



## Environmental sustainability and quality assessment of new raspberry genotypes cultivated in a soilless system

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### ABSTRACT

Sustainable and high-quality raspberry production is a priority in Europe, but breeding programs often focus solely on yield and nutritional qualities. This study addresses this gap by evaluating the environmental performance of new raspberry genotypes grown in soilless high tunnels (Italy) using Life Cycle Assessment (LCA) based on the ISO 14040/44 standards. A cradle-to-farm gate assessment was conducted to analyze the environmental impact of these new genotypes during standard production cycles for floricanes (field trial 1) and primocanes (field trial 2). Primary data from the nursery and cultivation phases were used. The functional unit (FU) selected was 1 kg of fresh raspberry, and environmental impacts were evaluated using the Environmental Footprint 3.1 method. Additionally, various quality parameters, including marketable yield, shelf-life, and taste, were assessed for each genotype. Results indicate similar environmental performance for field trial 1 and field trial 2. Electricity for storing sowing material dominated the nursery phase, while infrastructure was the main contributor during cultivation. Adjusting impact scores for quality parameters also revealed differences in environmental performance ranking among the new cultivars. This study expands the knowledge of environmental sustainability in raspberry production and highlights the importance of including environmental considerations in breeding programs for a multi-criteria approach to selecting breeding materials.

### List of acronyms

EC	Electrical conductivity
EF	Environmental footprint
EPD	Environmental Product Declaration
FT	Field trial
FU	Functional unit
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCIA	Life cycle impact assessment
LDPE	Low density polyethylene
NRF	Nutrient Rich Foods
PCR	Product Category Rules
PE	Person equivalent
SCS	Soilless cultivation system
TA	Titratable acidity
TSS	Total soluble solids

### Impact assessment categories

ADP	Abiotic depletion potential
GWP	Global warming potential
CC	Climate change
OD	Ozone depletion
HTC	Human toxicity, cancer effects
HTNC	Human toxicity, non-cancer effects
PM	Particulate matter
IR	Ionising radiation
POF	Photochemical ozone formation
A	Acidification
ET	Eutrophication, terrestrial
EF	Eutrophication, freshwater
EM	Eutrophication, marine
ETF	Ecotoxicity, freshwater
LU	Land use
WU	Water use
RUF	Resource depletion, fossils
RUMM	Resource depletion, minerals and metals
NRE	Non-renewable energy

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## 1. Introduction

The pursuit of sustainable production and distribution within agri-food chains has become increasingly important, shaping marketing strategies for fruit and vegetable products in Europe. Rising consumer consciousness regarding environmental concerns has prompted producers to communicate their sustainability efforts, often employing “green” initiatives to convey commitments to consumers (Eurobarometer., 2009; Tobler et al., 2011; Mancuso et al., 2021). Sustainable fruit and vegetable production relies on the involvement of value chain actors. However, given that environmental impacts in small fruit production are primarily linked to the cultivation phase, producers can play a proactive role in enhancing the environmental performance of their products, as they deal directly with the product from the inception (Peano et al., 2015). Implementing sustainable strategies relating to all aspects of cultivation, including the selection of breeding materials, can have a positive ripple effect on the overall sustainability of the sector. Therefore, it is crucial to evaluate the environmental performance of new cultivars as part of breeding programs across various indicators while identifying factors that influence the results to select the most suitable cultivars and production systems for a given context.

Raspberry (*Rubus idaeus* L.) is a small niche fruit predominantly cultivated in Europe. Among berries, it ranks second in terms of production volume globally. According to data from FAOSTAT (Food and Agriculture Organization of the United Nations, 2022), Europe produces approximately 617,000 metric tons of fresh raspberries annually, accounting for an estimated 65 % of global output. Italy is a significant producer of raspberries, with an output of approximately 2600 tons from 350 ha. Although considered a luxury fruit for special occasions due to its high price, raspberry is mainly consumed for its nutritional and health benefits from its phytochemical content (Lopez-Corona et al., 2022; Popović et al., 2024). Consequently, as the target market's interest in the environmental aspects of the berries they consume continues to grow, it has become evident that producers should be transparent about the environmental performance of these products. To promote sustainable and competitive berry production across Europe, efforts are underway to develop new cultivars that meet the demand for innovative cultivation systems and high-quality produce (Senger et al., 2022). This initiative is particularly important given the challenges of climate change and the need for environmental preservation. Therefore, to enhance the environmental sustainability of small fruits, it is necessary to assess the environmental impacts of raspberry production.

The life cycle assessment (LCA) approach is commonly used in the agricultural industry to evaluate the environmental impact of food products. This method is a comprehensive tool that systematically assesses the potential environmental effects of goods and services, and it is based on the ISO 14040 and 14044 standards (ISO, 2006a; ISO, 2006b). LCA has been widely employed to evaluate the environmental performance of agricultural products in different production systems, allowing for informed decision-making at multiple levels (Alhashim et al., 2021).

Numerous factors influence the environmental performance of agricultural products, particularly fruits and vegetables (Parajuli et al., 2019). These factors include the production method (e.g., organic or integrated) and the structural environment, which determines the level of control over external conditions. Systems range from open-field agriculture to soilless cultivation systems (SCS). The use of protected cultivation, such as tunnels, greenhouses, and shade nets, as well as controlled-environment agriculture like hydroponics, aeroponics, aquaponics, and vertical farming, can also influence the environmental performance of crops (Nemecek et al., 2011; Boakye-Yiadom et al., 2023; Dorr et al., 2021; Ilari et al., 2021). Additionally, breeding material or cultivar selection can significantly affect the environmental

impact of crop production (McDevitt and Milà i Canals L., 2011). Despite allocating resources to develop cultivars that address various production and quality issues, like increasing resilience to biotic and abiotic stress, adaptability to diverse climatic conditions, improved fruit quality, and increased yields (Sattar et al., 2021; Sabbadini et al., 2021; Savadi et al., 2021), this aspect is mostly overlooked in LCA studies.

Traditional raspberry cultivation often relies on open-field systems. However, recent advancements in agricultural technology, such as SCS and protected cultivation structures like high tunnels, offer promising avenues for enhancing sustainability and productivity. SCS, which involves growing plants in inert or organic substrates, offers several environmental benefits (Gruda, 2019; Joshi et al., 2022). By replacing soil, SCS allows for precise control over water, nutrients, and other inputs, leading to reduced water consumption, fertilizer use, and overall environmental impact (Joshi et al., 2022; Licastro et al., 2024; Roupheal et al., 2004). High tunnels, characterized by their simple structure and lower operational costs compared to greenhouses, provide a valuable intermediate level of environmental control (Heindenreich et al., 2012). These structures offer protection against adverse weather conditions, such as hail, rain, and frost, mitigating the risk of crop damage and disease outbreaks (e.g., Botrytis). By creating a more controlled environment, high tunnels facilitate improved plant growth, resulting in increased yields, enhanced fruit quality (size, color, sweetness), and an extended harvest season (Heindenreich et al., 2012; Gaskell, 2004; Thompson et al., 2009; Hanson and Weihe, 2011). The integration of SCS with high tunnel cultivation systems has the potential to significantly enhance the sustainability of raspberry production. By combining the benefits of controlled growing environments with the resource efficiency of SCS, this approach can optimize resource use, improve crop yield and quality, and minimize environmental impacts.

Regarding LCA studies on SCS, the production phase is the most impactful, with electricity, fertilizers, and infrastructure being the main contributors (Licastro et al., 2024). However, a comprehensive LCA is crucial to fully understand the environmental implications of these innovative cultivation systems.

## 2. Literature review

The environmental impact of raspberry production has been the focus of limited studies compared to strawberry cultivation (Ilari et al., 2021; Parajuli et al., 2022; Mousavi et al., 2023; Pergola et al., 2023) due to the latter's dominance in the market. Nonetheless, some studies have examined different aspects of raspberry production, providing valuable insights into its environmental challenges and opportunities. Foster et al. (Foster et al., 2014) analyzed the environmental impact of raspberry production in polytunnels in Spain and its variations throughout the year when delivered to retailers in the UK. Their findings highlighted that nitrous oxide (N<sub>2</sub>O) emissions were the primary contributor to global warming potential (GWP), accounting for over 75 % of the total impact. Additionally, polyethylene, used extensively in polytunnel structures, was identified as a major contributor to abiotic depletion potential (ADP). Long-distance refrigerated transport also significantly contributed to environmental impacts, underscoring the importance of logistics and supply chain management in reducing the carbon footprint of raspberry production. Girgenti et al. (Girgenti et al., 2013) investigated the GWP and non-renewable energy (NRE) of raspberry production in an integrated system using a cradle-to-grave approach in Italy. They identified traditional plastic materials used during the field phase (nursery and cultivation) and post-harvest phase (packaging) as the primary contributors to environmental impacts. Their findings emphasized the need for sustainable alternatives in packaging and agricultural inputs to reduce the life cycle environmental impact of raspberry production. Peano et al. (Peano et al., 2015) also conducted a study to evaluate the GWP of raspberry fruits and the carbon dioxide offsetting of the same production system in Northern Italy, focusing on ecobranding efforts. In Chile, Vásquez-Ibarra et al. (Vásquez-Ibarra

et al., 2021) examined the influence of variability in management practices on the environmental impacts of smallholder raspberry production in soil-based open fields. This study identified agrochemicals, particularly fertilizers and pesticides, as the main contributors to environmental impacts. The authors emphasized the importance of technical training and the adoption of efficient management practices, such as selecting appropriate agricultural inputs and optimizing application rates, to reduce environmental hotspots and enhance the sustainability of smallholder production systems. Rantanen et al. (Rantanen et al., 2024) also compared the environmental performance of open-field and tunnel raspberry production in Finland. Their results revealed that while tunnel cultivation significantly improved yields compared to open-field production, the overall environmental impacts of the two systems were comparable. The sources of impact differed between the systems, in tunnel cultivation, the production of inputs such as fertilizers, substrates, and tunnel structures accounted for approximately two-thirds of the climate change impact, whereas in open-field cultivation, growing activities such as soil preparation and pesticide application were the primary contributors to climate change. These findings suggest that while tunnel cultivation offers productivity advantages, it also demands careful consideration of input efficiency to reduce its environmental burden.

Despite these contributions, several critical aspects of raspberry production remain unexplored. Key opportunities for further research include assessing the role of emerging technologies such as precision agriculture and biodegradable materials, investigating region-specific variations in production systems, and evaluating the environmental performance of raspberry production under different production systems. Furthermore, the influence of raspberry genotypes on environmental performance has yet to be investigated. These knowledge gaps highlight the need for more targeted research to better understand the environmental sustainability of raspberry production and to identify context-specific strategies for improving its environmental performance. This study aims to address these gaps by evaluating the environmental performance of different raspberry genotypes cultivated in soilless high tunnels. We consider standard production cycles for primocane and floricaneraspberries, providing insights into the environmental implications of genotype selection and advanced cultivation systems.

### 3. Materials and methods

We calculated the environmental performance of the product following the ISO 14040/14044 standards (ISO, 2006a; ISO, 2006b) and specific product rules published within the framework of the International Environmental Product Declaration (EPD) System for arable and vegetable crops (European Commission, Joint Research Centre, 2010). We conducted this study using the SimaPro software version 9.5. Background data for ancillary materials and energy were obtained from the Ecoinvent database version 3.9 – allocation, cut off by classification (Wernet et al., 2016).

#### 3.1. Goal and scope of the study

The goal of the study was to evaluate the environmental performance of primocane and floricaneraspberry genotypes grown in high tunnel systems on a soilless substrate in Italy. The objective was to evaluate new raspberry varieties as part of a breeding program before commercialization. Two separate field trials were conducted for the primary cultivars, primocanes and floricanes, which differ in their growth cycle. Field trial 1 was for floricaneraspberry, a biennial fruiting cultivar where the vegetative growth occurs during the first year, and flowering and fruiting occur in the second year. In contrast, field trial 2 involved primocaneraspberry, which undergoes a single cycle of vegetative growth, flowering, and fruiting within a year. Each field trial was comprised of different genotypes. Field trial 1 (floricanes) included the following genotypes: Dafne, Lagoria Plus, Tulameen, SOU321, SOU201,

and SOU012. Field trial 2 (primocanes) also included the following genotypes: Atena, Dafne, SOR628, SOR701, and SOR720.

Following a cradle-to-farm gate approach (Fig. 1), the study encompassed the nursery phase (for floricanes) and the cultivation phase (for floricanes and primocanes). The pre-nursery phase, which covers seed raising via plant propagation in a heated greenhouse, was excluded due to the unavailability of data. Post-harvest operations, including cooling, storage, transport, retail, and waste management (residual plant biomass), were also excluded due to unavailability of primary data. Primary data for foreground processes were collected directly from a major Italian berry producer (Sant'Orsola) operating a 1.4 ha experimental field in Trento. Data refers to the 2022 and 2023 production. No allocation was necessary as the system had a single main output. The selected functional unit was 1 kg of freshly harvested raspberry at the farm gate cultivated in a soilless high tunnel in 2022 and 2023.

#### 3.2. Life cycle inventory analysis

The inventory analysis of the raspberry production is organized into the nursery phase and the cultivation phase. Key inputs included land use, infrastructure (tunnels and irrigation pipes), agrochemicals (fertilizers and pesticides), water, electricity, and diesel fuel. The primary outputs of the system were harvested raspberries and emissions released to air, soil, and water. These emissions stemmed from agrochemical use and diesel consumption. Direct and indirect emissions from fertilizers were estimated using established Product Category Rules (PCR) for arable crops (International EPD® System, 2020). Pesticide and herbicide emissions were calculated based on their fate within the environment: 85 % to soil, 10 % to air, and 5 % to water (Margni et al., 2002). Data collection relied on detailed questionnaires and official documents.

##### 3.2.1. Nursery phase

The initial propagation of primocane and floricaneraspberries involves a similar process. Root cuttings obtained from the previous year's nursery are repotted in coconut fibre (coir) substrate and allowed to root under nebulization. After acclimatization, primocane plug plants are directly transplanted for production. However, floricaneraspberries undergo an additional nursery phase. These plants are transplanted into coir for vegetative growth in a 2 L vase with two plants per vase, allowing them to develop into long canes of approximately 1.8 m within seven months (May to November). These canes are stored in a cold room (−1.2 °C) for 7–10 days before transplanting into the production field. Table 1 provides an inventory of resources used during the floricaneraspberry nursery phase. The nursery tunnel measured 12.8 m in length, 9.8 m in width, and 10 m in height. Infrastructure materials were estimated to have a lifespan of 30 years, while irrigation pipes were expected to last 10 years.

##### 3.2.2. Cultivation phase

The refrigerated long canes of the floricanes are removed from cold storage, thawed, and transported to the production field for transplantation into 10 L pots, with two long canes per pot and a total density of 16,000 plants/ha. For the primocanes, Fresh seedlings (plug plants) were transplanted into 6.5-l pots (one plant per pot) at a density of 12,000 plants per hectare. A 2.1 m bamboo stake was placed in each pot to support plant growth. The soilless substrate utilized is coconut fiber. The transplantation date for primocanes is after mid-April, while for floricanes, it occurs within the first week of May. Both primocanes and floricanes were cultivated in tunnels measuring 20 m (length) x 5 m (width) x 3.5 m (height), covered with a low-density polyethylene rainproof material. Within the tunnels, plant support structures consist of iron rods interconnected by metal wires (see supplementary material). Upon transplantation, the long canes of the primocanes are secured to the central wires. At the same time, the floricanes are fastened to bamboo supports to maintain an upright position during the vertical

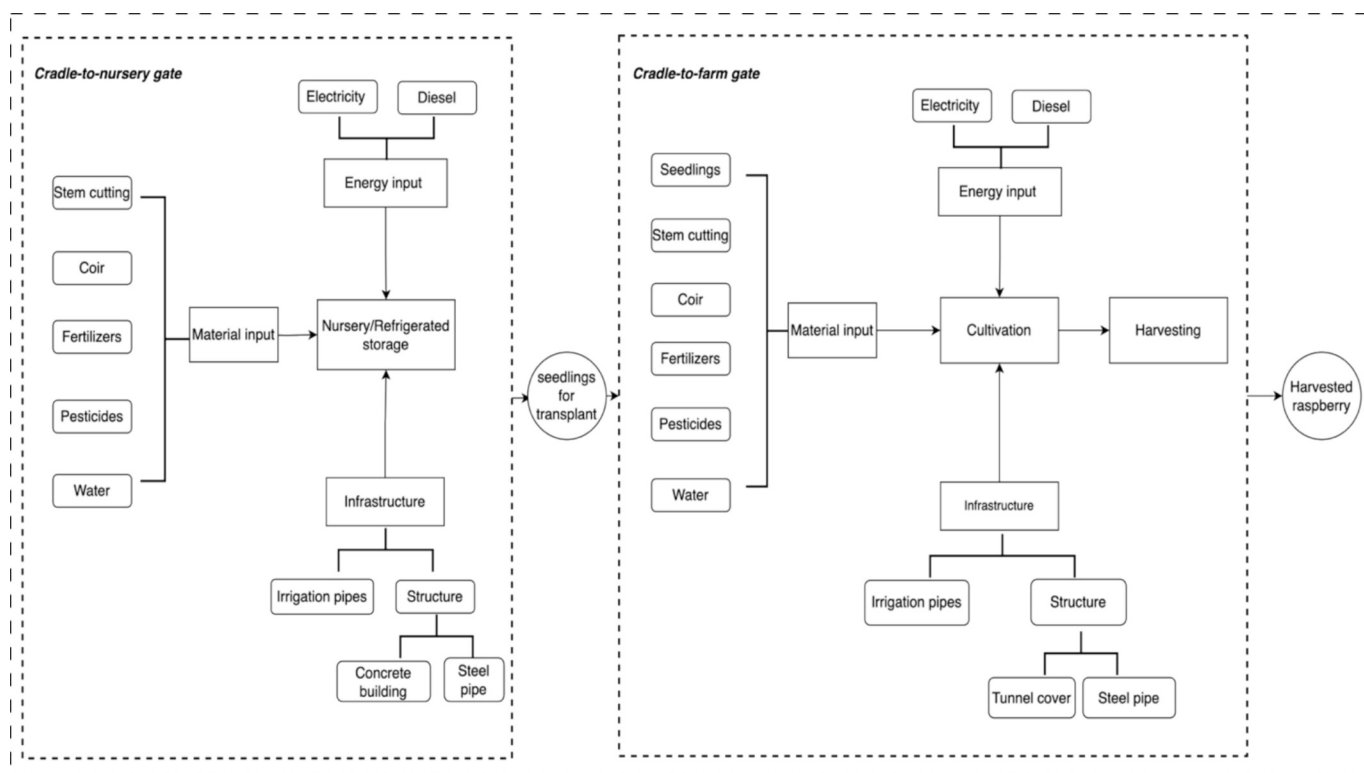


Fig. 1. The system boundary for the LCA of primocane and florican raspberry production considered in this study. NB: Cradle-to-nursery gate applies to only field trial 1 (florican raspberry).

growth phase. The estimated lifespan of the galvanized iron structure is 30 years, with the plastic cover requiring replacement every 3 years. A drip irrigation system equipped with self-compensating 3 L/h drippers was used for both cultivation cycles. The system included a T-joint with two capillary LDPE tubes and two self-compensating rods. The number of drippers varied based on the number of pots: 8000 for floricanes and 12,000 for primocanes. The estimated lifespan of the irrigation tubes is 10 years.

During the growth phase, several management activities are carried out. Turf management involved 3–4 cycles of mowing and trimming root suckers using a lawnmower and brush cutter. FertiDrip irrigation, controlled by an electronic unit, ensured optimal fertilizer levels, electrical conductivity (EC), and pH values. Phytosanitary treatments were implemented periodically using a self-propelled diesel sprayer. Biological agents, such as cucumeris mite (*Amblyseius cucumeris*) and hoverfly larvae (*Sphaerophoria rueppellii*), were also introduced to control pests. Floricanes were harvested from mid-July to mid-August, while primocanes were harvested from mid-August to October. Harvesting was performed manually using recycled plastic baskets lined with absorbent mats and placed in recycled cardboard trays. Harvested fruit was stored at 1.5 °C for a maximum of 7 days, with an average storage time of 3 days. A continuous cold chain was maintained from harvest to customer delivery. Residual plants were chopped in the field and utilized as soil improvers for other crops or given to other companies that reuse them to obtain new cultivation substrates. The plastic materials of the substrate and fertilizer bags and the rainproof covers at the end of their life were modeled as the disposal mix of polyethylene in Italy (55 % sanitary landfill and 45 % municipal incineration). Table 2 provides an inventory of input data for the florican and primocane raspberry genotypes. Detailed inventory data of the individual genotypes are provided in the supplementary material.

Dashes (–) indicate the absence of the compound or active ingredient in the agrochemical used.

### 3.3. Life cycle impact assessment

We evaluated the impacts for raspberry production expressed per the functional unit, using the Environmental Footprint (EF) 3.1 midpoint life cycle impact assessment (LCIA) method (Fazio et al., 2018). The impact categories were categorized into three groups: (i) Common impacts – climate change (CC) estimated over a 100-year horizon, ozone depletion (OD), ionising radiation (IR), photochemical ozone formation (POF), particulate (PM), acidification (A), eutrophication freshwater (EF), eutrophication marine (EM), eutrophication terrestrial (ET), (ii) Toxicity-related impacts – human toxicity, non-carcinogenic (HTNC), human toxicity, cancer (HTC), ecotoxicity freshwater (ETF), and (iii) Resource-related impacts – land use (LU), water use (WU), resource use, fossils (RUF), and resource use, minerals and metals (RUMM).

### 3.4. Interpretation

The interpretation included midpoint impact results, contribution or hotspot analysis, and sensitivity analysis. The midpoint characterization results were expressed per 1 kg of raspberry at the farm gate. The LCIA results were also normalized and expressed in units of Person equivalent (PE) based on the total impact of a reference region for an impact category in the EF 3.1 method. Each Person equivalent represents the amount of environmental impact that equals one person's average yearly share of the total impact of a reference region for a specific impact category in 2010 (Sala et al., 2018). The life cycle impact analysis was based on average point estimates of parameter values. Thus, the mean and standard deviation of the midpoint impacts were reported. For the sensitivity analysis, we conducted two scenario analyses. We explored the substitution of grid electricity with renewable energy (solar energy) at the nursery phase and the effect of extending the lifespan of the infrastructure (chromium steel pipes) from 30 years to 40 or 50 years.

This study compared the environmental impacts of different primocane and florican raspberry genotypes. Traditionally, LCA studies in

**Table 1**  
Floricanes nursery phase inventory (data refers to 100 seedlings per cycle).

Parameter	Unit	Value
<i>Input</i>		
Planting material	p	100.00
Coconut fiber (coir)	kg	53.65
Water	m <sup>3</sup>	55.65
Inorganic N fertilizer	kg	4.21
Inorganic P <sub>2</sub> O <sub>5</sub> fertilizer	kg	5.30
Inorganic K <sub>2</sub> O fertilizer	kg	5.25
Copper sulfate	g	17.45
Pesticides	g	44.73
Diesel	kg	8.58
Chromium steel pipe	kg	0.33
Concrete block	kg	14.79
Low-density polyethylene	kg	7.25
Electricity	kWh	246.40
<i>Emissions to air</i>		
Ammonia	kg	0.15
Nitrogen monoxide	kg	0.25
Dinitrogen monoxide	kg	0.23
Copper sulfate	g	1.57
Abamectin	g	0.06
Clofentazine	g	0.90
Boscalid	g	0.90
Pyraclostrobin	g	0.23
Cyprodinil	g	0.84
Fludioxonil	g	0.56
Spinosad	g	0.11
Acetamiprid	g	0.20
Difenoconazole	g	0.23
<i>Emissions to water</i>		
Nitrate	kg	5.59
Phosphorus	kg	0.14
Copper sulfate	g	0.18
Abamectin	g	0.01
Clofentazine	g	0.10
Boscalid	g	0.10
Pyraclostrobin	g	0.03
Cyprodinil	g	0.09
Fludioxonil	g	0.06
Spinosad	g	0.01
Acetamiprid	g	0.02
Difenoconazole	g	0.03
<i>Emissions to soil</i>		
Copper sulfate	g	15.73
Abamectin	g	0.57
Clofentazine	g	9.00
Boscalid	g	9.01
Pyraclostrobin	g	2.26
Cyprodinil	g	8.44
Fludioxonil	g	5.63
Spinosad	g	1.08
Acetamiprid	g	2.03
Difenoconazole	g	2.25

agriculture utilize a mass-based functional unit (e.g., 1 kg of raspberry). However, this study incorporates quality parameters into the LCA methodology to provide a more comprehensive assessment. Quality parameters, such as marketability, shelf-life, total soluble solids (TSS), and titratable acidity (TA), are crucial for different stakeholder along the supply chain, like consumers and producers. However, integrating these diverse parameters with varying units, scales, and relative importance into a single, standardized metric presents a significant challenge. To address this, the study adopted an approach of functional unit-adjusted scoring. This method considers not only the mass of harvested raspberries (the typical functional unit) but also their quality attributes, providing a more meaningful evaluation of the environmental performance of each genotype.

To calculate the functional unit-adjusted score (Eq. 1), the environmental impact score of each genotype (expressed per kg of raspberry) was divided by the corresponding value for each quality parameter (see supplementary material). Using this method, we assumed a linear relationship between the parameter value and its desirability (e.g., higher

**Table 2**  
Inventory of the agricultural phase (data refers to 1 kg of freshly harvested raspberry).

Parameters	Unit	Quantity/FU (Floricanes)	Quantity/FU (Primocane)
<i>Input</i>			
Plant density	plants/ha	0.46–0.71	0.37–0.99
Water	m <sup>3</sup>	0.04–0.06	0.10–0.26
Berry seedlings	p	0.42–0.76	0.33–1.02
Coconut fiber (coir)	kg	0.11–0.17	0.12–0.37
Electricity	kWh	0.007–0.011	0.006–0.016
Diesel	kg	0.01–0.02	0.010–0.032
Inorganic N fertilizer	kg	0.002–0.003	0.004–0.011
Inorganic P <sub>2</sub> O <sub>5</sub> fertilizer	kg	0.002–0.004	0.005–0.014
Inorganic K <sub>2</sub> O fertilizer	kg	0.002–0.004	0.005–0.014
CuSO <sub>4</sub>	g	0.003–0.022	–
Pesticide, unspecified	g	0.007–0.012	0.012–0.071
Chromium steel pipe	kg	0.04–0.07	0.03–0.10
LDPE, granulate - tunnel cover	kg	0.11–0.18	0.089–0.27
LDPE, granulate - irrigation pipe	kg	0.010–0.016	0.008–0.024
<i>Emissions to air</i>			
Ammonia	kg	$2.69 \times 10^{-5}$ –4.68 × 10 <sup>-5</sup>	$6.11 \times 10^{-5}$ –1.60 × 10 <sup>-4</sup>
Nitrogen monoxide	kg	$4.64 \times 10^{-5}$ –8.08 × 10 <sup>-5</sup>	$1.06 \times 10^{-4}$ –2.76 × 10 <sup>-4</sup>
Dinitrogen monoxide	kg	$4.24 \times 10^{-5}$ –7.37 × 10 <sup>-5</sup>	$9.63 \times 10^{-5}$ –2.52 × 10 <sup>-4</sup>
CuSO <sub>4</sub>	g	$2.89 \times 10^{-4}$ –1.99 × 10 <sup>-3</sup>	–
Abamectin	g	$2.99 \times 10^{-5}$ –5.41 × 10 <sup>-5</sup>	$3.19 \times 10^{-5}$ –9.64 × 10 <sup>-5</sup>
Clofentazine	g	$4.76 \times 10^{-4}$ –8.59 × 10 <sup>-3</sup>	$5.06 \times 10^{-4}$ –1.53 × 10 <sup>-3</sup>
Acetamiprid	g	–	$2.28 \times 10^{-4}$ –6.89 × 10 <sup>-4</sup>
Spinosad	g	$1.27 \times 10^{-4}$ –2.06 × 10 <sup>-4</sup>	$1.47 \times 10^{-4}$ –3.67 × 10 <sup>-4</sup>
Penconazole	g	$9.53 \times 10^{-5}$ –1.66 × 10 <sup>-4</sup>	$2.02 \times 10^{-4}$ –5.82 × 10 <sup>-4</sup>
Boscalid	g	–	$1.01 \times 10^{-3}$ –2.91 × 10 <sup>-3</sup>
Pyraclostrobin	g	–	$2.54 \times 10^{-4}$ –7.31 × 10 <sup>-4</sup>
<i>Emissions to water</i>			
Nitrate	kg	$1.02 \times 10^{-3}$ –1.78 × 10 <sup>-3</sup>	$2.33 \times 10^{-3}$ –6.08 × 10 <sup>-3</sup>
Phosphorus	kg	$2.66 \times 10^{-5}$ –4.62 × 10 <sup>-5</sup>	$6.01 \times 10^{-5}$ –1.57 × 10 <sup>-4</sup>
Copper sulfate	g	$3.21 \times 10^{-5}$ –2.21 × 10 <sup>-4</sup>	–
Abamectin	g	$3.44 \times 10^{-6}$ –6.02 × 10 <sup>-6</sup>	$3.65 \times 10^{-6}$ –1.07 × 10 <sup>-5</sup>
Clofentazine	g	$5.29 \times 10^{-5}$ –9.55 × 10 <sup>-5</sup>	$5.6 \times 10^{-5}$ –1.70 × 10 <sup>-4</sup>
Acetamiprid	g	–	$2.53 \times 10^{-5}$ –7.65 × 10 <sup>-5</sup>
Spinosad	g	$1.41 \times 10^{-5}$ –2.29 × 10 <sup>-5</sup>	$1.63 \times 10^{-5}$ –4.08 × 10 <sup>-5</sup>
Penconazole	g	$1.06 \times 10^{-5}$ –1.84 × 10 <sup>-5</sup>	$2.25 \times 10^{-5}$ –6.47 × 10 <sup>-5</sup>
Boscalid	g	–	$1.13 \times 10^{-4}$ –3.24 × 10 <sup>-4</sup>
Pyraclostrobin	g	–	$2.84 \times 10^{-5}$ –8.18 × 10 <sup>-5</sup>
<i>Emissions to soil</i>			
Copper sulfate	g	$2.89 \times 10^{-3}$ –1.99 × 10 <sup>-2</sup>	–
Abamectin	g	$3.0 \times 10^{-4}$ –5.41 × 10 <sup>-4</sup>	$3.19 \times 10^{-4}$ –9.64 × 10 <sup>-4</sup>
Clofentazine	g	$4.76 \times 10^{-3}$ –8.59 × 10 <sup>-3</sup>	$5.06 \times 10^{-3}$ –1.53 × 10 <sup>-2</sup>
Spinosad	g	$1.27 \times 10^{-3}$ –2.06 × 10 <sup>-3</sup>	$1.47 \times 10^{-3}$ –3.67 × 10 <sup>-3</sup>

(continued on next page)

Table 2 (continued)

Parameters	Unit	Quantity/FU (Floricanes)	Quantity/FU (Primocane)
Penconazole	g	$9.53 \times 10^{-4}$ –1.66 $\times 10^{-3}$	$2.02 \times 10^{-3}$ –5.82 $\times 10^{-3}$
Acetamiprid	g	–	$2.28 \times 10^{-3}$ –6.89 $\times 10^{-3}$
Boscalid	g	–	$1.01 \times 10^{-2}$ –2.91 $\times 10^{-2}$
Pyraclostrobin	g	–	$2.54 \times 10^{-3}$ –7.31 $\times 10^{-3}$

TSS indicates higher quality). This assumption ensures that the elaboration is valid within the context of the study and aligns with the expectation that improved quality parameters positively influence the environmental impact assessment. The approach used enables a relative comparison of the environmental impacts of different genotypes while recognizing the uncertainties and complexities associated with integrating qualitative parameters into the LCA. Therefore, the functional unit-adjusted scores themselves should not be interpreted as having intrinsic standalone meaning beyond this comparative context. It is also important to note that the relationship between some quality parameters and fruit quality may not always be strictly linear.

$$\text{Functiona unit – adjusted score} = \frac{\text{Impact score}}{\text{Quality parameter value}} \quad (1)$$

The four quality parameters assessed included are:

- (i) Marketability – ratio of marketable production to total production. Total production is the sum of marketable production plus waste. It is measured on a scale of 0 to 1, with 0 being the worst value and 1 as the best value. Indicatively, values higher than or around 0.9 are excellent results for the floricanes raspberry, while for the primocane, around 0.85.
- (ii) Shelf-life – ability of fruit to be stored in cold storage. It was determined by evaluating fruit stored for nine days at  $2^\circ\text{C} \pm 1^\circ\text{C}$ , followed by one day at ambient temperature. A 0–1 scale assessed fruit quality, with 1 representing optimal condition and 0 indicating no marketability. A score above 0.7 indicated exceptional shelf life, while 0.55–0.65 represented a satisfactory level. The value represents a synthetic judgment expressing the commercial value of the fruit. Factors such as appearance (color, size, shape), damage, storage-related issues (e.g., botrytis or loss of juice), and sensory attributes (texture, flavor) influenced the final score.
- (iii) Total soluble solids (TSS) ( $^\circ\text{Brix}$ ) – total content of soluble solids in an aqueous solution as an index of the sugar content of the fruit. It is measured with a digital refractometer. At each harvest date, we randomly sample 3 fruits that are directly frozen. Values generally range from 6 to 13, with an average reference value of 9.0 to 10. Higher values indicate higher sugar content of the fruit and sweeter fruits.
- (iv) Total soluble solids/Titratable acidity (TSS/TA) ( $^\circ\text{Brix}/\text{Meq. NaOH}/100\text{ g fruits}$ ) – relationship between sugar and acid content to determine fruit sweetness. Acidity is measured on the same sample on which TSS was also measured. Values range between 0.2 and 0.5. An average reference value can be from 0.3 to 0.35. The higher the value, the sweeter the fruit should be. Conversely, lower values indicate the prominence of acidic sensation.

## 4. Results and discussion

This section presents the midpoint, contribution analysis, and normalized environmental impact results for floricanes and primocane raspberry production systems (Sections 3.1, 3.2, and 3.3). Additionally,

the environmental performance ranking of genotypes is analyzed, considering both environmental impact and selected quality parameters (Section 3.4). Scenario analysis is in Section 3.5, and a comparison of the findings on the climate change impact with those from previous studies is in Section 3.6.

### 4.1. Midpoint impact results

The average midpoint impact results and the standard deviations of the floricanes and primocane raspberry are reported in Table 3. The results showed that floricanes and primocanes had similar scores across various impact categories despite differences in genotype, plant density, growth cycles, and cultural practices (e.g., floricanes require an initial nursery phase for vegetative growth). Floricanes raspberry genotypes (field trial 1) had a higher plant density (16,000 plants/ha) and yield (26 t/ha) compared to primocane raspberry genotypes (field trial 2) (12,000 plants/ha and 19 t/ha). The variation in scores was marginal considering the standard deviations (see Supplementary Material).

#### 4.1.1. Common impacts

The midpoint results of the common impacts of new raspberry genotypes grown in two production cycles (floricanes - FT1 and primocane - FT2) are reported in Table 3. The average climate change (CC) impact score for FT1 (0.95 kg CO<sub>2</sub> eq./FU) was lower than FT2 (1.27 kg CO<sub>2</sub> eq./FU) (Table 3). This difference can be attributed to cultivar characteristics, life cycle stages, plant density, yield variability, and seasonality. Even though FT2 did not have the environmental burden of the nursery stage, FT1's higher yield resulted in a better overall environmental performance. Fig. 2 illustrates the variation in climate change scores among the genotypes, ranging from 0.76 to 2.07 kg CO<sub>2</sub> eq./FU. SOU201 (FT1) showed the best performance, while SOR701 (FT2) had the highest impact, nearly three times higher. This significant difference in the average score of FT2 is mainly due to the low yield of SOU701 (8.5 t/ha). The average yields achieved in this study, 26 t/ha for floricanes (FT1) and 19 t/ha for primocanes (FT2), significantly exceed the yield range of 7.2 to 12 t/ha reported in previous studies (Foster et al., 2014; Girgenti et al., 2013; Vázquez-Ibarra et al., 2021). However, these high yields are comparable to those reported for tunnel-grown raspberries, which can reach 20–35 t/ha (Rantanen et al., 2024). This highlights the potential for significant yield increases through optimized cultivation practices, including the use of high tunnels and potentially other protected cultivation systems.

The key contributors to the climate change impact score were infrastructure (62 %) and nursery (16 %) for FT1, while infrastructure dominated FT2 (69 %) (Figs. 3 and 4). The infrastructure comprised of steel pipes and plastic cover for the tunnels, and plastic irrigation pipes. Similar trends were observed for other environmental impact categories like acidification (A), eutrophication terrestrial (ET), eutrophication freshwater (EF), eutrophication marine (EM), ionising radiation (IR), and photochemical ozone formation (POF) (Table 3).

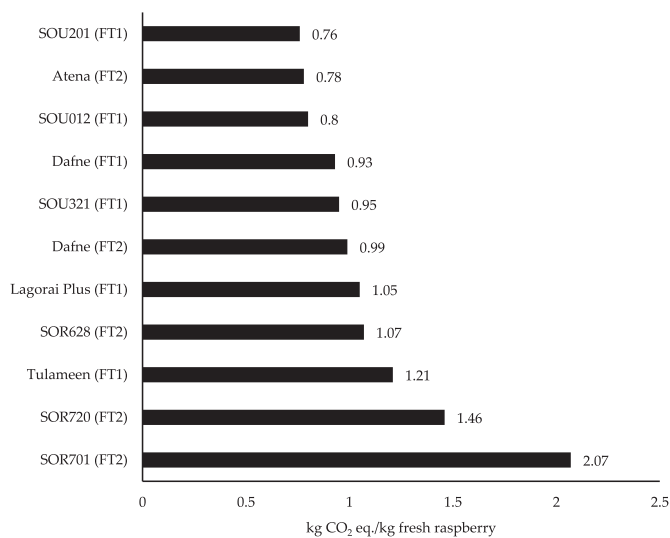
Overall, floricanes cultivation (FT1) demonstrated a better environmental performance than primocane (FT2) for most impact categories. Infrastructure emerged as the major contributor across both production cycles, followed by the nursery stage for FT1 and fertilizer emissions for FT2 (Figs. 3 and 4). The ranking of environmental performance for other impact categories among genotypes followed a similar trend observed in Fig. 2 (see Supplementary Material for details).

#### 4.1.2. Toxicity-related impacts

Table 4 shows the human toxicity impacts for floricanes (FT1) and primocane (FT2) raspberry production. The estimated human toxicity, cancer (HTC) and human toxicity, non-cancer (HTNC), were slightly lower for FT1 compared to FT2. FT1 had scores of  $1.65 \times 10^{-9}$  CTUh/FU (HTC) and  $1.03 \times 10^{-8}$  CTUh/FU (HTNC), while FT2 had scores of  $2.22 \times 10^{-9}$  CTUh/FU (HTC) and  $1.25 \times 10^{-8}$  CTUh/FU (HTNC). Infrastructure was the primary contributor to human toxicity in both FT1 (92

**Table 3**  
Midpoint impact scores for primocane and floricane raspberry, expressed per 1 kg of fresh raspberry.

Impact category	Unit	Floricane (Field trial 1)	Primocane (Field trial 2)
A	mol H <sup>+</sup> eq.	$4.26 \times 10^{-3} \pm 6.44 \times 10^{-4}$	$5.50 \times 10^{-3} \pm 2.21 \times 10^{-3}$
CC	kg CO <sub>2</sub> eq.	0.95 ± 0.17	1.27 ± 0.51
ETF	CTUe	6.28 ± 0.82	7.91 ± 3.46
PM	disease inc.	$4.42 \times 10^{-8} \pm 7.43 \times 10^{-9}$	$6.03 \times 10^{-8} \pm 2.42 \times 10^{-8}$
EM	kg N eq.	$1.77 \times 10^{-3} \pm 2.02 \times 10^{-4}$	$1.94 \times 10^{-3} \pm 7.94 \times 10^{-4}$
EF	kg P eq.	$3.13 \times 10^{-4} \pm 4.17 \times 10^{-5}$	$3.48 \times 10^{-4} \pm 1.52 \times 10^{-4}$
ET	mol N eq.	$1.03 \times 10^{-2} \pm 1.43 \times 10^{-3}$	$1.25 \times 10^{-2} \pm 5.08 \times 10^{-3}$
HTC	CTUh	$1.65 \times 10^{-9} \pm 3.11 \times 10^{-10}$	$2.22 \times 10^{-9} \pm 9.39 \times 10^{-10}$
HTNC	CTUh	$1.03 \times 10^{-8} \pm 1.70 \times 10^{-9}$	$1.25 \times 10^{-8} \pm 5.42 \times 10^{-9}$
IR	kBq U-235 eq.	$5.01 \times 10^{-2} \pm 7.76 \times 10^{-3}$	$5.74 \times 10^{-2} \pm 2.61 \times 10^{-2}$
LU	Pt	4.32 ± 0.73	5.71 ± 2.24
OD	kg CFC11 eq.	$9.28 \times 10^{-9} \pm 1.26 \times 10^{-9}$	$1.03 \times 10^{-8} \pm 4.57 \times 10^{-9}$
POF	kg NMVOC eq.	$3.17 \times 10^{-3} \pm 5.16 \times 10^{-4}$	$4.05 \times 10^{-3} \pm 1.64 \times 10^{-3}$
RUF	MJ	15.8 ± 2.68	20.5 ± 8.31
RUMM	kg Sb eq.	$8.28 \times 10^{-6} \pm 1.39 \times 10^{-6}$	$1.03 \times 10^{-5} \pm 4.47 \times 10^{-6}$
WU	m <sup>3</sup> depriv.	3.74 ± 0.49	7.09 ± 3.12



**Fig. 2.** Climate change scores for the different raspberry genotypes expressed per 1 kg of raspberry.

% for HTC) and FT2 (97 % for HTC and 84 % for HTNC) (Figs. 3 and 4). However, for HTNC in FT1, the nursery stage also played a significant role (29 %). Regarding ecotoxicity freshwater (ETF), FT1 had a lower average score (6.28 CTUe/FU) compared to FT2 (7.91 CTUe/FU). Fertilizer application was the major contributor to EFT in both production cycles (22 % for FT1 and 56 % for FT2). Infrastructure also played a notable role (27 % for FT1 and 34 % for FT2). The nursery stage also significantly impacted the EFT score of FT1 (45 %).

#### 4.1.3. Resource-related impacts

Land use (LU) impact, as shown in Table 3, was slightly lower for floricane (FT1) compared to primocane (FT2) raspberry production. FT1 had a score of 5.71 Pt/FU, while FT2 had a score of 4.32 Pt/FU. This difference can be attributed to the higher yield achieved by FT1 genotypes despite having the same dedicated cultivation area as FT2. However, FT1 required additional land for the nursery stage. With average yields of 26 t/ha for floricane raspberry genotypes (FT1) and 19 t/ha for primocane raspberry genotypes (FT2), the land use in this study can be considered highly efficient and productive. These yields significantly exceed those reported in other studies, where average yields typically range from 7.2 to 12 t/ha (Foster et al., 2014; Girgenti et al., 2013; Vázquez-Ibarra et al., 2021).

Water use (WU) impact was significantly higher for FT2 (7.09 m<sup>3</sup> depriv./FU) compared to FT1 (3.74 m<sup>3</sup> depriv./FU) (Table 3). Field

irrigation during the vegetative growth phase was the main contributor in both systems. However, FT1 required additional irrigation for young shoots in the nursery, unlike FT2. Irrigation plays a crucial role in raspberry production, ensuring consistent water supply, preventing drought stress, and optimizing plant growth. Adequate irrigation is essential for maximizing yield and fruit quality. Water stress can negatively impact plant growth and development, including flower and fruit sets, leading to smaller fruit size, reduced yield, and compromised fruit quality (Ortega-Farias et al., 2022).

Similar trends were observed for resource use, fossil (RUF), and resource use, minerals and metals (RUMM), with FT1 having slightly lower impacts. Infrastructure contributed to nearly 90 % of the total impact in FT2, while in FT1, the nursery stage (around 24 %) and infrastructure (around 66 %) were the major contributors. Although infrastructure significantly contributes to environmental impacts, protected cultivation systems such as high tunnels with plastic covers offer several advantages for raspberry production. These systems can greatly extend the growing season (Gaskell, 2004). High tunnels also mitigate the impact of adverse weather conditions, including hail, strong winds, frost, excessive rain, and humidity. This protection reduces the risk of fruit damage (cracking), disease outbreaks (e.g., gray mold), and loss of fruit firmness. Furthermore, high tunnels provide a more controlled growing environment, leading to more consistent fruit size, color, and sweetness. These systems can enhance plant growth, flower set, and overall fruit production by optimizing growing conditions, such as temperature, humidity, and light levels (Thompson et al., 2009; Hanson and Weihe, 2011).

#### 4.2. Contribution analysis of the dominant contributors

Given that most of the impacts were related to the infrastructure and nursery phase (FT1), a further hotspot analysis was conducted to identify the significant inputs. In the nursery, electricity consumption for water pumping and storing young plants in refrigerated cells before transplanting was the primary contributing input for most of the impact categories (Fig. 5). Considering the cells were operating at full maximum capacity, decreasing the number of plants stored could significantly reduce efficiency. Other notable contributors were fertilizer application in EFT, accounting for nearly 55 %, emissions from nitrogen and phosphorus fertilizers in EM, EF, and ET, and irrigation water in WU (Fig. 5). Regarding infrastructure, the main contributors were steel pipes and LDPE cover for the high tunnel structure (Fig. 6). The short lifespan of the plastic cover (3 years) compared to the irrigation pipes (10 years) and the steel pipes (30 years) highlights an improvement opportunity. Extending the lifespan of the plastic cover coupled with potential environmental credits from efficient recycling of the plastics and metals at the end-of-life could substantially improve the results. However,

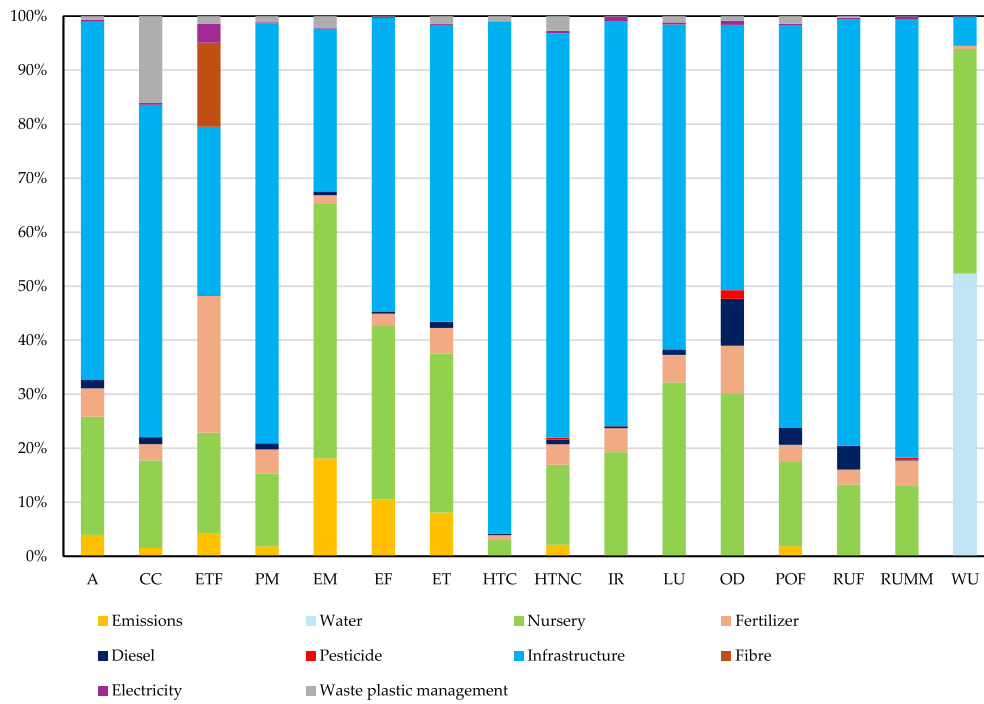


Fig. 3. The relative contribution analysis of floricane raspberry (field trial 1).

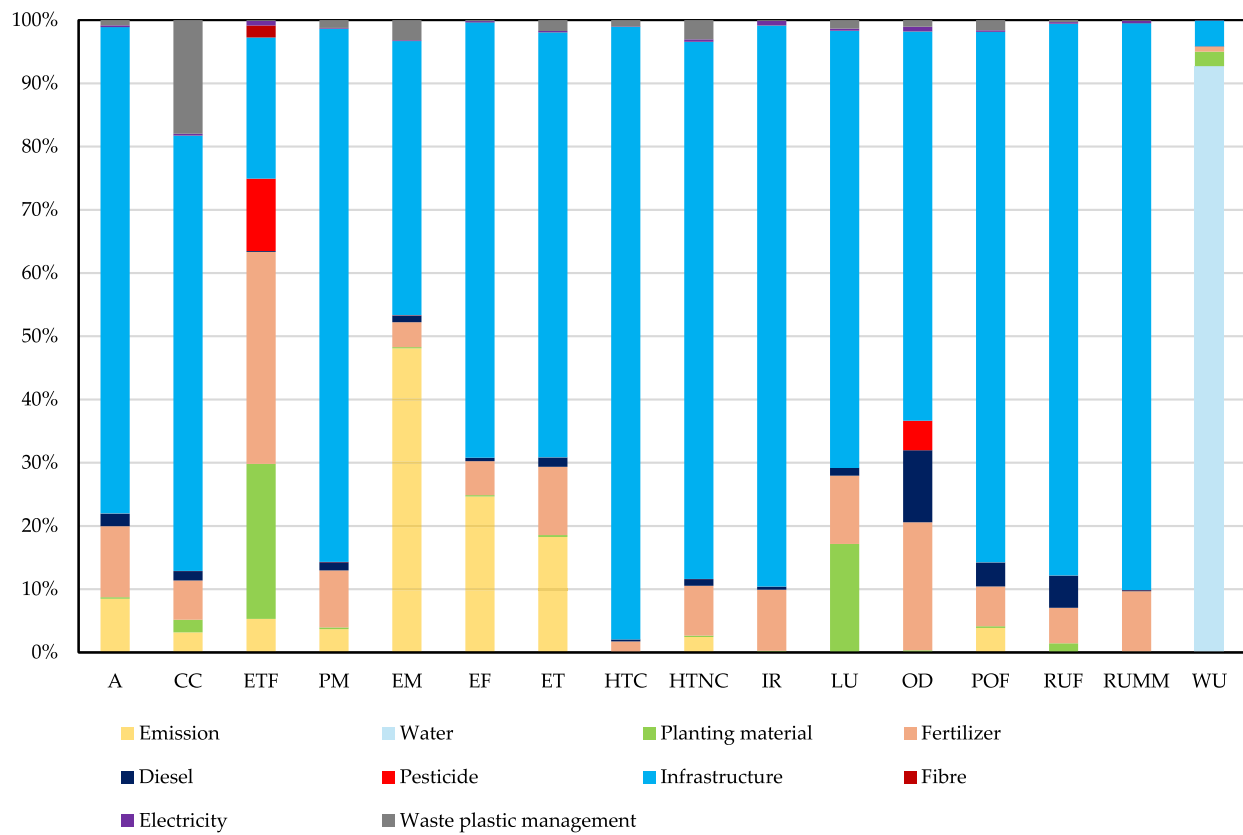


Fig. 4. The relative contribution analysis primocane raspberry (field trial 2).

waste management was not included in the study.

#### 4.3. Normalized results

The mean normalized results based on the EF 3.1 LCIA method revealed that floricane raspberry (FT1) generally had lower

**Table 4**  
Scenario analysis of electricity for the nursery phase: average Italian electricity mix (baseline) vs 100 % photovoltaic (alternative), expressed per 1 raspberry seedling at the nursery gate.

Impact category	Unit	Baseline	Alternative
A	mol H <sup>+</sup> eq.	1.71 × 10 <sup>-3</sup>	1.46 × 10 <sup>-3</sup>
CC	kg CO <sub>2</sub> eq.	0.28	0.21
ETF	CTUe	4.19	4.11
PM	disease inc.	1.08 × 10 <sup>-8</sup>	1.02 × 10 <sup>-8</sup>
EM	kg N eq.	1.57 × 10 <sup>-3</sup>	1.54 × 10 <sup>-3</sup>
EF	kg P eq.	1.86 × 10 <sup>-4</sup>	1.79 × 10 <sup>-4</sup>
ET	mol N eq.	5.58 × 10 <sup>-3</sup>	5.13 × 10 <sup>-3</sup>
HTC	CTUh	8.94 × 10 <sup>-11</sup>	7.46 × 10 <sup>-11</sup>
HTNC	CTUh	2.77 × 10 <sup>-9</sup>	2.52 × 10 <sup>-9</sup>
IR	kBq U-235 eq.	1.76 × 10 <sup>-2</sup>	7.56 × 10 <sup>-3</sup>
LU	Pt	2.52	2.14
OD	kg CFC11 eq.	5.18 × 10 <sup>-9</sup>	4.26 × 10 <sup>-9</sup>
POF	kg NMVOC eq.	9.07 × 10 <sup>-4</sup>	7.02 × 10 <sup>-4</sup>
RUF	MJ	3.8	2.6
RUMM	kg Sb eq.	1.96 × 10 <sup>-6</sup>	2.12 × 10 <sup>-6</sup>
WU	m <sup>3</sup> depriv.	2.88	2.84

environmental impact scores compared to primocane raspberry (FT2) across most impact categories (Fig. 7). The highest scores were reported in WU and RUF, with WU (FT2) having the highest score of 7.7 × 10<sup>-4</sup> PE/FU. However, IR, LU, and OD impact scores were negligible (less than 3.0 × 10<sup>-5</sup> PE/FU). Like the previous midpoint analysis, the main contributors to environmental impact were LDPE plastic cover and steel pipes for the infrastructure and electricity consumption in the nursery phase.

4.4. Environmental performance of genotypes based on assessed quality parameters

Adjusting the environmental performance ranking based on selected

quality parameters (marketability, shelf-life, and taste) revealed significant differences (Fig. 8 a-d) compared to the assessment considering only CC impact (Fig. 2). While floricanes (FT1) and primocanes (FT2) showed no clear difference in performance ranking trend, individual genotypes exhibited variations. SOR701 (FT2) consistently ranked lowest across all assessed quality parameters, while SOU201 (FT1) consistently ranked highest. This outcome can be attributed to several factors, including the significantly higher CC score associated with SOR701 (FT2) and the relatively lower CC score of SOU201 (FT1). Furthermore, the relatively small differences in quality parameter scores among the genotypes contributed to the pronounced influence of the CC impact scores on the overall ranking.

Regarding marketability, all the floricanes were within the acceptable range of 0.85 to 1, with SOU012(FT1) recording the highest value of 0.93. In contrast, none of the primocane genotypes reached the acceptable marketability threshold, with Atena (FT2) and SOR701 (FT2) recording the lowest scores (0.75). Marketability is a crucial economic factor that affects farmers and cooperatives because it determines the quantity of fruit available for sale for the same total production. This metric significantly impacted the overall ranking, as evidenced by Atena (FT2) moving from the second best-performing genotype based on CC impact to the third-best performer when marketability was considered due to its low marketability score. SOU12 (FT1) ranked top, while SOR701 (FT2) remained at the bottom. Given the significant economic implications of marketable yield, this analysis underscores the importance of considering multiple factors, including marketability, in addition to environmental impact, when selecting genotypes for commercial raspberry production. This integrated approach can contribute to achieving both economic and environmental sustainability in raspberry cultivation.

Fig. 8b shows the adjusted environmental performance ranking of genotypes based on shelf-life scores. Shelf life was evaluated on a scale of 0 to 1, with 1 representing a perfect fruit. A threshold of 0.55 was

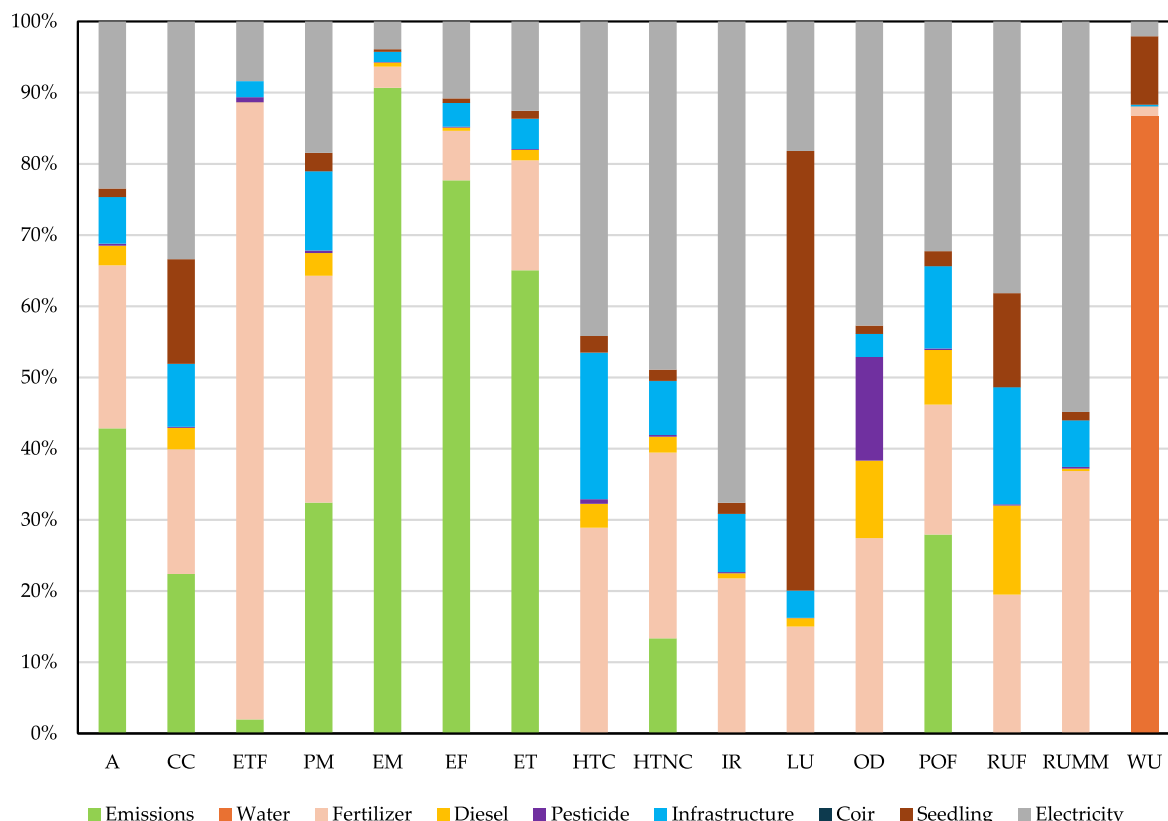


Fig. 5. Relative contribution analysis for the nursery phase (floricanes).

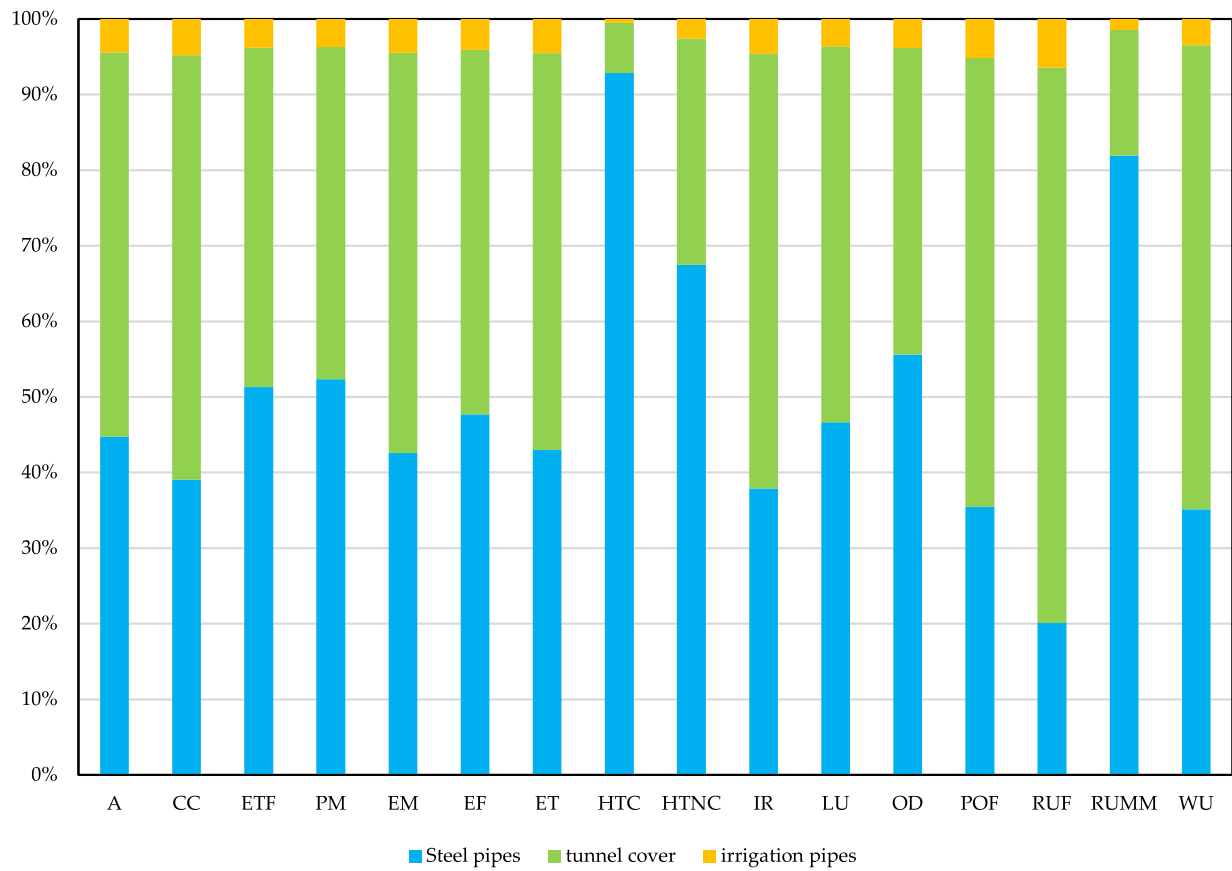


Fig. 6. Relative contribution analysis for the infrastructure.

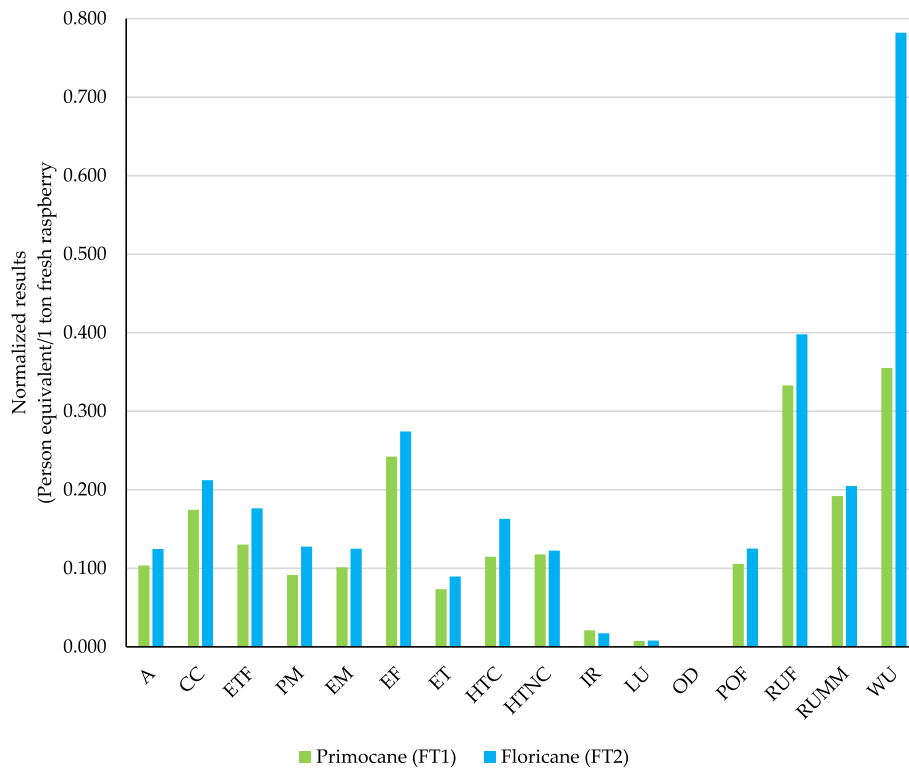
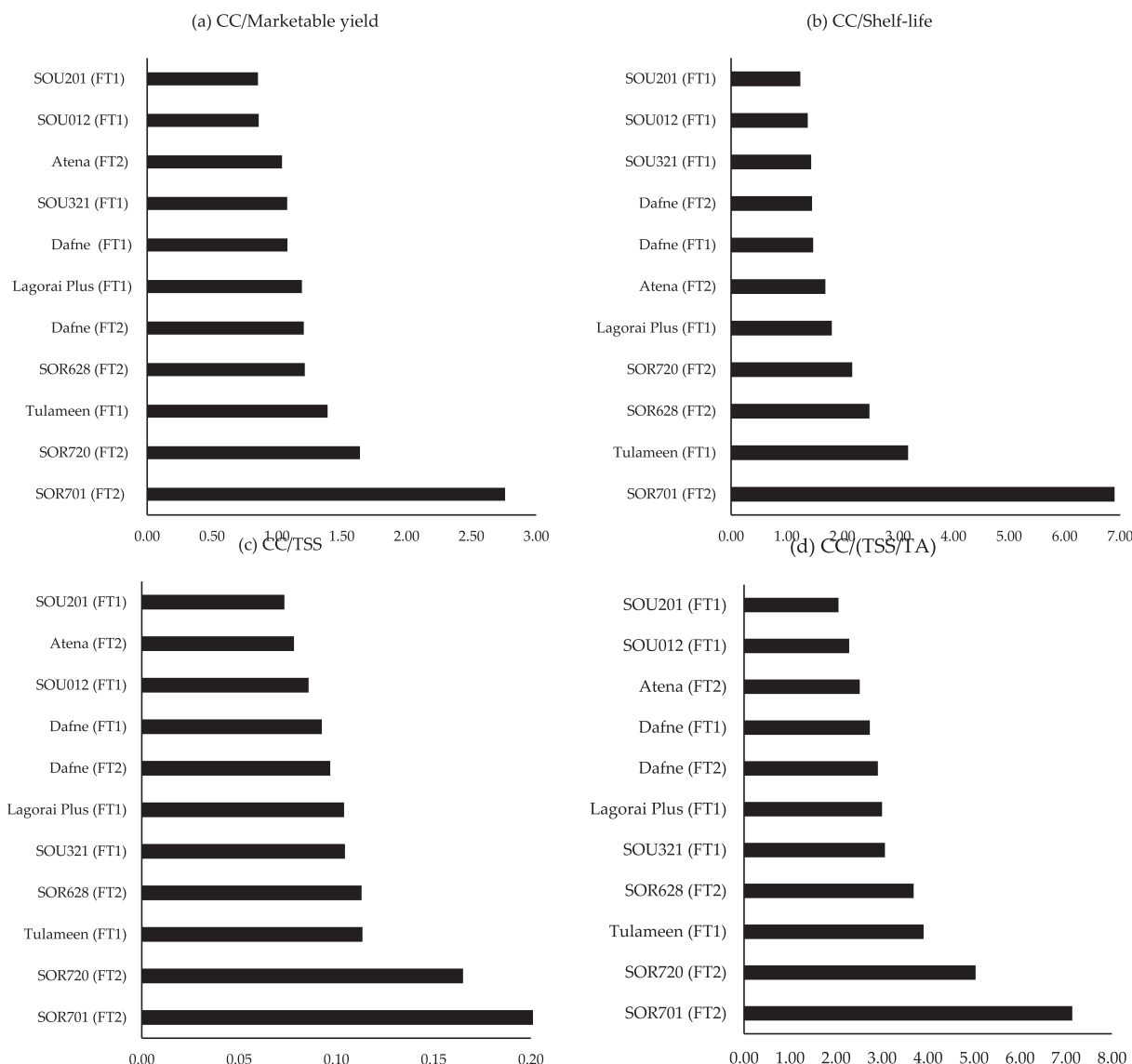


Fig. 7. Normalized results for raspberry production, cradle-to-farm gate. FT- Field trial.



**Fig. 8.** Environmental performance (climate change) ranking of raspberry genotypes based on selected quality-adjusted indices of the functional unit. CC – climate change, TSS- total soluble solids, TA – titratable acidity.

established, as most fruits exhibit some storage defects. The floricanes generally demonstrated superior shelf-life, with all genotypes exceeding the threshold except Tulameen (0.38). SOU321 achieved the highest score (0.66). Among primocanes, Atena, SOR628, and SOR701 fell below the threshold with scores of 0.46, 0.43, and 0.30, respectively. Dafne displayed the best floricanes shelf-life (0.68). SOU201 (FT1) achieved the highest overall ranking when combined with climate change impact due to its low environmental impact and good shelf-life. Conversely, Tulameen (FT1) and SOR701 (FT2) ranked lowest. Shelf life significantly influences the entire supply chain and is the most important quality index to producers and retailers, impacting economic, health, and environmental factors. A longer shelf life reduces post-harvest waste, maintains fruit quality and high sales value, and ultimately benefits retailers and consumers.

The adjusted environmental performance ranking considering TSS and the TSS/TA ratio is presented in Fig. 8c and d, respectively. Both parameters are closely linked to fruit sweetness. Typically, TSS values range from 9 to 10, with a minimum threshold of 6, while TSS/TA ratios typically fall between 0.3 and 0.35. All genotypes assessed fell within these acceptable ranges. Therefore, the adjusted ranking was similar to the initial CC-based ranking. Higher TSS values indicate increased

sweetness, while lower TSS/TA ratios suggest a more pronounced acidic taste. With their naturally high acidity, raspberries often exhibit lower TSS/TA ratios compared to other fruits. However, TSS and TSS/TA provide a limited representation of overall fruit taste, as the analyses conducted do not detect and account for volatile chemical compounds and aroma, which significantly contribute to flavor perception. Despite these limitations, these metrics remain commonly used by breeders, varietal testers, and consumers to assess fruit sweetness and acidity.

Considering the complex nature of food supply chains, informed decision-making requires a comprehensive understanding of product attributes, including environmental impacts and quality characteristics. While recent advancements in LCA have incorporated nutritional quality into evaluating food products, this perspective remains largely consumer-centric. The LCA of food is fast evolving from solely mass-based comparisons of products to more complex but realistic methodological approaches since pure mass-based comparisons may not be adequate for fair comparisons. The execution of LCA is always dependent on the context. Therefore, to achieve a more holistic sustainability assessment, LCA methodologies must consider the needs and perspectives of various stakeholders, such as farmers, breeders, and retailers. This could provide more robust and reliable results and encourage

stakeholders to adopt strategies to improve the product's overall sustainability, given their interests were considered. This study demonstrates that integrating multiple quality indices beyond environmental impact can significantly influence product performance assessment.

However, a major challenge lies in normalizing and weighting these parameters, which differ in units, scales, and relative importance. The significance of each quality parameter can vary based on market demand, consumer preference, and breeder priority. For instance, sweetness and acidity levels may hold varying importance depending on the intended market or consumer group. These complexities make it difficult to develop a single universally applicable index that accurately reflects the combined influence of these diverse quality parameters. Future studies should explore the development of a more comprehensive sustainability index for raspberry genotypes. This index should incorporate a wider range of quality attributes, including nutritional aspects (e.g., vitamin content and antioxidant capacity), and consider the varying preferences of different consumer groups and market demand. Such an index would provide a more comprehensive understanding of the environmental and socio-economic impacts of different raspberry genotypes, ultimately supporting more sustainable production practices.

#### 4.5. Sensitivity analysis

A scenario analysis exploring the substitution of grid electricity with solar energy at the nursery phase revealed significant reductions in certain impact categories (Table 4). IR (57%), RUF (31%), and CC (26%) recorded the highest reduction in impact scores, while WU, EFT, and EM were unaffected. However, this substitution led to a 10% increase in the RUMM score, likely due to significant amounts of raw materials, including silicon, silver, and other metals required for manufacturing photovoltaic panels. The extraction and processing of these materials can also be energy and resource-intensive (Tawalbeh et al., 2021; Bošnjaković et al., 2023). While solar energy adoption at the nursery level positively impacted some environmental indicators, its benefits did not translate substantially to the farm gate level for the floricanes (Supplementary material). Although a modest 11% improvement was observed for IR, reductions in other impact categories remained below 5%. These findings suggest that while solar energy can be a valuable mitigation strategy for nursery operations, its broader application within the raspberry production system may require further investigation to assess its overall environmental sustainability.

Infrastructure was the main hotspot input for most impact categories,

primarily due to the plastic tunnel cover and the steel pipes. While chromium steel pipes are known for their durability due to their corrosion resistance, with potential lifespans exceeding 50 years under optimal conditions (Arifin, 2023), this study assumed a 30-year lifespan. Extending the lifespan by 10 and 20 years generally decreased the impacts by 5% to 35% (Fig. 9). HTC, HTNC, and RUMM had the highest reductions, exceeding 15%. Due to the additional contribution from the nursery phase, field trial 1 had a slightly less relative reduction than field trial 2. Prioritizing infrastructure durability through regular maintenance and material selection offers a more sustainable approach than the conventional dismantling, recycling, and replacement cycle. Extending the lifespan of the materials reduces waste generation and decreases the demand for new resources (Silva et al., 2017; Zhang et al., 2022). Consequently, investing in high-quality, long-lasting infrastructure components is crucial for improving the overall environmental sustainability of the food production system.

#### 4.6. Comparison of climate change impact with other raspberry production systems

The climate change scores obtained in this study were consistent with past LCA studies on raspberry cultivation in tunnels and open fields (Table 5). High values of about 7 kg CO<sub>2</sub> eq./kg raspberry were reported for open-field and tunnel-grown raspberry in Spain and the UK, respectively. Electricity consumption was the main contributor to the CC score in Spain. In Finland, findings similar to those obtained in this study were reported for tunnel-grown and open-field raspberries. Infrastructure accounted for about 20% of the total CC score in the tunnel production. In northern Italy, the climate change impact for open field raspberry to the point of sale was between 0.2 and 0.4 kg CO<sub>2</sub> eq./kg raspberry, which is comparable to results obtained in this study, given that infrastructure accounted for more than 50% of the total CC impact. While these results offer valuable insights, direct comparisons between LCA studies should be interpreted cautiously due to variations in system boundaries, methodological choices, and geographical contexts.

## 5. Conclusions

Using the LCA method, the present study evaluated the environmental impacts of growing different primocane and floricanes raspberry genotypes in soilless high tunnels. Field trials were conducted in Italy, assessing five floricanes genotypes (Dafne, Lagoria Plus, Tulameen,

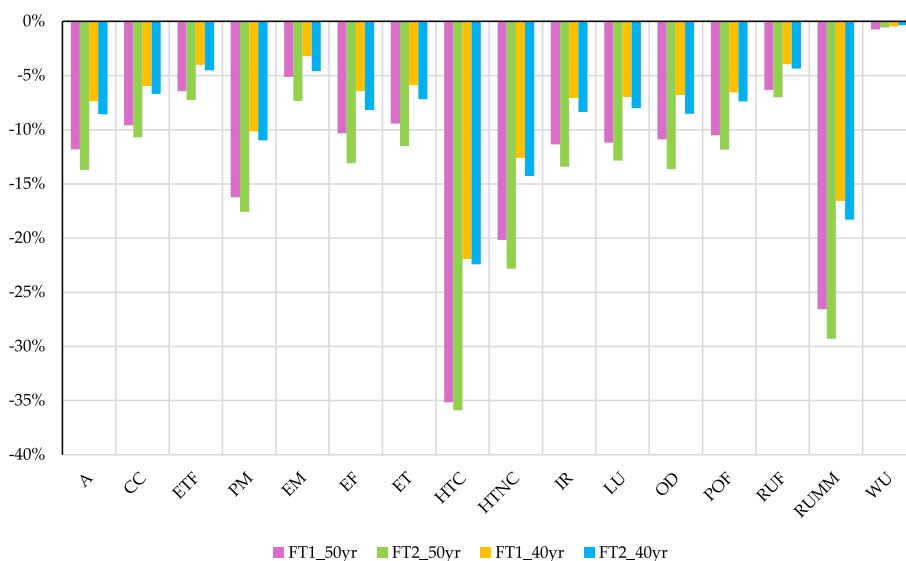


Fig. 9. Sensitivity analysis of infrastructure: relative change of lifespan extension of steel pipes from 30 years to 40 years and 50 years for floricanes and primocane raspberry production. FT1 (field trial 1 – floricanes) and FT2 (field trial 2 – primocanes).

**Table 5**  
Comparison of climate change impact with other raspberry production systems.

Author (s)	Production system	Country	System boundary	CC score/kg raspberry
This study	High tunnels	Italy	Cradle-to-farm gate	0.76–2.07
Rantanen et al. (Rantanen et al., 2024)	Tunnels	Finland	Cradle-to-farm gate	0.5–0.95
Rantanen et al. (Rantanen et al., 2024)	Open field	Finland	Cradle-to-farm gate	0.6–1.3
Pérez et al. (Pérez et al., 2024)	Open field	Spain	Cradle-to-farm gate	7.78
Vásquez-Ibarra et al. (Vásquez-Ibarra et al., 2021)	Open field	Chile	Cradle-to-farm gate	0.52 ± 0.4
Foster et al. (Foster et al., 2014)	Tunnels	UK	Cradle-to-retail gate	7.3–7.4
Girgenti et al. (Girgenti et al., 2013)	Open field	Italy	Cradle-to-farm gate	0.22
Peano et al. (Peano et al., 2015)	Open field	Italy	Cradle-to-retail gate	0.42

SOU321, SOU201, and SOU012) and six primocane genotypes (Atena, Dafne, SOR628, SOR701, and SOR720). Both cultivars were cultivated under identical external and environmental conditions, which were optimized and adequate for raspberry growth.

The analysis of the results showed similar environmental performance between the primocane and floricanes despite differences in genotype, plant density, growth cycles (floricanes require a two-year cycle, while primocanes are annual), and cultural practices (e.g., floricanes require an initial nursery phase for vegetative growth). While the study observed no significant differences in the environmental performance of florricane and primocane raspberries, it is important to acknowledge potential limitations. The relatively short study period (two years) may not fully capture the long-term variability in yield and environmental conditions.

The high tunnel structure, composed of steel pipes and a plastic cover, emerged as the primary environmental hotspot in the production system. Extending the lifespan of steel pipes to 10 and 20 years significantly reduced impacts, with reductions ranging from 5 % to 35 %. Other major contributors to environmental impacts included agrochemical use, related emissions, and electricity consumption, particularly during the nursery phase. However, replacing grid electricity with solar energy at the nursery level yielded only marginal environmental benefits.

This study underscores the importance of optimizing infrastructure lifespan and resource use to improve the sustainability of soilless raspberry production systems.

Integrating environmental sustainability assessment in breeding programs as part of the multi-criteria decision analysis can help foster sustainable and competitive berry production. The LCA method allows the coupling of other quality parameters besides the yield or product mass for fairer comparative assessment. Given that one primary goal of berry breeding programs is to develop high-quality berries that respond to consumer quality, particularly health promotion, nutritional quality assessment of the different genotypes should have been included. However, information on this aspect was lacking. Therefore, we incorporated additional quality parameters, such as marketability, shelf life, and taste-related characteristics (e.g., TSS and TA), into the functional unit-adjusted values. This approach demonstrates how environmental performance can vary when considering quality aspects to comprehensively assess genotype performance.

While berries like raspberries are valued for their health-promoting properties (e.g., antioxidants, bioactive compounds, and phytochemicals) rather than solely for their basic nutritional profile, existing scoring

systems like the Nutrient Rich Food (NRF) Index are not designed to fully capture these benefits. By integrating non-nutritional quality parameters relevant to stakeholders across the supply chain, the study provides a more comprehensive perspective on sustainability in raspberry production. Although challenges exist in developing a single, universally applicable sustainability index due to varying stakeholder priorities, incorporating multiple quality attributes is essential for informed decision-making. Future research should focus on developing a weighted index that reflects the diverse needs of stakeholders within the berry supply chain. By expanding the scope of LCA to encompass nutritional quality and other critical factors, the berry industry can make more informed decisions to produce high-quality and sustainable products that meet evolving consumer demands.

#### CRediT authorship contribution statement

**Kofi Armah Boakye-Yiadom:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Alessio Ilari:** Writing – review & editing, Validation, Software, Methodology, Formal analysis. **Lucia Olivi:** Investigation, Formal analysis, Data curation. **Paolo Zucchi:** Writing – review & editing, Resources, Investigation, Conceptualization. **Loris Osti:** Writing – review & editing, Resources, Investigation. **Bruno Mezzetti:** Project administration, Funding acquisition, Conceptualization. **Daniele Duca:** Writing – review & editing, Validation, Supervision, Software, Methodology, Data curation, Conceptualization.

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#### 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.spc.2025.01.020>.

#### Data availability

Available on request.

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