







Comparative climate change impacts of different strawberry cultivation systems in Southeastern Europe: A study across open-field and protected cultivation systems towards sustainable production models

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ABSTRACT

The current study evaluated the climate change impacts of three different strawberry cultivation systems (open-field, protected soil-based, and protected soilless cultivation) across four Southeastern European countries: Serbia, Greece, Cyprus and Italy. To this aim, a Life Cycle Assessment (LCA) was employed in accordance with ISO 14040/14044 standards and ReCiPe2016 (H) was chosen as the impact assessment methodology. The objectives of the study were twofold: first, to develop a life cycle inventory (LCI) encompassing all flows and processes related to strawberry production, and second, to identify the practices and processes contributing the most significant environmental burden.

The scope of the study was focused on crop production; thus, the boundaries of the system were set as cradle-to-farmgate and the assessment covered all in-field processes: the land preparation, the planting, the fertilization and pesticides' use, the irrigation and the harvest. Post-harvest management practices were assumed to be similar across the different systems and thus fall outside the scope of this study. Results indicated significant differences across the countries examined and the cultivation systems tested. Cyprus exhibited the highest global warming potential, primarily due to excessive fertilizer use in soilless cultivation, while Serbia showed the lowest impact, reflecting more sustainable-sourced agricultural practices. Among the different countries and cultivation systems examined, the open field cultivation in Cyprus and protected soilless cultivation in Serbia exhibited the highest water consumption, driven by climate conditions and plant density differences. The trade-offs reported herein illustrate that no cultivation system performs best across all impact categories; instead, each system's advantages come at a cost in another environmental dimension. Our findings underscore the importance of adopting region-specific strategies to optimize sustainability in capital-intensive strawberry production systems.

1. Introduction

The global population is estimated to reach up to 10 billion by 2050, leading to an inevitable increase in the demand for energy, water, and food, as well as a greater impact on the environment [1]. The

agricultural sector is a key contributor to the economies of countries with favorable conditions for its growth, alongside industry and trade. However, agricultural development without the integration of scientific, technical, and sustainable practices can have detrimental effects on the environment and biodiversity. For instance, agriculture is the largest

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water consumer compared to other sectors, accounting for ca. 70 % of the total annual water withdrawal [2,3]. Furthermore, the agricultural sector accounts for around 15 % of global greenhouse gas emissions, driven by factors such as overuse of machinery, inefficient electricity consumption, and excessive reliance on fossil fuels [4].

These challenges underscore the importance of aligning agricultural practices with Environmental, Social, and Governance (ESG) principles, aligned with the United Nations' Sustainable Development Goals (SDGs). ESG-aligned agriculture supports SDG 13 (Climate Action) by reducing greenhouse gas emissions, SDG 15 (Life on Land) through biodiversity preservation, and SDG 12 (Responsible Consumption and Production) by improving resource efficiency. Socially, it advances SDG 8 (Decent Work and Economic Growth) by promoting fair labor practices and empowering rural communities, while governance frameworks ensure transparency and accountability across the supply chain. Ensuring that agricultural practices are sustainable sourced is essential for achieving these global goals.

Sustainable production and distribution is gaining growing significance in shaping strategies for promoting and marketing fruits and vegetables. Efforts to reduce greenhouse gas emissions, influenced by frameworks like the Kyoto Protocol, the "20-20-20" Directive (2009/29/EC) and the 17 SDGs, alongside the rise of environmentally-conscious consumer groups, have shifted the competitive landscape towards eco-innovation and energy efficiency. This shift highlights the increasing importance of sustainability in maintaining business competitiveness in the agricultural sector [5]. The climate change impact of agricultural activities is often influenced by the cultivation practices employed by farmers. The past years, these practices were primarily focused on maximizing profits. However, in recent years, their climate change impact has become increasingly significant, and cultivation methods are now seen as a strategic asset for both the farmers and the agri-food companies [6].

Over the recent years, a significant increment in the production volumes of specialty berry crops, as strawberry, was monitored. In particular, strawberry (*Fragaria x ananassa* Duch.) production rose considerably; over the past 15 years, global production has seen a substantial increase rising from 6.5 million tons to 10.4 million tons [7]. Strawberry is a crop cultivated worldwide under different production systems: greenhouse, plastic tunnels, and open field. Ranking among the most widely cultivated fruit crops globally, strawberries are known for their adaptability and popularity, thriving in an array of climates [8,9]. The climate change impacts of agricultural activities in strawberry cultivation systems can vary significantly based on the cropping methods, crop management techniques, and the socioeconomic and climatic conditions in place. Therefore, a comprehensive assessment and understanding of the climate change impacts of strawberry production in Europe is crucial, requiring an in-depth analysis of different farming practices.

To date, the primary methods used for assessing climate change impacts have largely been eco-balances, which rely on a series of sustainability and climate change impact indicators grounded in robust theoretical frameworks. These frameworks effectively support decision-making processes and provide tangible results for monitoring environmental performance [5]. One of the most commonly employed methodologies for evaluating climate change impacts, including CO₂ emissions, greenhouse gases, and resource consumption, is LCA [10,11]. This approach is effective for identifying and quantifying climate change impacts throughout the life cycle of a crop production system, offering objective support for decision-makers.

Studies have shown that different cultivation systems, such as mulched soil in tunnels and soilless systems, have varying impacts on the environment. For instance, in central Italy, the global warming potential was found to be similar for both systems, with slight differences in the use of crop inputs and materials [12,13]. The choice of growing medium also plays a significant role in climate change impact. In Italy, using dredged sediments as a substrate resulted in a higher environmental

footprint compared to peat. However, mixing these sediments with other materials helped reduce the impact [14]. In Southern Italy, applying compost tea improved strawberry yield and profitability. However, the overall sustainability of organic systems is depended on irrigation and fertigation practices [15]. Previous research has highlighted that soil management, fertilizers, and pesticides remain key environmental challenges in strawberry cultivation. In Switzerland and Italy, differences in cultivation practices significantly influenced climate change impacts, with Italian practices generally resulting in lower impacts [6]. In Spain, innovative systems like macro-tunnel soilless integrated systems proved more sustainable than traditional methods. While organic cultivation had lower climate change impacts per hectare, it is characterised from reduced productivity [16]. Current research on the climate change impact of strawberry cultivation in Europe primarily focuses on countries such as Italy [5,6,12,15–19].

To the best of our knowledge, there are no existing studies that specifically examine the sustainability of strawberry cultivation practices in a comparative manner among different countries. Previous studies suggested that crop production is the primary contributor to most climate change impacts evaluated through LCA. Consequently, our research has focused on the agricultural practices involved in strawberry production systems to identify the impact of both climate and cultivation system applied. This study represents the first comprehensive assessment of the climate change impacts of key strawberry production systems across different countries of the broader Southern Europe through the application of LCA. It covers different cultivation systems, offering a detailed overview of strawberry farming practices with a focus on environmental sustainability.

2. Materials and methods

2.1. Case study description

Four countries of South Europe that are particularly vulnerable to adverse climate change scenarios were used for the needs of the current study: Serbia, Greece, Cyprus and Italy. Its case study and its special characteristics in terms of strawberry cultivation is described in the next paragraphs.

In Serbia, strawberry is considered to be an economically important berry crop, whose production volume ranges between 23,704 tons (year 2023) and 32,943 tons (year 2022) covering a total area of around 7000 ha [20]. The vast majority of strawberry production (more than 90 %) is taking place in the open field on raised beds covered with polyethylene black foil in a single-row or double-row system [21]. Plastic tunnels and greenhouses are present to a lesser extent with a tendency of expansion in order to enable off-season production and prevent adverse effects of climatic factors. Soilless cultivation system slightly increased in high tunnels, and consists of growing plants in substrates at a higher density (8–14 plants/m²) aiming to reach maximum production per unit area. In contrast, cultivation on raised beds covered with polyethylene foil is mainly applied in greenhouses. In the open field conditions, plantations are maintained for three years. Planting is usually conducted during the summer (July–August) with frigo bare root plants imported from Italian and Dutch nurseries. Strawberry plants are spaced 30 cm in-the-row by 30 cm between the rows on the bed at a density of approximately 40,000 plants/ha in a double-row system, while a spacing of 18 cm is applied in a single-row system making a density of 43,000 plants/ha. The main harvest season starts at the beginning of May and lasts to mid-June. Soon after harvest, all leaves are removed for disease and pest control and plantation is prepared for the following season. Since 2005, the Italian cultivar 'Clery' has taken over a dominant place in strawberry plantations due to its early ripening time, excellent fruit quality and high adaptability to different growing systems in both seasonal and off-season production, including soilless system in tunnels. Over the last 10 years, short-day Italian cultivars 'Alba', 'Aprica', 'Joly', 'Asia', and 'Roxana' have also spread in the production and more recently the early ripening

cultivar 'Quicky' and the mid-late cultivars 'Federica' and 'Tea' that showed promising results in terms of yield and fruit quality [22,23]. The growing of day-neutral cultivars ('Monterey', 'Irma', 'Albion', 'Malga' etc.) that can expand harvest season from May to the late fall is lately receiving accumulating interest. The fruits are mainly intended for fresh consumption on domestic and foreign markets, while the rest of the fruit is used for freezing.

Strawberry cultivation in Greece is a rapidly expanding agricultural sector, valued at approximately €240 million annually. As one of the earliest producers in southern Europe, Greece exports 90 % of its strawberries to markets in the Europe and the Gulf countries. According to FAO statistics, the total area dedicated to strawberry cultivation was doubled, from 2014 (1147 ha) to 2022 (2310 ha). This substantial growth highlights the sector's optimization and its critical role in both the domestic and export markets. The primary cultivation area is the western Peloponnese, specifically the Iliia region around Manolada, which accounts for 95 % of national production. While Pieria was historically the leading production hub until 1996, the shift to the Peloponnese has been accompanied by advancements in cultivation practices, including the extensive use of high tunnels [24]. Most strawberries are grown on raised beds covered with black polyethylene, supporting one- or two-year production cycles. The sector predominantly relies on short-day or day-neutral cultivars, such as 'Victory', 'Fortuna', and to a lesser extent on 'Arwen', and 'Red Sagma (1075)', which are well-suited to the region's climate and market requirements. The harvesting season, traditionally limited to March–June, has been now extended, spanning from November until June through the adoption of fresh tray plants into the production systems. This growth has been facilitated by a skilled workforce comprising of over 300 growers, many of whom are horticulture graduates. Advanced practices, including soil solarization, the use of resilient cultivars, and technical expertise, ensure high-quality output and efficient resource utilization. These developments underscore Greece's transformation into a prominent player in the international strawberry market.

Cyprus is the most southeastern part of Mediterranean Europe. The climate is on the borderline of coastal Mediterranean, like Greece and Spain, and sub-tropical, such as Israel and Egypt. Strawberry cultivation is adopted to the local market and the touristic demand. A big percentage of strawberries is cultivated in soil, near the coasts of Ammochostos, Larnaka, Limassol and Paphos. Most of the soil is fertile loamy clay and is irrigated with a mixture of reservoir and semi-salted watered, with 800 $\mu\text{S}/\text{cm}$. Typical electrical conductivity of Cyprus irrigation waters is depending on the raining season, ranging from 700 to 1500 $\mu\text{S}/\text{cm}$ (N. Valanides, personal communication). Most growers cultivate soil in small tunnels or very low tunnels, whereas open field and common multitunnels are also being used. Some growers use soil-less cultivation in coco-coir. The coastal regions start planting in September and harvest period spans from November until May, depending on the weather conditions, protection system and the mesoclimate. To extend availability window, some growers have introduced day-neutral strawberries in the mountainous areas of Cyprus, either in sandy soils or soil-less cultivation, that provide production from May until December.

Strawberry cultivation in Italy is a crucial sector of agriculture, with an annual market value of €360 million although the hectares dedicated to this crop have gradually declined from 5517 ha in 2013 to 4350 ha in 2023, representing a significant decrease in total production by ca. 20 % [15]. The average current yield is ca. 27.5 tons/ha. The regions of Campania, Basilicata and Sicily accounts for 26 %, 24 %, and 8 % of total production, respectively. The rest production is distributed among the northeast, particularly in the Veneto region (8 %) and the central-northern Emilia-Romagna region (6 %). Trentino and Alto Adige regions produce strawberries during the summer period. In 2019, exports increased by 24 % to 12,921 tons, generating a business worth of €32.3 million, while imports reached 42,000 tons, up by 19 % compared to 2018. This disparity highlights the low competitiveness of the Italian market in off-season production [25]. Regarding cultivars, the Centre for

Fruit and Vegetable Services (CSO) in Italy reports that in the 2021–2022 growing cycle, the most grown cultivars were 'Candonga®' (52 %) and 'Inspire*' (12 %) in Basilicata region. In Campania region, the dominant cultivars currently are 'Melissa*', 'NSG203* Marimbella®', and 'Sabrina*', comprising over 70 % of the total production. In Emilia-Romagna region, 'Sibilla*' (23 %) and 'Joly*' (11 %) are the most grown cultivars. Finally, in the Veneto region, 'Aprica*' (18 %) led cultivation, followed by 'Agnese*', 'Antea*®', 'Garda*', and 'Portola*'. Despite the positive market growth in 2023 compared to 2022, the implementation of new cultivation systems to expand the production market is still in development. The symbol ® represents legally protected brand for commercial marketing, while the symbol * represents plants' breeder rights on the cultivar.

Life Cycle Assessment (LCA) was conducted in order to assess and compare the climate change impacts of product systems that examined strawberry cultivation farms in the four European countries (Serbia, Cyprus, Greece and Italy), following the methodology defined in ISO 14040/44 (International Organization for Standardization, 2006), that encompasses four main stages: Goal and Scope Definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation. The aforementioned stages are being presented below.

2.2. Goal and scope definition

The aim of the study was to assess the climate change impacts of different strawberry production systems, including the type of production (open field and protected) and the type of growing media (soil or soilless). This comparison was conducted across four European countries: Serbia, Greece, Cyprus and Italy. The production systems studied are representative of strawberry production in each country and are presented in Table 1. The objective of the study were twofold: first, to assess and compare the climate change impact of the different strawberry production systems across the four different, and second, to identify the practices and processes contributing the most significant environmental burden.

The scope of the study was focused on crop production; thus, the boundaries of the system were set as cradle-to-farmgate and the assessment covered all in-field processes, by considering the land preparation, the planting, the fertilization and pesticides' use, the irrigation and the harvest. Postharvest management practices were assumed to be similar across the different systems and thus fall outside the scope of this study.

Each system represents the farms in the respective country, producing fresh strawberries using the specific cultivation method. For all countries except for Serbia, biogenic waste generated during each cultivation cycle, namely pruning residues and fruit waste, was assumed to remain in the field for natural decomposition. This approach closes the biogenic carbon cycle, as the CO₂ captured by the plants during growth is returned to the soil through organic matter decomposition, resulting in a net-zero carbon impact for this process. In the case of Serbia, aligning with the information gathered during interviews, fruit

Table 1
The various systems studied, distinguished by country and cultivation method.

Country	Production System	Growing media	Acronym
Serbia	Open Field	Soil	OF
	Protected in high tunnel	Soil Peatmoss	PCS PCSs
Cyprus	Open Field	Soil	OF
	Protected in high tunnel	Soil Peatmoss/Cocopeat	PCS PCSs
Greece	Open Field	Soil	OF
	Protected in high tunnel	Soil Peatmoss/Cocopeat	PCS PCSs
Italy	Protected in high tunnel	Soil	PCS
		Peatmoss/Cocopeat	PCSs

waste was assumed to be directed to composting, with relevant credits applied for fertilizers based on its nitrogen (N), phosphorus (P), and potassium (K) contents. The product system is presented in Fig. 1. All inputs, including fuel, fertilizers, pesticides, water, and materials used for setting up the irrigation system, were considered. The functional unit (FU) of reference was 1 ton of marketable strawberries at the farm gate, produced during 2023. In the field, all references were related to an area of 1 ha. For the purpose of the LCIA, all relevant LCI data and results were calculated to represent the FU.

The LCI data for the product system were based on data collected from the representative farms, through distribution of questionnaires (Supplementary material S1). Data for upstream activities, such as the supply of raw materials [(e.g., fertilizers, fuels, nursery plants, high-density polyethylene (HDPE)] and the treatment of waste, are sourced from the Ecoinvent 3.10, Agri-footprint 6.3 and Agribalyse 3.1 databases.

2.3. Life cycle inventory

The geographical region of focus for the study was the broader Southern Europe, where Serbia, Greece, Cyprus and Italy are included. The study evaluated three types of cultivation systems: protected in high tunnel cultivation in soil, protected in high tunnel soilless cultivation and open field cultivation. The LCI included regional data collected from the questionnaires and face-to-face interviews with producers or local advisors of each country during the 2023–2024 cropping season, depicting the most common scenarios encountered for a given region (Supplementary material S3). Fertilizer and pesticide quantities, irrigation requirements, energy consumption and strawberry yields for the

different systems were calculated based on responses collected through tailored questionnaires. These questionnaires were designed to capture data on input flows such as the number of plants per hectare, water usage, chemical fertilizers and pesticides, cultivated area, electricity consumption (for irrigation systems and motors), diesel fuel (for machinery) and materials (e.g., HDPE). The data were collected from a total of 57 questionnaires: 21 from Serbia, 12 from Greece, 11 from Cyprus and 13 from Italy. For each system, the data from the relevant farms were evaluated, with outliers—data deviating more than ± 2 from the average—being removed, and average values were then calculated and applied. Data were aggregated using simple arithmetic means, as each participating farm was considered representative of the respective production system. The average values were assumed to be representative for each country and each system, exception made for Italy given the fact that strawberry cultivation methods may vary considerable among regions (see Section 2.1).

As country-specific datasets were not available for several key inputs (e.g., plantlets, pesticides, manure, diesel, irrigation), the most relevant datasets (European or global) were used from Ecoinvent to ensure consistency across systems. Moreover, as country-specific supplier locations were not available, estimated road distances from a European distribution hub (Rotterdam) to the case-study countries are provided in Supplementary Material S3; these distances were used to parameterize the farm-level transport (truck) processes. For Cyprus, pesticide transport was modelled as a multimodal route consisting of road transport from Rotterdam to Athens (2800 km by truck), sea freight from Athens (Piraeus port) to Limassol (850 km by container ship), and a final road delivery to the farm (50 km by truck). Transport was modelled using standard Ecoinvent truck processes (16–32 t lorry). The infrastructure

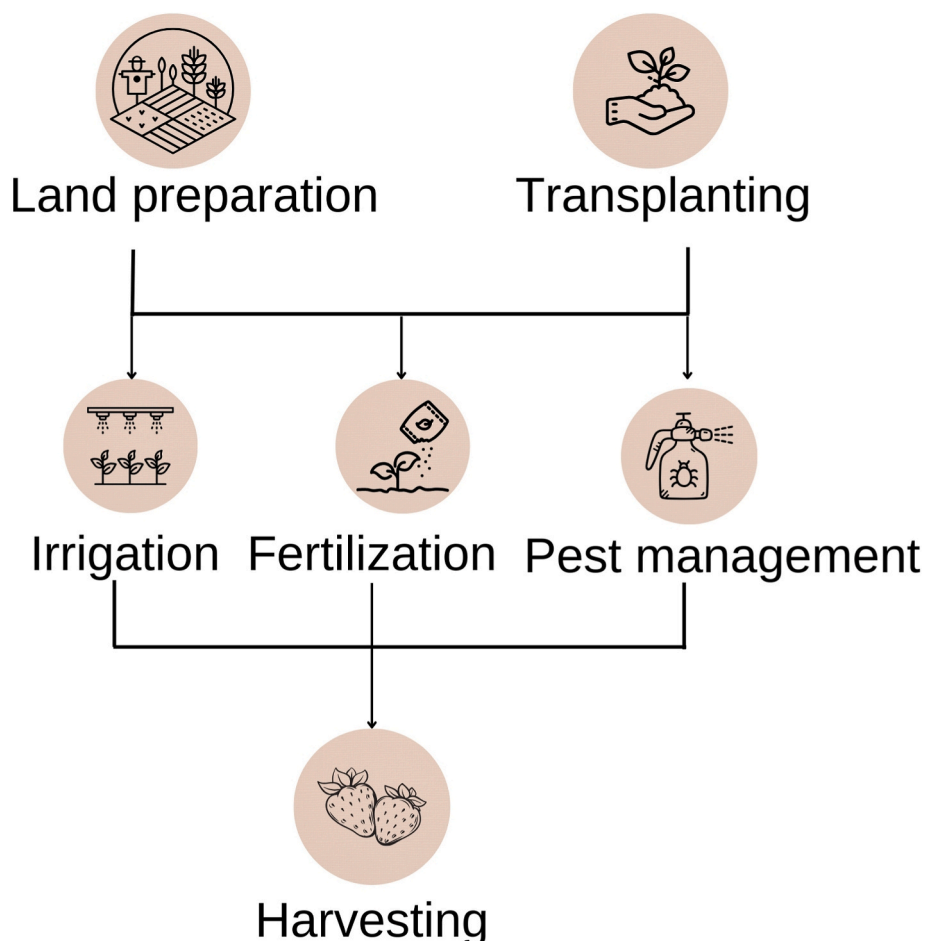


Fig. 1. Product system – system boundaries of the LCA of strawberry cultivation.

for the irrigation system used in open field cultivation was included into the “Irrigation|irrigation, drip | Cut-off, U” dataset of the Ecoinvent database. The infrastructure for the plastic tunnel (unheated) used in protected cultivation systems was included into the “Plastic tunnel | plastic tunnel construction | Cut-off, U” dataset of the Ecoinvent database. The plastic tunnel is made of a structure of galvanized steel, covered with an ethylene vinyl acetate (EVA) copolymer sheet. The plastic cover is assumed to be replaced every 4 years and the tunnel lifetime is typically 25 years. The plastic tunnel also includes a fertigation system made of a network of polyethylene pipes. Other auxiliary facilities were also considered.

Where polyethylene coverage is mentioned, 100 % soil coverage was assumed. The raised bed is externally covered with polyethylene and has a height of 40 cm. Two planting rows per raised bed are assumed, as this is the most common cultivation system. A pathway is required for workers to move through the field and is not covered with polyethylene. The width of the pathway ranged between 40 and 50 cm. Pesticides’ application was performed only between the planting rows. In the protected cultivation, the size of the tunnels was estimated to be 7 m in width, 100 m in length and 3.5 m in height. In the soilless cultivation, each polyethylene growing bag was assumed to accommodate 5 plants. All soilless protected cultivation systems in the surveyed farms operated as open hydroponic systems, meaning that the nutrient solution was not recirculated.

Any additional data required were gathered through an extensive literature review. The climate change impacts of supply chain inputs, including raw material extraction, production, and market activities, were assessed using Ecoinvent 3.10, AgriFootprint 6.3, and Agribalyse 3.1 databases. The study considered key farming operations, including soil preparation, fertilization, disease control, irrigation, and harvesting. Direct and indirect emissions were calculated based on the active ingredients in products and the quantities of consumed fuel, water, and energy. The estimation of direct emissions from diesel was performed using SimaPro’s LCI databases. The embodied emissions associated with the production of electricity, diesel, and the construction of materials such as HDPE, were evaluated using the international Ecoinvent 3 database. The emissions from fertilizers were calculated according to the IPCC guidelines [26]. The PestLCI Consensus Model has been applied for the calculation of the initial emission distribution fractions from pesticides taking into account that the studied crops belong to the archetype crop class “Berries”, subcategory of the “Herbaceous fruits and vegetables” class [27]. In the case of Serbia, the agricultural residues were composted, whereas in the other 3 cases they were assumed to be landfilled. The nutrient content (N, P, K) of the composted residues was calculated to estimate the amount of synthetic fertilizer that could be avoided. The equivalence of composted residues to N, P, and K fertilizers was determined based on values reported in the literature for agricultural composted residues [28]. This approach allows the application of relevant fertilizer credits in the LCA model.

2.4. Life Cycle Impact Assessment

The environmental burdens associated to the strawberry cultivation were calculated through the ReCiPe2016 methodology, using a midpoint approach. ReCiPe2016, midpoint (Hierarchist) was selected as the most appropriate methodology for the calculation of the impact assessment, as it is a recent and updated impact assessment method, widely recognized within the LCA community and is being extensively used on recent agricultural studies [29]. The selected midpoint indicators based on ReCiPe2016 are presented in Table 2. The systems were modelled, and the climate change impacts assessed using SimaPro software version 9.6.0.1 (PRé Sustainability B.V., 2024), in accordance with the classification and characterization phases outlined in ISO-14040 [10,11].

Table 2
ReCiPe2016 - midpoint impact indicators.

Impact category	Impact acronym	Unit
Global Warming Potential	GWP	kg CO ₂ eq
Ozone depletion	ODP	kg CFC-11eq
Ionising radiation	IRP	kBq U-235eq
Photochemical ozone formation	PCOP	kg NMVOCeq
Particulate matter	PM	disease incidence
Human toxicity, non-cancer	HTPNC	CTUh
Human toxicity, cancer	HTPC	CTUh
Acidification	AP	mol H + eq
Eutrophication, freshwater	FEP	kg Peq
Eutrophication, marine	MEP	kg Neq
Eutrophication, terrestrial	TEP	mol Neq
Ecotoxicity, freshwater	ETP	CTUe
Land use	LU	Pt
Water use	WDP	m ³
Resource use, fossils	ADPF	MJ

3. Results

Questionnaire results revealed substantial variation in input use and yield across cultivation systems and countries. Plant density was higher in Serbian protected soilless systems, reaching 130,000 plantlets per ha, compared to 40,000–50,000 in open-field and protected soil systems in Serbia and Cyprus, respectively. Fertilizer application varied both by nutrient and system type. The inorganic nitrogen was the highest under protected soil systems in Greece (467.5 kg/ha) and the lowest in open field and protected soil systems (105 kg/ha) in Serbia. Phosphorus and potassium inputs peaked in Greek and Cypriot protected soilless systems, reaching 400 kg/ha and 1083.3 kg/ha, respectively. Pesticide use also varied significantly, with insecticide application reaching 80 kg/ha in open-field systems in Cyprus, while remaining below 6 kg/ha in Italian protected systems. Water use was greatest in Serbian protected soilless systems, reaching 9600 m³/ha, whereas Greek protected soilless systems required only 1260 m³/ha. Yield per hectare ranged from 22 ton/ha in Serbian open-field and protected soil systems to over 48 ton/ha in Greek protected soil cultivation.

3.1. The case of Serbia

The impact assessment and the contribution analysis conducted for each of the studied systems provided an in-depth evaluation of the climate change impacts associated with different strawberry cultivation methods in Serbia. This analysis highlights the key processes and inputs that drive various environmental burdens. Fig. 2 illustrates the results of the Life Cycle Impact Assessment per cultivation system, regarding the most affected and important midpoint indicators: global warming potential, freshwater eutrophication, terrestrial acidification, terrestrial ecotoxicity, fossil resource scarcity and land use.

The climate change impacts per ton of marketable strawberries varied across the studied systems, depending on the specific impact category evaluated. The contribution analysis revealed that strawberry plantlet production, the use of HPDE materials for the plastic tunnel infrastructure, and the diesel combustion are the most predominant contributors to climate change impacts across all cultivation systems. The soilless protected systems exhibited the highest intensity of impacts specifically for global warming potential, terrestrial acidification, and fossil resource, while open-field systems showed higher impacts for freshwater eutrophication, terrestrial ecotoxicity and land use, rather than a uniform pattern across all categories. This higher intensity was primarily due to the additional materials required for soilless systems, including polyethylene growing bags, substrates and tunnel infrastructure, increasing material production and disposal impacts.

Open-field cultivation had the lowest overall climate change impact (212.4 CO₂ eq) among the examined 4 countries but still is facing significant challenges. The preparation of plant material was the primary

Serbia

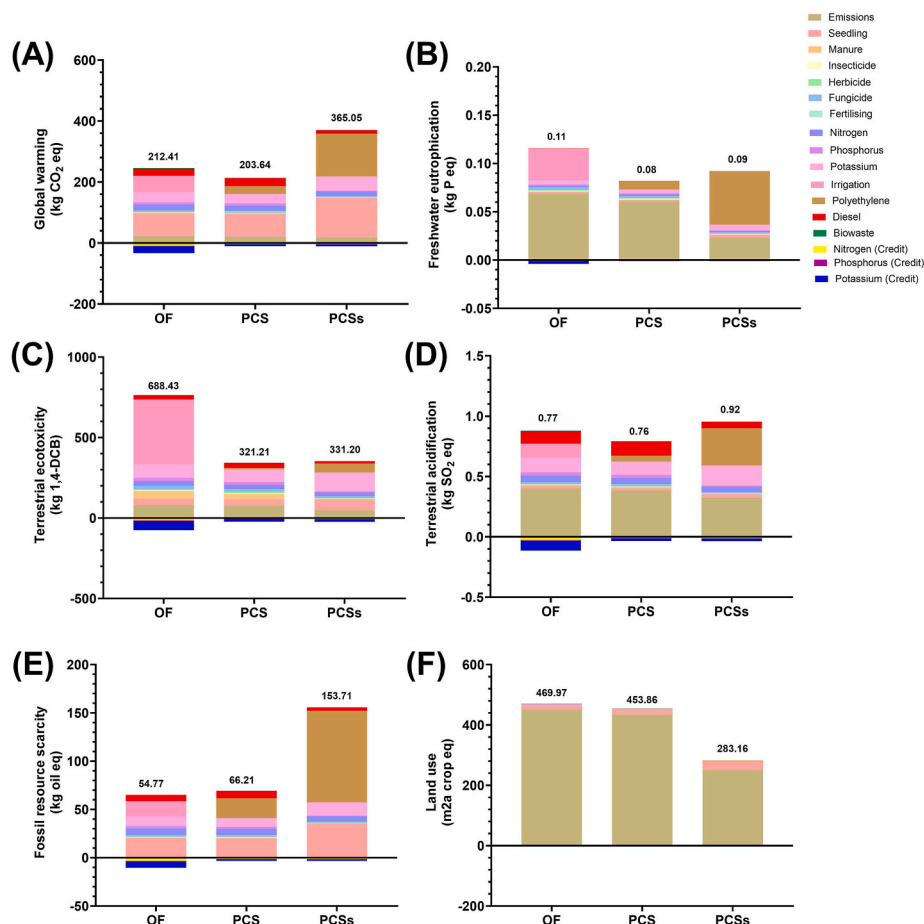


Fig. 2. Comparison of selected midpoint impact categories between different cultivation scenarios of strawberry cultivation in Serbia in terms of (A) global warming, (B) freshwater eutrophication, (C) terrestrial ecotoxicity, (D) terrestrial acidification, (E) fossil resource scarcity and (F) land use. [OF: Open field, PCS: Protected cultivation, in soil, PCSs: Protected cultivation, soilless].

contributor to global warming, with an estimated carbon footprint of 73.9 CO₂ eq, due to the energy-intensive production process, transportation, use of fertilizers and chemicals and plastic use associated with preparation of plantlets. The emissions from the use of fertilizers were considered the main secondary contributors to the overall carbon footprint of open field strawberry cultivation due to their direct and indirect effects on greenhouse gas emissions. Fertilizers, particularly nitrogen-based ones, release nitrous oxide when they are applied to soil. Additionally, the production and transportation of synthetic fertilizers themselves require significant energy, contributing indirectly further to carbon emissions. Terrestrial acidification was primarily driven by the use of fertilizers and pesticides in agricultural activities, as both contribute to the release of compounds that can acidify soil. Fertilizers, particularly nitrogen-based ones, are a significant source of ammonia and nitrogen oxides, both of which can contribute to acidification. Pesticides, while primarily designed for pest control, also contribute to acidification through the release of sulfur compounds, such as sulfur dioxide, during their production and application. In addition to fertilizers and pesticides, the use of diesel fuel for agricultural machinery also played a significant role in terrestrial acidification. Diesel combustion releases nitrogen oxides and sulfur dioxide, both of which are precursors to acid rain. When these emissions are deposited into the land, they can lower soil pH, leading to soil degradation and negatively affecting the growth of crops. Freshwater eutrophication (0.11 kg P eq) in strawberry production was primarily driven by phosphorus from fertilizers and other nutrients transported through irrigation water. Excess phosphorus

can enter water bodies, leading to nutrient overload and promoting algal blooms. Open-field cultivation in Serbia had also significant impact on human non-carcinogenic toxicity, primarily due to diesel combustion in agricultural machinery. Open-field cultivation had the highest terrestrial ecotoxicity, with an impact of 6.88E+02 kg 1,4-DCB, due to the use of a substantially larger amount of HDPE in the drip irrigation system which must cover the entire field surface with multiple parallel lateral lines. In contrast, protected cultivation systems require fewer and shorter fertigation lines within a controlled space, resulting in lower HDPE use and reduced end-of-life impacts. In the open-field system, additional contributions, such as the manure use and the emissions resulting from fertilizer application further increased the release of ecotoxic substances to the soil. These factors contributed to the release of harmful substances into the soil, leading to significant ecotoxicological effects. This system had the highest land-use impact, as plant density per hectare was significantly lower than in protected cultivation. However, it had the lowest fossil resource scarcity impact, as HDPE is primarily used for soil cover rather than intensive greenhouse applications. Water use was the lowest among all systems, benefiting from natural rainfall, though irrigation remains an essential factor in overall resource consumption.

The protected soil-based cultivation system exhibited moderate climate change impacts across an array of indicators. Similar to the open-field system, the strawberry plantlet market was a key contributor to global warming, with an effect of 73.8 kg CO₂ eq, alongside the use of potassium fertilizer and diesel combustion. Terrestrial acidification was

substantial, primarily influenced by the emissions from fertilizers' use, as well as from diesel combustion for agricultural activities and the indirect effect of fertilizers' production. Notably, freshwater eutrophication in this system was quite low (0.08 kg P per ton of marketable strawberries), likely due to efficient nutrient management, which minimized the impact of fertilizers on water quality. Terrestrial ecotoxicity levels were moderate, with emissions from fertilizers' use in the soil accounting significantly to the impact, alongside contributions from manure use, diesel combustion and fertilizers' production. Land use was higher than in soilless systems due to lower plant density per hectare, and fossil resource scarcity was indirectly driven by HDPE use and energy required for the strawberry plantlet production. Water use was significant but lower than in soilless cultivation, as soil-based systems still benefited from some natural soil moisture retention.

The protected soilless cultivation system had the highest climate change impact across multiple categories. The production of strawberry plantlets was the dominant contributor to global warming potential (total value: 365 kg CO₂ eq), with an effect of 131 kg CO₂ eq, followed by the use of HDPE for the whole infrastructure and its end-of-life disposal. Terrestrial acidification was 64 % higher than in open-field systems due to the intensive use of HDPE. Similarly, terrestrial ecotoxicity was influenced by the embodied footprint of potassium fertilizers, strawberry plantlets production, emissions from fertilizer use, and the plastic components involved in cultivation. Despite these impacts, soilless

cultivation had the lowest land-use intensity, approximately 60 % lower compared to the other systems, as it supported a higher plant density per hectare compared to soil-based systems. However, it also had the highest fossil resource scarcity impact due to the reliance on plastic materials and the intensive production of strawberry plantlets. Water use was also the highest among all systems, driven by increased plant density, controlled high-evaporation environments, and the absence of natural rainfall, necessitating frequent irrigation. The most significant contributor to human non-carcinogenic toxicity was diesel combustion in agricultural machinery, while the use of HDPE and potassium fertilizer use also cumulatively contributed.

Overall, the climate change impact of strawberry cultivation varied significantly among the different systems, with protected soilless cultivation exhibiting the highest overall impact due to its resource-intensive nature.

3.2. The case of Greece

The three different strawberry cultivation systems in Greece were compared across various impact categories, revealing several environmental burdens (Fig. 3). Global warming contributors in open-field strawberry production primarily stemmed from plantlet production, similarly to the case of Serbia, as well as the production and the use of fertilizers to supplement plants with potassium and nitrogen. Although

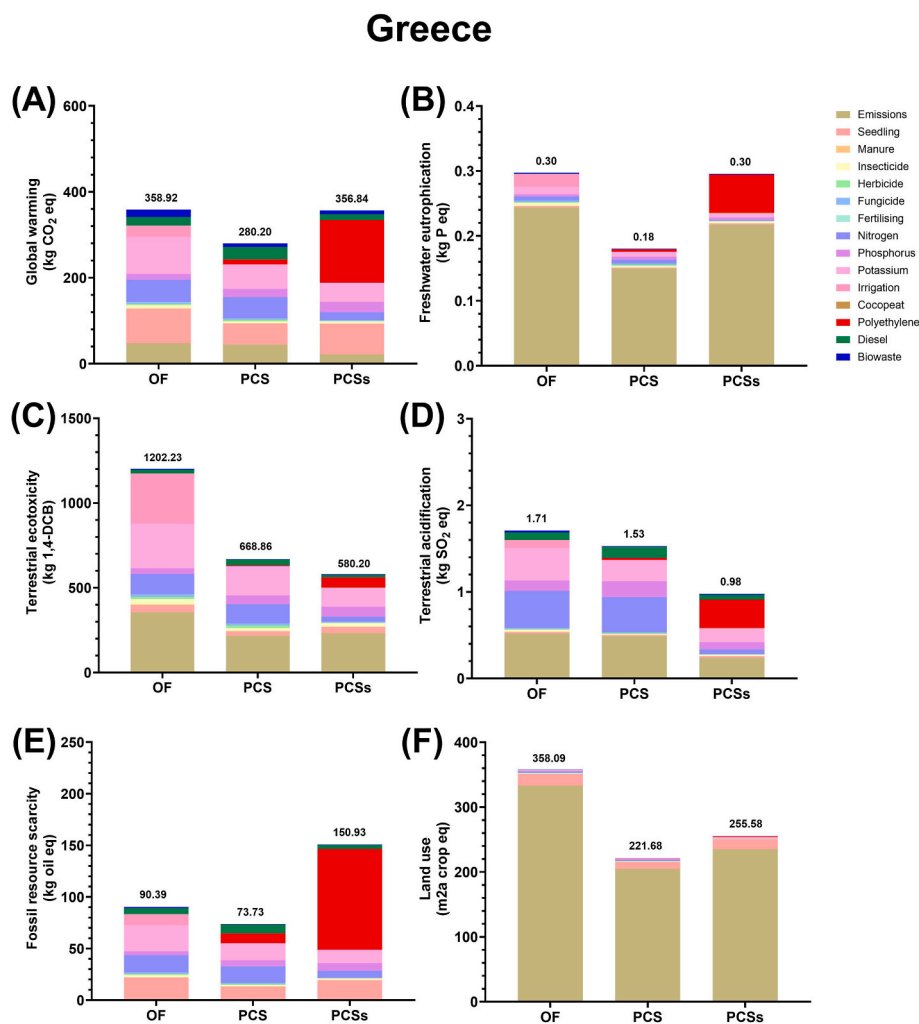


Fig. 3. Comparison of selected midpoint impact categories between different cultivation scenarios of strawberry cultivation in Greece in terms of (A) global warming, (B) freshwater eutrophication, (C) terrestrial ecotoxicity, (D) terrestrial acidification, (E) fossil resource scarcity and (F) land use. [OF: Open field, PCS: Protected cultivation, in soil, PCSs: Protected cultivation, soilless].

protected systems require additional materials and structures, such as HDPE tunnels, their higher yields and more efficient nutrient management reduce the global warming impact per ton of strawberries. Similarly, the open field system also had the highest climate change impact on terrestrial acidification due to the application of inorganic fertilizers such as potassium, phosphorus, and nitrogen. In freshwater eutrophication, open-field cultivation had an intermediate impact, largely influenced by inorganic potassium and nitrogen fertilizer use and drip irrigation. It also contributed significantly to terrestrial ecotoxicity, mainly due to drip irrigation and inorganic fertilizer application. Drip irrigation can lead to the accumulation of salts and chemicals in the soil, affecting microbial communities and soil health. Moreover, the use of potassium and nitrogen fertilizers introduced excess of nutrients into the soil, which can lead to soil acidification and disrupt natural microbial balance. In open-field systems, drip irrigation covers the entire field and fertilizers are applied directly to the soil, whereas in protected systems fertigation is achieved through shorter pipe networks within tunnels, with precise nutrient dosing. Combined with lower yields per hectare, this means that the same amount of materials (fertilizers, pesticides, water, etc) is distributed over fewer marketable strawberries in the open field system, leading to higher freshwater eutrophication and terrestrial ecotoxicity impacts. This system also exhibited the highest land use impact, where strawberry plants play the most significant role. In addition, open-field cultivation in Greece presented a 47 % higher water

consumption impact than protected cultivation in soil and 3.2-fold higher than protected soilless cultivation.

The protected soil-based cultivation appeared to be the least impactful system in terms of global warming, with its major contributors being similar to those of open-field cultivation, namely plantlet production and inorganic fertilizer use. This system ranked between open-field cultivation and soilless production regarding terrestrial acidification and ecotoxicity, mainly due to the use of fertilizers rich in potassium, phosphorus, and nitrogen. The land use was lower in the protected soil-based systems (221.7 m²a crop) compared to the open-field production (358.1 m²a crop), but remained substantial. Water consumption in this system (134.9 m³) was lower than in open-field cultivation (198.0 m³) but still significantly higher than in soilless production (47.0 m³).

The protected soilless cultivation system presented higher global warming contributions compared to soil-based cultivation also due to the use and end-of-life disposal of HDPE, plantlet production and emissions from fertilizers and pesticides. In terms of terrestrial acidification, this system was the least impactful, due to the use of less soil-applied inorganic fertilizers compared to soil-based cultivation, with its environmental footprint primarily dependent on the emissions from fertilizers, HDPE utilization and, indirectly from the production of inorganic potassium fertilizer use, and HDPE production and thermoforming. Freshwater eutrophication in this system was, similarly to the

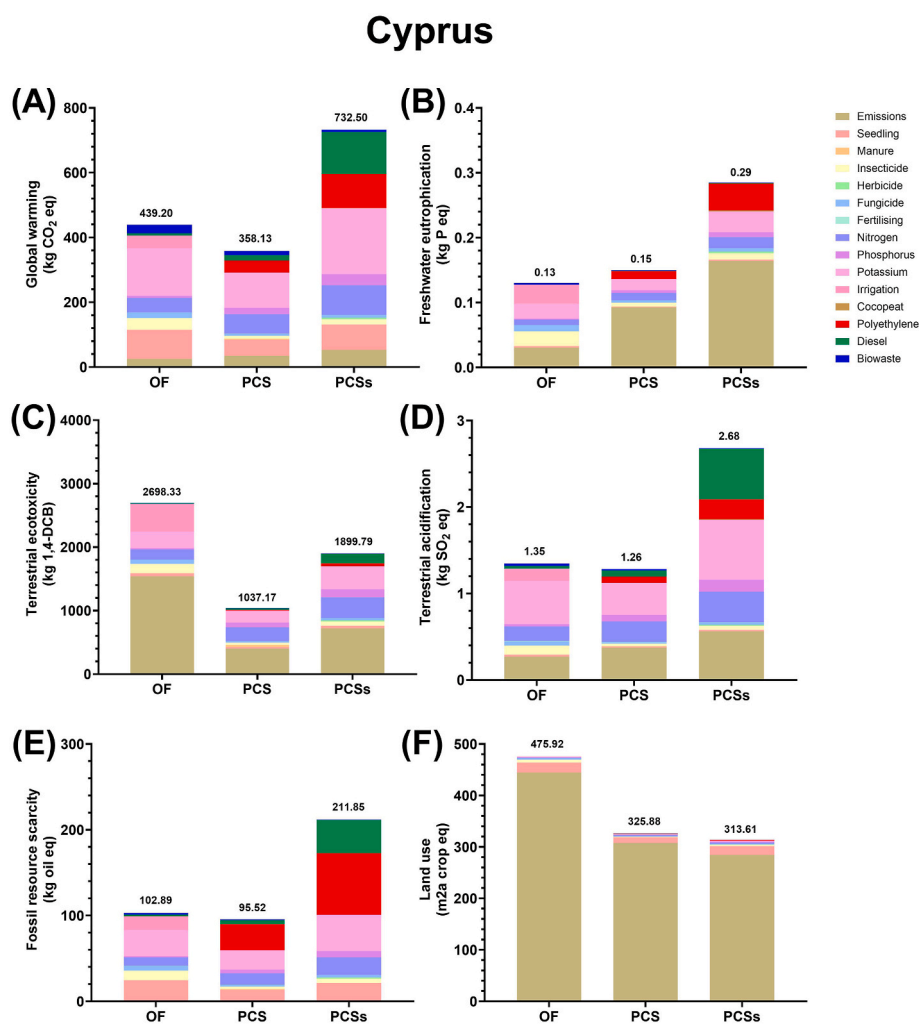


Fig. 4. Comparison of selected midpoint impact categories between different cultivation scenarios of strawberry cultivation in Cyprus in terms of (A) global warming, (B) freshwater eutrophication, (C) terrestrial ecotoxicity, (D) terrestrial acidification, (E) fossil resource scarcity and (F) land use. [OF: Open field, PCS: Protected cultivation, in soil, PCSs: Protected cultivation, soilless].

open field cultivation, driven by the use of fertilizers and reaching up to 0.3 kg P eq. Freshwater ecotoxicity was also higher than in soil-based high tunnels but lower than in open-field cultivation. In terrestrial ecotoxicity, this system had the lowest impact, mainly due to inorganic fertilizers use and production. Regarding land use, this system had a lower impact than open-field production but ranked similarly to soil-based tunnels. Finally, water consumption in the protected soilless system was the lowest among the three systems. To summarize, protected soil-based systems had the lowest global warming impact, being the most sustainable option for strawberry cultivation in Greece.

3.3. The case of Cyprus

The three strawberry cultivation systems in Cyprus were compared in various impact categories and were found to have varying environmental burdens in specific categories, namely global warming, terrestrial acidification, freshwater eutrophication, terrestrial ecotoxicity, fossil resource scarcity, land use, and water consumption (Fig. 4).

The open-field system had significant climate change impacts across multiple categories. Global warming was influenced by the production of strawberry plantlets, which may involve energy-intensive greenhouse cultivation, plastic use, soil disturbance, irrigation, transportation emissions, and the application of fertilizers and pesticides, all of which generate greenhouse gases. Moreover, the use of inorganic fertilizers in strawberry cultivation, particularly nitrogen and potassium, significantly contributed to global warming. Terrestrial acidification was also mainly driven by the use of inorganic nitrogen fertilizers. The available irrigation water supported nitrification, nitrates leaching and salt buildup, therefore contributing to terrestrial acidification. Freshwater eutrophication remained at 0.13 kg P eq primarily resulting from fertilizer use and runoff through irrigation. The system also had a notable impact on terrestrial ecotoxicity due to emissions occurring by the inorganic fertilizers use. It had the greatest land use impact, with strawberry plants as the primary drivers, and the highest water consumption, where irrigation was the main contributing factor. Last but not least, open field cultivation in Cyprus exhibits a 1.1- and 3.6-fold higher water consumption compared to protected soilless and soil-based systems, respectively.

The protected soil-based cultivation system had a comparatively lower climate change impact. Its global warming contribution was the least among the three different systems, with similar contributing factors to the open field system. Terrestrial acidification resulted from the use of inorganic fertilizers, including nitrogen, potassium, and phosphorus. Freshwater eutrophication was moderately influenced by inorganic potassium and nitrogen fertilizer use and production. The system also exhibited terrestrial ecotoxicity, with fertilizers being the main contributors. Fossil resource scarcity in this system was relatively minor, with contributing factors similar to those found in other systems. Water consumption was significantly lower than in open field systems, making it a more sustainable alternative in this regard.

The protected soilless cultivation system exhibited climate change impacts that were generally higher than those of the other two systems. Freshwater eutrophication was at high to intermediate levels, with inorganic nitrogen and potassium fertilizers and insecticide application as primary contributors. Terrestrial toxicity was also increased, influenced by inorganic fertilizers and insecticides. The system had also the highest impact on fossil resource scarcity, largely due to the higher reliance on HDPE use and its end-of-life disposal as well as on diesel combustion. Water consumption was lower compared to the open field system, at similar levels with the protected soil-based cultivation system, being efficient in terms of irrigation needs. Land use impact was moderate, as the number of plants per hectare was significantly higher compared to the other two systems, thus requiring less land per ton of marketable strawberries produced. Among the studied systems, protected soil-based cultivation system was the most efficient in terms of climate change impact, being a sustainable solution.

3.4. The case of Italy

The climate change impacts of two strawberry production systems in Italy were analyzed: protected soil-based and soilless cultivation systems. Actually, in Italy, according to the data provided by the centre for Fruit and Vegetable Services [31], about 84 % of strawberry farming areas are grown in protected cultivation (tunnel and soilless), while the remaining 16 % is grown in open fields. The results showed which production system contributed the most to the environmental load in all impact categories. (Fig. 5). In contrast to the previous cases, the soil-based cultivation system had a larger climate change impact than the soilless cultivation system across several categories. The reported amounts of fertilizers and pesticides were similar or even higher in some cases in the soil-based systems. At the same time, the soilless systems supported a higher number of plantlets per ha, producing significantly more strawberries per ha. Thus, while the climate change impacts per ha could be similar, they were distributed over a greater mass of strawberries, leading to lower impacts per ton of strawberries in the soilless systems. In terms of global warming, the major contributors were strawberry plantlet production, the use of HDPE, and inorganic fertilizers. This system also had a 21 % higher environmental footprint in terrestrial acidification, driven by inorganic fertilizers use and production, diesel used by agricultural equipment, and use of HDPE. Additionally, it had a higher impact on terrestrial ecotoxicity, with manure application and inorganic fertilizers playing a key role. The soil-based system also presented higher fossil resource scarcity, with diesel consumption and use of polymer materials being the major contributors. In terms of land use, the soil-based system had a more significant environmental pressure due to strawberry plant cultivation. Finally, the soilless system consumed more water overall compared to the soil-based system, primarily due to the water usage for the more intense strawberry plant cultivation. Although higher yields partially offset this additional water consumption per ha due to the higher plant density, evapotranspiration and substrate evaporation maintain elevated water use per ton of strawberries. Overall, the soilless strawberry cultivation system exhibited the lowest climate change impact across the most impact categories.

4. Discussion

In the current study, the climate change impacts of four different countries were compared (Fig. 6). A significant variation in global warming potential was observed among the countries, with Cyprus exhibiting the highest contribution, particularly in the soilless cultivation system. This elevated global warming potential was primarily attributed to the substantial use of fertilizers in Cypriot agricultural practices. The application of more sustainable fertilization strategies to mitigate climate change impacts is needed. The lowest impact on global warming potential was observed in the case of Serbia, reflecting more efficient fertilizer and pesticide management in the surveyed farms.

Freshwater eutrophication varied significantly among the different countries, ranging from 0.08 in the case of protected cultivation in Serbia to 0.30 kg N eq in the case of both open-field and soilless cultivation in Greece. The lowest values were observed in Serbia and Italy, suggesting that fertilizer application in these cases was more efficient and environmentally sustainable. This could be attributed to smaller quantities of nitrogen fertilizer applied. Specifically, nitrogen inputs ranged from 104.6 to 152.4 kg N/ton of strawberries in Serbia, 199.2–256.1 kg N/ton of strawberries in Italy, 200.0–467.5 kg N/ton of strawberries in Greece, and 122.0–396.3 kg N/ton of strawberries in Cyprus. Similarly, the modelled nitrate emissions to water ranged from 46.3 to 67.5 kg/ton of strawberries in Serbia, 88.2–113.4 kg/ton of strawberries in Italy, 88.6–207.0 kg/ton of strawberries in Greece, and 54.0–135.0 kg/ton of strawberries in Cyprus. These lower application rates and the associated nitrate emissions reduce the potential for nitrogen runoff and leaching into freshwater systems. Additionally, factors

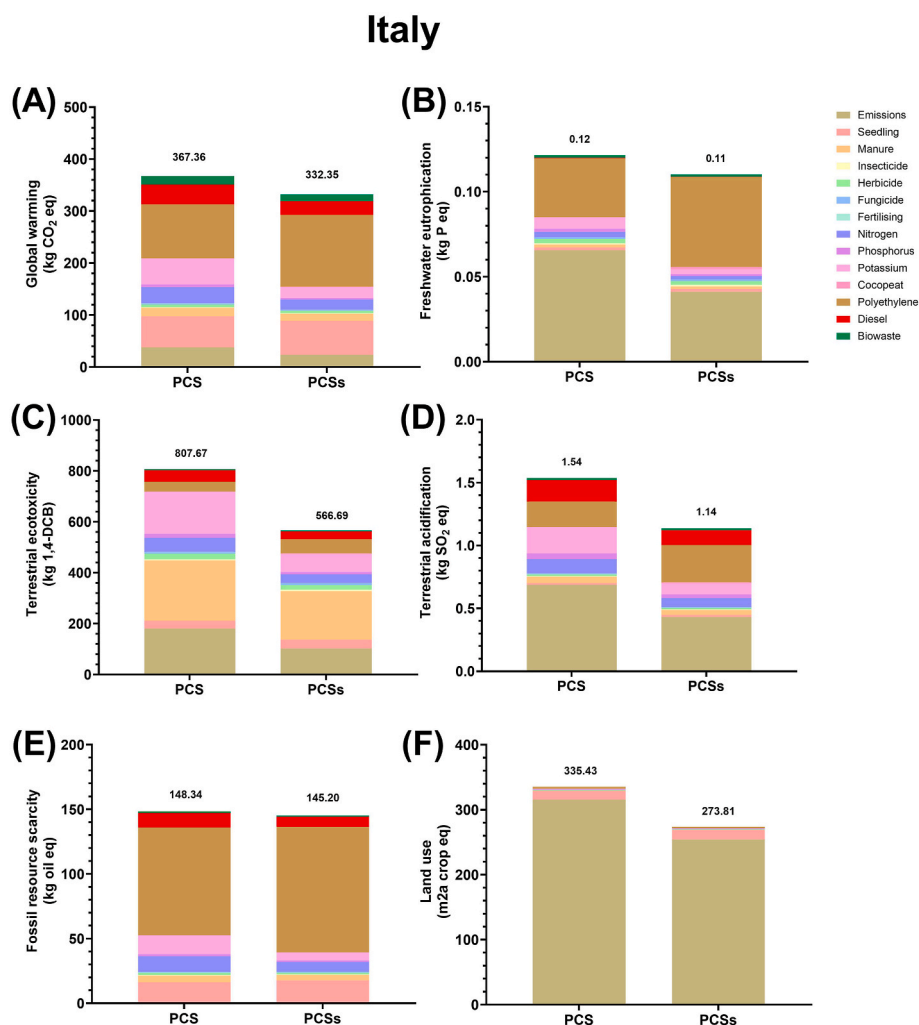


Fig. 5. Comparison of selected midpoint impact categories between different cultivation scenarios of strawberry cultivation in Italy in terms of (A) global warming, (B) freshwater eutrophication, (C) terrestrial ecotoxicity, (D) terrestrial acidification, (E) fossil resource scarcity and (F) land use. [OF: Open field, PCS: Protected cultivation, in soil, PCSs: Protected cultivation, soilless].

such as soil characteristics and climate conditions in these countries may contribute to more controlled nutrient losses, reducing their impact on eutrophication. Excessive use of fertilizers, particularly those based on nitrogen and phosphorus, can result in nutrient runoff and soil accumulation, leading to increased soil acidification and toxicity to microorganisms and plants.

In the case of Serbia, the efficient application of fertilizers, coupled with the controlled use of pesticides (15.0–17.1 kg/ha total amount of pesticides in Serbia, 50–120 kg/ha total amount of pesticides in Cyprus, 29.3–47.6 kg/ha total amount of pesticides in Greece, 20.5–24.5 kg/ha total amount of pesticides in Italy), contributed to reduced terrestrial ecotoxicity and acidification, especially in protected cultivation systems. An additional factor that contributed to the lower impacts in this case is the treatment of crop residues. In Serbia, fruit waste is commonly composted, and this practice was reported consistently during farm interviews. As modelled in the LCI, composting generates credits for avoided mineral fertilizer production, since nutrients contained in the compost (N, P, K) partially replace synthetic fertilizers. This credit reduces upstream impacts associated with fertilizer manufacturing and contributes to the reduction of several potential climate change impacts. In contrast, farmers in Greece, Italy, and Cyprus reported that crop residues were either left to decompose naturally or removed as waste (landfilled). This is consistent with broader Mediterranean agricultural trends, where on-farm composting is limited due to the absence of

dedicated infrastructure or regulatory requirements, and the additional labor and cost associated with compost management. Consequently, these systems receive no fertilizer credits and rely entirely on industrial fertilizers, which increases their associated climate change, acidification, and ecotoxicity impacts. While Greece and Italy contributed even more to these climate change impacts, they remained consistent with values reported for conventional strawberry production in Mediterranean regions [15]. The use of fertilizers and pesticides in Cyprus, particularly in open-field systems, appeared to exceed levels reported for Serbia or Italy. Optimization of their application could help make these practices more sustainable, thereby improving the environmental performance of open-field farming in Cyprus.

Fossil resource scarcity showed similar trends across the four countries, with an increase observed from the open-field system to protected cultivation, and then further elevated in the soilless protected cultivation scenario. This increase can be attributed to the greater use of polymer materials required for plastic tunnel structures and the additional plastic bags necessary for soilless cultivation systems. Water consumption in strawberry cultivars is determined by climate, plant density and irrigation practices. The higher water use was reported in open-field systems in Cyprus due to high air temperatures and low rainfall. High evapotranspiration and very low rainfall substantially increase irrigation requirements, and when combined with the comparatively moderate yields obtained in open-field systems, this

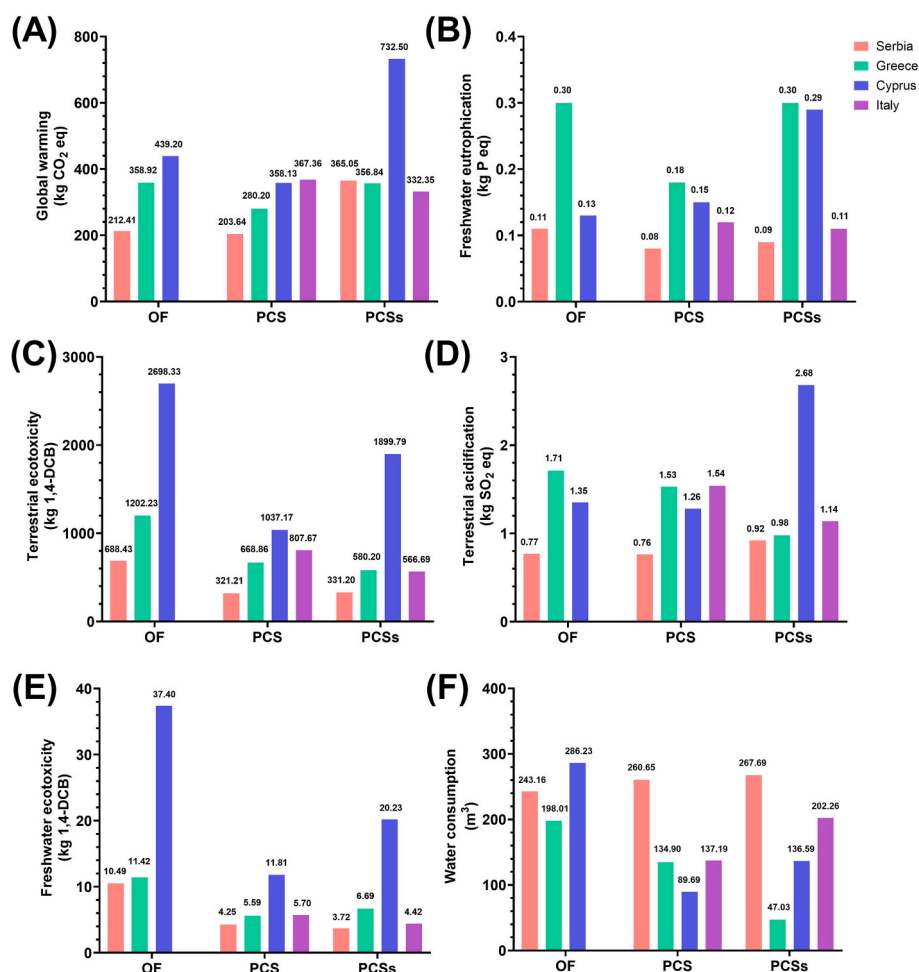


Fig. 6. Comparison of selected midpoint impact categories between different cultivation scenarios in the 4 different European countries. [OF: Open field, PCS: Protected cultivation, in soil, PCSs: Protected cultivation, soilless].

results in greater water use per ton of product. In contrast, in soilless protected cultivation the highest water consumption was in Serbia, due to a higher plant density (130,000 vs. 75,000 plants/ha in Greece, 40,000 plants/ha in Cyprus and 63,200 plants/ha in Italy) that led to higher overall water demand. Higher plant density increases evapotranspiration because a denser canopy has a larger total leaf area, resulting in more transpiring surfaces and higher canopy humidity, which in turn increases water loss through both transpiration and evaporation from the substrate. Although high plant density can increase yield, the additional water demand offset this increase, resulting in higher water consumption per ton of strawberries. Furthermore, Serbia's irrigation costs, based on irrigated area rather than actual consumption, differ from EU pricing models, impacting water use practices. Several research groups across Europe are actively addressing water deficiency by continuously evaluating the resilience of various strawberry genotypes in different climatic regions [30].

The results highlight several important trade-offs among the different studied systems. Protected and especially soilless systems lead to higher yields per ha and thus reduced land use per ton of strawberries. However, these cultivation systems require increased use of materials such as polymers for the tunnel infrastructure and substrates, contributing to higher fossil resource depletion and global warming potential. On the other hand, open field systems tend to require fewer materials, resulting in lower resource depletion; however, they usually exhibit lower production yields which can amplify the relative contribution of field emissions per ton of product. These trade-offs illustrate that no cultivation system performs best across all impact categories; instead,

each system's advantages come at a cost in another environmental dimension. Soilless protected systems achieve higher yields per hectare and lower land use per ton of strawberries but require more water and additional polymer-based materials for infrastructure and substrates, contributing to higher fossil resource depletion and global warming potential. Open-field systems, in contrast, generally demand fewer materials, but their lower yields amplify the relative impact of field emissions per ton of product. Country-specific practices and conditions, including fertilizer use, crop waste management, and local climate, further influence the environmental outcomes, with Serbia showing consistently lower impacts in several categories. These results highlight that optimizing strawberry production requires considering both the choice of cultivation system and the regional context. Such insights can guide farmers in selecting management practices, inform policy-makers on sustainable agricultural strategies, and help consumers understand the environmental implications of different production methods.

5. Conclusions

The findings of this study highlighted the critical role of sustainable fertilizer management, optimized resource use, and improved agricultural practices in minimizing climate change impacts. Serbia demonstrated the most sustainable strategies, reducing global warming potential, eutrophication, and other environmental burdens. In contrast, Cyprus, particularly in open-field farming, requires targeted interventions to enhance sustainability. Additionally, the increasing demand for fossil resources and water in intensive cultivation systems

underscored the need for a balanced approach that considers both productivity and climate change impact. This study also revealed significant environmental differences not only among open-field, protected soil-based, and protected soilless cultivation systems but also among different countries of South Europe, where the detrimental effects of climate change are more intense. Variability in climate change impacts arises from differences in local practices, climate conditions, and crop management techniques, making it challenging to generalize findings across regions.

The differences reported herein highlight important trade-offs between cultivation systems. Protected and especially soilless systems achieve higher yields per hectare and lower land use per ton of strawberries but require more water and additional polymer-based materials for infrastructure and substrates, contributing to higher fossil resource depletion and climate change impacts. Open-field systems generally demand fewer materials, but their lower yields amplify the relative impact of fertilizer and pesticide use per ton of strawberries. Country-specific practices, such as fertilizer management, crop residue handling, and local climate conditions, further influence these outcomes, with Serbia showing consistently lower impacts across several categories. Understanding these trade-offs can guide farmers in selecting management practices, inform policymakers on sustainable agricultural strategies, and help consumers understand the environmental implications of different production methods.

To reduce environmental burdens, optimizing cultivation techniques is essential. The replacement of conventional HDPE materials used in tunnels, growing bags, and/or irrigation systems by biodegradable polymers, can reduce climate change impacts by lowering fossil resource consumption and reducing plastic waste and end-of-life disposal impacts. Moreover, the efficient use of fertilizers and pesticides, and the adoption of integrated crop management practices can significantly mitigate climate change impacts. Closed-loop hydroponic systems in the soilless systems can substantially reduce fertilizer use and minimize nutrient emissions to water, thereby improving environmental performance. Similarly, the breeding programs must work on the high plasticity of the strawberry genotypes, to find the appropriate material in response to the new market requirements and new environmental conditions. Furthermore, applying circular economy principles—such as using recycled materials and optimizing nutrient management—can enhance the sustainability of strawberry production.

Some climate change impacts can be directly reduced by farmers through on-farm practices, including optimization of fertilizer and pesticide application, improvement of irrigation efficiency, adoption of circular economy practices such as utilization of biodegradable polymers and adoption of integrated crop management strategies. Other impacts, such as the production of these materials and transportation emissions, are influenced by upstream suppliers or downstream actors in the supply chain. Although certain factors, such as local climate conditions and soil type, are region-specific and cannot be modified, management practices can be adjusted to mitigate their effects as described above. It is important to note the need for action and collaboration across the entire value chain (including farmers, suppliers, and policymakers) to improve the sustainability of strawberry production based on these recommendations. Future research should, also, explore the potential of emerging technologies, including precision agriculture and renewable energy sources, to further reduce the environmental footprint of strawberry cultivation.

CRediT authorship contribution statement

Georgia Frakolaki: Writing – original draft, Validation, Formal analysis, Conceptualization. **Maria Parcharidou:** Writing – original draft, Formal analysis. **Christos Boukouvalas:** Writing – review & editing, Visualization, Validation, Software, Methodology, Data curation, Conceptualization. **Sofia Papadaki:** Writing – review & editing. **Nikolaos Panagiotou:** Validation, Software, Funding acquisition.

Nicolas Valanides: Investigation. **Anna Kokkini:** Investigation, Formal analysis. **Egli C. Georgiadou:** Writing – review & editing. **Jasminka Milivojević:** Writing – review & editing, Investigation. **Evangelos Tsormpatsidis:** Investigation. **Davide Raffaelli:** Writing – review & editing, Investigation. **Bruno Mezzetti:** Writing – review & editing, Investigation. **George A. Manganaris:** Writing – review & editing, Investigation, Funding acquisition. **Magdalini Krokida:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jafr.2025.102589>.

Data availability

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

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