39. Mapei, G. Manuale di installazione Mapeplan T FpO. Available online: https://cdnmedia.polyglass.com/docs/librariesprovider71/lines-technical-documentation/mapeplan-fpo-tpo-installation-manual.pdf?sfvrsn=69192b71_6 (accessed on 30 December 2020).
40. Irrigazione Riccini. *Modello Serbatoi Serie*; Irrigazione Riccini: Perugia, Italy, 2020.
41. Elbi S.p.A. *Autoclavi a Membrana per Acqua Sanitaria*; Elbi S.p.A.: Limena, Italy, 2021.
42. Amazon Catalog. *Valvola a Sfera SUS304 Neufday*; Amazon Catalog. 2020. Available online: https://www.amazon.it/Neufday-Valvola-Filetto-Femmina-Inossidabile/dp/B08B6D (accessed on 3 November 2020).
43. Calpeda. *Pompe con Girante Periferica CT61*; Calpeda: Montorso Vicentino, Italy, 2021.
44. Leroy Merlin. *Tubo Polietilene in Rotolo L 100 m Ø 25 mm*; Leroy Merlin: Lezennes, France, 2020.
45. Irrigazione Riccini. *Ala Gocciolante Multibar*; Irrigazione Riccini: Perugia, Italy, 2020.
46. Claber. Catalogo. 2020. Available online: https://www.claber.com/en/prodotti/catalogo/2020/18/ (accessed on 1 January 2021).
47. Irrigazione Riccini. *Cathalog*; Irrigazione Riccini: Perugia, Italy, 2020.
48. Catalog, A. Contatore per flusso d'acqua, per la casa e il giardino, 1.5 m^3/h, per Connettori da Giardino, per Acqua Fredda, DIAMOND. 2020. Available online: https://www.amazon.it/Contatore-flusso-dacqua-giardino-connet (accessed on 6 November 2020).

49. Rosenbaum, R.K.; Hauschild, M.Z.; Boulay, A.M.; Fantke, P.; Laurent, A.; Núñez, M.; Vieira, M. *Life Cycle Assessment*; Springer International Publishing: Cham, Switzerland, 2018; Chapter 10. [CrossRef]
50. Beer, H.R. Longevity and Ecology of Polyolefin Roof Membranes. In Proceedings of the Fourth International Symposium on Roofing Technology, Sarnen, Switzerland, 17–19 September 1997; pp. 14–20.
51. Agribalyse. *Tomate de Saison, Crue*; ADEME: Angers, France, 2020.
52. Paolini, R.; Zinzi, M.; Poli, T.; Carnielo, E.; Mainini, A.G. Effect of ageing on solar spectral reflectance of roofing membranes: Natural exposure in Roma and Milano and the impact on the energy needs of commercial buildings. *Energy Build.* **2014**, *84*, 333–343. [CrossRef]
53. Paolini, R. An Overview on the Performance over time of Cool and Green Roofs as Countermeasures to Urban Heat Islands. *TEMA: Tempo Mater. Archit.* **2015**, *1*, 9–14. [CrossRef]
54. Dominguez-Delgado, A.; Domínguez-Torres, H.; Domínguez-Torres, C.A. Energy and economic life-cycle assessment of cool roofs applied to the refurbishment of social housing in southern Spain. *Sustainability* **2020**, *12*, 5602. [CrossRef]
55. Akbari, H.; Berhe, A.A.; Levinson, R.; Graveline, S.; Foley, K.; Delgado, A.H.; Paroli, R.M. Aging and weathering of cool roofing membranes. In Proceedings of the First International Conference on Passive and LowEnergy Cooling for the Built Environment, Santorini, Greece, 19–21 May 2005.
56. Alfred Kärcher SE & Co. KG. *Technical Data K 7 Premium Full Control Plus*; Technical Report; Alfred Kärcher SE & Co. KG: Winnenden, Germany, 2020.