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Breeding for Sustainable Strawberries: Evaluating the Environmental Impact of Different Cultivation Systems Across Europe

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ABSTRACT

This study was conducted to quantify the variation in environmental impacts of strawberry production across Europe to inform breeders and fruit producers on practical ways to improve the sustainability of their products. We assessed the environmental impact of different strawberry genotypes and cultivation systems, including open field and protected systems, conducted by seven different partners in Europe. The Life Cycle Assessment (LCA) methodology was applied. Fifty-seven strawberry genotypes were included in the analysis, covering 19 different field trials. The functional unit (FU) was 1 kg of freshly harvested ripe strawberry fruit at the farm gate, produced between 2017 and 2024. The results for the climate change impact category showed an average of 0.58 kg CO_2 eq./FU among all the genotypes analyzed. The highest value was 3.8 kg CO_2 eq./FU for a greenhouse system, and the lowest was 0.21 kg CO_2 eq./FU for a polyethylene-covered tunnel system. The results highlighted the crucial roles of cultivation systems, genotype selection, produced yield, and various input and management practices in the environmental performance of strawberry production. The work was based on trials connected to the breeding and testing of strawberry genotypes. The results thus help breeders to develop high-quality strawberry cultivars designed to meet sustainable production under different climatic environments by showing the critical environmental impacts associated with their products. The comparison of the environmental performance of different strawberry cultivation systems across Europe even provides a benchmark to support fruit producers and policymakers in decision-making for shaping sustainable strawberry production in Europe.

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1 | Introduction

The agricultural sector accounts for nearly 21% of global greenhouse gas emissions, making it a major driver of climate change (Lamb et al. 2021). Therefore, given agriculture's close link to the environment and the significant threat climate change poses to food security, improving the environmental sustainability of agricultural products is crucial. In this context, breeding new, more resilient, and resource-efficient cultivars has become essential to ensuring food security and improving sustainable food production while preventing economic losses. This is the primary goal of the BreedingValue project, funded by the European Commission under the Horizon 2020 program (https://breedingvalue.eu/). This initiative includes strawberry (*Fragaria × ananassa*), as well as other fruits like raspberry and blueberry (Mezzetti et al. 2023, 2018).

The production of strawberries, together with other small fruits, represents a significant component of the European economy. Strawberry is one of the most popular and cultivated crops in the world (Mezzetti et al. 2018). In 2023, the agricultural production value of strawberries was estimated to be USD 26.0 billion in the world and almost USD 5.0 billion in Europe. The European Union contributed 22% to the total global production, producing around 1.2 million tons of strawberry on 77,860 ha of cultivated area (FAO 2023). Strawberry is a high-value fruit widely used in prepared foods like beverages, preserves, confectionery, and desserts, as well as fresh. The distinctive aroma, bright red color, juicy texture, and sweetness, as well as the recognized beneficial effects on human health that its regular consumption brings (Charoenwoodhipong et al. 2025; Nemzer et al. 2020) make it popular among consumers. It has a high content of antioxidants and other beneficial compounds such as vitamin C, flavonoids (mainly anthocyanins), hydrolysable tannins (ellagitannins and gallotannins), and dietary fiber (Afrin et al. 2016; Hotchkiss et al. 2024; Newerli-Guz et al. 2023; Sarıdaş et al. 2022), the amount of which depends on the genotype, cultivation techniques, postharvest practices, and storage conditions (Akhatou and Fernández Recamales 2014; Ariza et al. 2021; Lozano et al. 2016; Martínez-Ferri et al. 2016; Nemzer et al. 2020).

Strawberry cultivation is highly resource-intensive, requiring specialized knowledge and resource-intensive inputs for its production, such as water, infrastructure (protected systems), fertilizers, and plant protection (Qaderi et al. 2023). The plant is highly vulnerable to water stress and other aspects of the changing climate, including pests and diseases, which can reduce productivity (Husaini and Xu 2016; Lahiri et al. 2022). For this reason, strawberry cultivation is often associated with large use of pesticides, which can negatively affect human health and the environment (Mezzetti et al. 2018; Paula Cecatto et al. 2013).

Sustainable strawberry production can be influenced by cultivar selection and cultivation system. According to Prohaska et al. (2024), there is a relevant genotype-dependent response to environmental conditions that influence phenotypic traits. Therefore, the development of new high-performing strawberry genotypes is important to sustainable strawberry production. Furthermore, it is important to consider the cultivation system. In Europe, this choice for strawberries depends not only on the climate but also on the tradition of production. Open field cultivation is commonly used in mild-temperature regions of Southern Europe, such as Italy and Spain, but also in Nordic countries. However, modern methods allow strawberry cultivation in a wide range of environmental conditions (Akhatou and Fernández Recamales 2014). These methods include protected cultivation such as polyethylene-covered tunnels with soil beds, greenhouses, and soilless systems. The latter offers alternatives that can be rather independent of environmental conditions (Akhatou and Fernández Recamales 2014). Different cultivation systems have varying environmental impacts, influenced by factors like infrastructure, resource inputs, and management practices. These environmental impacts often correlate with differences in productivity, input efficiency, and crop quality. As a result, conducting a comprehensive assessment of the environmental impacts associated with key parameters, such as cultivar selection, use of agrochemicals, infrastructure, growing media, and energy use, is essential for identifying the most sustainable approaches to strawberry cultivation.

One of the most widely used approaches to evaluate environmental sustainability is the Life Cycle Assessment (LCA) method. This standardized methodology is used to assess the environmental burdens of a product or service throughout its entire life cycle, considering all the inputs and outputs (ISO 2006a, 2006b). LCA is commonly used to evaluate the environmental performance of agricultural products to help improve the production system, promote sustainable products, and support decision-making at different levels of production (Alhashim et al. 2021).

LCA on strawberries has been largely investigated. Several studies conducted on different strawberry growing systems show that agrochemicals like fertilizers, pesticides, and plant protection compounds, and their related emissions, are key contributors to the impacts of open-field production systems (Parajuli et al. 2022; Romero-Gámez and Suárez-Rey 2020). Building/construction materials are the relevant contributors to tunnel and soilless systems, while electricity consumption also represents a critical factor in greenhouse systems due to heating and climate control (Ilari et al. 2021; Mousavi et al. 2023). However, protected growing systems, in general, offer the advantage of reducing the use of pesticides and other plant protection substances (Ilari et al. 2021; Khoshnevisan et al. 2013; Valiante et al. 2019). A review of the scientific literature indicates that the carbon footprint of strawberry production falls within a wide range of 0.1–10.2 kg CO_2 eq./kg of marketable strawberry fruit. However, it is important to note that these studies are often difficult to compare due to key differences in areas such as the type of cultivation system, system boundaries considered, and the LCA methodological choices.

Many studies have focused on assessing the environmental impact of strawberry cultivation by comparing different production systems in a limited number of cases or regions. For instance, Soode et al. (2015) compared the carbon footprint of various horticultural products, including strawberries, grown in Germany under both open-field and greenhouse conditions. Their results indicated that the greenhouse cultivation systems had the highest environmental impact. The results revealed that consumers were responsible for a large part of the product's impact if shopping trips occurred by private car, followed by electricity input for production and fuel for soil management. Soode-Schimonsky et al. (2017) also examined different strawberry cultivation systems (organic, conventional, polyethylene-covered tunnel, and greenhouse) located in Estonia and Germany. The greenhouse system was the most impactful, mainly due to electricity for climate control, followed by the organic system, which was attributed to a low yield and the use of machinery.

Galafton et al. (2023) used LCA to compare strawberry plasticulture production methods in Germany to open-field production. Plasticulture generally reduced environmental burdens and increased yield. Mulching with row covers was the best plasticulture scenario, while macro tunnels and greenhouses were the worst. Plastic emissions varied by plastic type. For example, a biodegradable mulch film led to high plastic emissions but lower plastic pollution scores due to its degradability, while polypropylene mulch film caused the highest plastic pollution. The study emphasized the need to integrate plastic pollution into LCA. In Spain, Legua et al. (2021) explored innovative substrates for strawberry cultivation. They found that replacing 50% of peat with dredged sediment slightly increased the environmental impact. However, this substitution could have a positive environmental effect by reducing the use of peat (considered a non-renewable resource) and by valorizing the sediment material without compromising yields. In Italy, Ilari et al. (2021) compared the environmental impact of two strawberry cultivation systems (mulched soil in tunnels vs. soilless cultivation in tunnels) and packaging and found very similar global warming potential (GWP) for both production methods. These results highlight the difficulty in sometimes determining the most sustainable production system, as it depends on the specific environmental objective. However, despite similar GWP scores, the contribution analysis revealed substantial differences among impact categories.

Girgenti et al. (2014) also conducted an LCA study comparing traditional mulching systems and polyethylene packaging with bio-based alternatives, biodegradable mulch, and compostable basket packaging. The bio-based alternatives showed a 20% reduction in non-renewable energy use and greenhouse gas (GHG) emissions, eliminated plastic waste, and extended strawberry shelf life. Valiante et al. (2019) also investigated the impact assessment from crop-cycle duration and regional variability perspectives. They analyzed strawberry production in Northern Italy (2 or 3-year open field cycles) and Switzerland (1-year tunnel cultivation system). The Swiss system had higher environmental impacts than the Italian system across all categories, mainly due to soil sterilization. The study suggested switching to renewable energy for steam sterilization to improve environmental performance. In Italy, the 2-year production cycle had lower impacts than the 3-year cycle because the lower yield in the third year did not offset the high environmental costs of crop protection.

Genotype × Environment interactions play a fundamental role in determining the yield potential of plants (Egea-Gilabert et al. 2021). In this context, the BreedingValue project aimed to explore diverse berry germplasm to develop high-quality cultivars that support sustainable production across EU countries. The project involved 20 partners from eight countries (European Commission 2021). For the LCA study, selected strawberry genotypes were assessed in 19 field trials by BreedingValue partners at various cultivation sites across two growing seasons, covering the major climate regions in Europe. The selection considered traits including plant yield, fruit quality parameters (size, color, shape, firmness, and sugar content), and resilience to water stress and diseases (Senger et al. 2022). Therefore, this study investigated the agronomic performance and environmental sustainability of new and existing strawberry cultivars across different cultivation systems.

Our study aimed to provide, for the first time, a large-scale assessment of the environmental impact of strawberry by LCA, useful to provide a guideline for fruit producers, breeders, and future breeding programs for fostering a more sustainable production in Europe and in other countries. The strength of this work lies in the representativeness of the analysis. The assessment covers key aspects of cultivation, including location, yield, growing system (typically represented by an open field, high tunnel, and greenhouse), infrastructure (materials for protected systems and irrigation systems), mulching techniques, fertilization practices, irrigation systems, electricity usage, substrates, and field operations. Each European partner tested the most suitable strawberry genotypes for their geographical location and climate, ensuring an optimized approach to regional growing conditions. While the study considers a wide range of variables, it maintains a consistent time boundary and functional unit, and is conducted by the same LCA practitioners. These factors enhance the representativeness and reliability of the study, making it a valuable reference for sustainable and efficient strawberry production in Europe.

2 | Methodology

2.1 | Goal and Scope Definition

This LCA was conducted to assess the environmental performance of various strawberry cultivation systems in test trials across multiple European countries as part of a breeding program. An attributional LCA framework was followed, focusing on how strawberry production influences environmental impacts rather than evaluating the consequences of its consumption. Thus, the decision context aligned with Situation A (micro-level decision support) as outlined in the ILCD Handbook (Joint Research Centre—Institute for Environment and Sustainability 2010). The results will inform decision-making at the breeding and farm levels and within the strawberry supply chain without necessitating structural changes. Given that the overall objective was to establish a baseline sustainability assessment for strawberry cultivation in Europe, to guide breeders and producers in enhancing the environmental performance of production under various cultivation systems, this study identifies the key environmental hotspots associated with each system. Special attention is given to the significant influence that cultivation system choices have on the overall sustainability of strawberry production. The findings are intended for a broad audience, including strawberry breeders, producers, processors, retailers, agricultural experts, and policymakers, to support the development of strategies that reduce the environmental impact of the strawberry value chain.

The scope of the study followed a cradle-to-farm gate approach and considered all the input and output flows of resources in terms of materials, energy, and emissions (Figure 1). Transportation of materials, packaging, distribution, and waste management were excluded, as they were considered outside the scope of the study. The function of the system was to produce ripe strawberry fruit for the fresh market. Therefore, the selected functional unit (FU) was defined as 1 kg of freshly harvested ripe strawberries at the farm gate, produced between 2017 and 2024. No allocation was considered, as the system only produced one main product.

The environmental impact of different strawberry production systems, including the type of production (open field and protected—greenhouse, high tunnels) and kind of growing media (soil and soilless), was evaluated in different countries. The summary of partner profiles and the production system they represent is reported in Table 1.

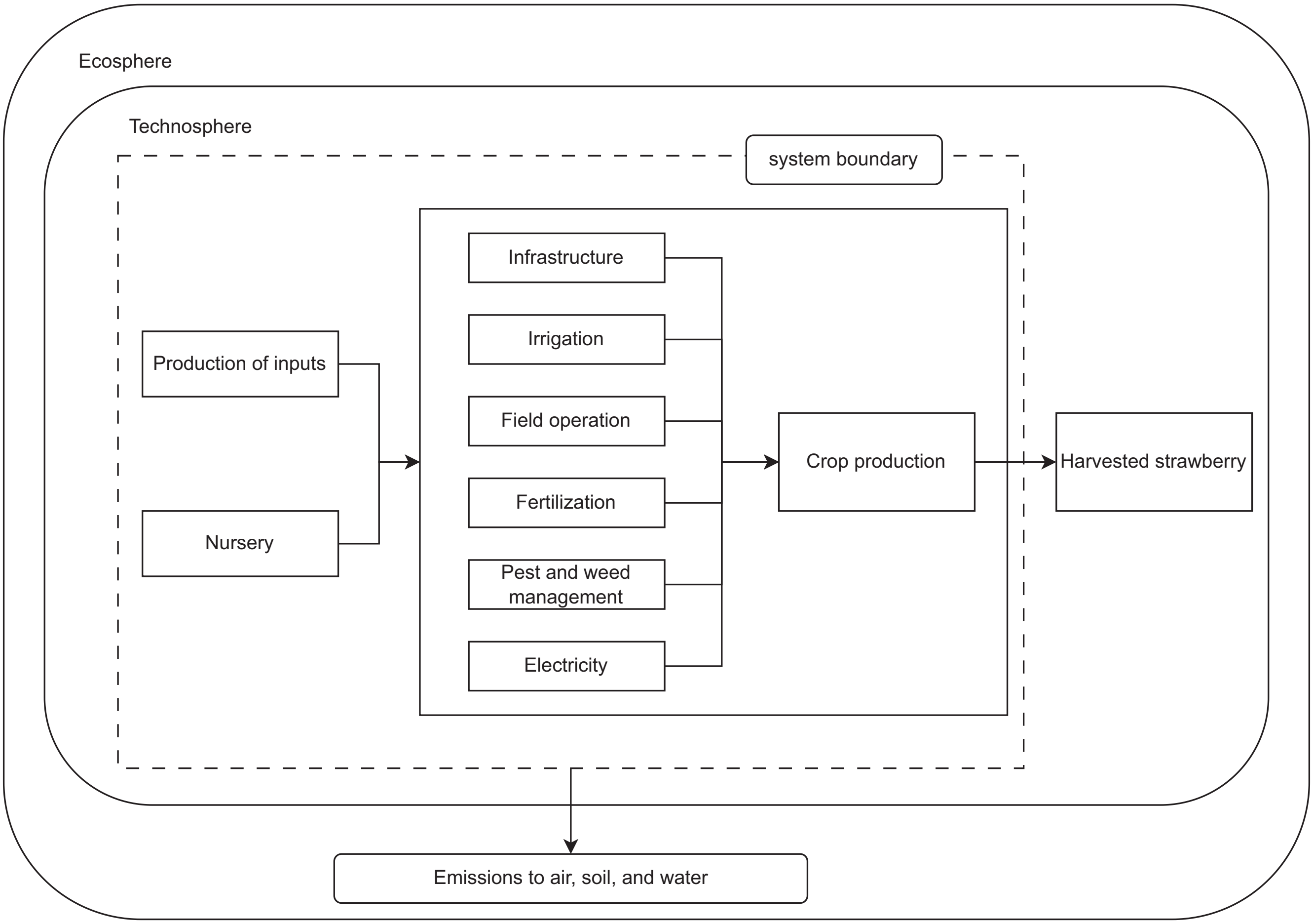


FIGURE 1 | The system boundaries of the presented LCA case studies of strawberry cultivation systems considered in this study.

TABLE 1 | The main characteristics of the strawberry production systems assessed by each partner.

Partner	Production system		Culture medium	Number of genotypes	Location	Year
1	Open field	Open field	Soil	5	Italy	2021–2022
2				11	Finland	2017–2019
3a				10	Germany	2022–2024
3b	Protected	Glass greenhouse	Soilless–peat	10	Germany	2022–2024
4		High tunnel	Soilless–coir	10	UK	2022
5			Soilless–peat	3	Italy	2022–2023
6			Soilless–peat (50%) + coir (50%)	4	Italy	2022–2024
7			Soil	4	Turkey	2022

2.2 | System Description and Life Cycle Inventory

Primary data for this study were provided by seven partners in the BreedingValue project, who evaluated several different strawberry genotypes in test trials (Table 1). These partners, comprised of universities, research institutions, breeding companies, and strawberry producers, tested new genotypes developed to meet specific regional needs. Testing was conducted under different cultivation systems to determine optimal growing conditions for each genotype within its respective geographic context. Information on the cultivation system and practices (sequence of field operations, infrastructure, and agricultural inputs, e.g., plants, fertilizers, plant protection compounds) was obtained from the partners through questionnaires (Tables 2 and 3). Secondary data were obtained from databases for LCA studies (Ecoinvent version 3.9), or they were estimated using data from other partners to supplement missing data, especially on the infrastructure.

Open field systems involved cultivation on soil beds covered with plastic mulch. Depending on specific needs (e.g., pedoclimatic conditions, varietal characteristics, or selected experimental setups), the systems include variations such as raised beds (P2), additional coverings on top of the plastic mulch, such as dry straw (P3a). Regarding high tunnels, protection is ensured by installing arched metal structures, forming a frame over which a plastic film is secured. The type and thickness of the plastic covering vary across partners based on agronomic and technical choices specific to each context. All partners used unheated tunnels with fixed walls. For the same tunnel infrastructure type, some partners cultivated directly in the soil, while others used substrate. In the case of the greenhouse, the structure consists of a metal frame and glass walls. Plants are grown in pots placed on elevated aluminium scaffolding (seedling tables), to which the heating system pipes are attached. The floor is covered with a plastic film. The irrigation setup was consistent across both open field and protected cultivation systems, and similar among partners. In general, all systems are based on drip irrigation, characterized by a main tubular line running along the crop rows (larger diameter), branching into secondary lines (smaller diameter) equipped with either bronze nozzles (P3a) or direct emitter outlets in the main plastic pipes (trickle irrigation) (all other partners). The type of plastic used varied according to the experimental conditions and application context. Water was distributed via dedicated pumps.

Data were provided in aggregated form. Most partners directly reported quantities per material type, while some provided aggregated primary data on infrastructure from which specific quantities were calculated. For all infrastructures, the indicated lifespans reflected either values communicated by the suppliers or estimates provided by the partners based on prior experimental trials conducted with the same kind of materials. Where primary data were missing, they were supplemented using either qualitative or quantitative (average) primary data from other partners applying the same variable. However, for the glass greenhouse (P3b), the external metal structures for supporting the glass walls were not included due to the unavailability of representative data. The data collection form, standardized across all partners, was designed to remove redundant entries for certain elements (e.g., fertilizers → total N content and commercial product names, including N concentration). This approach enabled partners to complete the form in line with the available level of qualitative and quantitative detail. Emissions from fertilizers (nitrogen and phosphorus compounds) were calculated following the rules presented in the PCR for arable and vegetable crops (Product Category Rules (PCR) 2020). Emissions due to the application of pesticides and herbicides were calculated based on the dispersion rate of active ingredients within the environment: 85% to soil, 10% to air, and 5% to water (Margni et al. 2002). Background data regarding the production of the different production factors used (fertilizers, plants, pesticides, energy, agricultural equipment, infrastructure) were obtained from the Ecoinvent database version 3.9 (allocation, cut off by classification) (Wernet et al. 2016).

2.3 | Life Cycle Impact Assessment

The characterization of inventory data for potential environmental impacts was carried out using the characterization factors provided by the Environmental Footprint (EF) 3.1 midpoint life cycle impact assessment (LCIA) method (Fazio et al. 2018). We evaluated the impacts of strawberry cultivation expressed per the functional unit. The impact categories were climate change (CC) estimated over a 100-year horizon, ozone depletion (OD), ionising radiation (IR), photochemical ozone formation (PCOF), particulate matter (PM), acidification (A), eutrophication freshwater (EF), eutrophication marine (EM), eutrophication terrestrial (ET), human toxicity, non-carcinogenic (HTNC), human toxicity, cancer (HTC), ecotoxicity freshwater (ETF), land use (LU), water use (WU), resource use, fossils (RUF), and resource use, minerals and metals (RUMM). We conducted this study using the SimaPro software version 9.5.

2.4 | Interpretation

The range of absolute midpoint characterization results for the cultivated strawberry genotypes from the various case studies, per the selected functional unit, is presented in this study. Results are reported for multiple impact categories, focusing on climate change due to its global significance. A detailed analysis of the key processes and substances (hotspot analysis) is provided to contextualize and interpret these findings.

3 | Results

The first part of the results presents the absolute midpoint characterization scores, expressed per the functional unit (1 kg of strawberries). The environmental performance of the strawberry genotypes in different cultivation systems is shown using scatter plots, with each point representing the individual score of a genotype (Figure 2). A horizontal line indicating the overall mean was added to serve as a benchmark for comparison. The graphs show the variation in scores across the genotypes and cultivation systems, highlighting those that perform above or below the population average. This

TABLE 2 | Life cycle inventory data for strawberry cultivation systems: Partner data, expressed per hectare.

Parameter	Unit	P1	P2	P3a	P3b	P4	P5	P6	P7
Water, irrigation	m^3	6600	4510–4695	—	1167–1326	1425	4300–6103	2333	1710
Water, rain	m^3	7500	18782	4514–5722	—	—	—	—	—
Plants (seedlings)	p	55000	32000–37000	30000–40000	90500	36000	58000	56000	70500
Field operations									
Tillage, ploughing	ha	1	1	1	—	—	—	—	—
Tillage, harrowing	ha	1	1	1	—	—	—	—	—
Application of plant protection	ha	1	1	1	—	—	—	—	1
Fertilizers									
Inorganic nitrogen fertilizer, as N	kg	215.40	249–273	82.5–112.5	227.50	200.7	77–232	326.72	151.44
Inorganic phosphorus fertilizer, as P_2O_5	kg	276.30	90–109	82.5–112.5	75.83	7.97	290–882	99.07	34.50
Inorganic potassium fertilizer, as K_2O	kg	158.30	453–460	82.5–112.5	227.50	388.15	160–486	574.6	34.14
Magnesium oxide, MgO	kg	—	—	—	—	—	—	107.33	—
Quicklime, as CaO	kg	—	—	—	—	—	—	348.32	—
Sulfur trioxide, SO_3	kg	—	—	—	—	—	—	309.54	—
Magnesium sulfate	kg	—	—	—	—	84	—	—	20
Zinc mono sulfate	kg	—	—	—	—	6.07	—	—	10
Iron sulfate	kg	—	0.248	—	—	22.63	—	—	—
Ethylenediaminetetraacetic acid (EDTA)	kg	—	—	—	—	43.5	—	—	—
Soilless substrate/media									
Coir (coconut fiber)	kg	—	—	—	—	6000	—	19600	—
Peat	m^3	—	—	—	218.4	—	116	31.11	—
Perlite	kg	—	—	—	2426.67	—	—	—	—
Expanded clay	kg	—	—	—	5200	—	—	—	—
Plant protection compounds									
Pesticide, unspecified	kg	11.76	3.5–4.56	1.08–1.15	1.74–4.57	4.32	2.25–30.8	8.91	8.11

(Continues)

TABLE 2 | (Continued)

Parameter	Unit	P1	P2	P3a	P3b	P4	P5	P6	P7
Potassium bicarbonate	kg	—	—	—	7.04–28.05	—	7.65–30.6	—	—
Potassium carbonate	kg	—	—	—	—	5.94	—	—	—
Silicon product-adjuvant	kg	—	—	—	—	0.32	—	—	—
Copper sulfate	kg	—	—	—	—	0.09	0.36	—	—
Glyphosate	kg	—	16.64	—	—	—	—	—	—
Fuel									
Diesel, low-sulfur	kg	—	—	—	—	147	346–352	—	—
Electricity									
Electricity, low voltage	kWh	—	821–823	—	962.5	—	741–1052	4500	1080
Output-yield									
Marketable strawberry	t	24.75–33	13.9–44.5	8.85–25.13	14.62–34.44	17.80–33.19	47.33–65.28	26.43–58.41	28.88–35.44

Note: P1–open field (Italy), P2–open field (Finland), P3a–open field (Germany), P3b–greenhouse (Germany), P4–high tunnel—soilless (UK), P5–high tunnel—soilless (Italy), P6–high tunnel—soilless (Italy), P7–high tunnel—soil (Turkey). Estimated emissions from the agrochemicals are not included in the table.

visualization allows for the identification of genotypes with particularly high or low performance, as well as the general distribution trend of the dataset. Additionally, the results are presented on a partner-specific basis using box-and-whisker plots (Figure 3). These plots also show both the mean values and potential outliers. For brevity, only four of the 16 assessed impact categories are presented, namely climate change, land use, resource use (minerals and metals), and water use. The complete results are available in the Supporting Information. The second part of the section focuses on the hotspot analysis for each partner. This analysis identifies the primary activity data contributing to the environmental impacts within each cultivation system.

3.1 | Absolute Midpoint Environmental Results

Figure 2a–d shows the variability in the selected midpoint impact scores for strawberry cultivation among European partners (per kg of harvested and marketable strawberries). Although some individual data points showed notable differences, the overall trend revealed that most results were comparable. The average impact scores were calculated as an indication of the baseline results for a comparative basis and possible improvement. The remaining results are reported in the Supporting Information.

3.1.1 | Climate Change (CC)

The average climate change (CC) score of the assessed strawberry genotypes was 0.58 kg CO_2 eq./FU (Figure 2a). However, greenhouse-grown strawberries had substantially higher CC scores (1.49–3.8 kg CO_2 eq./FU). Some tunnel-soilless genotypes also had recorded CC values slightly exceeding the overall average. Inter-partner comparisons (Figure 3a) revealed a wide range of CC scores, spanning from 0.2 to 3.8 kg CO_2 eq./FU, highlighting the influence of specific production practices. Specifically, open field (P1, P2, and P3a) and tunnel-cultivated (P4, P5, P6, and P7) strawberries generally presented CC scores within the range of 0.2 to 1.0 kg CO_2 eq./FU, with mean scores below 0.5 kg CO_2 eq./FU, except for P4 and P5. Despite these variations, the data did not demonstrate substantial differences in CC impacts between open field and tunnel-grown strawberry production.

3.1.2 | Land Use (LU)

The average land use score was 14.4 Pt/FU. Like CC impact, greenhouse-cultivated strawberries recorded the highest LU scores. Some open field and tunnel-soilless systems also exceeded the average, while all tunnel-soil systems were below it (Figure 2b). P3b (greenhouse) showed the greatest impact (approximately 40–110 Pt/FU), indicating a greater LU impact compared to other partners (Figure 3b). In contrast, P1 and P2 (open field), P6 (tunnel-soilless), and P7 (tunnel-soil) had scores below average. P3a (open field) and P4 and P5 (tunnel-soilless) had average scores slightly above the overall average (15–22 Pt/FU). These findings suggest that greenhouse cultivation could be more land-intensive than other production systems, due to infrastructure and management

TABLE 3 | Life cycle inventory: Infrastructure and other auxiliary equipment materials used in the different cultivation systems, expressed per hectare.

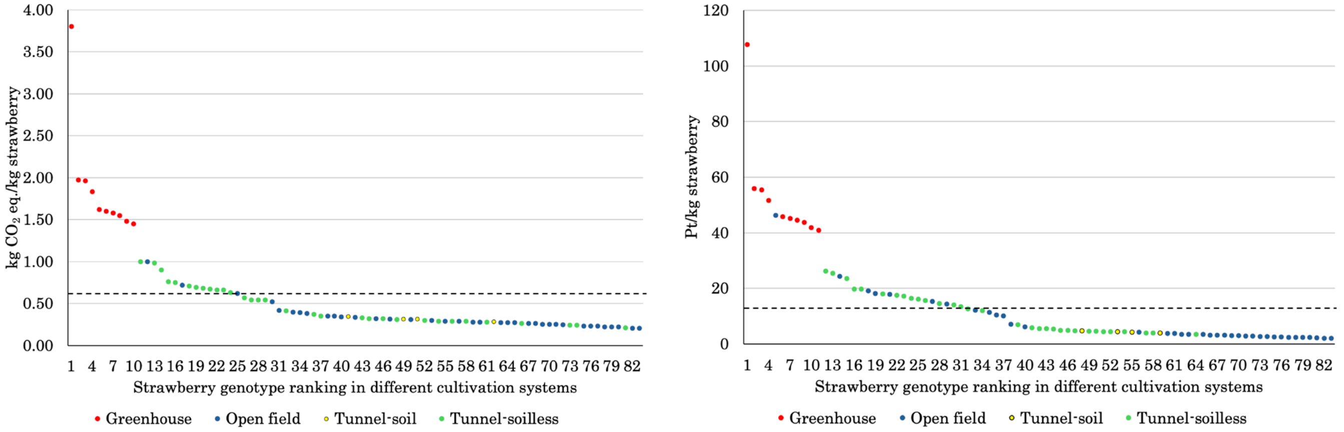
Partner	Material	Use	Unit	Value	Lifespan (years)
P1	Low density polyethylene	Irrigation system	kg	92.21	3
	Polypropylene	Mulching	kg	170.77	3
P2	High density polyethylene	Irrigation system	kg	353	3.25
	Low density polyethylene	Mulching	kg	295	3.25
P3a	Bronze	Irrigation system	kg	0.09	10
	High density polyethylene	Irrigation system	kg	10.51	10
	Polypropylene	Mulching	kg	3.07	6
	Straw	Mulching	t	20	1
P3b	High density polyethylene	Irrigation system	kg	113	10
	Polypropylene	Irrigation system	kg	105	6
	Polypropylene	Pot	kg	713	4
	Polypropylene	Floor covering	kg	175	6
	Greenhouse, glass walls, and roof	Greenhouse	m^2a	814	25
	Aluminium	Greenhouse structure	kg	647	25
P4	High density polyethylene	Irrigation system	kg	88[1]	3
	Chromium steel pipe	Tunnel	kg	725[2]	30
	Low density polyethylene	Tunnel	kg	2125[3]	3
P5	Low density polyethylene	Irrigation system	kg	332	10
	Chromium steel pipe	Tunnel	kg	828	30
	Low density polyethylene	Tunnel–cover	kg	2125	3
P6	High density polyethylene	Irrigation system	kg	29	3
	Low density polyethylene	Growing bag	kg	170	3
	Chromium steel pipe	Tunnel	kg	763	30
	High density polyethylene	Tunnel–anti-hail net	kg	54	10
P7	High density polyethylene	Irrigation system	kg	122.5	3
	Polypropylene	Mulching	kg	213.5	1
	Chromium steel pipe	Tunnel	kg	583.30	30
	Ethyl vinyl acetate, foil	Tunnel	kg	7.68	3

Note: Cultivation systems: P1 (Open field, Italy), P2 (Open field, Finland), P3a (Open field, Germany), P3b (Greenhouse, Germany), P4 (High tunnel, UK), P5-P6 (High tunnel, Italy), P7 (High tunnel, Turkey). Data sources: 1 (Avg. P6-P7), 2 (Avg. P5-P7), 3 (P5).

practices when productivity is low. The comparable LU impact between tunnel and open field systems suggests that the increased land use associated with infrastructure in tunnel systems may be offset by the potential for more efficient land management or higher yields per unit area compared to open field systems.

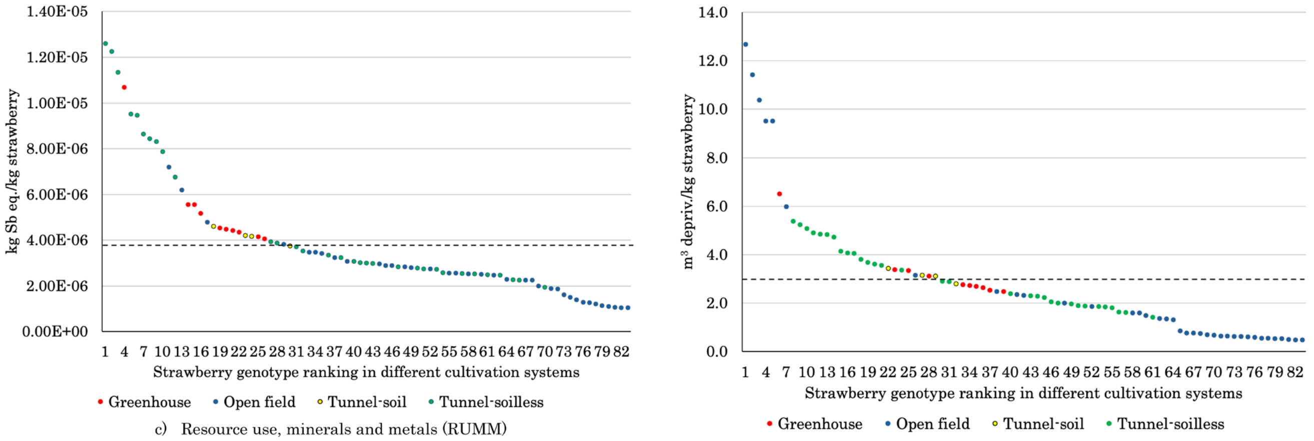
3.1.3 | Resource Use, Minerals and Metals (RUMM)

Tunnel-soilless cultivated strawberry had the highest impact scores for RUMM, more than twice the average value of 3.9 $\times 10^{-6}$ kg Sb eq./FU (Figure 2c). All the cultivation systems had some scores above the mean, with the greenhouse strawberry having almost all its scores above the mean value. Concerning the performance of the partners (Figure 3c), P4 had the highest value compared to all other partners, with an average of 9.5 $\times 10^{-6}$ kg Sb eq./FU and a range extending between 7.0 and 12 $\times 10^{-6}$ kg Sb eq./FU. In contrast, the other partners had values ranging between 2.0 and 6 $\times 10^{-6}$ kg Sb eq./FU, with a mean around 4.0 $\times 10^{-6}$ kg Sb eq./FU except for P3b, which had a slightly higher mean of 5.0 $\times 10^{-6}$ kg Sb eq./FU.



a) Climate change (CC)

b) Land use (LU)



c) Resource use, minerals and metals (RUMM)

d) Water use (WU)

FIGURE 2 | (a–d). Midpoint impact characterization results for the strawberry cultivation systems with different genotypes (on the x-axis) across various field trials conducted by multiple partners. Dotted lines refer to the average score. (a) climate change, (b) land use, (c) resource use (minerals and metals), (d) water use.

3.1.4 | Water Use (WU)

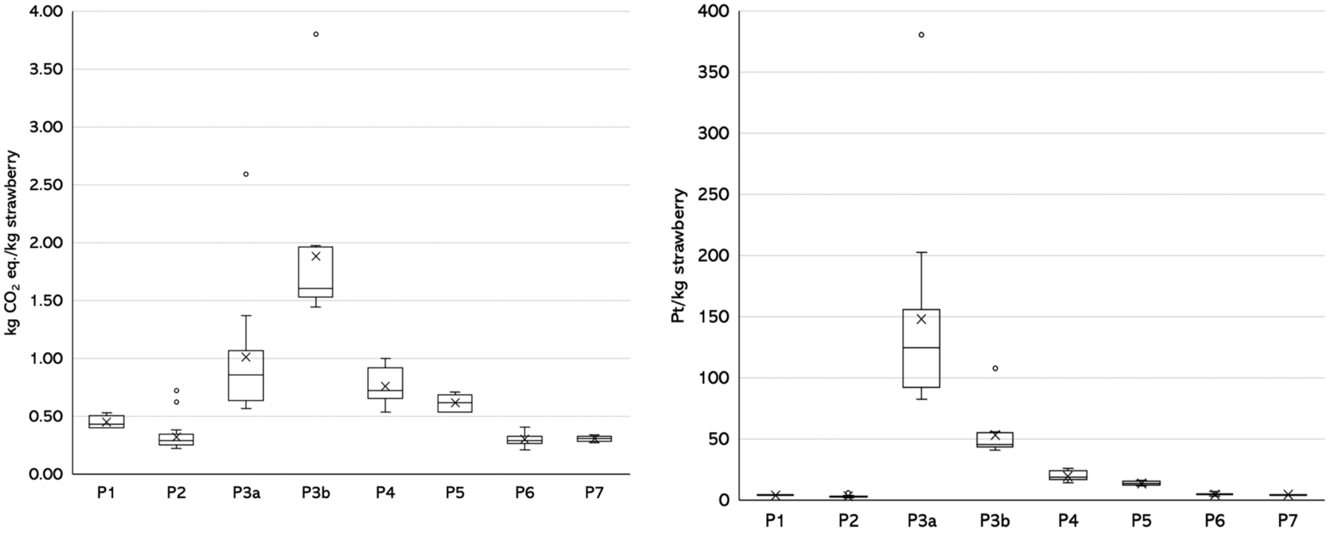
For water use, the average value for different genotypes across various field trials conducted by multiple partners was 2.9 m^3 depriv./FU. Strawberries cultivated in open field systems exhibited both the highest and lowest WU values (Figure 2d). All other cultivation systems reported some values above and below the average. Regarding the individual partners (Figure 3d), the highest WU potential was observed for P1 (open field), with a mean over 10 m^3 depriv./FU and a range exceeding 12 m^3 depriv./FU. P4 and P5 showed moderate WU, with P5 slightly higher (mean around 4.6 m^3 depriv./FU). P3b and P7 had comparable and lower WU, clustered around 3 m^3 depriv./FU. However, P2 (open field) had the lowest WU potential, clustered around 0.82 m^3 depriv./FU.

3.2 | Relative Contribution Analysis

Figure 4a–h presents the contribution analysis for the various strawberry cultivation systems evaluated for each partner. For each environmental impact category, the relative contribution of different inputs and outputs was identified. The figures highlight key activity data, including materials, energy use, emissions, and associated processes.

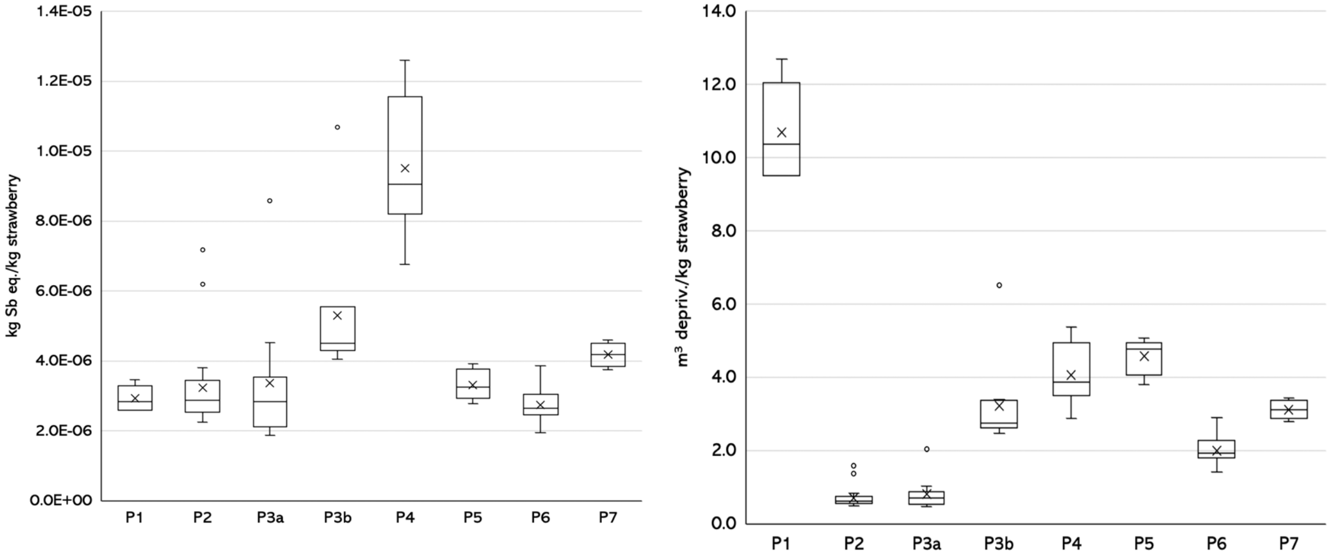
3.2.1 | Open Field

Figure 4a–c shows the contribution analysis of the different open-field strawberry cultivation systems assessed across the three partners (P1, P2, and P3a). The results revealed that the relative contributions of activity data varied across environmental impact categories and partners. For P1, fertilizer use and associated emissions from agrochemical applications were among the most significant contributors to environmental impacts. Fertilizer use accounted for over 30% of the total impacts across all assessed categories, except LU, EFT, MEU, FEU, and WU. Emissions related to agrochemicals were particularly dominant in ETF, MEU, FEU, and TEU, in which they contributed to more than 50% of the total impacts in each category. In the CC category, the main contributors were identified as plants (35%), fertilizer use (32%), and agrochemical emissions (18%). Similarly, in the case of P2, fertilizer use and associated emissions were the dominant contributors across most impact categories, accounting for over 30% of the total impact. Agrochemical emissions contributed significantly to the ETF (96%), MEU (82%), FEU (54%), and HTNC (95%). In both P1 and P2, plants also made contributions to LU. Regarding P3a, the primary environmental hotspot across several categories was the mulching material (straw), which contributed to over 50% of the total impact of A, PM, MEU, TEU, HTC, HTNC, and PCOF. Other



a) Climate change

b) Land use



c) Resource use, minerals and metals

d) Water use

FIGURE 3 | (a–d). The midpoint impact characterization results of the strawberry cultivation systems by partners with different production systems. P1 (Open field, Italy), P2 (Open field, Finland), P3a (Open field, Germany), P3b (Greenhouse, Germany), P4 (High tunnel—soilless, UK), P5 (High tunnel—soilless, Italy), P6 (High tunnel—soilless, Italy), P7 (High tunnel—soil, Turkey). (a) Climate change, (b) Land use, (c) Resource use (minerals and metals), (d) Water use.

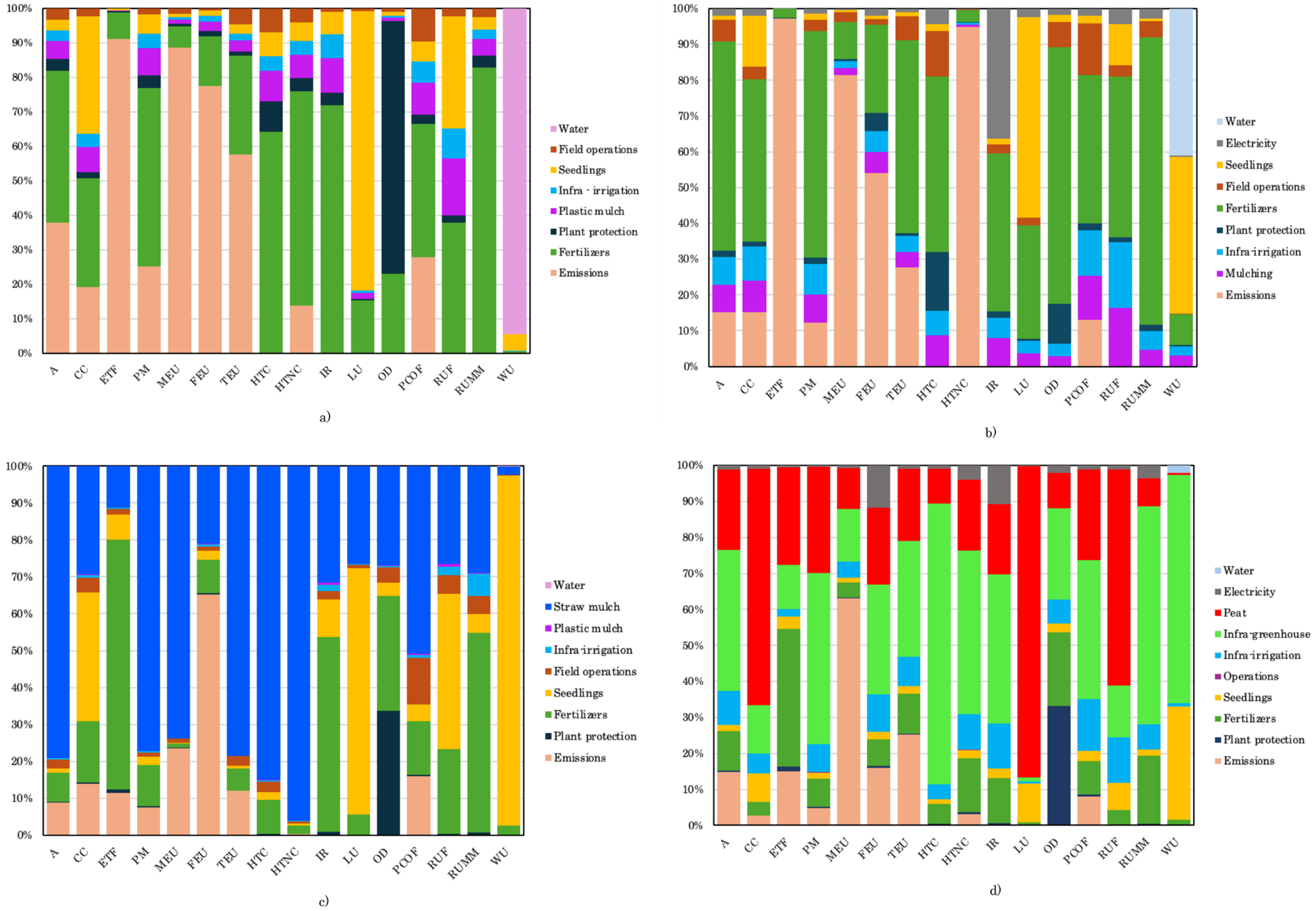
key contributors included plants for WU (90%), LU (68%), CC (35%), and RUF (41%); fertilizers for ETF (68%), IR (53%), and RUMM (55%); emissions for FEU (65%); and plant protection for OD (33%).

3.2.2 | Greenhouse

Regarding the glass greenhouse system of P3b, various activity data contributed to the overall environmental impacts, with the most significant being the greenhouse infrastructure, peat, fertilizers, and agrochemical emissions (Figure 3d). The greenhouse infrastructure, comprising glass walls and roofing, aluminum support poles, and polypropylene floor coverings, was a major contributor, accounting for over 40% of the impacts in categories such as A, PM, HTC, HTNC, IR, PCOF RUMM, and WU. Peat also had a big share of several categories, with its highest contributions recorded in CC (65%), LU (84%), and RUF (60%). Other major contributions were made by fertilizer use in ETF (41%); agrochemical emissions in MEU (63%); plant protection compound use in OD (33%); and plants in WU (22%).

3.2.3 | Tunnel—Soilless

For soilless tunnel strawberry cultivation systems (Figure 3e–f), the primary environmental hotspots across most impact categories were identified as tunnel infrastructure, fertilizers, soilless growing media (coir and peat), and agrochemical emissions. The degree to which these components contributed varied between



a)

b)

c)

d)

FIGURE 4 | The relative contribution analysis of the strawberry cultivation systems. (a) P1 (Open field, Italy), (b) P2 (Open field, Finland), (c) P3a (Open field, Germany), (d) P3b (Greenhouse, Germany), (e) P4 (High tunnel—soilless, UK), (f) P5 (High tunnel—soilless, Italy), (g) P6 (High tunnel—soilless, Italy), (h) P7 (High tunnel—soil, Turkey). A = acidification, CC = climate change, ETF = ecotoxicity freshwater, PM = particulate matter, MEU = eutrophication, marine, FEU = eutrophication, freshwater, TEU = eutrophication, terrestrial, HT = human toxicity (_c = carcinogenic, _nc = non-carcinogenic), IR = ionising radiation, LU = land use, OD = ozone depletion, POCF = photochemical ozone formation, RUF = resource depletion, fossils, RUMM = resource depletion, minerals and metals, WU = water use.

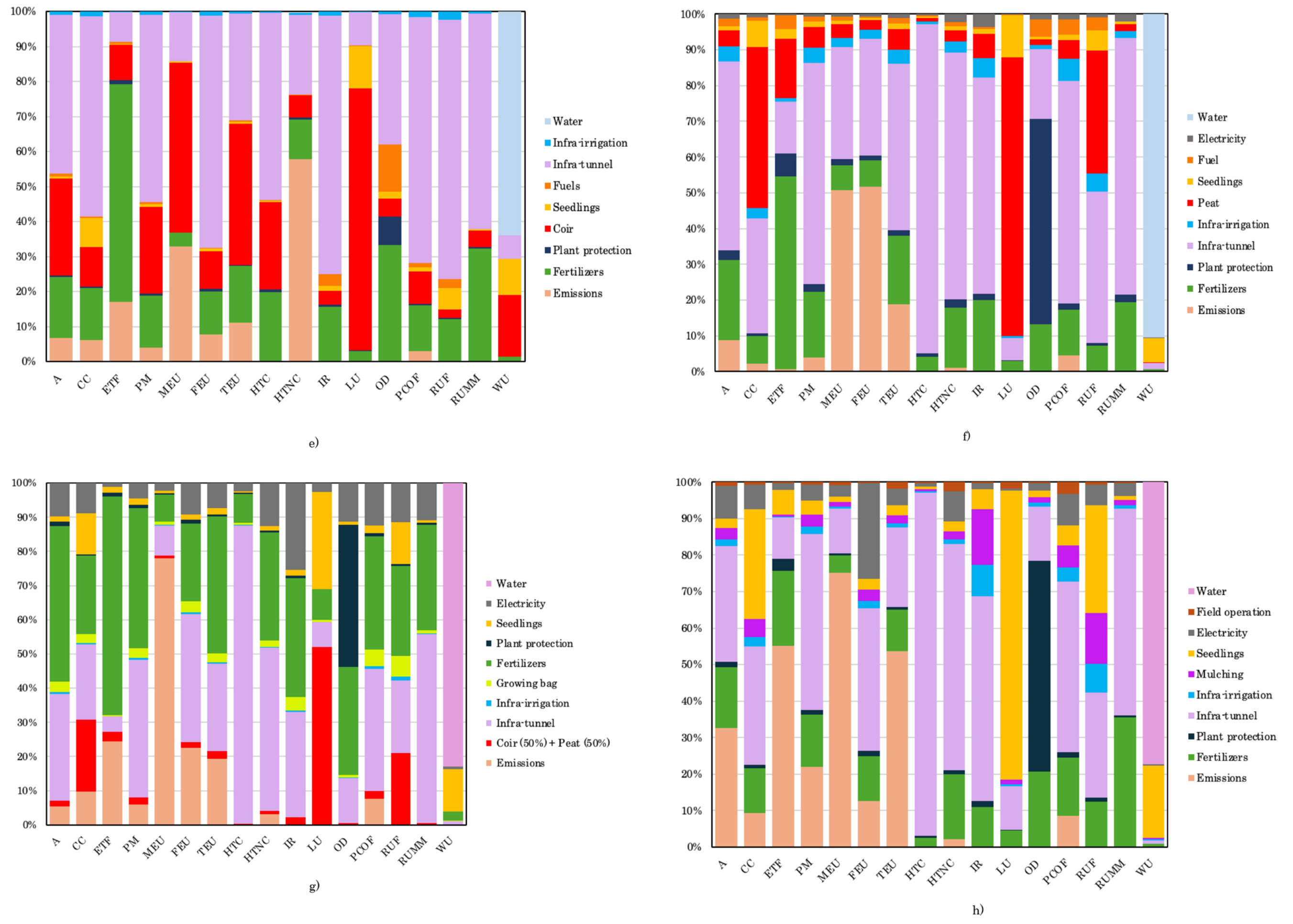
partners, P4, P5, and P6. For example, in the CC category, the tunnel infrastructure and soilless medium contributed 56% and 10% to P4, 32% and 45% to P5, and 23% and 22% to P6, respectively. Coir was a major contributor to LU for all three partners. However, electricity was relevant in P6, contributing substantially to several categories like HTNC, IR, PCOF, OD, RUF, and RUMM. Other minor contributions included plant protection product use in the OD category for P5 and P6, as well as plants, which impacted both LU and WU.

3.2.4 | Tunnel—Soil

Figure 4h illustrates the relative contribution analysis for the tunnel-based soil strawberry cultivation system for P7. The key contributing activities were tunnel infrastructure, emissions, fertilizer use, and electricity consumption. Tunnel infrastructure was a major contributor to CC, PM, FEU, HTC, HTNC, IR, and PCOF. Agrochemical emissions were a dominant contributor, particularly in A (32%), ETF (55%), MEU (76%), and TEU (53%). Fertilizers also significantly impacted several categories, including ETF, PM, and RUMM. Electricity had a share of 26% in FEU. Plants (seedlings) also contributed to impact categories like LU, WU, CC, and RUF. Plant protection contributed mainly to OD, with a share of 58%. Irrigation water was also a major contributor in the WU category.

4 | Discussion

The environmental sustainability of strawberry cultivation is evidently influenced by a range of interrelated factors, particularly yield, type of cultivation system, selected cultivar, and seasonal variability. Based on our results, the genotypes grown in the glass greenhouse system (P3b) showed the lowest relative yields among all systems. Consequently, this system had the worst environmental performance across several impact categories, including CC. However, it is important to emphasize that the glass greenhouse used in the study was not exclusively dedicated to strawberry production. It also supported the cultivation of high-value ornamental plants, bringing about the need for a more specific allocation procedure. As such, the system and the plant material may not be fully optimized for strawberry cultivation, which largely



e)

f)

g)

h)

FIGURE 4 | (Continued)

explains the relatively low productivity and associated inefficiencies. In contrast, the highest yield was recorded in the tunnel-soilless system (P5). Despite this high productivity, P5 had the best performance only in the MEU impact category. This suggests that higher yields do not necessarily translate to better overall environmental sustainability, as other contributing factors, such as infrastructure, growing medium inputs, and agrochemical requirements, play a significant role in shaping environmental outcomes.

Although open field strawberry cultivation generally had lower yields, it had lower environmental impacts than the protected systems, except for strawberries cultivated in greenhouses. Open field cultivation is more vulnerable to climatic variability compared to protected systems, often resulting in greater year-to-year fluctuations in yield. This reflects a trade-off between the environmental burden of infrastructure in protected systems and the yield benefits they may provide. The field trials conducted by P1, P2, and P3a revealed different environmental hotspots within the open field cultivation systems. For P1 and P2, the primary contributors to environmental impact were fertilizers and their associated emissions in most impact categories. In contrast, for P3a, the main hotspot was the use of straw as a mulching material, which dominated across several impact categories.

These findings indicate that case-specific strategies are necessary to enhance the sustainability of open field strawberry cultivation. Regarding fertilizer use, if optimal production is achieved, there may be limited room for further reduction without compromising yield. However, mitigation strategies could focus on the mulching material. Mulching with straw, commonly applied at around 20 t/ha to achieve a coverage thickness of approximately 5 cm, serves multiple agronomic functions like protecting plants from frost injury, suppressing weed growth, retaining soil moisture, and preventing erosion (El-Beltagi et al. 2022; Iqbal et al. 2020). While effective, its environmental impact can be considerable. A potential strategy would be to optimize the application rate, identifying the minimum quantity required to achieve desired agronomic benefits through field trials. Additionally, exploring alternative mulching materials with lower environmental impacts, such as residual wood chips, shredded leaves, or grass clippings, may offer a more sustainable solution (El-Beltagi et al. 2022).

For protected cultivation systems, tunnel-based systems yielded significantly higher productivity, although the associated infrastructure made substantial contributions to the environmental impacts. The tunnel infrastructure included metal rods, trellis systems, plastic covers, and, in some cases, anti-hail nets. The lifespan of the materials plays a critical role in determining the sustainability of strawberry production under these systems. For instance, in the case of P6, using an anti-hail net with a 10-year lifespan contributed to better environmental performance when compared to other tunnels, in which the plastic covers had a lifespan of only 3 years. This highlights the importance of not only selecting durable materials but also accurately quantifying their weight and estimating their service life, which is often overlooked by breeders and producers who tend to prioritize data collection on yield and agrochemical use. To improve sustainability, it is important to consider the entire life cycle of infrastructure materials. Regular maintenance can extend the lifespan of materials by reducing the frequency of replacement and the associated environmental burden. Moreover, the development of innovative tunnel systems using more sustainable materials, such as bioplastics, could lead to impact reduction (Mohanty et al. 2002). However, it is crucial that these alternatives are functionally equivalent to conventional materials and do not compromise strawberry yield or fruit quality.

The choice and quantity of growing medium, specifically peat and coir, influenced the environmental impacts of soilless strawberry cultivation systems, contributing to the relatively higher impact scores for P3b, P4, P5, and P6. While P3b and P5 used peat, P4 used coir, and P6 used a 50:50 mix of both substrates. The environmental performance was strongly affected by the type and amount of substrate used, which may also influence the yield. For instance, P6 used over three times the amount of coir per ha compared to P4. However, due to P6's higher yield, the environmental difference was offset. In contrast, although P3b used more than three times the amount of peat compared to P5, its yield was significantly lower, increasing its environmental burden. Considering the greater environmental impact of peat (carbon release during extraction and habitat destruction) compared to coir (a renewable byproduct of coconut processing) (Gruda 2019; Machado et al. 2021), replacing peat with coir and optimizing the amount of growing medium used (while maintaining functionality, fruit yield, and quality) could present a viable strategy for improving the sustainability of soilless strawberry production systems.

In this study, the sustainability assessment was conducted using a mass-based functional unit, because producers traditionally prioritize yield as a key indicator of performance. While this approach is practical and aligns with commercial production goals, it does not fully capture the broader aspects of fruit quality, which are increasingly important to consumers and the market. Strawberry quality encompasses attributes such as sensory properties (e.g., flavor, texture, appearance) and nutritional characteristics (e.g., antioxidant content, vitamin levels), both of which can vary significantly across different cultivation systems and farm management practices. Factors like irrigation techniques, fertilization regimes, and growing environments can influence these quality parameters (Ariza et al. 2021; Roussos et al. 2022; Xu et al. 2025). Therefore, there is a need to adopt a more holistic functional unit that integrates both quantity and quality dimensions. A possible solution could be to develop a strawberry quality index, which would aggregate key sensory and nutritional metrics into a standardized framework. Integrating such an index, coupling both the quality and quantity of yield, into sustainability assessments would allow for a more comprehensive evaluation of the performance of different strawberry genotypes. This would enable the selection of cultivars that offer optimal fruit quality alongside superior environmental performance (Boakye-Yiadom et al. 2025). Future research efforts should aim to characterize these quality parameters systematically and explore how they correlate with environmental impacts. This would enhance the ability of breeders, producers, and policymakers to make more informed decisions that balance productivity, quality, and sustainability objectives in strawberry production systems.

5 | Conclusions

This study provides a comprehensive baseline assessment of the environmental sustainability of strawberry cultivation under different systems in Europe using the EF 3.1 method. By evaluating new genotypes across different cultivation systems and management practices, the study provides valuable insights not only for fruit producers but also for breeders. This information enables them to prioritize genotypes that balance high productivity with a reduced environmental impact in strawberry cultivation.

In addition to genotype selection, the results also support the development of environmental benchmarks for strawberry production in Europe. These benchmarks can serve as reference points for fruit producers and policymakers seeking to ensure sustainable production. For instance, in terms of climate change, the global average impact was 0.58 kg CO_2 eq./kg strawberry. Such values offer a clear indication of what is typical across diverse systems and can be used to assess whether specific operations are performing above or below expected sustainability thresholds.

Results from the study demonstrate that the environmental performance of strawberry production is highly influenced by the type of cultivation system, yield levels, infrastructure inputs, and farm management practices. Open-field systems generally had lower environmental impacts, although they were characterized by greater yield variability and sensitivity to climatic conditions. Tunnel-soilless systems, while achieving higher productivity, showed variable impacts depending on substrate type and infrastructure lifespan. The glass greenhouse system gave rise to the highest environmental burdens, largely due to infrastructure and low yield efficiency, though it is important to note that the facility was not solely dedicated to strawberry production.

The findings from the study emphasize the complex trade-offs between productivity and environmental impact, highlighting the need for a holistic approach to evaluating the sustainability of strawberry production systems. Hotspot analyses identified fertilizers, agrochemical emissions, substrates, and infrastructure materials as major contributors, with differences in the partner-level results reflecting both technical and operational variability. These insights underline the importance of site-specific strategies to mitigate impacts, such as optimizing fertilizer regimes, extending infrastructure lifespan, and selecting lower impact growing media. Additionally, exploring the potential of alternative substrates and biodegradable materials, along with innovative low-impact cultivation technologies, may further support the transition toward more sustainable strawberry production systems in Europe. By establishing both environmental performance-based benchmarks and identifying low-impact plant breeding materials, this study provides actionable guidance for advancing more resilient and sustainable strawberry production systems across Europe.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

Afrin, S., M. Gasparrini, T. Y. Forbes-Hernandez, et al. 2016. "Promising Health Benefits of the Strawberry: A Focus on Clinical Studies." *Journal of Agricultural and Food Chemistry* 64: 4435–4449 American Chemical Society. https://doi.org/10.1021/acs.jafc.6b00857.

Akhatou, I., and Á. Fernández Recamales. 2014. "Influence of Cultivar and Culture System on Nutritional and Organoleptic Quality of Strawberry." *Journal of the Science of Food and Agriculture* 94, no. 5: 866–875. https://doi.org/10.1002/jsfa.6313.

Alhashim, R., R. Deepa, and A. Anandhi. 2021. "Environmental Impact Assessment of Agricultural Production Using lca: A Review." *Climate* 9: 164. https://doi.org/10.3390/cli9110164.

Ariza, M. T., L. Miranda, J. A. Gómez-Mora, et al. 2021. "Yield and Fruit Quality of Strawberry Cultivars Under Different Irrigation Regimes." *Agronomy* 11, no. 2: 261. https://doi.org/10.3390/agronomy11020261.

Boakye-Yiadom, K. A., A. Ilari, L. Olivi, et al. 2025. "Environmental Sustainability and Quality Assessment of New Raspberry Genotypes Cultivated in a Soilless System." *Sustainable Production and Consumption* 54: 502–515. https://doi.org/10.1016/J.SPC.2025.01.020.

Charoenwoodhipong, P., M. L. Zuelch, C. L. Keen, R. M. Hackman, and R. R. Holt. 2025. "Strawberry (*Fragaria × Ananassa*) Intake on Human Health and Disease Outcomes: A Comprehensive Literature Review." *Critical Reviews in Food Science and Nutrition* 65, no. 25: 4884–4914. https://doi.org/10.1080/10408398.2024.2398634.

Egea-Gilabert, C., M. A. Pagnotta, and P. Tripodi. 2021. "Genotype × Environment Interactions in Crop Breeding." *Agronomy* 11, no. 8: 1644. https://doi.org/10.3390/AGRONOMY11081644.

El-Beltagi, H. S., A. Basit, H. I. Mohamed, et al. 2022. "Mulching as a Sustainable Water and Soil Saving Practice in Agriculture: A Review." *Agronomy* 12, no. 8: 1881. https://doi.org/10.3390/AGRONOMY12081881.

European Commission. 2021. "CORDIS_Article_428881-Launch-of-New-eu-Research-Project-Breedingvalue-Developing-New-Breeding-Strategies-for-Resili_en." https://cordis.europa.eu/article/id/428881-launch-of-new-eu-research-project-breedingvalue-developing-new-breeding-strategies-for-resili.

FAO. 2023. "Food and Agriculture Organization of United Nations." https://www.fao.org/faostat/en/#home.

Fazio, S., F. Biganzioli, V. De Laurentiis, L. Zampori, S. Sala, and E. Diaconu. 2018. "Supporting Information to the Characterisation Factors of Recommended EF Life Cycle Impact Assessment Methods-Publications Office of the EU." https://op.europa.eu/en/publication-detail/-/publication/de9a732b-130c-11e9-81b4-01aa75ed71a1/language-en.

Galafton, C., D. Maga, G. Sonnemann, and N. Thonemann. 2023. "Life Cycle Assessment of Different Strawberry Production Methods in Germany With a Particular Focus on Plastic Emissions." *International Journal of Life Cycle Assessment* 28, no. 6: 611–625. https://doi.org/10.1007/s11367-023-02167-9.

Girgenti, V., C. Peano, C. Baudino, and N. Tecco. 2014. "From "Farm to Fork" Strawberry System: Current Realities and Potential Innovative Scenarios From Life Cycle Assessment of Non-Renewable Energy Use and Green House Gas Emissions." *Science of the Total Environment* 473: 48–53. https://doi.org/10.1016/j.scitotenv.2013.11.133.

Gruda, N. S. 2019. "Increasing Sustainability of Growing Media Constituents and Stand-Alone Substrates in Soilless Culture Systems." *Agronomy* 9, no. 6: 298. https://doi.org/10.3390/AGRONOMY9060298.

Hotchkiss, A. T., H. K. Chau, G. D. Strahan, et al. 2024. "Structural Characterization of Strawberry Pomace." *Heliyon* 10, no. 9: e29787. https://doi.org/10.1016/J.HELIYON.2024.E29787.

Husaini, A. M., and Y. W. Xu. 2016. "Strawberry: Growth, Development and Diseases." In *Challenges of Climate Change to Strawberry Cultivation: Uncertainty and Beyond*, 262–287. CABI. https://doi.org/10.1079/9781780646633.0262.

Ilari, A., G. Toscano, K. A. Boakye-Yiadom, D. Duca, and E. Foppa Pedretti. 2021. "Life Cycle Assessment of Protected Strawberry Productions in Central Italy." *Sustainability* 13, no. 9: 4879. https://doi.org/10.3390/su13094879.

Iqbal, R., M. Aown, S. Raza, et al. 2020. "Potential Agricultural and Environmental Benefits of Mulches—A Review." *Bulletin of the National Research Centre 2020 44:1* 44, no. 1: 1–16. https://doi.org/10.1186/S42269-020-00290-3.

ISO. 2006a. "ISO 14040:2006-Environmental Managements-Life Cycle Assessment-Requirements and Guidelines." https://www.iso.org/standard/37456.html.

ISO. 2006b. "ISO 14044:2006-Environmental Management-Life Cycle Assessment-Principles and Framework." https://www.iso.org/standard/38498.html.

Joint Research Centre—Institute for Environment and Sustainability. 2010. "Analysing of Existing Environmental Impact Assessment Methodologies for Use in Life Cycle Assessment." International Reference Life Cycle Data System (ILCD) Handbook. Luxembourg. http://lct.jrc.ec.europa.eu/.

Khoshnevisan, B., S. Rafiee, and H. Mousazadeh. 2013. "Environmental Impact Assessment of Open Field and Greenhouse Strawberry Production." *European Journal of Agronomy* 50: 29–37. https://doi.org/10.1016/j.eja.2013.05.003.

Lahiri, S., H. A. Smith, M. Gireesh, G. Kaur, and J. D. Montemayor. 2022. "Arthropod Pest Management in Strawberry." *Insects* 13, no. 5: 475. https://doi.org/10.3390/INSECTS13050475.

Lamb, W. F., T. Wiedmann, J. Pongratz, et al. 2021. "A Review of Trends and Drivers of Greenhouse Gas Emissions by Sector From 1990 to 2018." *Environmental Research Letters* 16: 73005. https://doi.org/10.1088/1748-9326/abee4e.

Legua, P., F. Hernández, F. Tozzi, et al. 2021. "Application of Lca Methodology to the Production of Strawberry on Substrates With Peat and Sediments From Ports." *Sustainability* 13, no. 11: 6323. https://doi.org/10.3390/su13116323.

Lozano, D., N. Ruiz, and P. Gavilán. 2016. "Consumptive Water Use and Irrigation Performance of Strawberries." *Agricultural Water Management* 169: 44–51. https://doi.org/10.1016/j.agwat.2016.02.011.

Machado, R. M. A., I. Alves-Pereira, R. Ferreira, and N. S. Gruda. 2021. "Coir, an Alternative to Peat—Effects on Plant Growth, Phytochemical Accumulation, and Antioxidant Power of Spinach." *Horticulturae* 7, no. 6: 127. https://doi.org/10.3390/HORTICULTURAE7060127.

Margni, M., D. Rossier, P. Crettaz, and O. Jolliet. 2002. "Life Cycle Impact Assessment of Pesticides on Human Health and Ecosystems." *Agriculture, Ecosystems & Environment* 93, no. 1-3: 379–392. https://doi.org/10.1016/S0167-8809(01)00336-X.

Martínez-Ferri, E., C. Soria, M. T. Ariza, et al. 2016. "Water Relations, Growth and Physiological Response of Seven Strawberry Cultivars (Fragaria×Ananassa Duch.) to Different Water Availability." *Agricultural Water Management* 164: 73–82. https://doi.org/10.1016/j.agwat.2015.08.014.

Mezzetti, B., F. Giampieri, Y. T. Zhang, and C. F. Zhong. 2018. "Status of Strawberry Breeding Programs and Cultivation Systems in Europe and the Rest of the World." *Journal of Berry Research* 8, no. 3: 205–221. https://doi.org/10.3233/JBR-180314/ASSET/57645688-DFA9-406F-9CD9-C59AB7EDD36A/ASSETS/GRAPHIC/10.3233_JBR-180314-IMG3.JPG.

Mezzetti, B., S. Osorio, K. Olbricht, et al. 2023. "Pre-Breeding Strategies for Obtaining New Resilient and Added Value Berries." *Acta Horticulturae* 1381: 109–114. https://doi.org/10.17660/ActaHortic.2023.1381.15.

Mohanty, A. K., M. Misra, and L. T. Drzal. 2002. "Sustainable Bio-Composites From Renewable Resources: Opportunities and Challenges in the Green Materials World." *Journal of Polymers and the Environment* 10, no. 1–2: 19–26. https://doi.org/10.1023/A:1021013921916.

Mousavi, M., M. Taki, M. G. Raeini, and F. Soheilifard. 2023. "Evaluation of Energy Consumption and Environmental Impacts of Strawberry Production in Different Greenhouse Structures Using Life Cycle Assessment (LCA) Approach." *Energy* 280: 128087. https://doi.org/10.1016/J.ENERGY.2023.128087.

Nemzer, B. V., D. Kalita, A. Y. Yashin, and Y. I. Yashin. 2020. "Bioactive Compounds, Antioxidant Activities, and Health Beneficial Effects of Selected Commercial Berry Fruits: A Review." *Journal of Food Research* 9, no. 5: 78. https://doi.org/10.5539/jfr.v9n5p78.

Newerli-Guz, J., M. Śmiechowska, A. Drzewiecka, and R. Tylingo. 2023. "Bioactive Ingredients With Health-Promoting Properties of Strawberry Fruit (*Fragaria × Ananassa* Duchesne)." *Molecules* 28, no. 6: 2711. https://doi.org/10.3390/MOLECULES28062711.

Parajuli, R., M. D. Matlock, and G. Thoma. 2022. "Environmental Life Cycle Impact Assessment of Fresh California Strawberries: A Full Supply Chain Perspective." *Cleaner and Responsible Consumption* 6: 100073. https://doi.org/10.1016/J.CLRC.2022.100073.

Paula Cecatto, A., E. O. Calvete, A. A. Nienow, R. C. da Costa, H. F. Constâncio Mendonça, and A. Celso Pazzinato. 2013. "Sistemas de cultivo na produção e qualidade de cultivares de morangueiro." *Acta Scientiarum Agronomy* 35, no. 4: 471–478. https://doi.org/10.4025/actasciagron.v35i4.16552.

Product Category Rules (PCR). 2020. "Arable and Vegetable Crops." https://www.environdec.com.

Prohaska, A., A. Petit, S. Lesemann, et al. 2024. "Strawberry Phenotypic Plasticity in Flowering Time Is Driven by the Interaction Between Genetic Loci and Temperature." *Journal of Experimental Botany* 75, no. 18: 5923–5939. https://doi.org/10.1093/JXB/ERAE279.

Qaderi, R., B. Mezzetti, F. Capocasa, and L. Mazzoni. 2023. "Stability of Strawberry Fruit (*Fragaria × Ananassa* Duch.) Nutritional Quality at Different Storage Conditions." *Applied Sciences (Switzerland)* 13, no. 1: 313. https://doi.org/10.3390/app13010313.

Romero-Gámez, M., and E. M. Suárez-Rey. 2020. "Environmental Footprint of Cultivating Strawberry in Spain." *International Journal of Life Cycle Assessment* 25, no. 4: 719–732. https://doi.org/10.1007/S11367-020-01740-W/TABLES/10.

Roussos, P. A., A. Triantafillidis, E. Kepolas, et al. 2022. "Effects of Integrated and Organic Management on Strawberry (cv. Camarosa) Plant Growth, Nutrition, Fruit Yield, Quality, Nutraceutical Characteristics, and Soil Fertility Status." *Horticulturae* 8: 184. https://doi.org/10.3390/HORTICULTURAE8020184.

Sarıdaş, M. A., E. Ağ¸am, F. C. Akbaş, A. Akyıldiz, and S. Paydaş Kargı. 2022. "Comparison of Superior Bred Strawberry Genotypes With Popular Cultivars in Terms of Fruit Bioactive Compounds Over the Full Range of Harvest Dates." *South African Journal of Botany* 147: 142–152. https://doi.org/10.1016/J.SAJB.2022.01.010.

Senger, E., S. Osorio, K. Olbricht, et al. 2022. "Towards Smart and Sustainable Development of Modern Berry Cultivars in Europe." *Plant Journal* 111, no. 5: 1238–1251. https://doi.org/10.1111/tpj.15876.

Soode, E., P. Lampert, G. Weber-Blaschke, and K. Richter. 2015. "Carbon Footprints of the Horticultural Products Strawberries, Asparagus, Roses and Orchids in Germany." *Journal of Cleaner Production* 87, no. 1: 168–179. https://doi.org/10.1016/j.jclepro.2014.09.035.

Soode-Schimonsky, E., K. Richter, and G. Weber-Blaschke. 2017. "Product Environmental Footprint of Strawberries: Case Studies in Estonia and Germany." *Journal of Environmental Management* 203: 564–577. https://doi.org/10.1016/j.jenvman.2017.03.090.

Valiante, D., I. Sirtori, S. Cossa, et al. 2019. "Environmental Impact of Strawberry Production in Italy and Switzerland With Different Cultivation Practices." *Science of the Total Environment* 664: 249–261. https://doi.org/10.1016/j.scitotenv.2019.02.046.

Wernet, G., C. Bauer, B. Steubing, J. Reinhard, E. Moreno-Ruiz, and B. Weidema. 2016. "The Ecoinvent Database Version 3 (Part I): Overview and Methodology." *International Journal of Life Cycle Assessment* 21, no. 9: 1218–1230. https://doi.org/10.1007/s11367-016-1087-8.

Xu, S., D. Shi, H. Chen, et al. 2025. "Substrate Cultivation System Improved the Quality of 'Hongyan' Strawberry Fruits Compared With the Soil Cultivation System." *Food Chemistry* 485: 144430. https://doi.org/10.1016/J.FOODCHEM.2025.144430.

Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Figure S1:** (a–l). Midpoint impact characterization results for the strawberry cultivation systems, presented for different cultivars across various field trials conducted by multiple partners. Dotted lines refer to the average score. **Figure S2:** (a–l) shows the variability in some selected midpoint impact scores for strawberry cultivation among European partners (per kg of harvested and marketable strawberries). The results are presented using box-and-whisker plots, which highlight the distribution of the data, the degree of variability, and the presence of potential outliers. **Figure S2:** (a–l). The midpoint impact characterization results of the strawberry cultivation systems. (a) P1 (Open field, Italy), (b) P2 (Open field, Finland), (c) P3a (Open field, Germany), (d) P3b (Greenhouse, Germany), (e) P4 (High tunnel—soilless, UK), (f) P5 (High tunnel—soilless, Italy), (g) P6 (High tunnel—soilless, Italy), (h) P7 (High tunnel—soil, Turkey).