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A comprehensive assessment of life cycle environmental impact and economic feasibility of different red raspberry (*Rubus idaeus* L) cultivation systems

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A R T I C L E I N F O

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A B S T R A C T

Red raspberry is considered a knowledge- and capital-intensive crop that targets a niche market globally; its quality attributes and enhanced health-promoting properties are highly appreciated by the consumers. In the context of the exponential growth in demand for this specialty crop that suffers from limited shelf life, it is imperative to expand raspberry cultivation by employing sustainably-sourced production models. In the current study, we used Cyprus as a case study that is characterised by increased production costs and lack of year-round production despite the fact that the latter is feasible under different production systems and cultivation methods in different altitude-related meso-climates. Towards that goal, the current study assessed the life cycle environmental impact and life cycle costs of two different cultivation methods - open-field production that took place from May to November 2022 and protected cultivation in high-tunnels, from August 2023 to April 2024, using in both cases the same cultivar (Kwanza®) and plant type. The results indicated that protected cultivation has better environmental performance (3.7 mPt - milli eco-points - per kg of raspberry produced compared to 7.4 mPt for open-field production). Noteworthy, production cost is excessive and substantially higher compared to other countries; open-field production has a life cycle cost of 22.5 €/kg, while protected cultivation achieved a lower life cycle cost, equal to 14.0 €/kg yet still high. From an output perspective, a key observation is the increased yield of raspberries in protected cultivation as well as the enhanced water use efficiency of the crop, due to a reduction of the water footprint by 76 %. It is also important to highlight the increased harvest efficiency of the crop under high tunnel, with 500 g per plant compared to 350 g on open field cultivation. Hence, it is safe to conclude that despite the increased start-up costs and knowledge-intensive practices, the productivity of the crop is increased during the off-season months, that can be sold for a premium. The results highlight the environmental and economic impact of the two cultivation methods and will be useful for producers and crop advisors seeking to expand the raspberry cultivation in climates that resembles south-eastern Europe and are characterised as vulnerable to adverse climate change scenarios.

1. Introduction

Raspberry (*Rubus idaeus* L.) is an economically significant crop with a growing popularity and exponential growth in demand and production volumes (IRO, 2024). This is partially due to the fact that raspberry fruit represents an excellent natural source of biologically active components

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that provide significant health-promoting benefits (reviewed in Manganaris et al., 2014 and is also getting increasingly recognized for its efficacy in preventing chronic diseases, including cancer and cardiovascular disorders (Burton-Freeman et al., 2016).

In the 21st century, several commercially important red raspberry cultivars have been developed through hybridisation or selective breeding from diverse genetic sources, extending their productivity and seasonality in tropical, sub-tropical, and Mediterranean regions (Kempler et al., 2012). These cultivars are characterised by enhanced traits, such as larger fruit size, better flavour, disease resistance and tolerance, enhanced harvest efficiency, and adaptability to different climates. Such improvements rendered raspberry cultivation commercially viable and contributed to its popularity as a widely cultivated fruit (Hall et al., 2011). Multiple public and private breeding programs around the world contribute to the development and release of new cultivars with a growing number of releases having royalties that increase farmers' overall costs of production.

The consumption of locally grown fruits minimises carbon footprint; however raspberries cannot be grown in open fields year-round in many regions (Reisch et al., 2013). On top of that, farmers must implement cost-effective cultivation practices to minimize financial risks and maintain profitability. Overall, the year-round availability of a specialty crop like raspberry requires a high level of technical expertise and is achieved through a combination of adopting appropriate plant material (different cultivars), using superior production protocols and cultivating across different climates.

Raspberry is considered a perennial fruit crop, yet it develops biennial canes that vary temporally and spatially with regards to fruit production, depending on raspberry type. The first type is floricane-fruiting (i.e., non-remontant or summer-bearing). This type produces vegetative primocanes in the first year. These canes go through acclimation in autumn and overwinter, accumulating chilling units that induce floricanes into bearing flowers and fruits on lateral branches the following year. In contrast, primocane-fruiting (i.e., remontant, ever-bearing, or fall-bearing) types produce flowers and fruits at the top of first-year primocanes as well as on second-year floricanes after accumulating sufficient chilling units in winter (Manganaris et al., 2024).

Raspberry cultivation encompasses several labour-intensive techniques that are tailored to raspberry type, market requirements, and environmental conditions. Traditional raspberry cultivation involves open-field production, where plants are grown directly into the soil or sometimes containers, and the canopy is supported by trellises or stakes (Dale et al., 1994). Protected cultivation is an alternative production method that uses, plastic high tunnels, greenhouses, or other covers that extend the raspberry production season and enable harvest through modifications in the microclimate, while protecting against unpredictable weather patterns (Dale 2012; Palonen et al., 2017). Protected cultivation is generally more dependent on the use of containers with soilless media, such as coir and peat, which enables hydroponic techniques to be used whereby nutrients are dissolved and provided frequently in irrigation water (Ragaveena et al., 2021). Overall, protected cultivation conceptually provides many benefits to raspberry production, leading to optimised growing conditions, but it is highly intensive and requires a high financial investment from growers (Dale, 2012). A careful selection of the production system must be made to ensure maximum production and profitability leading to economic viability.

Understanding the environmental footprint of agricultural practices can reveal information on whether the water, energy, and land are being used inefficiently or excessively (Gruda et al., 2019; Janick 2003). As a commodity with a very short shelf life that requires cooling to maximize product longevity and quality, the raspberry supply chain has a significantly high environmental impact (Blanc et al., 2018). Several studies have been conducted to improve raspberry cultivation techniques, focusing on optimising plant growth, increasing yield, and improving fruit quality (Girgenti et al., 2013; Foster et al., 2015; Kailasam et al., 2020; Sangiorgio et al., 2021; Ponder and Hallmann., 2019; Valiante et al., 2019). However, all these studies focus on regions located in mainland Europe, where the climate is temperate.

In the current study, Cyprus case study is characterized by extreme temperatures and heatwaves compared to the rest of Europe. Additionally, its nature as an island poses significant challenges in terms of access to resources and higher production costs. More specifically, Cyprus is a Mediterranean island located in the easternmost part of the basin. It is characterised by different mesoclimates: a temperate climate in the mountainous areas with hot and dry summers, while the mainland and coastal areas are categorised as hot and arid, according to the Köppen–Geiger system (Peel et al., 2007; Zittis et al., 2017). The mean annual precipitation is approximately 470 mm, and most of the water resources originate in the Troodos mountains, covering nearly 30 % of the island (Christofi et al., 2020). The average precipitation in mountainous Cyprus is estimated to be 600 mm (Katsanos et al., 2016; Michaelides et al., 2009). Over the last decades, the observed rainfall trends in this part of the Mediterranean have been mostly declining (Papadaskalopoulou et al., 2020). Cyprus is among the EU Member States with the least available water per capita and remains vulnerable to climate change due to droughts and water scarcity (RoC, 2021), therefore the selection of sustainable cultivation practises that minimizes the use of water is crucial for the overall sustainability of Cypriot agriculture (EC, 2023). The rise of average air temperatures and more frequent heatwaves during the harvest season have caused problems to farmers who are still using traditional cultivation practices. Considering these challenges, there is an emerging need to explore alternative strategies that safeguard farmers' livelihoods (del Pozo et al., 2019).

Despite climate change concerns, the production of small fruits has expanded in the past two decades in the mountainous regions of Cyprus. In these areas the milder summer months and the relatively colder winter conditions permit open-field cultivation in the soil, which is considered an easier, low-cost production method. Growers use primocane-fruiting cultivars, and the production seasonality is limited to few months, mainly spanning from May until September (Lazoglou et al., 2024). Extreme heatwaves (over 30 °C) and lack of precise fertigation management techniques accelerate the ripening process, having a detrimental effect on fruit quantity and quality. Additionally, the induction of new flowers for next year's production is usually disrupted by high fall and winter temperatures, resulting in relatively small yields from the floricane crop.

As a direct response to these challenges, the establishment of low-cost high tunnels made of plastic ("poly") has emerged as a promising solution, particularly in the flatlands of Cyprus. Notably, these regions experience significantly higher temperatures, reaching up to 40 °C during summer and ca. 17 °C during winter periods. These passively modified environmental conditions extend the cultivation period of plants and permit off-season production from fall through spring when conditions are generally unfavourable for traditional, open-field cultivation. Due to lower solar radiation and wind speeds, high-tunnel-grown plants are likely to require a reduced amount of water owing to their relatively lower vapour pressure deficit.

Another challenge for Cyprus is that due to its remote nature, as an island, all resource and energy prices are significantly higher than the average European ones. This is also reflected in the competitive prices of imported raspberries. The objective of this study was to compare Kwanza® primocane raspberry production in two distinct environments with different cultivation techniques and associated production periods in Cyprus: (i) open-field cultivation from May until December 2022 and (ii) protected cultivation in high tunnels from August 2023 until April 2024. The overarching aim was to compare the two cultivation techniques and generate recommendations whether farmers can consider replacing or complementing traditional open-field cultivation with protected cultivation without jeopardising yield and profitability, while minimizing their environmental impact. To our knowledge, this is the first reported attempt to evaluate the cultivation of raspberries in a decentralised location with temperature extremes and water scarcity such as the conditions found in Cyprus. Another contribution of our study is the use of real-world data collected from the vegetative stage of a young Kwanza® planting until the end of primocane harvest in two distinct environments, with unique climatic conditions and cultivation methods in order to determine which is more profitable for Cyprus's red raspberry cultivation.

2. Methodology

A Life Cycle Assessment (LCA) was employed to evaluate the environmental performance of the two different raspberry cultivation methods. The current study adopted a methodological approach aligned with the LCA framework outlined in ISO14040/44:2006 (ISO, 2006), which includes four key stages:

1. Goal and Scope Definition, by establishing the study's objective and delineating the spatial and temporal boundaries of the chosen system.
2. Life Cycle Inventory (LCI), by compiling an inclusive inventory of all incoming and outgoing exchanges between the system and the environment.
3. Life Cycle Impact Assessment (LCIA), by calculating the environmental impact indicators, drawing from the inventory flows, and corresponding characterisation factors.
4. Interpretation of Results to discern the broader significance of the LCA assessment findings.

Table 1
Selected set of midpoint impact indicators.

Impact category	Impact acronym	Unit
Climate change	GWP	kg $CO_{2,eq}$
Ozone depletion	ODP	kg CFC-11_{eq}
Ionising radiation	IRP	kBq U-235_{eq}
Photochemical ozone formation	PCOP	kg $NMVOC_{eq}$
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 P_{eq}
Eutrophication, marine	MEP	kg N_{eq}
Eutrophication, terrestrial	TEP	mol N_{eq}
Ecotoxicity, freshwater	ETP	CTUe
Land use	LU	Pt
Water use	WDP	m^3
Resource use, fossils	ADPF	MJ
Resource use, minerals	ADPM	kg Sb_{eq}

The Life Cycle Assessment was performed using the SimaPro 9.2 Academic License, with the ecoinvent v3.7 database. The Environmental Footprint 3.0 was chosen as the assessment method. Environmental Footprint 3.0 is affiliated with the Environmental Footprint initiative and is the preferred method of LCA practitioners, since it provides both midpoint and endpoint indicators, and it is widely used by recent studies on the same sector (Valiante et al., 2019). The midpoint impact indicators employed to evaluate the environmental impact of raspberry production in this study, together with the abbreviations used and the units of measurement, are illustrated in Table 1. The endpoint single score indicator of this impact assessment method is the Environmental Footprint, and it is expressed in ecopoints (Pt). One milli ecopoint (mPt) corresponds to the annual environmental impact of an average European citizen.

2.1. Goal and scope definition

As previously mentioned, the scope of the study was to compare the environmental impact of raspberry production using two distinct cultivation methods: (a) soil-less open-field cultivation, with lower establishment costs but possibly higher water usage and lower yield, and (b) soil-less protected cultivation with a high-tunnel, entailing higher initial investment but with higher yield potential while conserving water. The research seeks to guide producers toward more cost-effective and eco-efficient production options, particularly in Mediterranean decentralized microclimates, as exemplified by the case study in Cyprus. Hence, the geographical scope refers to Southeastern Europe.

A cradle-to-gate approach was adopted for comparing both cultivation systems, focusing specifically on pre-harvest activities from nursery supply to primocane harvest. Data for the soil-less open-field cultivation method was sourced from a field located in Chandria village (altitude ca. 1200 m) in the upper highlands of Troodos, Cyprus (Fig. 1a). This cultivation cycle spanned from May to December 2022. Data for the protected cultivation system was sourced from an operation, located in Peristerona (altitude ca. 600 m), situated northwest of Nicosia (Fig. 1b). The protected cultivation cycle spanned from August 2023 to April 2024.

The system boundaries include all in-field processes (irrigation, fertiliser application and plant protection), while post-harvest processes fall beyond the scope of the study and are assumed to be the same regardless of the cultivation method (Fig. 2). During the cultivation period, a mix of different fertilizers and pesticides was applied to maintain plant growth while electricity was consumed by irrigation pumps and smart farm management equipment.

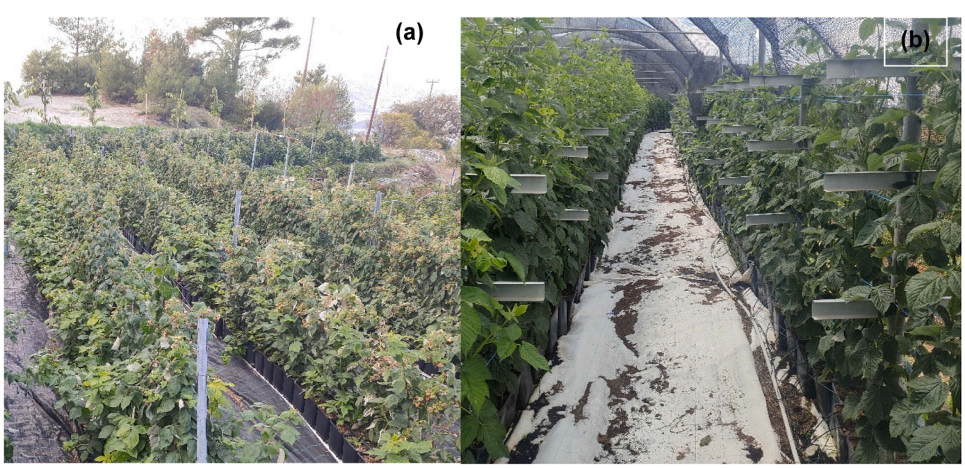

Fig. 1. (a) Open-field cultivation at harvesting stage and (b) Protected cultivation at flowering stage.

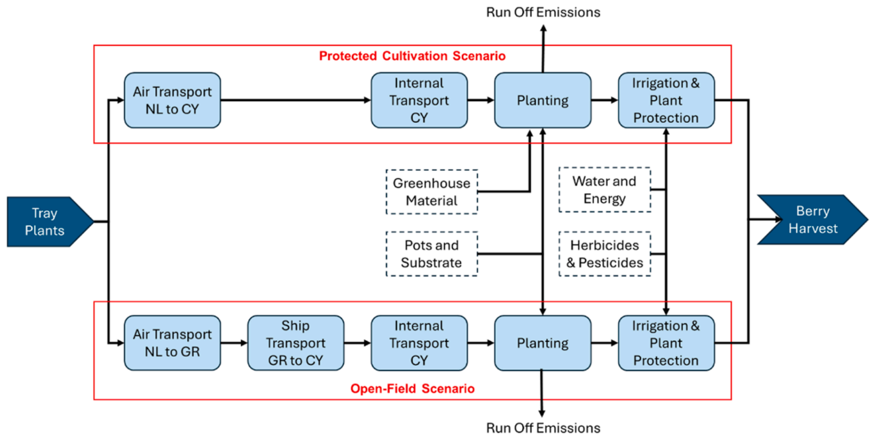

Fig. 2. System boundaries for the two examined scenarios. Market values were used as the characterisation factors of all resources used (fertilisers, pesticides, soil, pots, irrigation and construction material, cover, pots). Such values consider both the impact of the production process of each resource and a typical transportation impact. However, a separate consideration was made for plant delivery from the nursery located in The Netherlands (either via ship or plane) and transportation of plant material via truck to the field, since the itinerary is different for each type of cultivation.

The functional unit (FU) is defined as the physical quantity that is used to provide the reference to which all data in the system are normalized and enables the comparison of the findings. In this study, the FU was chosen to be 1 kg of fresh fruit produced (mass-based FU), which is the most used unit for agricultural products (Pergola et al., 2017; Vinyes et al., 2015).

2.2. Life cycle inventory (LCI)

The LCI was constructed using data from the two cultivation models being compared and it was assumed they were representative of small fruit cultivation in the greater area. To collect these data, a questionnaire was distributed to a local agronomist, and the responses were processed and utilized accordingly.

The Life Cycle Inventory is illustrated in Table 2, using normalized data per hectare (ha) of cultivated area. As far as the use of land is concerned, the total number of hectares per farm was 0.2 hectares, typical of small-scale farm holdings. However, the data provided in Table 2 were normalised for 1 hectare of cultivated land. The data presented are referring to the most recent agricultural year that consisted of two individual cycles, from May 2022 to December 2022 and from August 2023 to April 2024. The assumptions used for the formulation of the inventory are presented in the following sections. It needs to be noted that the quantities presented in the material section of Table 2 correspond to the annual equivalent value. For example, since the drip emitters are replaced every five years, then the annual equivalent value is one fifth of the total number of drip emitters used.

2.2.1. Plant sourcing and potting

Juvenile plants were initially propagated and grown in The Netherlands. Each plant was provided as a fresh tray plant with healthy leaves and roots (average root length 5 cm). Propagation and nursery production are beyond the scope of this analysis, as these are not directly related to the operation in Cyprus and are the same regardless of the production system. The same cultivar (Kwanza®) and plant type were planted in both locations but at different time points for each location. Plantlets were transplanted into pots as soon as possible to avoid plant stress. Specifically, for the open field, the tray plants were transported by truck from The Netherlands to Greece and then from Greece to Cyprus by ship, reaching the plot (Chandria, 1200 m altitude) by truck . The tray plants were transplanted into 10 L pots in May 2022 and placed in the open field (Fig. 3). This trip from The Netherlands to the field takes about a week to complete. However, when planting takes place during the summer, air freight is imperative due to weather conditions so that the plants arrive within a day without being affected by the high temperatures. Thus, for the protected cultivation scenario, the tray plants were transported by airplane from The Netherlands to Cyprus directly and then by truck to the plot (Peristerona) and were transplanted in 10 L pots in September 2023 under protected cultivation conditions in a high-tunnel. In both cases, pot dimensions were 24.7 × 24.7 × 25.6 cm and were made of polypropylene.

2.2.2. Fertilizer and plant protection

Before planting, a space of 1.8 m between lines of plants was created, while 4 pots were put in one linear meter. There was no ploughing, tillage, harrowing, or hoeing because propylene ground cover of 50–100 µm was used under the pots to avoid weed emergence. Primocane yield was determined at different periods of the year for each plot. In the protected cultivation system (Peristerona), harvest was conducted weekly from December 2023 until April 2024, while in the open field system (Chandria) harvest was conducted every two days from October to December 2022. Fertigation was carried out using a standard drainage calculation that factored in retention of approximately 25 % during the vegetative stage from pots after the irrigation interval of the day. However, to avoid accumulation of salts from flowering to the end of harvest, 35 % of drainage was applied (Ben Hadj Daoud et al. 2024).

Common practices including pest management through the utilisation of a backpack mist blower and necessary weed and canopy management were carried out manually. Irrigation and fertilisation were conducted multiple times every day using a drip irrigation system. Fertilisation was set using targeted Electrical Conductivity (EC) and pH value was adjusted at 6. EC values fluctuated around 2 µS/cm during the vegetative state, 1.6 µS/cm during flowering, and 1.4 µS/cm during harvest. Crop management involved several treatments against pests (five per year) and diseases (five per year) that were carried out by operators equipped with a portable sprayer. Two alternative pesticides were used, with active ingredients sulphur (70 %), natural pyrethrins (5 %), and flupyradifurone for the first one and copper for the second one. Monopotassium phosphate (0–52–34), potassium sulphate (0–0–50), potassium nitrate (13–0–36), calcium nitrate (15.5–0–0–26.5Ca) and trace elements were used as solid fertilisers dissolved in 1000 L tanks and injected at 1 % rate in each irrigation (Malghani et al., 2010). The substrate used was a combination of coco peat (40 %), peat-moss (40 %) and perlite (20 %). Fertilizer run-off was assumed to be 5 % for N (nitrates) and 2 % for P and K, (Song et al., 2023). No specific fertiliser run-off data were collected in this study given the system used, drip fertigation and there were no measurements from the field.

Table 2
Life Cycle Inventory for the two raspberry cultivation methods in Cyprus, open-field and protected cultivation. Data were collected from May to December 2022 and from August 2023 to April 2024, respectively.

Resource	Unit	Open-field	Protected-cultivation
Land	ha	1	1
Plants	Unit	18,200	18,200
Plants	kg	3640	3640
Perlite	kg	36,400	36,400
Coco peat	kg	72,800	72,800
Peat moss	kg	72,800	72,800
Transportation			
Air transport of tray plants (NL to CY)	tkm	N/A	10,920
Road transport of tray plants (NL to GR)	tkm	10,192	N/A
Ship transport of tray plants (GR to CY)	tkm	3640	N/A
Road transport of tray plants (Internal CY)	tkm	146	146
Material			
Containers (Polypropylene)	Unit	3640	3640
Containers (Polypropylene)	kg	3640	3640
Irrigation Pipes (Polyvinyl chloride)	m	910	910
Irrigation Pipes (Polyvinyl chloride)	kg	364	364
Drip Emitters (Polyvinyl chloride)	Unit	3280	3280
Drip Emitters (Polyvinyl chloride)	kg	1640	1640
Ground Cover (Polypropylene)	kg	250	250
High-tunnel Arches (Iron)	kg	N/A	8000
High-tunnel Material (Polyethylene)	kg	N/A	80
Fertilizers & Pesticides			
P	kg	108	96
K	kg	324	288
N	kg	216	192
Pesticides	kg	198	158
Water and Energy			
Electricity for irrigation	kWh	19,980	3960
Diesel for irrigation	L	250	200
Water for irrigation	m^3	52,998	17,666
Run-off Emissions			
P	kg	10.8	9.6
K	kg	6.48	5.76
N	kg	2.16	1.92
Products			
Raspberries	kg	6370	9100

2.2.3. *Utilities and resources*

For pumping purposes, electricity was used to operate a submersible pump (Franklin Electric, Model n. 236 616 9061 at 50 Hz). Levelling/terracing took place two times per year, each one before the beginning of each cycle. Regarding water consumption, the values differ significantly for the two cultivation methods (Table 2). For pesticide application, it was calculated that 250 L/ha of diesel were used in the open-field while 200 L/ha were used in protected cultivation. Regarding irrigation, PVC pipelines provide water through the drippers with the boost of a submersible pump. It is estimated that 1640 emitters were required for 0.1 ha for both cultivation types. A gutter made of polypropylene, with 0.8 mm thickness and 150–600 mm wide was used in both production scenarios.

The high tunnel consists of 7 arches in a row, with netting on the side, while the front and back were closable with plastic and were sealed during periods with winter frost risks. The arches are made of galvanised iron, and consists of 6 m of DN50 pipes, 6 m of DN32 pipes and 6 m of DN20 pipes. The total weight of the pipes is 40 tonnes. Each arch was 5.4 m wide, and the tunnel length was 42 m This means that the total area covered by the high tunnel was 7 × 5.4 × 42 m or approximately 1600 m^2. The peak of the arch was 3.5 m in height, so the plastic (polyethylene) cover required is approximately 2300 m^2 or 400 kg, assuming 170 gsm for the high tunnel cover. The plastic cover and the pipes require replacement every 5 years.

2.2.4. *Background systems*

Background systems in the ecoinvent database refer to the pre-existing data and processes used in LCA to model the broader environmental impacts of a product or service. These systems refer to the entire supply chain, including the production of raw materials, energy, transportation, and other inputs, providing comprehensive coverage of upstream and downstream activities. They rely on global (GLO) or regional average data, ensuring consistency and standardization across LCA studies. By connecting with the foreground system, i.e. the processes directly under study, background systems offer a holistic view of environmental impacts, essential for transparency, comparability, and informed decision-making in LCA. Table 3 summarises all the background systems retrieved from the ecoinvent database for the modelling. The Allocation at the Point of Substitution (APOS) factors were selected, since these were the only ones available with the academic license. However, since there the system studied does not involve multifunctional processes, then the choice between Allocation at the Point of Substitution (APOS) and Consequential (CONS) allocation does not have a significant impact to the results.

2.3. *Life cycle costing data*

The Life Cycle Costing (LCC) methodology international standards published in 2008 (ISO15686–5) define the general approach of an LCC

Fig. 3. (a) Rooted tray plant in 10 L pot with drip irrigation 15 days after planting (b) Raspberry canes 2 months after planting.

Table 3
Background systems – emission factors (Source: ecoinvent database v3.7).

Resource	Emission Factor Reference
Containers	Polypropylene, granulate {GLO}| market for | APOS, U
Ground cover	Polypropylene, granulate {GLO}| market for | APOS, U
High-tunnel material	Polyethylene, high density, granulate {GLO}| market for | APOS, U
High-tunnel arches	Pig iron {GLO}| market for | APOS, U
Irrigation emmitters	Polyvinylchloride, bulk polymerised {GLO}| market for | APOS, U
Fertiliser	Nitrogen fertiliser, as N {GLO}| market for | APOS, U Phosphate fertiliser, as P2O5 {GLO}| market for | APOS, U Potassium fertiliser, as K2O {GLO}| market for | APOS, U
Pesticide	Pesticide, unspecified {GLO}| market for | APOS, U
Perlite	Perlite {GLO}| market for | APOS, U
Peat moss	Peat moss {GLO}| market for | APOS, U
Fertiliser application	Application of plant protection product, by field sprayer {RoW}| processing | APOS, U
Electricity	Electricity, medium voltage {CY}| market for | APOS, U
Diesel	Diesel {Europe without Switzerland}| market for | APOS, U
Water	Tap water {Europe without Switzerland}| market for | APOS, U
International transportation (road)	Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U
National transportation (road)	Transport, freight, lorry 3.5-7.5 metric ton, euro5 {RER}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO5 | APOS, U
International transportation (air)	Transport, freight, aircraft, unspecified {GLO}| market for transport, freight, aircraft, unspecified | APOS, U
International transportation (sea)	Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | APOS, U

analysis. However, since there are no shared methodologies to perform the analysis (Mohamad et al., 2014), for this study we have adopted an ad hoc method, including the costs of the whole life cycle of raspberry production "from cradle to gate", following the "whole life costing" method expressed by Gluch and Baumann (2004). The LCC analysis uses the same functional unit and has the same system limitations that have been considered in the LCA. Table 4 reports the purchase costs per unit of raw materials, utilities, and chemicals that were used during the two cultivation periods for each method. These have been collected by a questionnaire that was distributed to local farms, and the average values were utilised. For protected cultivation, there is an extra labour cost of 5 workers for two working weeks at 5 €/h.

3. Results and discussion

3.1. Environmental impact assessment

Fig. 4 presents the environmental impact of the two raspberry cultivation methods in Cyprus. Protected cultivation led to an improved environmental performance, reduced by 49.6 % compared to open-field cultivation. More specifically, the environmental footprint of protected cultivation was at 3.7 mPt per kg of raspberry produced, whereas the environmental footprint of open-field cultivation was 7.4 mPt per kg of raspberry produced.

Table 4
Purchase cost of resources for open-field and protected cultivation using high tunnels of raspberries in Cyprus.

Resource	Price	Unit
Raspberry plants	2	€/unit
Containers	2.5	€/unit
Substrate	0.09	€/kg
High-tunnel cover	0.8	€/m^2
Nozzles and tubes	2.5	€/m^2
Pesticides	300	€/kg
Fertilisers	0.5	€/kg
Water	0.45	€/m^3
Electricity	0.2	€/kWh
Diesel	1.7	€/L

Furthermore, protected cultivation was superior in all 17 indicators. Among all 17 indicators, land use and water use were the most dominant components, followed by resource usage (fossil fuels) and climate change.

Table 5 presents the absolute values of these four indicators for the two scenarios, expressed in physical units per kg of raspberry produced. Water usage is the indicator with the highest relative improvement between the two types of cultivation (dropping from 0.361 m^3 to 0.085 m^3 per kg of raspberry, thus improving by 76 %), which was anticipated since the protected cultivation has significantly lower water demand. The other three indicators are improved by 30 % (global warming potential), 37 % (land use) and 33 % (fossil fuel depletion) and are the main responsible factors for the superior performance of protected cultivation.

Fig. 5 illustrates the same results with a different point of view. The overall environmental footprint (expressed in ecopoints per cultivated hectare) is broken down into the different resource types contributing to it. This allows for the identification of environmental hotspots among the two cultivation methods. While the material and the transportation impacts are increased (the latter almost doubled) for the protected cultivation scenario, due to high tunnel material and the air transportation of the plants respectively, their relative importance is very small compared to the impact of water, fertilisers and soil used (in that order). Although the substrate impact is the same for both scenarios, the water and the plant protection contributions are significantly reduced, leading to an overall improved environmental performance for the protected cultivation method. These results agree with the findings by Foster et al. (2015) and Valiente et al. (2019), who identified the water footprint and the use of fertilisers as the main factors that contribute to the overall environmental impact of raspberry cultivation. Similarly, Vásquez-Ibarra et al. (2021) underscored the crucial role of irrigation systems, cultivation support, and coverings to the overall environmental impact.

3.1.1. Impact of rainfall

Since water is the most critical resource affecting the environmental performance, one environmental factor that could potentially improve the performance of open field cultivation is the rainfall. The previous scenarios have assumed that the open-field water requirements are fully covered by irrigation. This assumption is based on the fact that during the cultivation period of the open field system there is no significant rainfall and supplemental irrigation is necessary. Rainfall for the open field cultivation in the mountains occurs only between November and May, so the only months that can be affected are November and December. Even if we consider the extreme, where the entire water requirements for 2 months are satisfied by rainfall, the overall environmental footprint of open-field cultivation will drop to 6.4 mPt per kg of raspberry produced, which is still significantly higher compared to the environmental footprint of protected cultivation (3.5 mPt per kg of raspberry produced).

3.2. Economic analysis

Based on the price of the resources and utilities (Table 4) and the life cycle inventory (Table 2), the cost breakdown of the compared raspberry cultivation methods is presented in Table 6. The fact that certain resources need to be replaced after a certain time period is also considered. The results reveal that the life cycle cost of protected cultivation is 37.8 % lower compared to the open-field production (14.0 €/kg for the high-tunnel compared to 22.5 €/kg for the open-field). Even though the total annual expenses are similar for the type of cultivation (127,262 € for protected cultivation and 143,341 € for open-field), the

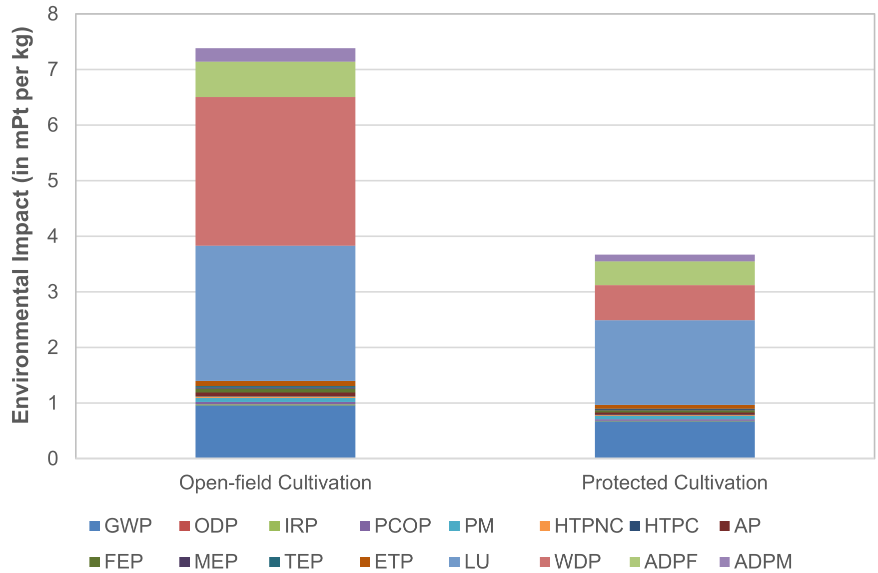

Fig. 4. Environmental impact assessment for the two cultivation methods, open-field and protected cultivation using high tunnels in Cyprus (expressed in mPt per kg of raspberry produced).

Table 5
Selected midpoint impact indicators for the two cultivation methods, open-field and protected cultivation using high tunnels in Cyprus (expressed in unit per kg of raspberry produced).

Indicator	Open-field cultivation	Protected cultivation	Unit
GWP	0.037	0.026	kg CO_2 eq
LU	25.118	15.724	Pt
WDP	0.361	0.085	m^3 depriv.
ADPF	0.498	0.336	MJ

critical factor here is the improved yield and water use efficiency for protected cultivation.

4. Conclusions and further perspectives

Currently in Cyprus, there is a relatively small number of raspberry and other small fruit growers, mostly located in the mountainous and more temperate parts of the island, even though the different meso-climates can be considered appropriate for year-round production. This is mainly due to the lack of knowledge and risk-adverse nature of farmers, as they are concerned about the costs of introducing new cultivars and cultivation methods. Additionally, concerns over economic losses due to environmental factors, including heat stress during the summer period or heavy rains during winter, are important factors influencing farmers choice to use the mountainous areas for production. Moreover, small-scale enterprises in the agricultural sector in Cyprus and worldwide lack specialised and scientific guidance to make evidence-based decisions that would enable them to flourish (Bechtsis et al., 2022; Kasimati et al., 2024).

The selection of plant material, planting period, and cultivation method between protected cultivation in poly tunnels and open-field depends on various factors like the local climate, the availability of human resources, and market demand. While open-field cultivation is

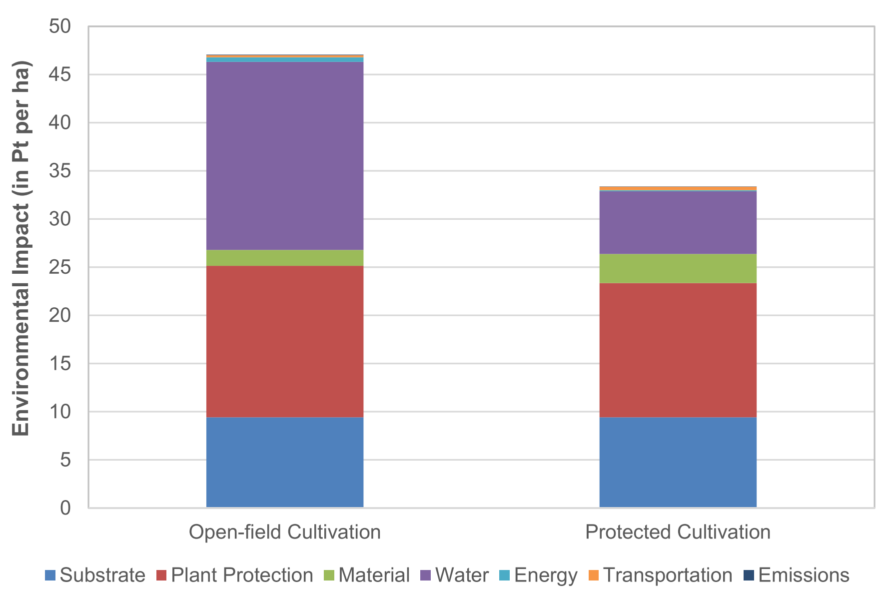

Fig. 5. Environmental hotspots for the two cultivation methods, open-field and protected cultivation using high tunnels in Cyprus (expressed in mPt per ha of cultivated area) for open-field and protected cultivation in high-tunnels in Cyprus.

Table 6
Overall cost analysis for open-field and protected raspberry cultivation methods using high tunnels in Cyprus.

Resource	Price		Change every		Open-field	Protected cultivation
Ground cover	8000	€/ha	5	year	1600	1600
High-tunnel cover	13,600	€/ha	5	year	0	2720
Nozzle/tubes	25,000	€/ha	5	year	5000	5000
Plants	2	€/unit	1	year	36,400	36,400
Pots	2.5	€/unit	5	year	9100	9100
Substrate	0.09	€/L	1	year	16,380	16,380
Electricity	0.2	€/kWh	1	year	3996	792
Water	0.15	€/m^3	1	year	7950	2650
Diesel	1.7	€/L	1	year	425	340
Pesticides	300	€/L	1	year	59,250	47,400
Fertilisers	0.50	€/kg	1	year	3240	2880
Labour	5	€/h	1	year	0	2000
	Total Cost (€)				143,341	127,262
	Yield (kg)				6370	9100
	Cost per kg (€/kg)				22.5	14.0

believed to be suitable for a more concentrated, cost-efficient harvest, protected cultivation with high tunnels has the potential for higher yields, with improved water use efficiency, while extending the raspberry harvest season throughout the year which in turn may allow growers to sell their fruits to the market during the "off season" for a premium. The careful selection of cultivation methods holds the potential to mitigate the adverse impacts of climate change for small fruit cultivation in Cyprus while still maintaining on-farm profitability. By embracing innovative solutions, farmers may not only adapt to the changing environment but also secure their economic prosperity in the years to come.

Our analysis has revealed that complementing or replacing traditional open-field cultivation in the mountains with protected cultivation using plastic high tunnels on the plains will have a lower environmental impact while being more financially profitable for the farmer. More specifically, protected cultivation will have a 49.6 % lower total environmental footprint. Additionally, the yield in protected cultivation is 43 % higher than open-field cultivation resulting to greater profit margin for growers. More importantly, the amount of water used is 4-times less in protected cultivation, subsequently limiting the electricity costs of the production. This is a very critical point for Cyprus, since water usage is crucial for sustainable production, especially in areas with water scarcity issues (Dale, 2012; Jain and Janakiram, 2016).

In addition to higher yield efficiency, water use if more effective due to lower evapotranspiration losses. The raspberry cultivar Kwanza is cultivated globally with an observed yield of 1.5 to 2.5 kg per plant in a climate-controlled Dutch Glasshouse (Herckens et al., 2019), while a yield of 1.8 to 2.4 kg per plants has been observed under Californian Mediterranean Climate (Daugovish et al., 2021). The variations are due to the planting density, planting date and the local mesoclimate. The literature agrees with our findings that Kwanza is more suited to a protected environment, rather than open field, since it allows higher precision in climate and irrigation management, higher yield and less water usage.

The life cycle production cost for 1 kg of raspberries is 37.8 % lower for the protected cultivation compared to open field. Higher profitability is achieved from off-season as well as limited operational costs, despite the increased start-up and worker costs which can be depreciated and managed more efficiently. It must be noted though that the production cost per kg is still relatively high compared to other European countries where fresh raspberries are sold around 16 € per kg. The remote nature of the island of Cyprus, with no road interconnections to mainland, results to significantly higher resource and energy prices (on average 30 % higher than in Europe), as it can be observed in Table 5. This also means that imported raspberries, although they may arrive in Cyprus in bad shape, are still sold at higher prices compared to the rest of the Europe (at approximately 21–22 € per kg). Additionally, the yield of each plant for the conventional cultivation techniques is relatively low, resulting in high operational labour cost to harvest. For example, harvesting efficiency in Europe is 4–6 € per hour per person while in Cyprus it is no more than 2 € per hour per person. Thus, the initial focus of the local farmers is to compete with the imported berries.

The local production of raspberries in protected cultivation using high tunnels in Cyprus (not only in the plains, but potentially in the mountains) can also have a lower environmental footprint, compared to imported fruits from other countries. Also, more heat-tolerant and short-cycle crops can be used as an alternative when raspberries are not being produced and buffer against plastic environmental footprint. Recycling of used tunnel plastic at the end of its useable life will also lessen the environmental impact of protected cultivation.

In terms of the limitations of our study, the analysis is performed on a cradle-to-gate basis (from the acquisition of nursery plants until the raspberries leave the gate of the field at the end of their productive lifespan), and the Life Cycle Inventory is populated using real data for the years 2022, 2023 and 2024, collected from two farms located on the island of Cyprus. One main limiting factor is that these values encompass data from only one primocane harvest cycle (8-month duration), which may not reflect conditions over a longer term due to year-to-year variations. A wider sample, either for multiple harvesting cycles, from multiple farms in Cyprus and abroad would be an appropriate next step to validate the results. Moreover, the use of data from questionnaires (sourced in their majority from utilities/suppliers' bills and smart meters on the field) may offer a very realistic and representative view of the problem but does not allow a complete understanding of the relationship between different factors and their potential further improvement of the situation. Thus, a model of the cultivation systems could be developed, relating irrigation, fertilisation, choice of substrate mixture in pots, and other pre-harvest factors on field activities with the expected raspberry yield, to enable us to analyse alternative scenarios.

CRediT authorship contribution statement

Angeliki Xyderou Malefaki: Writing – original draft, Visualization, Software, Resources, Investigation, Data curation. **Nicolas Valanides:** Writing – original draft, Investigation, Data curation, Conceptualization. **George A Manganaris:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Lisa Wasko DeVetter:** Writing – review & editing, Validation, Supervision. **Sofia Papadaki:** Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Magdalini Krokida:** Writing – review & editing, Supervision, Funding acquisition. **Antonia Vyrkou:** Writing – original draft, Visualization, Software, Resources, Methodology, Data curation. **Athanasios Angelis-Dimakis:** Writing – review & editing, Supervision, Software, Resources, Methodology, Conceptualization.

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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Data availability

Data will be made available on request.

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